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Flexural behavior of expansive concrete beams reinforced with hybrid CFRP enclosure and steel rebars

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HIGHLIGHTS

- Hybrid CFRP enclosure and steel rebar reinforcement was proposed to reinforce concrete.
- The expansive concrete beams reinforced with hybrid reinforcement performed best among all tested beams.
- New equations were put forward for calculating the crack width of the beams reinforced with hybrid reinforcement.

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ABSTRACT

To make full use of carbon fiber-reinforced polymer (CFRP) sheets and the advantages of prestressed structures, an expansive concrete beam reinforced with hybrid CFRP enclosure and steel is proposed in this study. Five expansive concrete (EC) beams and five conventional Portland cement concrete (PC) beams were tested under flexure. Reinforcement was designed by considering different layers of CFRP as well as steel reinforcement. Cracking loads, ultimate loads, mid-span deflections, and ductility were collected and analyzed. Test results show that beams reinforced with hybrid reinforcement perform superior than those reinforced only with steel in all aspects. The expansive concrete beams reinforced with hybrid reinforcement perform best among all in both mechanical properties and ductility. In addition, new equations were put forward for calculating the crack width of the beams reinforced with hybrid reinforcement and crack width-load relations are in good agreement with theoretical calculations.

1. Introduction

Due to the deterioration of the concrete and corrosion of reinforcements caused by environmental factors as well as the damage of the structures caused by earthquakes and other natural disasters, an increasing number of reinforced concrete structures have reached the end of their service life and many of the existing buildings must be strengthened or repaired [1–3]. Corrosion of steel has caused huge economic cost to repair and renovate concrete structures. In recent decades, especially after Northridge Earthquake in America and Hanshin-Awaji Earthquake in Japan, CFRP has been widely used for strengthening of structures because of its high strength-to-weight ratio, good fatigue properties, and excellent corrosion resistance [4–6]. Hollaway et al. [7] and Zhou et al. [8] reported that the application of CFRP sheets for strengthening reinforced concrete flexural members increased the cracking load, yield load and ultimate load and decreased deflections and crack width. In addition, it also protected the reinforcement.

Moreover, extensive research and practice in reinforced concrete beams strengthened with externally bonded carbon fiber-reinforced polymer (CFRP) sheets indicated that it is an efficient method for strengthening concrete structures. However, some drawbacks still appear in this processing, such as the deficient use of CFRP due to premature debonding between CFRP and concrete, the complexity of installing process and operation, the lag in CFRP strain as well as the large energy consumption and so on. The CFRP strain lag is because the steel bars have already yielded at the time when the CFRP sheets were installed on the beam. Therefore, the strain of CFRP is much smaller than those of steel bars. As a result, the performance of CFRP is very limited before the yielding of the main reinforcement, and the high strength of CFRP can only be utilized after that.

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Based on these, researchers proposed to use prestressed CFRP sheets to strengthen the structures and conducted comparative experiments versus unprestressed CFRP repaired structures. Experimental results indicated that the increment in cracking load, yield load and ultimate load of prestressed-CFRP strengthened beams were much higher than those of unprestressed CFRP reinforced beams [3,9,11,13]. It was also found that crack propagation was restrained and deflection of beams was decreased by prestressed CFRP strengthening. Additionally, it can avoid peeling failure to a certain extent so that the strength of CFRP can be fully utilized [2,3,9–14]. At the same time, research has also showed that strengthening with prestressed CFRP sheets displayed better anti-fatigue performance [15–18].

However, for a long time, the lack of anchorage schemes and prestressing equipments for CFRP sheets, the complexity of installing process and operation, and the large energy consumption of the mechanically prestressing method has limited the strengthening and rehabilitation of structures using FRP. To solve this problem, Cao and Ma [19] proposed a CFRP externally reinforced expansive concrete structural system and experimentally validated the prestress in the system. The prestress was generated by the expansion of the core concrete and the restraint of the external FRP reinforcement. This way, the anchorage instrument preparation and energy consumption of mechanical pretensioning of FRP were avoided. It also demonstrated that the corrosion of steel was eliminated and cracking resistance and ultimate capacity were improved. However, it was found that the cracking width was larger compared with control steel reinforced beam [20]. To improve the cracking control performance, it is critical to investigate the behavior of steel-CFRP double reinforced expansive concrete beams which have not been studied.

