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Analysis of interfacial bonding characteristics of CFRP-concrete under fatigue loading

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HIGHLIGHTS

- Failure modes of the CFRP-concrete interface under fatigue load are discussed.
- A formula is proposed to predict the fatigue life of the CFRP-concrete interface.
- A bond-slip model of the CFRP-concrete interface under fatigue load is developed.

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ABSTRACT

The paper presents the results of an experimental and analytical study involving the bond properties of nine specimens externally strengthened with carbon-fiber-reinforced polymer (CFRP) sheets under fatigue loading. The purpose of this study is to investigate the influence of concrete strength and fatigue amplitude on the bond performance of CFRP-concrete interface under fatigue loading. Firstly, modified beam specimens with different concrete strengths were designed and constructed. Secondly, the specimens were tested under fatigue loads with different fatigue amplitudes. The test results show that the fatigue life increased with an increase in concrete strength, but decreased as the fatigue load amplitude increased, and a formula was proposed to predict the fatigue life. Moreover, the concrete strength and fatigue loading amplitude have little effect on the effective bond length under fatigue loading. The test results of bond-slip relationship show that the bond-slip curves continuously degraded with an increase in the number of load cycles, that is, the maximum shear stress decreased with an increase in the number of load cycles. Finally, a bond-slip model was developed considering the effects of concrete strength and fatigue loading amplitude. The comparison between experimental results and this model demonstrated that this developed bond-slip model can be used to describe the bond-slip relationship of the CFRP-concrete interface under fatigue loading.

1. Introduction

As a kind of reinforcement material, CFRP with the properties of light weight, high strength and modulus, and superior anti-fatigue has made large advances in civil engineering construction, such as concrete structures, steel structures, timber structures and so on [1–3]. During the past several decades, concrete structure has rapidly developed, naturally the most of the damaged structural members are concrete structures. Traditional structural repairing methods such as external post-tensioning and strengthening with steel plates often suffer from the inherent disadvantages. Corrosion of steel and large self-weight are the main limitations to these applications [4,5]. Based on the new material CFRP, a reinforcement technique that repairing and strengthening the existing damaged reinforced concrete (RC) structures by externally bonded CFRP sheets was developed and has been widely used in concrete structures.

In order to investigate the working mechanism of the concrete structures reinforced with CFRP sheets, a lot of experimental and theoretical studies have been conducted in the last decades. A series of experiments has been done by Täljsten et al. [3,6] to investigate the strengthening performances of RC beams reinforced by CFRP sheets, i.e., the shear force capacity of the beams after strengthening. These test results show that bonding property is of great importance to achieve a good composite action between the adherents, and the interfacial shear and normal stresses also play a very important role in strengthening effect. Wang et al. [7] reported that the sustaining load levels at the time of strengthening have important influence on the ultimate strength of strengthened RC beams, and

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the failure modes of test beams are CFRP rupture when the initial load is not big. Jayaprakash et al. [8] conducted an experimental study on sixteen RC beams externally bonded with bi-directional CFRP. Test results shown that the shear capacity enhancement of the CFRP strengthened beams varied between 11% and 139% over the control beam. Fayyadh et al. [9] conducted an experiment on four RC beams, which were first damaged at different loading levels and then repaired by bonding CFRP sheets to the tension side. The results prove the effectiveness of the externally bonded CFRP sheets as a repair technique which increases the flexural stiffness and the ultimate load capacity whatever the pre-repair damage levels. Many other researches [10–15] have been done to investigate the strengthening performance of RC members externally bonded with CFRP sheets, and similar results can be derived that the ultimate capacity, shear capacity, flexural stiffness and ductility all increased in different levels. The main failure mode (debonding failure) in these tests indicates that the bond performance between CFRP and concrete plays an important role in improving the strengthening performance. In order to characterize the behavior of the bond between CFRP and concrete, some further studies were carried out. Teng et al. [16] presented a debonding strength model for intermediate crack debonding failures based on a variety tests on reinforced RC beams strengthened by bonding CFRP to their tension face. And the analysis results show that the proposed debonding strength model provides a good approximation to the strengths of such beams. Mazzotti et al. [17] investigated the effect of the number of strengthening layers on the FRP-concrete bond behavior. Lee et al. [18] experimentally studied the effects of repeated loads on the FRP-concrete bond strength by direct pullout tests, and the result show that the maximum bond strength under repeated loads differed from those obtained under monotonic loads.

