

Review Article

Interfacial Bond Performance of Concrete-Filled Steel Tubes under Fire and Postfire Conditions: State-of-the-Art Review

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The critical influencing factors of the interface bonding properties of concrete-filled steel tubes (CFSTs) under fire and postfire conditions are analyzed. This paper analyzes and summarizes the existing research related to the bonding performance of CFST interfaces under fire and postfire conditions at home and abroad, which includes the bonding mechanism of CFST structures, the bonding strength of CFSTs during and after fire exposure, and the main factors influencing bond strength. The analysis results indicate that the temperature has noticeable influences on the bond strength of a CFST during and after fire exposure. The bond strengths of the specimens are reduced more severely under high-temperature conditions than after high-temperature cooling. Shear connectors can significantly improve the bonding performance of CFSTs and effectively reduce the relative slip between steel tubes and concrete. The paper concludes with an analysis of the deficiencies in bond-slip research on the bonding properties of the CFST interface during and after fire exposure and future research directions. First, we can study the use of new technologies and materials to solve the problem of bonding and slipping of CFSTs during and after fire exposure. Second, we can perform extensive experimental research and theoretical simulation analysis to enrich the research in this field, which can provide a reference for engineering practice.

1. Introduction

In the last few decades, concrete-filled steel tube (CFST) elements have been widely utilized in civil structural applications, particularly in high-rise buildings and bridges, and this demand is due to their significant advantages, including favorable strength, good ductility, excellent seismic performance, and high fire resistance [1]. Their superior performance depends on the cooperation of steel tubes and concrete, but their interaction mechanism is complex. In the load transfer process, steel tubes and concrete coordinate deformation and joint forces, and the interface bonding force, especially the shear bonding force, plays an extremely important role. Fire degrades the material properties of steel tubes and concrete after heating because the difference in the lateral dilations of steel tubes and concrete can deteriorate their interface properties, resulting in the loss of the bond

strength at the steel and concrete interface and great reduction in the bearing capacity and stability of structural members. As a result, the steel-concrete composite bond must be good enough to act together as one element, especially during the early elastic stage.

At present, extensive research has been carried out by different researchers on the performance of CFST members under fire and postfire conditions. Earlier, Han [2] explored the behaviors of CFST axial compression members under high constant temperature. They observed that there are interactions between steel tubes and the core concrete of CFST members during fire exposure, and this characteristic should be considered for research on the behaviors of CFST members subjected to fire exposure. In recent years, Huo et al. [3, 4] conducted experimental studies on the impact behavior of CFSTs at elevated temperatures. Jiang et al. [5] conducted experimental studies on fire-exposed rectangular

CFST columns subjected to biaxial force and bending. Li et al. [6] studied the mechanical behavior of recycled aggregate CFST stub columns after exposure to elevated temperatures. Wang et al. [7] explored the axial compression performance of thin-walled T-shaped CFST columns at constant high temperature. A parametric study was conducted, showing that the temperature, thickness of the steel tube, yield strength of the steel tube, and compressive strength of concrete are the key factors contributing to the axial compressive performance of CFST stub columns. Karimi and Nematzadeh [8] investigated the axial compressive performance of steel tube columns filled with steel fiber-reinforced high-strength concrete containing tire aggregate after exposure to high temperatures. Based on the above study, CFST columns after exposure to fire retain high load-bearing capacity, stiffness, ductility, and energy absorption capacity, and the magnitude of the effect of high temperature on the mechanical properties of the members is directly related to the bond strength of steel tubes and concrete [9].

Previous studies have shown that the material properties of steel and concrete (such as strength and elastic modulus) are degraded to varying degrees after exposure to high temperatures. At high temperatures, the expansion of cement colloids and aggregates is inconsistent, leading to the occurrence of microcracks in concrete. The moisture in concrete migrates and evaporates with increasing temperature, which makes the chemical bonding force of cement colloids disappear [10]. The deterioration of the properties of CFSTs under fire and postfire conditions and their bonding performance has been a concern in engineering practice and for researchers. A large number of studies on the bonding performance of CFSTs have been conducted by domestic and foreign researchers. This paper reviews and discusses research related to the bonding performance of CFSTs under fire and postfire conditions, provides an outlook on the research to be carried out in the future, and makes some suggestions.

2. Bond Mechanism of CFSTs

The combination of steel tubes and concrete, materials with two different properties, exploits both the high load-bearing capacity of concrete and the high tensile and compressive strength and good elasticity of steel, thus enhancing the mechanical properties of steel tubes and concrete to a large extent. Under external loading, the two materials are jointly stressed, and the steel tube restrains the internal concrete, which puts the concrete in a multidirectional stress state and improves the strength and toughness of the concrete [11, 12], while the support provided to the core concrete by the steel tube endows the steel tube with enhanced load-bearing capacity and delays the local yielding of the steel tube; thus, the two materials with different properties work in concert to greatly improve their load-bearing capacity and strength [13]. CFSTs can be divided into circular CFSTs, square CFSTs, and polygonal CFSTs according to different section forms, as shown in Figure 1. Different cross-section forms are used under different conditions to maximize the mechanical properties and economic benefits.

Similar to the bonding mechanism between the reinforcement and concrete in reinforced concrete, the interface adhesion between the steel tube and concrete also includes three parts: the chemical adhesion force of the cement gel and concrete surface, the mechanical joint force between the steel and concrete interface, and the frictional force at the steel and concrete interface. The working mechanism of the CFST structure is shown in Figure 2.

3. Interfacial Bonding Performance of a CFST at Room Temperature

At present, the influencing factors and mechanism of bond slip at room temperature have been studied in depth and have achieved certain results. These results lay a foundation for the study of the bond properties of steel tube and concrete interfaces under fire and postfire conditions. The main factors affecting the bond strength of CFSTs are summarized as follows.

3.1. Concrete Strength. The results obtained by different researchers are controversial. Shakir-Khalil [14] depicted that the effect of concrete strength on the bond strength of concrete-filled steel tubular interfaces has no regularity. The bond strength increased as the concrete strength increased [15–23]. Zhang [24] displayed that the interfacial bond strength decreases to a certain extent with increasing concrete strength. Zhang [25] also indicated that the bond strength is nearly independent of concrete strength in stainless steel circular steel tube-reinforced concrete specimens and decreases with increasing concrete strength in square stainless steel tube-reinforced concrete specimens. Some studies [26–28] have shown that the average bond strength of the interface has no apparent relationship with the concrete strength.

