Research Article

Bonding Performance of CFRP-Steel Interface after Continuous High Temperature

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The bonded shear performance of CFRP-reinforced steel structures following continuous high-temperature natural cooling was investigated experimentally, and 30 CFRP-steel specimens were subjected to single-shear tensile testing. In analyzing the shear stress-displacement relationship in each working condition, the equation for the coupling effect of the heating temperature and duration on the ultimate shear stress was proposed. The results show that the ultimate shear stress at the CFRP-steel interface tends to decrease with the increase of heating temperature, and the ultimate shear stress at the heating temperature of 300 °C is 32.37% of that at 25 °C. The high-temperature duration has an obvious influence on the bonding performance of the CFRP-steel interface, and the CFRP-steel specimens fail when the heating temperature is 300 °C and lasts for 120 min.

1. Introduction

Carbon fiber-reinforced polymer (CFRP) has the advantages of high strength, excellent heat, corrosion resistance, etc., which is widely used in the reinforcement and renovation of structural buildings. The use of adhesive to reinforce the steel structure with CFRP can effectively enhance the carrying capacity and life of the original structure. The study of interfacial bonding between CFRP and reinforced steel structure is the key issue of this reinforcement method, and the failure mode of CFRP bonded steel structure is more complicated than that of CFRP bonded concrete structure. Also, a lot of research work has been carried out by scholars. The factors affecting the bonding performance of the CFRP-steel interface have been studied systematically, including the type of adhesive and CFRP [1–5], pasting method [6–8], loading method [9–14], and environmental conditions [15,16].

In the use of CFRP-reinforced steel structures, temperature is also an important factor influencing the load capacity of the reinforced elements. Biscaia and Ribeiro [17] carried out an experimental study at different temperatures to better understand the effect of temperature on CFRP-steel bonded joints and analyzed the local bond-slip behavior of the test samples. Silva et al. [18] conducted a study on the bonding performance and bending properties of CFRP-reinforced steel members with the use of temperature and bond length as variables. Lye et al. [19] used two different test methods, considering service temperature, number of CFRP layers, and bond length. The results of the study showed that the main failure mode of the CFRP-steel specimens changed as the operating temperature increased and the tensile strength increased by 25.62%. Zhou et al. [20] conducted a study on CFRP-steel joints under high-temperature conditions and showed that the load-displacement behavior of bonded joints is sensitive to temperature changes and that the maximum load on bonded joints depends on the ratio between load and heating. To study the effect of thermal action on bonded joints, the scholar Hugo C. Biscaia proposed a solution capable of simulating the interfacial bonding behavior between two structural materials subjected to thermal loading, which was validated by numerical simulations [21]. In addition, he proposed a series of solutions in closed form, mainly describing the interfacial slip, bond stresses, and strains of the two materials during the warming process [22]. Chandrathilaka et al. [23] used different initial curing temperatures for CFRP-steel specimens and performed shear tests of CFRP-steel in a high-temperature environment. The failure mode of the specimens was found to have shifted from CFRP fiber
fracture to adhesive layer damage as the temperature increased. Galvez et al. [24] conducted an experimental study of the thermal and mechanical properties of CFRP-reinforced steel structures using temperature and humidity as variables. Ke et al. [25] conducted fatigue performance tests on damaged steel structures reinforced by CFRP under the temperature influence. High temperatures have been shown to dramatically reduce the fatigue performance of CFRP-reinforced steel elements. It can be seen that the current research on CFRP-reinforced steel structures mainly focuses on its mechanical properties and structural reinforcement effects at room temperature or high temperature, and there are few studies related to the mechanical properties of CFRP-reinforced steel structures after natural cooling at sustained high temperature.

With the increasing application of CFRP reinforcement technology and the long-term risk of fire in buildings, the mechanical properties of CFRP-reinforced structures after a fire are not yet clear. Nguyen et al. [26] carried out tests on CFRP from 20°C to 600°C in order to study the mechanical properties of CFRP after a fire, and the study showed that the mechanical properties of the tested materials decreased with increasing temperature. The bonding adhesive is an important influencing factor in the performance of CFRP-reinforced structures, and it is necessary to investigate the change of bonding performance of the CFRP-sheet interface after natural cooling at sustained high temperatures of a fire. The external loads on CFRP-reinforced steel structures in high fire temperatures are generally not their ultimate values, and the structural members after high fire temperatures should meet the corresponding ultimate load-bearing capacity requirements but is the load-bearing capacity of CFRP-reinforced steel structures after high temperature heating by fire the same as at the time of fire? The issue of how the bonding properties of reinforced members change after a fire and the effect of heating temperature and duration on the load-bearing capacity of the members has not been studied in detail. Based on the above reasons, this paper conducts shear drawing tests on CFRP laminate specimens glued to the adhesive to explore the influence of the heating temperature and the duration of their bonding performance.

