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Experimental research on flexural behaviors of damaged PRC beams strengthened with NSM CFRP strips

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HIGHLIGHTS

- PRC beams strengthened with NSM CFRP strips were tested under overloading.
- Influence of cycle number, overload amplitude, and strengthening under loading was investigated.
- The above three variables had limited influence on the ultimate bearing capacity.
- The above three variables affected stiffness and ductility of the strengthened beams.

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ABSTRACT

This paper investigates the flexural behaviors of the damaged prestressed reinforced concrete (PRC) beams strengthened with near surface mounted (NSM) carbon fiber-reinforced polymers (CFRP) strips under overloading. A bending test was carried out to evaluate the effects of three variables: the cycle number, overload amplitude and strengthening under loading or unloading. Different damage degrees were mainly controlled by cycle number and overload amplitude. The test results showed that strengthening with NSM CFRP strips could effectively inhibit crack development. Compared with the un-strengthened beam, the flexural load-carrying and stiffness of the strengthened beams were enhanced evidently. With the increase of cycle number and overload amplitude, the yield loads increased. The yield load of strengthened beam under unloading was higher than that of strengthened beams under loading. These three variables had limited influence on the ultimate bearing capacity. The deformations of the strengthened beams were smaller than that of the control beam, and decreased with the increase of cycle number, but increased with the increase of overload amplitude. The deformations of the strengthened beams under loading were slightly greater than that of the strengthened beam under unloading in the early phase but smaller in the later phase. The ductility of strengthened beams was evidently reduced compared with that of the control beam. The displacement ductility factors of the strengthened beams under loading decreased with the increase of cycle number and overload amplitude, and were smaller than that of strengthened beam under unloading.

1. Introduction

With the increasing scaling-up and heavy-load tendencies of vehicles, the actual traffic volume of a few in-service bridges has exceeded the designed traffic volume. Moreover, the load design standards in new and old bridge design specifications are not uniform, thereby resulting in overload. Operation under an overload situation poses serious harm to the structure of bridge, thus occasionally causing bridge collapse accidents. Moreover, numerous bridges frequently experience overload [1–3]. Although overloaded bridges do not collapse, they pose severe potential structural hazards. The load-bearing properties of the bridges damaged by overloads have become the focus of researchers and engineering personnel. Strengthening of damaged bridges is necessary to improve the bearing capacities and stiffness, and lengthen their service life. Currently, fiber-reinforced polymers (FRP) are commonly used for strengthening [4–8]. The most common FRP strengthening method of reinforced concrete (RC) beams is to externally bond (EB) FRP laminates onto the soffit of a beam [9]. However, the effectiveness of this system is limited by the most common debonding failure mode, which occurs at an effective

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strain much lower than the ultimate strain achievable by the FRP composite materials [10]. In order to maximize the utilization of the FRP materials, the failure mode caused by debonding should be overcome. At present, strengthening with prestressed FRP material and NSM FRP technique have been introduced. The EB prestressed CFRP strips or sheets using nonmetallic necessary anchor systems can increase the load-carrying capacity [11,12]. The NSM FRP strengthening technique has attracted significant attention worldwide as one of the promising new techniques for structural strengthening [8]. NSM FRP technique involves cutting grooves in the concrete cover, filling the grooves with adhesive and embedding FRP bars or strips into the grooves [13,14]. NSM FRP has several advantages over EB FRP, including better protection of the FRP and a stronger bond between FRP and concrete [15]. The NSM technique can increase load carrying capacity significantly and improve the stiffness of the beams. This technique is more effective than EB CFRP reinforcement, provides higher strength capacity and higher utilization of the strips using the same material with the same axial stiffness [14,16–17].