3.2. Diameter-to-Thickness Ratio (D/T) or Width-to-Thickness Ratio (B/T) of the Steel Tube. The wall thickness of the steel tube will affect its ability to bind the core concrete, thus affecting the interfacial bond strength between the steel tube and concrete. Some studies [17, 21, 24, 25, 27–31] have shown that bond strength decreases with increasing diameter-to-thickness ratio or width-to-thickness ratio of steel tubes.

3.3. Length-to-Diameter Ratio (L/D) or Length-to-Width Ratio (L/B) of the Steel Tube. Research results have not been uniform. Some studies [9, 21, 28] have indicated that the bond strength increases with the slenderness ratio, whereas other studies [14, 31–33] have shown that the slenderness ratio of steel tubes has no obvious effect on the bond strength. Some studies [17, 34, 35] have shown that the bond strength of specimens decreases with an increasing slenderness ratio. Ren [36] showed that when the specimen width is smaller, the bond strength decreases first and then slightly increases with the increase in the slenderness ratio of the steel tube. However, when the width and thickness are

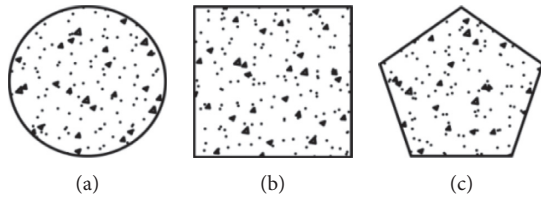


FIGURE 1: Cross-sectional profile of the CFST. (a) Circular. (b) Square. (c) Polygonal.

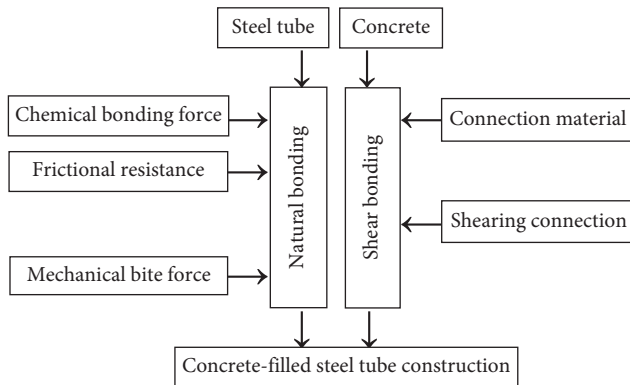


FIGURE 2: Schematic diagram of the working mechanism of CFST structures.

relatively large ($D/t=50$), the bond strength is basically unchanged by the slenderness ratio.

3.4. CFST Shear Connector. In engineering, when the bonding strength is insufficient, shear connectors are usually set to enhance the ability of the steel tube to bind concrete. Tao et al. [37] showed that the most significant factor improving the interface shear bonding strength is provided by welding shear studs, followed by welding shear rings. Some studies [14, 18, 30, 38–41] have shown that CFST columns with reinforcing rings or stiffeners have significantly improved the interfacial bond strength. Guo and Tong [42] studied the influence of diaphragms on square and rectangular CFST specimens and found that diaphragms prevent the relative slip of the interface. Compared with studs, diaphragms were rigid shear members and did not cause stress concentrations. It was suggested that diaphragms should be installed in beam-column joints. Xu et al. [43] added welded longitudinal ribs to the inner wall of a steel tube to substantially improve the bond strength, which is proportional to the rib length. Increasing the number of studs can increase the bond strength, but the position of the studs has little effect. Qian et al. [44] performed a push test on 10 CFST composite columns and compared the welded reinforcement ring, stud, and unwelded shear connector on the outer wall of the steel tube. The results showed that an increase in the diameter of the reinforcement ring or the number of studs and an increase in the diameter of the studs would improve the interfacial bond strength, and the reinforcement rings were more effective in improving the bond strength. Dong

et al. [45, 46] used different types of connectors, built-in bolts, built-in circular ribs, embedded ribs, embedded steel cages, and various combinations of the above. The results showed that the bonding strength can be substantially improved.

3.5. Concrete Type. Experimental studies on the bonding behavior of self-compacting concrete-filled rectangular steel tubular members have been performed, and the results show that self-compacting concrete can improve the bond strength between the steel tube and core concrete [17]. The test shows that the bond strength of the raw material form of limestone is greater than that of pebbles, and there is a clear cutoff point for the effect of stone powder content on the interfacial bond strength, which increases first and then decreases with increasing stone powder content [24]. The effect of using microexpansive concrete to improve the interfacial bond strength is obvious [37, 47]. The results show that the effect of the aggregate substitution rate on the ultimate bond strength is large, the ultimate bond strength increases first and then decreases with increasing substitution rate, and the optimal substitution rate of recycled aggregates is predicted to be approximately 40% [45, 48–50]. Research on the interface adhesion properties between self-compacting desulfurized slag and concrete-filled steel tubes has shown that the limiting bond strength increases with increasing desulfurization slag content [51]. Experimental research on the bond-slip behavior of red mud concrete-filled square steel tubes showed that the bond strength first increases and then decreases with the increase in the red mud substitution rate [52]. Increasing the steel fiber content is an effective measure to improve the bond strength of the CFST interface [53, 54].

In addition to the above influencing factors, researchers have also found that the internal surface condition of the steel tube, cross-sectional shape, and mineral additives are the main factors affecting the interfacial bond performance of CFSTs. Xu and Chen et al. [37, 43, 55] indicated that the rougher the inner surface of the steel tube is, the higher the bond strength between the steel tube and concrete is. Chen et al. [56] proposed a new type of concrete-filled checkered steel tube structure prepared by applying a checkered pattern to the inside wall of a steel tube to increase the natural bond strength of the steel tube and concrete. Morishita et al. [57–59] performed a push-off test on CFST columns, and the results showed that when the section shape changed from a circle to an octagon and then to a square, the bond strength decreased in turn. Radhika and Baskar [9] showed that mineral additives can improve the ductility and ultimate load capacity of components, but mineral addition of more than 20% will reduce the strength. Huang et al. [60] conducted repeated launch tests on self-compacting concrete columns with round steel tubes, and the results showed that an appropriate amount of expansive agent could increase the interfacial bond strength. Chen et al. [61] showed that the bond strength of steel tube-reinforced microexpansion concrete is 1.36–1.38 times that of ordinary concrete-filled steel tubes, and both the expansive agent and water-cement

ratio have an important influence on the expansive behaviors of the concrete core. Analysis shows that the amount of mineral added should be moderate, as too much will reduce the bond strength. The factors influencing bond strength at room temperature have been studied in depth, and specific relevant research results can be found in the literature [27, 37, 62, 63].