2. Test Overview

2.1. Materials. The CFRP widely used in the marketplace is primarily divided into two types: one-way and two-way. Compared with a bidirectional carbon fiber laminate, a one-way carbon fiber laminate is more suitable for common reinforcement projects, so this paper adopts a one-way carbon fiber laminate, with the strength of high strength I grade. The adhesive is epoxy resin A grade adhesive commonly used in engineering, and the weight ratio of epoxy resin to curing agent is 2 : 1. The steel plate type used in the test is Q235 B, with thickness of 6 mm, and the floating rust and oxide on the surface of the steel plate should be removed by angle grinder before use, and the treated steel plate should be wiped with alcohol. The main mechanical properties of the test materials are shown in Table 1.

2.2. Specimen Design. The specimen is made of two 6 mm thick Q235 B steel plates of different sizes to make the damage of the specimen occur in the small steel plate. The steel reinforcement is welded to the steel plate along the center line of the plate. The specimen size is shown in Figure 1. The specimen is pasted with carbon fiber laminate in two steps: the first step is to glue the carbon fiber laminate on the small steel plate, Curing time of at least 7 days in a state not less than 5°C, then high-temperature heating, and the second step is to paste the carbon fiber laminate on the large steel plate after the high-temperature treatment to reach the design strength and carry out the tensile test.

During the test, the two variables of maximum temperature and duration were mainly taken into account, and the test was divided into two steps: high-temperature processing and design testing. 13 groups of 30 single-shear specimens were designed and studied in batches for bonding performance tests, and the specimen design parameters are shown in Table 2.

2.3. Heating Equipment and Solutions. The high-temperature chamber furnace used for the test is shown in Figure 2, with the internal dimensions of the chamber, 500 mm in length, 100 mm in width, and 100 mm in height.

Once the specimens were cured, they were heated to elevated temperatures and cooled naturally. Using the maximum temperature of 300°C and the constant time of 20 minutes as an example, the temperature elevation curve of this test is illustrated in Figure 3.

2.4. Loading Solutions. Fix the specimen after high-temperature treatment on the universal testing machine through the fixture, and then two pull-ring displacement sensors would be fixed on both sides of the large steel plate for measuring the relative displacement between the two plates. Loading was done at a uniform speed of 10 N/s. The test loading device is shown in Figure 4.

3. Test Results and Analysis

3.1. Data Analysis. After averaging the data of the two displacement sensors, the curve of the shear stress measured experimentally in relation to the displacement is presented in Figure 5.

The test results show that the test curves under different working conditions mainly consist of rising and sudden falling sections and the damage forms of the specimens all belong to typical brittle damage. The rising section of the test curve is divided into 2 cases, one is the linear growth of shear stress and displacement; the other is from steep to slow; at the beginning of the loading, the curve grows very fast, while the displacement changes very slowly; with continued loading, the displacement growth becomes faster, and the shear stress rises more slowly.

Throughout all the test curves can also be found: the specimen is suddenly pulled off due to the reduced bonding
performance of the adhesive, and most of the curves show the “sharp angle” phenomenon when the limit value is reached.

3.2. Destruction of Form after High Temperature. The maximum temperature is less than 150°C. In part of the specimen in the shear test phase, there will be a “pop” sound, when the shear stress reaches about 80% of the ultimate shear stress. With continuous loading, the local damage of the specimen began to appear, until the specimen emitted a “boom” noise, adhesive bond damage, and the shear stress directly down. At the end of the test, it was found that most of the specimens were stripped of a carbon fiber laminate and a small number of fiber bundles were left on the steel plate, and individual specimens might have more fiber bundles on the steel plate due to stress concentration.

At the maximum temperature of 200°C, the gel melted with increasing duration, while the ultimate shear stress of the specimen decreased significantly. At the maximum temperature of 300°C, the separation of carbon fiber and steel plate appeared locally in the specimen after heating. There is a small amount of adhesive on the steel plate after the shear test and no carbon fiber, and the ultimate shear stress is significantly reduced. When the duration reaches 120 min, the colloid is completely melted and in the form of black powder, the carbon fiber laminate is almost separated from the steel plate, and the CFRP-steel plate specimen basically fails.

### Table 1: Mechanical properties of materials [27].

| Materials | Modulus of elasticity (GPa) | Yield strength (MPa) | Ultimate tensile strength (MPa) | Percentage elongation | Thickness (mm) |
|-----------|----------------------------|----------------------|-------------------------------|----------------------|----------------|
| Q235      | 200                        | 235                  | 380                           | 26%                  | 6              |
| CFRP      | 231                        | —                    | 3483                          | 1.69%                | 0.167          |
| Adhesive  | 2.5                        | —                    | ≥40                           | ≥1.5                 | —              |

**Figure 1:** Schematic diagram of bond shear test piece.
4. Factors Influencing the Bonding Performance of the CFRP-Steel Interface

4.1. Maximum Temperature. As shown in Figure 7, the ultimate shear stress of the specimen was decreasing with the increase of heating temperature when the duration was 0 min. At 25°C, the ultimate shear stress of the specimen is 5.87 MPa, which gradually decreases with the gradual increase in heating temperature; from 25°C to 150°C, the ultimate shear stress shows a decreasing trend but changes slowly; from 150°C to 300°C, the decreasing speed increases. When the temperature reaches 300°C, the ultimate shear stress decreases significantly. When the duration is 60 min, the trend of shear stress with temperature is similar to the curve of duration of 0 min, and the ultimate shear stress at 200°C is 60.48% of that at 25°C, and the specimen can still bear large shear stress and can continue to play a part of its mechanical properties.