2. Experimental program

2.1. Materials

Concrete was designed with 28-day strength of 40 MPa. Expansive agent was added at 10% of cementitious materials in mass to obtain high expansion [20,21]. Expansion and shrinkage of concrete was recorded by an automatic shrinkage measurement apparatus using 100 mm × 100 mm × 400 mm prisms as shown in Fig. 1. The compressive strength, splitting tensile strength and modulus of elasticity of concrete were tested by using 150 mm × 150 mm × 150 mm cube, 150 mm × 150 mm × 150 mm cube and 150 mm × 150 mm × 300 mm prism specimens respectively according to GB/T50081-2002 [22]. The mix proportion and

Fig. 1. Expansion test setup.

material properties of EC (expansive concrete) and PC (Portland cement concrete) are shown in Table 1 and Table 2 respectively. Steel rebar reinforcement and carbon fiber reinforced polymer reinforcement (CFRP) used in this experiment were tested according to GB/T 228-2002 [23] and GB/T 3354-2014 [24] respectively, and the tested mechanical properties are shown in Table 3.

2.2. Specimen design

All beam specimens are 1000 mm long with a sectional dimension of 120 mm × 180 mm and a clear span of 900 mm. The CFRP sheets were fabricated by manual lay-up process in the laboratory and serve as prefabricated formwork for casting concrete.

The detailed steel reinforcement layout in the beam specimen is shown in Fig. 2. For comparing the different mechanical properties and ductility of the beams, two kinds of concretes were tested consisting of regular Portland cement concrete and expansive concrete. A total of five expansive concrete beams and five Portland concrete beams were casted. The parameters of each beam are listed in Table 4. The numbers in parenthesis indicate the reinforcement ratio of each specimen. For consistency, CFRP reinforcement has been converted to steel reinforcement in accordance with the equal stiffness method ($E_{steel}A_{steel} = E_{frp}A_{frp}$). All beam specimens were fabricated in the laboratory and then cured at room temperature for 28 days before structural test.

2.3. Specimen fabrication process

For the beams with CFRP enclosure, the CFRP enclosures were made first in the laboratory which consisted of two steps. Firstly the previously-cut CFRP sheets were wrapped around the wooded frame which was the same size as the beam and saturated with the epoxy resin adhesive as shown in Fig. 3(a). After the epoxy resin solidified at room temperature which taken about 24 h, the CFRP enclosure was taken down from the wooden frame, see Fig. 3(b). Then the CFRP enclosure and the steel reinforcement cage were put into the wooden mould before the concrete was poured in, see Fig. 3(c). After the concrete was poured in, the beams were cured for 28 days until the testing program began.

For the beams without CFRP enclosure, all the fabrication process was the same but without putting the CFRP enclosure into the wooden mould.

2.4. Testing program

Four point bending tests were conducted at a 5000 kN MTS test machine. The loading speed was 0.05 kN/s. The load was recorded by a load cell with a capacity of 300 kN. Three linear variable displacement transducers (LVDTs) were positioned in the mid-span as well as two supports to record the displacement during loading process. The pre-arranged strain gauges on the reinforcement and CFRP sheets were aimed to record strain data. At the same time, three strain gauges were also applied along the mid-span section to verify whether plain section remains plane. Fig. 4 shows beam test setup with locations of LVDTs and strain gauges. All the data were collected by data acquisition system. Type DTCK-2 device was employed to measure the crack width at the end of each loading step, as seen in Fig. 5.

3. Results and discussion

3.1. Cracking load and ultimate load

Because the 28-day compressive strength of Portland cement concrete and expansive concrete are different, the cracking loads and ultimate loads were adjusted by dividing $f_c \times b \times h \times 10^{-6}$ so as to obtain dimensionless values for comparison. The tested cracking loads, ultimate loads and their adjusted values are listed in Table 5. Figs. 6 and 7 show the comparison of adjusted cracking loads and ultimate loads of the two kinds of concrete beams with different reinforcement ratios. From Fig. 6, it demonstrated that, as expected, cracking load increased as the layers of CFRP sheets increased for the beams reinforced by steel and CFRP. But this trend is not proportional, when CFRP sheets layers increased from one to two, the enhancement of cracking load is more than 40%; when the CFRP sheets layers increased from two to three, the enhancement of cracking load is about 1.68% for PC and 3.69% for EC. At the same time, the cracking loads of them are all higher than the beams reinforced by individual steel (SR- specimen) or individual CFRP (CFRP- specimen). The cracking load of F11-SR-P, F22-SR-P and F33-S-P are 184%, 261% and 271% respectively of that of SR-P which represents the regular reinforcement layout. Similarly,