4. Bonding Performance of the CFST Interface after Fire

Domestic and foreign scholars have conducted a series of studies on the interfacial bond performance of CFST columns after exposure to fire. Research parameters such as temperature, length-diameter ratio, and concrete strength have all been discussed. Compared with research performed at room temperature, research performed on CFSTs after fire exposure is scarce, and further research is needed to derive more laws of influencing factors to provide a reference for engineering design. The effects of some parameters on the bond strength of CFSTs after exposure to fire are summarized as follows.

4.1. Temperature. Temperature has a noticeable influence on the bond strength of a CFST after fire exposure. Tao et al. [64] considered several parameters and performed push-out tests on CFST column specimens. The heating curve control is the standard heating curve of a building fire specified in the International Committee for Standardization Standard ISO-834, and its expression is $T_g = T_{g0} + 345 \lg(8t + 1)$, in which T_{g0} is taken at room temperature of 20°C and t is the heating time. The results show that the interface bond strength decreases after fire exposure, but the interface bond strength of the specimens after fire exposure for 180 min is higher than that of the specimens after fire exposure for 90 min. Zhang [65] performed the push test on self-compacting CFSTs at 20–600°C. The test results showed that the bond strength first decreased and then increased with increasing temperature. Wu [66] pointed out that the bond strength decreases more after 3 hours of heating, resulting in a decrease that is 61.2% of that at room temperature. Xiang et al. [67] showed that the bond strength between the steel tube and concrete decreases obviously when the temperature rises to 200–400°C, and when the temperature rises to 400°C, the bond strengths of the specimens with circular and square cross sections are 16% and 14% of those at a normal temperature, respectively. Fawzy et al. [68] conducted tests at four temperatures ($T = 25^\circ\text{C}$, 70°C , 200°C , and 400°C) and showed that the bond strength decreased with increasing temperature. Liu [69] showed that the interfacial bond strength of a CFST is greatly improved after fire exposure, and the bond strength of most of these specimens is higher than that of specimens exposed to normal temperatures. Chen et al. [70] designed 22 specimens for push-out tests to study the bonding performance of a high-strength concrete-filled steel tube interface after high-temperature water spray cooling. The results showed that the bond strength of the specimens after high-temperature water spray cooling was

higher than that at room temperature. When the temperature is less than 600°C, the bond strength increases with increasing temperature, and the bond strength decreases when the temperature is more than 600°C.

A summary of the parameters used to study the bond performance of concrete-filled steel tubes after high-temperature treatment is shown in Table 1. Figure 3 shows the bond strength of each specimen after high-temperature exposure relative to that at normal temperature. The analysis results show that the bond strength of the specimens after high-temperature treatment is lower [64–68] or higher [69, 70] than that at room temperature. The results are inconsistent for the following reasons: (1) Interface adhesion between the steel tube and concrete mainly includes three parts: chemical adhesion force, mechanical joint force, and frictional force. A series of physicochemical reactions occur in concrete at high temperatures, resulting in the degradation of its properties, which can reduce the chemical adhesion force between the concrete interface and the steel tube. (2) Because of the “thermal expansion and cold contraction” effect of different materials, there are differences, especially in concrete materials at elevated temperatures, where irreversible microfractures are produced. Irreversible microfractures cause the concrete to shrink less during the cooling process than the steel tube, which in turn prevents the steel tube from shrinking, resulting in the interface forming a pair of compressive forces produced by the residual deformation difference after cooling. (3) At a certain temperature range, the higher the experienced temperature is, the greater the shrinkage difference between the two materials after cooling and the greater the mutual shrinkage squeezing pressure, thus effectively improving the mechanical joint force and frictional force between the two materials and gradually increasing the ultimate bond strength. With increasing temperature, the maximum temperature is high, which results in a greater loss in strength and an increased brittleness of the concrete. The concrete will be more easily broken after exposure to higher temperatures. Once the steel tube and concrete undergo relative sliding, a fine particle layer composed of concrete debris will form, forming a rolling friction layer and reducing the friction resistance between the interfaces, thus gradually decreasing the bond strength. (4) The results are also inconsistent because of the inevitable error in the test results and the different test conditions.

4.2. Compressive Strength of the Concrete. The strength of concrete has an obvious effect on the bond strength of a CFST after fire exposure. Tao et al. [64] showed that the bond strength of concrete-filled round steel tubes decreases with increasing concrete strength after exposure to fire, and the decrease is more obvious with increasing fire exposure time. The bond strength of a concrete-filled square steel tube increases with increasing concrete strength. Some studies [70, 71] showed that the bond strength of concrete-filled square steel tubes increases with increasing concrete strength. With increasing concrete strength, there is no obvious change in bond strength [72, 73].

TABLE 1: Parameters of the study of the bond behavior of a CFST after fire exposure.

Literature	Heating time (min)	Temperature (°C)	(L/D) or (L/B)	(D/t) or (B/t)	f_{cu} (MPa)	Cooling system	Notes
Tao et al. [64]	0	20	3	35.3	52.3	Natural cooling in a furnace	ISO834 standard fire
	90	1005					
	180	1109					
	0	20					
	90	1005					
Zhang [65]		20, 200, 300, 400, and 600	3.33	31.8	60	Natural cooling in a furnace	Muffle furnace heating (heating rate of 4°C/min)
	0	20	4.17	15	42.2	Natural cooling	Electric heating
180	1100						
Xiang et al. [67]		20, 200, 300, 400, 500, 600, 700, and 800	3	45	45.1	Natural cooling in a furnace	Electric heating (heating rate of 10°C/min) constant temperature of 420 min
Xiang et al. [67]		20, 200, 300, 400, 500, 600, 700, and 800	3	47.5	45.1	Natural cooling in a furnace	Electric heating (heating rate of 10°C/min) constant temperature of 420 min
Fawzy et al. [68]		25, 70, 200, and 400	3.5	28.6	33.85	Natural cooling	Electric heating
Liu [69]	0	20	2.5	36.5	50	Reduce the temperature by 10°C/min	ISO834 standard fire
	30	841					
	60	945					
	90	1005					
Chen et al. [70]		20, 200, 400, 600, and 800	2.87		60	Water spray cooling	A resistance furnace was heated at a steady rate and then cooled with water spray after maintaining a constant temperature for 60 min