When the duration is 120 min, the effect of the maximum temperature on the specimen is different from the aforementioned. Before 100°C, the ultimate shear stress decreases slowly and can be basically considered to remain unchanged, and the adhesive bonding performance is not affected after high temperature. The ultimate shear stress decreases sharply after 100°C. Compared with the ultimate shear stress at 25°C, it decreases by 37.65% at 150°C and by 65.25% at 200°C. At 300°C, the ultimate shear stress is only 0.14 MPa, which can be considered a complete failure of the specimen.

4.2. Duration of High Temperature. As can be seen from Figure 7, the ultimate shear stress decreases with increasing duration. When the heating temperature is 150°C, the ultimate shear stress before the duration of 60 min decreases slightly with the increase of duration, and the curve after 60 min shows a significant decreasing trend. The ultimate shear stress at 200°C showed a significant decreasing trend after 30 min. The ultimate shear stress of each temperature at a duration of 120 min was 77.52%, 62.35%, 34.75%, and 2.39% at 25°C, respectively.

Based on the above analysis, the duration of high temperature has an obvious influence on the bonding performance of the CFRP-steel interface. Among them, the bonding performance does not change when the temperature is 150°C and the duration is 60 min, and it can still play a part of the mechanical properties of the adhesive at 120 min. The ultimate shear stress was 0.14 MPa at 300°C and a duration of 120 min, which was significantly lower than before, at which time the CFRP-steel specimen failed completely.

5. Analysis of the Coupling Effect of Heating Temperature and Duration on Ultimate Shear Stress

Using the numerical simulation software MATLAB, a binary quadratic equation (equation (1)) was fitted for the ultimate shear stress, heating temperature, and maximum temperature duration, with a coefficient of determination $R^2 = 0.9734$. The
Figure 4: Test loading device.

Figure 5: Continued.
Figure 5: Shear stress–displacement curves under different conditions. (a) 25°C. (b) 100°C, 120 min. (c) 150°C, 0 min. (d) 150°C, 60 min. (e) 150°C, 120 min. (f) 200°C, 0 min. (g) 200°C, 30 min. (h) 200°C, 60 min. (i) 200°C, 90 min. (j) 200°C, 120 min. (k) 300°C.
comparison between the fitted surface and the experimental values is shown in Figure 8, and it can be seen that the surface plotted based on equation (1) is similar to the experimental results, indicating that the fitted curve matches the experimental data. Overall, the ultimate shear stress tends to decrease as the heating temperature increases and the duration of the high-temperature rise increases, which corresponds to the results of previous tests.
τ_u = \(-5.8848 \times 10^{-5}T^2 - 1.3217 \times 10^{-4}t^2 + 0.0049T - 5.1755 \times 10^{-4}t - 4.4053 \times 10^{-6}Tt + 5.9174,\) 

\[25°C \leq T \leq 300°C \] \[0\text{ min} \leq t \leq 120\text{ min},\]

(1)

where \(\tau_u\) is the ultimate shear stress, MPa; \(T\) is the temperature, °C; and \(t\) is the maximum temperature duration, min.

According to equation (1), the theoretical bond strengths at different temperatures and durations can be obtained, while introducing the carbon fiber strength reduction factor, defined in equation (2), and the reduction factors at different temperatures and durations are shown in Table 3.

\[\mu = \frac{-5.8848 \times 10^{-5}T^2 - 1.3217 \times 10^{-4}t^2 + 0.0049T - 5.1755 \times 10^{-4}t - 4.4053 \times 10^{-6}Tt + 5.9174}{6.0006},\]

\[25°C \leq T \leq 300°C \] \[0\text{ min} \leq t \leq 120\text{ min},\]

(2)
where $\mu$ is the carbon fiber strength reduction factor under the influence of duration (take 0 if $\mu < 0$).

6. Conclusion
(1) The ultimate shear stress at the CFRP-steel interface tends to decrease with the increase in the heating temperature. The bonding performance is unchanged before the temperature rose to 150°C, and the bonding decreased significantly after 150°C. When reaching 300°C, the ultimate shear stress of the specimen decreases to 32.37% of that at 25°C.

(2) Duration has an obvious influence on the bonding performance of the CFRP-steel interface. Before 150°C, the shorter duration has little influence on the bonding performance of the adhesive; when the duration increases, the adhesive can still play a large bonding role. At 200°C, the duration increases and the bonding performance of the specimen decreases significantly; at the temperature of 300°C for 120min, the CFRP-steel specimen fails completely.

(3) Analysis of the fitting equations for ultimate shear stress versus heating temperature for different durations and the corresponding fitting surfaces revealed that the heating temperature corresponding to the complete loss of ultimate shear stress decreases sequentially with increasing duration.

Data Availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

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