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Fatigue behavior of reinforced concrete beams strengthened with prestressed fiber reinforced polymer

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ABSTRACT

A series of experiments were conducted to investigate the fatigue damage behavior of reinforced concrete (RC) beams strengthened with prestressed fiber reinforced polymer (FRP) under three-point bending. Based on the experimental results, the fatigue failure mechanism of the strengthened beams and the propagation process of the fatigue interface cracks were presented, and an empirical formula was developed to predict the fatigue lives of such members. Moreover, a theoretical method was proposed to quantify the dynamic flexural stiffness of the strengthened beams. Based on the flexural stiffness, a fatigue accumulative damage model was established to describe the fatigue fracture process of the strengthened beams. The results show that the theoretical model is in good agreement with the experimental data.

1. Introduction

Fiber reinforced polymer (FRP) has been extensively applied to strengthen concrete structures in recent years. This material is of interest to rehabilitation engineers because of the high-strength/weight ratio, ease of handling and application, the elimination of the need for heavy equipment, a faster construction rate and the fact that they do not corrode [1,2]. Traditionally, non-prestressed FRP laminates bonded to the tension face of a concrete member supplement the flexural reinforcement of the deficient member. However, only a portion of the strength of FRP is effective in the non-prestressed strengthening system. To improve the strengthening efficiency, FRP may be prestressed prior to bonding. This strengthening technique with prestressed FRP offers the benefits of both a bonded system that sustains a significant portion of the load, and a prestressed system that contributes to limiting deformation occurs in the member [3,4].

Although many researchers have investigated the mechanical behavior of the member strengthened with prestressed FRP laminates using either experimental or analytical methods, their studies almost focused on the static performance of the strengthened members [3–8]. With regard to the fatigue behavior, a few of works have been conducted on the strengthened member with non-prestressed FRP [9–19]. In these studies, some have demonstrated that the application of FRP can reduce the longitudinal steel stress and correspondingly increase the fatigue life of the member [9,10]. However, other studies have showed that, while the stress level of reinforcing steel was initially reduced due to the presence of FRP, it subsequently returned to the stress level corresponding to the non-strengthened specimens [11,12]. Local debonding of the interface between FRP and concrete resulting in stress redistribution is believed to explain this behavior [13,14]. Thus, debonding is an important aspect for the strengthened members during the damage procession under fatigue loads.

Recently, an increasing but still limited numbers of studied have been directed to investigate the fatigue behavior of concrete member strengthened with prestressed FRP. A cyclic load test on reinforced concrete (RC) slabs strengthened prestressed CFRP showed that strengthening RC slabs with bonded CFRP, especially prestressed CFRP, increases fatigue life [20]. Nevertheless, in the published studies, the attention paid on the fatigue performance of the FRP-concrete interface is not enough, especially the fatigue damages evolvement of such strengthened member. It should be mentioned that the damage evolvement is directly related to the fatigue life of the member, and it is advisable that the engineering designer has a good understanding of the relationship between the cycle number and the fatigue damages. In this study, the main objective is to establish an accumulative damage model to predict

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the fatigue failure process of RC beam strengthened with prestressed FRP. The study reported here is part of a research series into the mechanical behavior of RC beam flexurally strengthened with FRP laminates. In the previous work [21], a set of strengthened beams with non-prestressed FRP were tested under fatigue loads.

2. Experimental program

This section describes the main characteristics of the tested specimens, the properties of their constituent materials, the experimental loading apparatus, the instrumentation and the data acquisition systems.

2.1. Specimens details

A total of ten specimens were designed in this study. The typical geometry and reinforcement of the tested beams are shown in Fig. 1. The specimens were fabricated from ordinary portland cement. The cube compressive strength and the elastic modulus of the concrete are 53.3 MPa and 35.2 GPa, respectively. The internal reinforcement was made of smooth bars, and the main tensile steel exhibited a yield strength of 307 MPa and an elastic modulus of 226 GPa.

All the beams were externally strengthened with a new kind of carbon fiber laminates as indicated in Fig. 1. This FRP laminates was knitted by the pultrusion process with CFRP silks and epoxide resin [22]. The elastic modulus of the FRP laminate was 240 MPa, with an ultimate tensile strength of 2830 MPa. The laminates of 100 mm wide were cut down to the required 1600 mm length, and the FRP laminates have a nominal thick of 0.23 mm.

The FRP laminates were indirectly prestressed by compressing beam in this study. Firstly, the RC beams were eccentrically compressed (Fig. 2a). The FRP was then bonded on the tension face of the beams (Fig. 2b). After the adhesive was cured, the FRP was prestressed by releasing the compressive force (Fig. 2c). A mechanical anchorage system was developed to indirectly prestress the FRP laminates, which is shown in Fig. 2d. The strengthened system was cured for at least one week after releasing prestress in order to keep a stable prestress level before the fatigue test. At the time of testing, the FRP prestress level of the specimens is as shown in Table 1. Prior to testing, all specimens were instrumented with strain gauges. One gauge was placed on the concrete surface, two on the steel bars, and at least two gauges were installed on the FRP, as shown in Fig. 1. Details of the specimens are shown in Table 1.