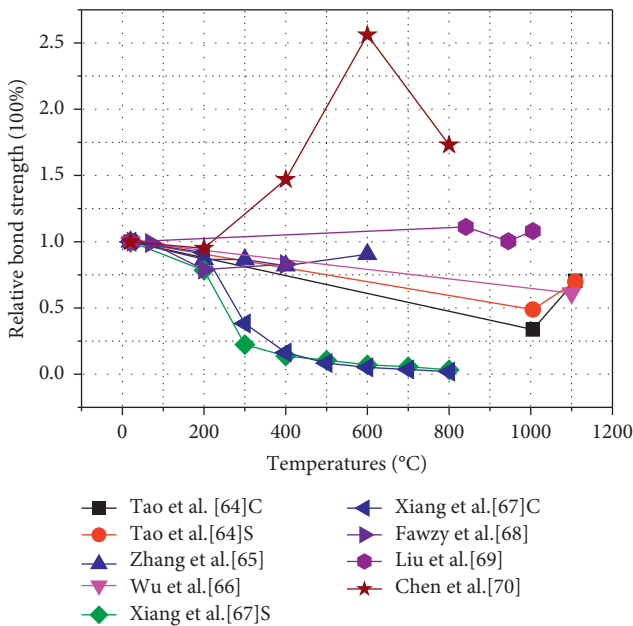


FIGURE 3: Relative bond strength of each test piece. Note. C stands for circular CFST specimens. S stands for square CFST specimens.

4.3. Length-to-Diameter Ratio or Length-to-Width Ratio of a Steel Tube. Tao et al. [64] showed that the interface bond strength of concrete-filled square steel tube specimens

exposed to fire for 180 min increases with an increasing length-to-width ratio, while that of concrete-filled round steel tubes decreases with an increasing length-to-diameter ratio. Liu [69] showed that the bond strength of concrete-filled round steel tubes decreases with an increasing length-to-diameter ratio. Zou et al. [71] showed that the interfacial bond strength of concrete-filled square steel tubular specimens increases with an increasing length-to-width ratio. The analysis of the above experimental results shows that the bond strength decreases with an increasing length-to-diameter ratio of a concrete-filled circular steel tube and increases with an increasing length-to-width ratio of a concrete-filled square steel tube.

4.4. Other Influencing Factors. (1) Concrete type: Tao et al. [64] showed that the interfacial bond strength of self-compacting CFST columns containing fly ash is lower than that of ordinary CFST columns after fire exposure. Zou et al. [71] studied the bond performance of recycled coarse aggregate concrete on steel tubes after high-temperature exposure, and the results showed that the more the recycled coarse aggregate that was added, the greater the bond strength would be. (2) Cross-section shape: circular columns generally had much higher bond strength than square columns [64, 68, 69], which is basically consistent with the observation made at room temperature [37, 57–59]. (3) Cooling method: Chen et al. [70] showed that the ultimate

TABLE 2: Parameters of the study of the bond behavior of a CFST during fire exposure.

Literature	Serial number	Incubation time (h)	Constant temperature (°C)	L/D	D/t	f_{cu}	τ_u (MPa)		
Fawzy et al. [68]	CNR-a		25			33.85	1.35		
	CNF70		70				1.17		
	CNF200		200				1.08		
	CNF400		400				0.937		
	CR4R-a		25			33	1.185		
	CR4F70		70	3.5	28.6		1.125		
	CR4F200		200				0.975		
	CR4F400		400				1.04		
	CR8R-a		25				1.185		
	CR8F70		70				1.17		
	CR8F200		200				1.035		
	CR8F400		400				1.05		
Chen et al. [74]	C8A20	0	20					50	2.36
	C8A100	9	100			2.21			
	C8A300	8	300	2.74	27.38	0.13			
	C8A500	9	500			0.38			
	C8A700	8	700			0.62			
	C8A900	7	900			0.37			
Amirreza and Mahdi [75]	LCFT0-20		20					22	1.967
	LCFT0-200		200			3.39	44.3	20.9	1.548
	LCFT0-400		400	18.7	0.137				
	LCFT0-600		600	13.3	0.055				

bond strength of specimens cooled by water spray was lower than that of specimens cooled naturally. (4) Cross-sectional dimension: Tao et al. [64] demonstrated that the bond strength decreased significantly when D (diameter of a round steel tube) or B (width of a square steel tube) increased. This is basically consistent with the observations made by Roeder et al. [27] and Liu [69].

5. Bonding Performance of the CFST Interface during Fire Exposure

Domestic and foreign scholars have conducted a small number of studies on the interfacial bond performance of CFST columns during fire exposure. Research parameters such as temperature, length-diameter ratio, and diameter-thickness ratio have all been discussed. The effects of some parameters on the bond strength of CFSTs during fire exposure are summarized as follows.

5.1. Temperature. Chen et al. [74] showed that, at 20°C~900°C, temperature has a significant influence on the average bond strength of concrete with round steel tubes, and the average bond strength first decreases and then increases and decreases with increasing temperature. As the expansion deformation of the steel tube is obviously greater than that of concrete at the beginning of the temperature increase and the concrete undergoes water vapor volatilization at high temperature, the chemical bonding force between the steel tube and concrete decreases, leading to a reduction in the average bond strength. However, with the increase in temperature to a certain point, the unrecoverable expansion deformation of concrete also increases and is near

the expansion deformation of steel, which increases the extrusion pressure at the concrete and steel interface. Thus, the bonding force between the steel tube and concrete increases, and the average bond strength increases. When the temperature increases again, although the expansion deformations of the steel tube and concrete continue to increase and become closer to each other, the chemical bonding force between the steel tube and concrete basically disappears, and the strength and elastic modulus of the steel and concrete decrease significantly, leading to the decline in the average bonding strength. Amirreza and Mahdi [75] studied the bond behavior of lightweight concrete-filled steel tubes containing rock wool waste after exposure to high temperatures. It can be seen that the bond stress-slip behavior of the lightweight concrete-filled steel tube specimens after thermal loading at 400 and 600°C considerably deteriorated relative to that of the corresponding specimens exposed to the room temperature and 200°C. This deterioration was accompanied by a significant reduction in the contribution of chemical adhesion and microlocking components. After 200°C, the bond strengths of the lightweight concrete-filled steel tube specimens containing different contents of rock wool declined by up to 21% relative to those of the corresponding specimens at the room temperature, while after 400 and 600°C, the reduction values were on average 93 and 97%, respectively (independent from the rock wool content). The analysis of the above experimental results shows that the temperature has a great influence on the bond strength of CFST during fire exposure. However, the law of influence is not clear.