At present, the studies of FRP-concrete bond behavior under the static loadings have been widely and deeply researched by experiments and theories, and one important conclusion were recognized that the bond behavior of the FRP-concrete interface is a key factor to affect the behavior of members strengthened with FRP [19–23]. However, the current study of fatigue behavior of externally bonded FRP for reinforced concrete structure is not sufficient. Carloni et al. [24] conducted an experiment to investigate the fatigue behavior of the concrete member externally strengthened with FRP, and the results shown that the debonding occurred during fatigue loading and it was related to the amplitude of fatigue loads. Diab et al. [25] presented an analytical solution for the evolution and distribution of shear stresses of the FRP-concrete interface along the entire bond length under mode-II fatigue loading. Deng et al. [26] investigated the interracial fatigue behaviors of two RC beams strengthened with FRP, and the results show that the use of FRP high strength was restrained by the interracial fatigue failure and a prediction approach for interracial life was given. Although some factors that affect the fatigue performance of the FRP-concrete interface were investigated and some conclusions were drawn out, e.g., the interface debonding propagates progressively with an increase in the number of load cycles, the factors such as concrete strength were not considered in all these studies. Therefore, in this paper, the fatigue tests using modified beam specimens were conducted to investigate the fatigue behavior of the bond between CFRP sheets and concrete, and the influence of fatigue amplitude and concrete strength on the bond performance of the CFRP-concrete interface was studied.

2. Experimental program

2.1. Materials and specimens

At present, in the most experimental researches of FRP-concrete interface bond performance, the specimens are commonly designed as pure shear specimen, which can't fully reflect the mechanical properties of concrete beams reinforced with CFRP sheets. Therefore, a kind of modified beam specimen, as illustrated in Fig. 1, was designed by our research group (the patent of this method has been authorized [27]) to reflect the bending performance of concrete beams reinforced with CFRP sheets. The modified beam specimen consists of two concrete blocks (seen in Fig. 1(a)), which was connected by a steel hinge (seen in Fig. 1(b)) at the top and bonded by two layers of CFRP sheets at the bottom. Fig. 1 shows that both the two concrete blocks were of the same T section with a dimension of $200 \times 210 \times 400$ mm, and a 5 mm spacing was set between the two concrete blocks at midspan. In order to prevent CFRP sheets from fracturing in the middle span, the edges of both the two concrete blocks at the bottom of midspan were polished into a round corner with the radius of 20 mm. A non-bonded area with a size of 85 mm long was reserved at midspan.

In order to make sure there is effective bonding between CFRP sheets and concrete, some cleaning work should be done firstly, such as removing the dust on the concrete surface of the specimen by using an abrasive disk, and scrubbing with absolute ethanol, thus a rough and clean surface was formed. Then, the CFRP sheets were cut into strips with proper size using scissors. The adopted width b_f and length l_f of CFRP sheets for each specimen were listed in Table 1. In the meantime, the adhesive primer (SW-3P) was evenly brushed on the freshly treated concrete surface. After the primer was dried, the synthetic resin adhesive (SW-3C) was also brushed evenly on the dried primer, then the CFRP sheets was pressed on the surface with paying particular attention to avoiding air bubbles between the surface and CFRP sheets. Similarly, the U-shaped CFRP sheets was bonded on one side of the specimen (that is one of the two blocks, seen in Fig. 1), so as to make sure the bond failure always happen on the other side (monitored side). The bonded CFRP sheets at the bottom of the specimen were subjected to uniform pressure by applying a concrete block with weight of 20 kg on the bonded surface of each concrete block of the specimen, as shown in Fig. 2. After 7 days curing, the weights were removed and the bond quality was visually inspected.

A total of 9 specimens with 3 different concrete grades (C20, C30 and C60) were prepared. Three $150 \times 150 \times 150$ mm cubic concrete specimens were made for each concrete grade. Then the average 28-day compressive strength for each grade of concrete was experimentally obtained; the results are shown in Table 1 (25.1 MPa, 35.3 MPa and 62.2 MPa for specimens with concrete grades of C20, C30 and C60, respectively). According to the results of the tensile flat coupon test conducted on CFRP sheets, the average Young's modulus and tensile strength of the commercial CFRP sheets (CXS-200 with a thickness of 0.11 mm and a unitary weight of 200 g/m^2) were 225 GPa and 4150 MPa, respectively. As specified by the manufacturer, the bond strength (which was measured when the adhesive was used to bond CFRP sheets to concrete with the grade of C40, and only normal stress existed in the interface), shear strength (which was measured when the adhesive was used to bond two steel plates and only shear stress existed in the interface) and Young's modulus of the adhesive were 3.9 MPa, 16.1 MPa and 2857.8 MPa, respectively.

2.2. Testing setup and procedure

The 9 specimens were divided into two groups, as listed in Table 1, the specimens made of the concrete of high compressive strength (62.2 MPa) were included in group A and the other specimens with the concrete compressive strength of 25.1 MPa or 35.3 MPa were included in group B. All the specimens were tested by a servo-hydraulic testing machine (PME-50A) with a maximum capacity of 50 kN, as shown in Fig. 2. The loading point was applied