2.2. Testing procedure

All of the beams were submitted to three-point bending. The static tests were conducted on two specimens to determine the static carrying capacity of the specimens, including non-prestressed Specimen S_0 (control beam) and prestressed Specimen S_p. The fatigue loads were applied in a sinusoidal waveform with a frequency of 10 Hz. The upper limit load in the fatigue test was set to about 60% of the static capacity of the control beam, and the stress ratio was set to 0.1.

The loads were applied with a Material Testing System (MTS) hydraulic actuator of 100 kN capacity controlled by force mode, as showed in Fig. 3. Before testing, the specimens were loaded statically up to a low value for 5 min in order to eliminate the gap. The strains data were measured by a dynamic strain indicator (WaveBook-516E) during the test. The acquisition frequency of readings was set to 100 Hz in order to take more measurement points. Specimens P_{H1} and P_{H2} were designed to investigate the propagation behavior of the fatigue interface cracks. The crack length of the specimens was measured by a microscope (DJCK-2) with a measurement precision of 0.01 mm. All the beams were tested up to failure with the exception of P_{L1}, the test of which was stopped at the 2000,000th cycle.

3. Results and discussion

The experimental results are summarized in Table 1, including the load carrying capacity, the fatigue lives and the failure mode of the specimens. The results obtained from these tests are analyzed in the following, and some comparisons are discussed between these results and those of the previous work on the non-prestressed FRP beams [21]. The main characteristics and the test condition of the specimens in the previous experiments were the same as that in this study, in addition to the different stress ratio of 0.2.

3.1. Static test

FRP debonding following steel yield, as shown in Fig. 4, was the failure mode of the specimens in the static test. The curves of the loads versus the midspan deflection for Specimens S_0 and S_p are shown in Fig. 5.

As shown in the curves, the load carrying capacity of the beam with prestressed FRP is obviously larger than that of the non-prestressed FRP beam. The whole process of loading can be divided into three phases: (1) In the elastic phase, the relationship between the load and the midspan deflection is linear. (2) In the cracking and yielding phase, the same relationship is approximately linear, but the slope of the curve is less than that in the first phase. This is caused by the crack initiation and propagation and then the yield of the tensile steel. (3) In the failure phase, the curves are irregular. It is worth noting that the ductility of Specimen S_0 is better than that of Specimen S_p.

3.2. Fatigue test

3.2.1. Fatigue failure process

The fatigue failure of all beams but specimen P_{L1} occurred as a result of the main steel fracture followed by FRP debonding. The fatigue failure process of the strengthened beams with prestressed FRP is the same as that of the beams with non-prestressed FRP [21], which can be described into the following three stages.

(a) Cracks initiation stage (Fig. 6). In this stage, the concrete stress in the vicinity of midspan FRP reached its tensile strength resulting in the formation of some bending cracks, and then one of which rapidly expanded as the main crack. The generation and expansion of the main crack caused the stress concentration of the FRP-concrete interface at the crack root, leading to the interface soft or local debonding. Although the course of this phase was about 3–5% of the fatigue life, the stiffness of the beams had a rapid degeneration.
(b) Stable damage stage. After the first phase, the propagation of the fatigue cracks entered into a stable stage, but some new bending cracks generated away from midspan. Although the course of this phase was about 92–96% of the fatigue life, there was little change in terms of the deformation of the beam.
(c) Unstable failure stage. With the increase of load cycles, the tensile steel firstly fractured due to fatigue damage accumulation. Then, the cross-sectional stress redistributed resulting in a sudden increase of FRP stress. Thus, the interface

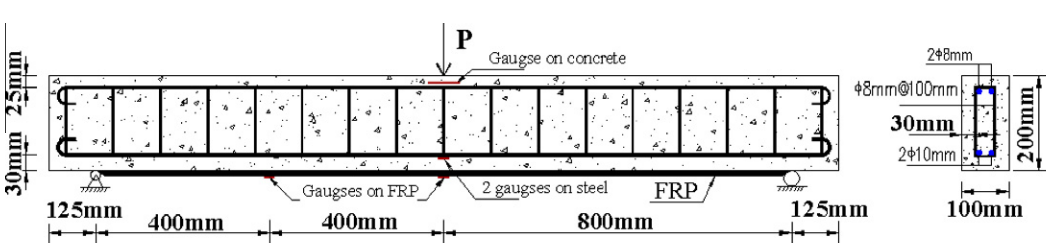

Fig. 1. Concrete beam-geometry, reinforcement and instrumentation details.