The inductive test data are shown in Table 2. A comparison with the effect of temperature on the relative bond strength after fire exposure is shown in Figure 4. The analysis

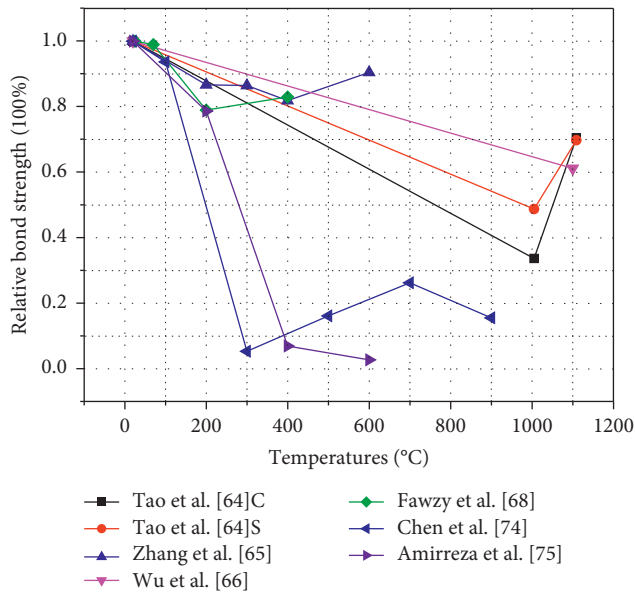


FIGURE 4: Comparison of relative bond strengths at high temperature and after exposure to high temperature. Note. C stands for circular CFST specimens. S stands for square CFST specimens.

results of the figure show that the bond strength of the specimens decreases more severely at high temperature than after high-temperature cooling, which is consistent with the experimental conclusion in the literature [68], as shown in Figure 5. Two main reasons can explain this. During cooling, microcracks form, potentially leading to radial expansion of concrete, which in turn increases the contact pressure between the concrete core and steel tube and increases friction resistance. On the other hand, after cooling, the concrete recovers part of its lost strength, and the residual expansion of concrete increases the bonding force between the concrete core and steel tube. Moreover, concrete may absorb some moisture, which also affects the size of the sample and thus increases the bonding strength.

5.2. Length-to-Diameter Ratio of Steel Tubes. Chen et al. [74] showed that the average bond strength decreases with an increasing length-to-diameter ratio of round steel tubes. This result is consistent with the effect of the length-to-diameter ratio on the bond strength of CFSTs after a high-temperature test.

5.3. Diameter-to-Thickness Ratio of Steel Tubes. Chen et al. [74] showed that the diameter-to-thickness ratio of steel tubes has little effect on the average bond strength. Because the hoop effect of steel tubes on concrete does not change obviously with the change in the diameter-to-thickness ratio in this test, it has little influence on the average bond strength.

6. Discussion

At present, experimental research on the bond performance of CFSTs is carried out in a press. The following methods are

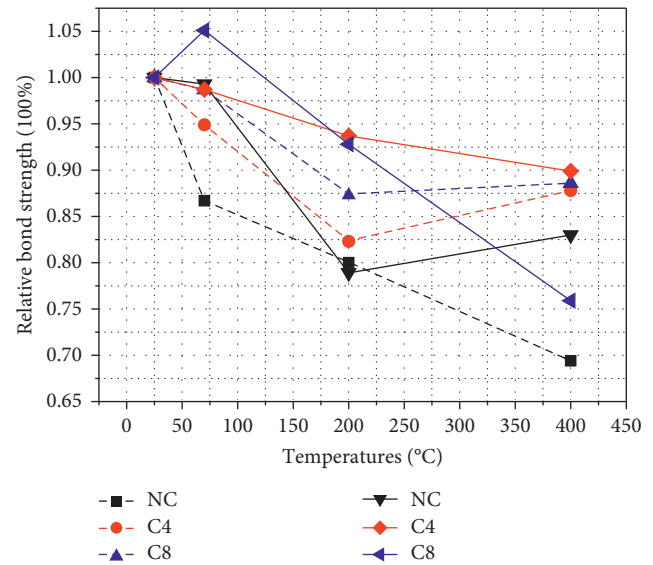


FIGURE 5: Effect of temperature on the relative bond strength (Fawzy et al. [68]). Note. The dashed and solid lines denote bond strengths during and after high-temperature exposure, respectively.

used to measure the change law of the interface bond-slip data of CFST specimens during and after fire exposure. (1) The longitudinal and transverse deformation of CFST specimens after fire exposure was measured by pasting strain gauges and installing displacement gauges. (2) A high-temperature resistant material was introduced at the free end of the specimen to indirectly measure the relative slip of the steel tube and concrete during fire exposure. However, due to the difference between the expansion coefficients of the steel tube and concrete during fire exposure, the interface slid slightly, and the lateral deformation of the CFST could not be measured in the whole test process. Therefore, it is necessary to adopt new test technology and test equipment to measure the stress and strain variation law of CFSTs during fire exposure.

7. Conclusions and Perspectives

7.1. Conclusions. This paper analyzes and summarizes the existing research related to the bonding performance of CFST interfaces under fire and postfire conditions at home and abroad, which includes the bonding strength of CFSTs during and after fire exposure and the main factors influencing bond strength. The following conclusions can be drawn:

- (1) The concrete strength, cross-sectional shape, diameter-to-thickness ratio, and length-to-diameter ratio of steel tubes are the main factors affecting the interface bonding performance of CFSTs at room temperature. The influence laws of the cross-sectional shape, diameter-to-thickness ratio of the steel tube, inner surface roughness of the steel tube, and mineral additives on the bond strength are clear, but the influence laws of the concrete strength and length-to-diameter ratio on the bond strength are

controversial. The type of concrete also has a certain influence on the bond strength of CFSTs, but research on this topic is scarce due to the various types of concrete materials.

- (2) Temperature, concrete strength, specimen cross-section type, and so on are the main factors affecting the bond performance of CFSTs after fire exposure. As the length-to-diameter ratio and section size D or B increase, the bond strength of the concrete-filled circular steel tube decreases. However, with the increase in the length-to-width ratio, the bond strength of the concrete-filled square steel tube increases. However, the effects of temperature and concrete strength on the bond strength of CFSTs are discrete, and the influence law is not clear.
- (3) The diameter-to-thickness ratio of specimens has little influence on the bond strength of CFSTs during fire exposure, while the temperature and length-to-diameter ratio have a great influence on the bond strength of CFST during fire exposure. However, due to the lack of research results, the law of influence is not clear.
- (4) Shear connectors can significantly improve the bonding performance of CFSTs and effectively reduce the relative slip between steel tubes and concrete. Note that a new type of concrete-filled checkered steel tube structure with a raised pattern on the inner wall of the steel tube can significantly improve the bond strength of the interface between the steel tube and concrete.

