Construction and Building Materials 161 (2018) 587–597

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Flexural behavior of partially fiber-reinforced high-strength concrete beams reinforced with FRP bars

Haitang Zhu [a], Shengzhao Cheng [a,*], Danying Gao [a,b], Sheikh M. Neaz [c], Chuanchuan Li [a]

[a] School of Water Conservancy & Environment, Zhengzhou University, Zhengzhou 450001, China
[b] Henan University of Engineering, ZhengZhou 451191, China
[c] School of Civil, Mining and Environmental Engineering, University of Wollongong, Wollongong, NSW 2522, Australia

HIGHLIGHTS

- The behavior of partially fiber-reinforced high-strength concrete beam was investigated.
- The optimum thickness of FRHSC layer was 0.57 times of the total depth of the beam.
- The addition of steel fibers only in the tension zone reduced the ductility of the beam.
- A simplified calculation method for predicting the moment of inertia of FRHSC beams was developed.

ARTICLE INFO

Article history:
Received 23 March 2017
Received in revised form 17 August 2017
Accepted 1 December 2017

Keywords:
Partially fiber reinforced concrete
BFRP bar
Steel fiber
Flexural behavior
Numerical calculation

ABSTRACT

In this paper, the flexural behavior of partially fiber-reinforced high-strength concrete (FRHSC) beams reinforced with FRP bars was investigated. A total of 12 beams were tested under four-point bending. The effects of the thickness of FRHSC layer, steel fiber volume fraction and FRP reinforcement ratio were studied. The failure mode, flexural capacity, deflection, crack width and ductility of the tested beams were investigated. The results showed that adding steel fibers in tension zone is an effective way to overcome the large deflection and large crack width of FRP bar reinforced concrete beams and reduce the cost, however, the ductility of tested beams decreased with the addition of steel fiber into tension zone. The optimum thickness of FRHSC layer in FRP bar reinforced concrete beams was 0.57 times of the total depth of the beam. Higher FRP reinforcement ratio provided better flexural performance including higher flexural capacity, post-cracking stiffness and ductility and smaller crack width. A simplified calculation method for predicting the effective moment of inertia of fully and partially FRHSC beams reinforced with FRP bars was developed. The beam deflections calculated by the proposed method match well with the experimental results.

1. Introduction

The durability of reinforced concrete structures is regarded as a major concern due to the corrosion of steel reinforcement. Reduction of mechanical strength of reinforced concrete structures and poor bond behavior between steel and concrete are often caused by the corrosion of steel reinforcement. Significant efforts have been devoted to in recent years to overcome the problems associated with the corrosion of steel reinforcement in reinforced concrete structures including the use of galvanized steel reinforcement [1] or addition of rust inhibitor in concrete [2].

In recent years, Fiber Reinforced Polymer (FRP) bar is considered an ideal alternative to steel reinforcing bar [3]. Compared to the traditional steel reinforcing bars, FRP bars have the characteristics of corrosion resistance, high specific strength and superior manufacturability [4]. However, the stress-strain behavior of FRP bars is linear without any obvious yield point. Also, FRP bar reinforced concrete members fail in a brittle manner. Furthermore, compared to steel reinforcing bars, the modulus of elasticity of the FRP bar is significantly low and the bond between FRP bar and concrete is relatively weak. Thus, large deflection and large crack width are often observed in FRP bar reinforced concrete structures [5]. Due to the linear stress-strain behavior and low modulus of elasticity of the FRP bar, the design of FRP bar reinforced concrete structures is usually controlled by the serviceability limit state requirements [6]. Hence, the high strength of FRP

* Corresponding author.
E-mail address: chengshengzhao@aliyun.com (S. Cheng).

https://doi.org/10.1016/j.conbuildmat.2017.12.003
0950-0618/

bars cannot be fully exploited and hence the engineering applications of FRP bars are still limited.

To mitigate the disadvantages of FRP bars, new FRP bar and FRP reinforcement system were investigated in a few research studies. For example, hybrid FRP bars were fabricated with different continuous fibers. Herris et al. [7] reported that stress-strain behavior of steel can be simulated by hybrid FRP bars which combined different types of fibers. The ductility of hybrid FRP bar reinforced concrete beams was found to be close to the corresponding steel bar reinforced concrete beams. However, the complex fabrication process and high manufacturing cost of hybrid FRP bars have limited the engineering applications of hybrid FRP bars in concrete structures. A new reinforcement system consisted of FRP bars and steel bars was also proposed in Qu et al. [8]. It was reported that reinforcing concrete beams with both FRP bars and steel bars was an effective way for improving the serviceability and ductility of FRP bar reinforced concrete beams. However, the corrosion of steel bars was not fully mitigated in the proposed hybrid reinforcement system in Qu et al. [8]. Hence, the corrosion of steel reinforcement still remains a critical issue for the hybrid reinforcement system.