At present, a few studies conducted in China and abroad deal with the mechanical properties of RC structure under overloading [1–3,18–19]. Numerous studies have been conducted on FRP-strengthened RC and PRC structures [20–21]; a relatively greater number of investigations used the NSM CFRP strips to strengthen RC beams [22–24], but only few studies about NSM CFRP strips strengthened PRC beam. For overload damage, X. Y. Sun and R. X. Wang [25–27] studied the mechanical properties of damaged RC beams strengthened with CFRP strips and steel plates under overloading, which results showed that the strengthening effect was mainly influenced by overload amplitude, cycle number, strengthening method and reinforcement ratio, and overload amplitude and cycle number had considerable effects on the service life of beams. However, studies on the influence of overload on PRC beams are seldom. The most direct approach is to study the flexural behaviors of PRC structure strengthened with CFRP strips under overloading to perform a destructive load test. However, considerable bridge collapse risk is apparent when real vehicles are used to conduct the overload test, and test objects are hardly available (bridges may experience severe structural damage, thereby hindering them from continuing service). As stipulated by the American Association of State Highway and Transportation Officials [28], the internal reinforcement stress of bridge member in service ability limit state shall not exceed 60% of the yield stress of the reinforcement, and any value that exceeds this limit shall be considered overload. Hence, in this study, 0.9 and 1.3 times yield load of the control beam are considered upper limits of overload amplitude, and 0.1 times yield load is the lower limit. Cyclic loading is implemented for test beams to simulate the overload damage state. Normally, the occurrence frequency of overload amplitude is low; hence, the cycle numbers are 1, 50, and 100 times. In addition, components that require strengthening in engineering are generally under the loading state. Therefore, strengthening tests with NSM CFRP strips are conducted for damaged PRC beams under overloading to investigate changes in bearing capacity and stiffness with the increase of cycle number and overload amplitude before and after strengthening and the influence of strengthening under loading on flexural behaviors.

2. Experimental program

2.1. Specimen design and production

A total of six specimens, which were all unbonded prestressed concrete T-beams, were designed in the test; one was the control beam, and five were strengthened beams with NSM CFRP strips. All beams had a length of 4.5 m and a net span of 4.3 m. The measured compressive strength of concrete cube was 32.5 MPa at 28 days. The beams were reinforced by two HRB-335 16 mm diameter longitudinal steel bars, four HPB-300 10 mm diameter steel bars, 6 mm diameter stirrups with spacing of 200 mm in the concrete flange, 8 mm diameter stirrups with the spacing of 120 mm in the concrete web, and two 15.2 mm diameter low relaxation seven-wire prestressing steel strands. The steel reinforcement and the CFRP reinforcement ratios were 1.02% and 0.1% respectively. The mechanical properties of steel reinforcements are listed in Table 1. The mechanical properties of CFRP strips and adhesive are listed in Table 2. Details of the beams are shown in Fig. 1. The specimen manufacturing process included reinforcement cage construction, formwork installation, concrete pouring, specimen maintenance, and prestressed steel strand stretching, as shown in Fig. 2.

2.2. Test scheme

A total of three test modes were considered in this process.

(1) Flexural capacity test of control beam (PCB0): flexural behaviors of un-strengthened control beam are studied, and yield load P_y and ultimate load P_{u0} are tested.
(2) Flexural capacity test of strengthened beams under loading (MPCB1-MPCB4): to simulate overload damages, the initial damages are performed on the beams by cycle loading through different cycle numbers and overload amplitudes before strengthening. After the initial damage, these beams are strengthened under different sustained loads. They are inversely erected on the loading device and reloaded to different sustained load 0.9 P_y or 1.3 P_y (MPCB1-MPCB3: 105 kN; MPCB4: 150 kN). The load is kept constant during the CFRP strengthening application. CFRP strips are embedded. Then the load test is continued until the failure after curing period to study the changes in flexural behaviors of beams before and after strengthening with the increase of cycle number and overload amplitude.
(3) Flexural capacity test of strengthened beam under unloading (MPCB5): After cycle loading, CFRP strips are embedded for strengthening under unloading, and the load test is implemented after the curing period to investigate the influence of strengthening under loading or unloading on flexural behaviors of beams.

The design parameters of the test beams are presented in Table 3.

Note: P_y is measured yield load value of control beam PCB0. A = Concrete crushing in the compressive zone. B = Wedge-shaped failure of concrete cover in the tensile zone.

2.3. Loading scheme

Two-point loading was adopted in this test, and the force was transferred to the test beams through spreader beams. A compression-testing machine was used as loading device in the cycle loading phase, as shown in Fig. 3. Test loading was controlled by the load, and the loading rate was 2 kN/s. Loading device under sustained loading is shown in Fig. 4. The deformation was measured by three linear voltage differential transformers (LVDTs), and the strain was recorded through the DH 3816 static strain test system. The concrete layout of strain gauges is shown in Fig. 5.