7.2. Perspectives

- (1) At present, although researchers have researched the main factors influencing the interfacial bonding performance of CFSTs during and after fire exposure, because of its many influencing factors and complex deformation mechanism, the results are discrete, and it is necessary to further analyze and study the law of the main factors influencing the bond properties of CFSTs during and after fire exposure.
- (2) The bond slip of the CFST interface is large during and after fire exposure, which seriously affects its later use. Therefore, new technologies and new materials can be used to solve the problem of the bond slip of CFSTs during and after fire exposure.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

Yuanyuan Xue and Jun Chen contributed to conceptualization; Yuanyuan Xue contributed to methodology, investigation, and original draft preparation; Zurong Cai and Yanhua Zou contributed to review and editing of the paper and supervision. All the authors have read and agreed on the published version of the manuscript.

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References

- [1] L.-H. Han, W. Li, and R. Bjorhovde, "Developments and advanced applications of concrete-filled steel tubular (CFST) structures: members," *Journal of Constructional Steel Research*, vol. 100, pp. 211–228, 2014.
- [2] L. H. Han, "Behaviors of concrete filled steel tubular axial compression member under high constant temperature," *Journal of Harbin University of Civil Engineering and Architecture*, vol. 71997, in Chinese.
- [3] J. Huo, Q. Zheng, B. Chen, and Y. Xiao, "Tests on impact behaviour of micro-concrete-filled steel tubes at elevated temperatures up to 400°C," *Materials and Structures*, vol. 42, no. 10, pp. 1325–1334, 2009.
- [4] J. S. Huo, Y. M. He, and B. S. Chen, "Experimental study on impact behaviour of concrete-filled steel tubes at elevated temperatures up to 800 °C," *Materials and Structures*, vol. 47, no. 1-2, 2014.
- [5] S. F. Jiang, Z. Q. Wu, and D. S. Niu, "Experimental study on fire-exposed rectangular concrete-filled steel tubular (CFST) columns subjected to Bi-axial force and bending," *Advances in Structural Engineering*, vol. 13, no. 4, 2010.
- [6] W. G. Li, Z. Y. Luo, Z. Tao, W. H. Duan, and S. P. Shah, "Mechanical behavior of recycled aggregate concrete-filled steel tube stub columns after exposure to elevated temperatures," *Construction and Building Materials*, vol. 146, 2017.
- [7] W. W. Wang, X. T. Lyu, Y. Z. Zhang, Y. Yu, and T. Zhang, "Axial compression performance of thin-walled T-shaped concrete filled steel tubular columns under constant high temperature: experimental and numerical study," *Structure*, vol. 27, 2020.
- [8] A. Karimi and M. Nematzadeh, "Axial compressive performance of steel tube columns filled with steel fiber-reinforced high strength concrete containing tire aggregate after exposure to high temperatures," *Engineering Structures*, vol. 219, 2020.
- [9] K. S. Radhika and K. Baskar, "Bond stress characteristics on circular concrete filled steel tubular columns using mineral admixture metakaoline," *International Journal of Civil and Structural Engineering*, vol. 3, no. 1, 2012.
- [10] G. Q. Li, L. H. Han, G. B. Lou, and S. C. Jiang, *Fire-Resistance Design of Steel Structures and Steel-concrete Composite Structures*, Architecture & Building Press, Beijing, China, 2006, in Chinese.