Recently, in a few research investigations, it was observed that the deflection and crack width of FRP bar reinforced concrete beams were restrained and the ductility was improved by the addition of randomly distributed fibers [9,10]. It is well known that the influence of fibers on the deflection and crack is mainly achieved by the fibers in the tension zone of concrete beams. The addition of fibers in a partial depth (in the tensile zone) of concrete beams can not only achieve the full effect of fibers but also can provide a considerable cost saving [11,12]. Therefore, the addition of fibers in a partial depth of FRP bar reinforced concrete beams may be a possible way to improve the flexural behavior and to reduce cost. The positive effect of fibers on flexural behavior of fiber reinforced concrete (FRC) beam reinforced with FRP bar was investigated in the literature. However, the flexural behavior of partially FRC beams has not yet been investigated adequately. Thus, the flexural behavior of partially FRC beams reinforced with FRP bars needs to be extensively investigated.

In this paper, the flexural behavior of partially fiber-reinforced high-strength concrete (FRHSC) beams reinforced with FRP bars including flexural capacity, deflection response, cracking response and ductility was investigated. In total 11 FRP bar reinforced partially FRHSC beams with various thicknesses of FRHSC layer, steel fiber volume fractions and FRP reinforcement ratios and one traditional steel bar reinforced FRHSC beams were cast and tested. The tested beam deflections at service loads were compared with the beam deflections calculated according to ACI 440.1R-15 for short term service load deflections. Considering the positive effect of steel fibers on beam deflection, a simplified method for beam deflection has been developed which was based on appropriate calculations of the effective moment of inertia of fully and partially FRHSC beams reinforced with FRP bars.

2. Experimental program

2.1. Materials and mix proportion of concrete

River sand with a maximum particle size of 5 mm was used as fine aggregate. Crushed limestone with the size ranging from 5 to 20 mm was used as coarse aggregate. Type Ⅰ Portland cement and fly ash (FA) were used as cementitious materials. Polycarboxylic acid water reducing agent was used to improve the workability of concrete. Five types of reinforcing bars were used in this experimental investigation: steel bars with diameters of 6 mm, 10 mm and 14 mm and basalt FRP (BFRP) bars with diameters of 12 mm and 14 mm. The surfaces of FRP bars were deformed to improve the bond performance between FRP bars and concrete. The mechanical properties of reinforcing bars are shown in Table 1. The fibers used in FRHSC are hooked steel fibers. The properties of the fibers are reported in Table 2 and shapes of steel fibers are shown Fig. 1. In the experimental program, five concrete mix proportions were designed and used, as reported in Table 3.

2.2. Test specimens

In this study, a total of 12 beam specimens were cast and tested under four-point bending. The specimen dimensions and reinforcement details are shown in Fig. 2 and Table 4. All tested beam specimens were 2100 mm long with 150 mm × 300 mm cross-section. The clear span of the beam specimens under four-point bending was 1800 mm. The concrete clear cover for the tension reinforcement was 25 mm. Each beam specimen was reinforced laterally with 10 mm diameter steel stirrup at a center-to-center spacing of 75 mm in the shear region. Compression reinforcements and stirrups were not used in the test zone (Fig. 2). It is noted that the test zone is under pure bending moment without any shear stress. Although the length of the steel fiber is greater than the thickness of concrete cover, the distribution of steel fibers in the pure bending region is not significantly affected by the concrete cover. The steel fibers with 0–2% by volume were added to the FRHSC (the depth is 90 mm–300 mm). Eleven beam specimens were reinforced longitudinally with FRP bars having the diameter of 12 mm and 14 mm and one beam specimen was reinforced longitudinally with steel bars having the diameter of 14 mm. The longitudinal reinforcement ratio of the beam specimens varied from 0.56% to1.65%. Meanwhile, the standard specimens with the size of 150 mm × 150 mm×150 mm were used for compressive strength test and splitting tensile strength test. Prisms with the size of 150 mm × 150 mm×300 mm were cast and tested for modulus of elasticity. The specimens were made of two types of concrete, i.e. plain concrete and FRHSC with the target compressive strength of concrete was equal to 60 MPa.

In the specimen identification in Table 4, the first character indicates the longitudinal reinforcement type, where B represents BFRP bar and S represents steel bar. The second character in the specimen identification indicates the steel fiber volume fraction, where 0 represents 0% by volume of steel fiber, 1 represents 0.5% by volume of steel fiber, 2 represents 1% by volume of steel fiber, 3 represents 1.5% by volume of steel fiber and 4 represents 2% by volume of steel fiber. The third character in the specimen identification indicates the steel fiber reinforcement form, where A represents fully steel fiber reinforced and P represents partially steel fiber reinforced. The forth character in the specimen identification indicates the longitudinal reinforcement area, where 1 represents 2Φ12, 2 represents 2Φ14, 3 represents 3Φ14 and 4 represents 4Φ14. The fifth character in the specimen identification represents the thickness of FRHSC layer in partially steel fiber-reinforced beams, where 1 represents 90 mm, 2 represents 130 mm, and 3 represents 170 mm.

2.3. Test setup and measurements

All beams were simply supported and were tested under the four-point bending, as shown in Fig. 3. The load was increased monotonically until beams failed. Before the appearance of the first crack, each load stage was 3 kN and after the appearance of the first crack, each load stage was 10 kN. All the deflections, strains in the reinforcement and concrete, crack widths and crack distributions were recorded after 3 mins of sustained loading. The deflections at mid-span, at two loading points, at two mid-points between the center of the beam and the loading points, and at supports were measured by seven linear voltage differential trans-