- [11] M. Shams and M. A. Saadeghvaziri, "State of the art of concrete-filled steel tubular columns," *ACI Structural Journal*, vol. 94, no. 5, pp. 558–571, 1997.
- [12] H. G. L. Prion and J. Boehme, "Beam-column behaviour of steel tubes filled with high strength concrete," *Canadian Journal of Civil Engineering*, vol. 21, no. 2, pp. 207–218, 1994.
- [13] C. W. Roeder, D. E. Lehman, and E. Bishop, "Strength and stiffness of circular concrete-filled tubes," *Journal of Structural Engineering*, vol. 136, no. 12, pp. 1545–1553, 2010.
- [14] H. Shakir-Khalil, "Push-out strength of concrete-filled steel hollow sections," *Structural Engineer*, vol. 71, no. 6, pp. 230–233, 1993.
- [15] L. H. Xue and S. H. Cai, "Experimental study on bonding strength of interface between steel tube and core concrete," *Engineering Mechanics*, vol. 6, no. suppl, pp. 569–574, 1994, in Chinese.
- [16] X. J. Ke, H. Y. Sun, Z. P. Chen, Y. S. Su, and W. D. Ying, "Interface mechanical behavior test and bond strength calculation of high-strength concrete filled circular steel tube," *Journal of Building Structures*, vol. 36, no. S1, pp. 401–406, 2015, in Chinese.
- [17] Y. F. Yang and L. H. Han, "Research on bond behavior between steel and concrete of self-compacting concrete filled steel tubes with rectangular sections," *Industrial Construction*, vol. 36, no. 11, pp. 32–36, 2006, in Chinese.
- [18] C. Petrus, H. Abdul Hamid, A. Ibrahim, and J. D. Nyuin, "Bond strength in concrete filled built-up steel tube columns with tab stiffeners," *Canadian Journal of Civil Engineering*, vol. 38, no. 6, pp. 627–637, 2011.
- [19] Z. P. Chen, J. J. Xu, J. Y. Xue, and Y. S. Su, "Push-out test on the interface bond-slip behavior and calculation on bond strength between steel tube and recycled aggregate concrete in RACFST structures," *Chinese Journal of Civil Engineering*, vol. 46, no. 3, pp. 49–58, 2013, in Chinese.
- [20] D. Shen, X. Shi, H. Zhang, X. Duan, and G. Jiang, "Experimental study of early-age bond behavior between high strength concrete and steel bars using a pull-out test," *Construction and Building Materials*, vol. 113, pp. 653–663, 2016.
- [21] B. Wu, Z. Y. Tan, J. Yin, S. Zhao, and K. Qi, "Experimental research on the bond-slip behavior of red mud concrete filled square steel tubes," *Concrete and Cement Products*, no. 1, pp. 36–40, 2020, in Chinese.
- [22] L. H. Xue and S. H. Cai, "Bond strength at the interfaee of concrete-filled steel tube columns (part 1)," *Architectural Science*, vol. 3, pp. 22–29, 1996, in Chinese.
- [23] L. H. Xue and S. H. Cai, "Bond strength at the interfaee of concrete-filled steel tube columns (part 2)," *Architectural Science*, vol. 4, pp. 19–23, 1996, in Chinese.
- [24] K. Zhang, *Experimental Study on Bonding Performance of Steel Tube High Strength Mechanized Sand Concrete*, Shenzhen University, Shenzhen, China, 2017, in Chinese.
- [25] X. T. Zhang, *Experimental Study on Bond-Slip Behavior of Thin Walled concrete-filled Stainless Steel Tube*, Huaqiao University, Quanzhou, China, 2017, in Chinese.
- [26] K. S. Virdi and P. J. Dowling, "Bond Strength in concrete Filled Circular Steel Tube," *CESLIC Report CCII*, Department of Civil Engineering, Imperial College, London, USA, 1975.
- [27] C. W. Roeder, B. Cameron, and C. B. Brown, "Composite action in concrete filled tubes," *Journal of Structural Engineering*, vol. 125, no. 5, pp. 477–484, 1999.
- [28] Y. J. Liu, J. P. Liu, and J. J. Chi, "Shear bond behaviors at interface of concrete-filled steel tube," *Journal of Guangxi University: Natural Science*, vol. 35, no. 1, pp. 17–23, 2010, in Chinese.
- [29] X. L. Kang, *Study on Compositing Mechanical Performance and Bond-Slip Performance of concrete Filled Steel Tube*, Xi'an: Doctoral Dissertation of Xi'an University of Architecture and Technology, Xi'an, China, 2008, in Chinese.
- [30] K. C. Xu, T. Ma, and F. Yuan, "Experimental study on the interfacial bonding strength of square steel tubular concrete," *Railway Construction*, no. 12, pp. 159–162, 2012, in Chinese.
- [31] J. Lv, T. H. Zhou, Q. Du, K. L. Li, and L. W. Jin, "Research on the bond behavior of preplaced aggregate concrete-filled steel tube columns," *Materials*, vol. 13, no. 2, pp. 1–15, 2020.
- [32] J. B. Wu, J. Y. Xue, and H. T. Zhao, "Experimental study on bond strength between steel and concrete in CFSST structures based on unascertained mathematics theory," *Concrete*, no. 7, pp. 17–19, 2007, in Chinese.
- [33] R. Y. Jiang, *Experimental Research on the Bond-Slip Aggregate concrete Pipe Lightweight*, Hubei University of Technology, Wuhan, China, 2017, in Chinese.
- [34] L. H. Xue and S. H. Cai, "The influence of load eccentricity on bond strength at the interface of concrete-filled steel tube columns," *Architectural Science*, vol. 2, pp. 22–25, 1997, in Chinese.
- [35] Q. W. Wang, Q. X. Shi, Z. D. Xu, and C. Y. Zhang, "Research on the interface bond-slip behavior of reactive powder concrete filled with circular steel tube," *Journal of Building Structures*, vol. 572020, in Chinese.
- [36] S. H. Ren, *Experimental Study on the Bond Properties and Critical Bond Length of concrete-filled Square Steel Tubes*, Master Dissertation, Xi'an University of Architecture and Technology, Xi'an, China, 2008.
- [37] Z. Tao, T.-Y. Song, B. Uy, and L.-H. Han, "Bond behavior in concrete-filled steel tubes," *Journal of Constructional Steel Research*, vol. 120, pp. 81–93, 2016.
- [38] X. Y. Zhao, *Experimental Research on Bond-Slip Behavior between Steel and concrete in concrete Filled Square Steel Tube Structure*, Master's Thesis, Xi'an University of Architecture and Technology, Xi'an, China, 2008.
- [39] Y. J. Liu, G. Cheng, N. Zhang, and J. G. Zhang, "Experimental research on concrete-filled square steel tubular columns stiffened with PBL," *Journal of Building Structures*, vol. 35, no. 10, pp. 39–46, 2014, in Chinese.
- [40] X. Y. Zhao, J. Y. Xue, H. T. Zhao, and J. B. Wu, *Research on Bond-Slip Mechanism of concrete Filled-Square Steel Tube Column-Beam Joints*, pp. 124–126, The 5th National Academic Forum for Civil Engineering Postgraduates, 2007, in Chinese.
- [41] H. Z. Deng, P. C. Fu, and Z. W. Yu, "Experimental study on bonding behavior between rectangular steel tube and concrete," *Special Structure*, vol. 22, no. 1, pp. 50–52, 2005, in Chinese.
- [42] L. X. Guo and G. S. Tong, "Shear strength on the interface between rectangular tubes and infilled concrete and its improvement by diaphragm," *Industrial Building*, vol. 45, no. 6, pp. 154–159, 2015, in Chinese.
- [43] K. C. Xu, C. L. Huang, and M. C. Chen, "Research on impact of steel tube inner surface roughness on interfacial bonding behavior of concrete-filled steel tube," *Journal of Building Structures*, vol. 34, no. 2013S1, pp. 420–424, 2013, in Chinese.
- [44] J. R. Qian, Z. Z. Zhao, and X. D. Ji, "Test study on shear-bond capacity of steel tube-out of tube concrete interface," *Building Structure*, vol. 45, no. 3, pp. 12–16, 2015, in Chinese.
- [45] H. Y. Dong, X. P. Chen, W. L. Cao, and Y. Z. Zhao, "Bond behavior of high-strength recycled aggregate concrete-filled large square steel tubes with different connectors," *Engineering Structures*, vol. 211, 2020.

- [46] H. Y. Dong, X. P. Chen, W. L. Cao, and Y. Z. Zhao, "Bond-slip behavior of large high-strength concrete-filled circular steel tubes with different constructions," *Journal of Constructional Steel Research*, vol. 167, 2020.
- [47] G. Zuo, Z. B. Wang, and Y. Qiao, "Experimental study on bond slip of micro-expansion recycled concrete," *Concrete and Cement Products*, no. 2, pp. 5–9, 2015, in Chinese.
- [48] J. J. Xu, Z. P. Chen, J. Y. Xue, and Y. S. Su, "Failure mechanism of interface bond behavior between circular steel tube and recycled aggregate concrete by push-out test," *Journal of Building Structures*, vol. 34, no. 7, pp. 148–157, 2013, in Chinese.
- [49] Z. P. Chen, J. J. Xu, W. N. Li, and J. Y. Xue, "Influence of recycled coarse aggregate content on bond strength and invalidation mechanism between steel tube and recycled aggregate concrete," *Engineering Mechanics*, vol. 31, no. 6, pp. 70–78, 2014, in Chinese.
- [50] X. N. Xue and Z. J. Zhong, "Experimental research on the bond slip behavior of recycled concrete-filled steel tubular column," *Journal of East China Jiaotong University*, vol. 35, no. 4, pp. 39–46, 2018, in Chinese.
- [51] L. H. Wei, *Research on Interface Adhesion Properties between the Self-Compacting Desulfurized Slag and the concrete-filled Tube Steel*, North University of China, Taiyuan, China, 2018, in Chinese.
- [52] B. Wu, Z. Y. Tan, Y. D. Zhang, Z. H. Zhao, and C. X. Liu, "Experimental research on the bond-slip behavior of red mud concrete filled square steel tubes," *IOP Conference Series: Materials Science and Engineering*, vol. 394, no. 3, pp. 1–6, 2018.
- [53] Q. J. Ding, X. J. Zhou, T. M. Mou, B. K. Fan, and Y. L. Yan, "Bond properties at interface of steel fiber reinforced micro-expansion concrete filled steel tube," *Functional Materials*, vol. 44, no. 6, pp. 809–813, 2013, in Chinese.
- [54] K. F. Wei, S. P. Jia, and Y. Gao, "Experimental study on interfacial bond strength of reactive powder concrete-filled steel tube," *Building Structure*, vol. 49, no. 22, pp. 101–107, 2019, in Chinese.
- [55] L. Chen, J. Dai, Q. Jin, L. Chen, and X. Liu, "Refining bond-slip constitutive relationship between checkered steel tube and concrete," *Construction and Building Materials*, vol. 79, pp. 153–164, 2015.
- [56] L. H. Chen, J. X. Dai, Q. L. Jin, and B. L. Sheng, "Push-out test study on the bond strength between square checkered steel tube and concrete," *Building Structure*, vol. 26, no. 3, pp. 17–20, 2015, in Chinese.
- [57] Y. Morishita, M. Tomii, and K. Yoshimura, "Experimental studies on bond strength in concrete filled circular steel tubular column subjected to axial loads," *Transactions of Japan Concrete Institute*, vol. 1, pp. 351–358, 1979.
- [58] Y. Morishita and M. Tomii, "Experimental studies on bond strength between square steel tube and encased concrete core under cyclic shearing force and constant axial force," *Transactions of Japan Concrete Institute*, vol. 4, pp. 363–370, 1982.
- [59] M. Tomii, K. Yoshimura, and Y. Morishita, "A method of improving bond strength between steel tube and concrete core cast in circular steel tubular columns," *Transaction of Japan Concrete Institute*, vol. 2, pp. 319–326, 1980.
- [60] H. Huang, Y. H. Ye, Y. J. Du, and R. L. Sun, "Experimental study on the bond-slip between steel tube and self-compacting concrete," *Concrete*, no. 4, pp. 23–27, 2010, in Chinese.
- [61] X. J. Chen, F. Yuan, M. C. Chen, and K. C. Xu, "Push-out test on bond property of micro-expansive concrete-filled steel tube columns," *Sichuan Building Science Research*, vol. 37, no. 4, pp. 9–12, 2011, in Chinese.
- [62] X. L. Kang, H. T. Zhao, J. Y. Xue, and Z. P. Chen, "Summarized review of the bond-slip problems of concrete filled steel tubes," *Journal of Xi'an University of Architecture and Technology*, vol. 38, no. 3, pp. 321–326, 2006, in Chinese.
- [63] L. H. Chen, J. X. Dai, Y. Lou, and S. T. Li, "Review analysis on study of bond behavior of concrete-filled steel tube," *Building Structures*, vol. 46, no. 22, pp. 78–83, 2016, in Chinese.
- [64] Z. Tao, L. H. Han, B. Uy, and X. Chen, "Post-fire bond between the steel tube and concrete in concrete-filled steel tubular columns," *Journal of Constructional Steel Research*, vol. 67, no. 3, pp. 484–496, 2010.
- [65] C. L. Zhang, *Experimental Research on Interfacial Properties of concrete-filled Steel Tube Structure after High Temperature*, Master's Dissertation, North China University of Technology, Beijing, China, 2014.
- [66] B. Wu, "Study on Bond prosperity at the Interface of composite Column with Core of concrete Filled Steel Tube Round about Fire", Master's thesis, Zhejiang University, Zhejiang, China, 2006.
- [67] K. Xiang, Y. C. Pan, and T. Y. Song, "Experimental study on bond-slip behavior of concrete-encased concrete-filled steel tubular stub columns after high temperature," *Journal of Building Structures*, vol. 40, no. S1, pp. 149–155, 2019, in Chinese.
- [68] H. M. Fawzy, S. A. A. Mustafa, and A. E. AbdEl-Badie, "Thermal effect on bond strength of rubberized concrete filled steel tubular sections," *Fracture and Structural Integrity*, vol. 14, no. 53, 2020.
- [69] Z. J. Liu, *Experimental Investigation of post-fire Bond-Slip Performances of Interface for concrete-filled Steel Tubular Columns*, Hunan University, Changsha, China, 2017, in Chinese.
- [70] Z. P. Chen, J. Zhou, J. J. Chen, and X. Y. Zhou, "Interface bond behavior of high strength concrete filled square steel tube subjected to high temperature and subsequent water cooling," *Journal of South China University of Technology*, vol. 48, no. 9, pp. 20–33, 2020, in Chinese.
- [71] W. J. Zou, J. F. Liang, G. W. Zhang, and H. F. Yang, "Bond properties of RAC-filled square steel tubes after high temperature," *Advances in Materials Science and Engineering*, vol. 2019, Article ID 2413613, 9 pages, 2019.
- [72] Z. P. Chen, X. Liu, J. J. Xu, and W. X. Zhou, "Study on interface bond behavior of high strength concrete filled square steel tube after high temperatures," *Journal of Building Structures*, vol. 38, no. 6, pp. 133–143, 2017, in Chinese.
- [73] Z. P. Chen, X. Liu, and W. X. Zhou, "Interface bond behavior between circle steel tube and high strength concrete after high temperatures," *Engineering Mechanics*, vol. 35, no. 8, pp. 192–200+256, 2018, in Chinese.
- [74] J. Chen, Y. Y. Xue, Q. H. Tan, and J. L. Wu, "Experimental study on bond behavior of interface for concrete-filled steel tube under constant high temperature," *China Civil Engineering Journal*, vol. 51, no. 3, pp. 11–18, 2018, in Chinese.
- [75] B. Amirreza and N. Mahdi, "Bond behavior of lightweight concrete-filled steel tubes containing rock wool waste after exposure to high temperatures," *Construction and Building Materials*, vol. 300, 2021.