Research on deformation characteristics and design method of concrete beams reinforced with GFRP bars

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Abstract. Two different glass fiber reinforced polymer (GFRP) bars were produced to reinforce concrete beams, including plain GFRP bars and ribbed surface GFRP bars. The flexural property of GFRP reinforced concrete beams was studied by testing four specimen beams under two point vertical loads. The crack development and stain distribution of beam cross section during loading were recorded, and the deformation characteristics and failure mode were also analyzed in this experiment. According to the test results, the bond property of plain GFRP bars was too poor to serve as reinforcement bars, while the ribbed surface GFRP bars showed good bond performance and worked well with concrete before final failure. The test beam reinforced with ribbed surface GFRP bars exhibited a uniform crack distribution, and the strain agreed with the assumption of plane cross section. Moreover, calculation method for bending capacity of concrete beam strengthened with GFRP bars was deducted based on this experiment.

1. Introduction

The high tensile strength, light weight and corrosion resistance of fiber reinforced polymer (FRP) bars make it an alternative reinforcement to strengthen concrete structure exposed in severe condition, such as salt environment and marine engineering [1-3]. FRP bars reinforced concrete structures possess relatively lighter weight and better durability compared to normal reinforced concrete structures. At present, the most adopted FRP bars in concrete structure are carbon FRP bars, glass FRP bars and aramid FRP bars.

A total of four specimen beams reinforced with GFRP bars were tested under two point vertical loads to investigate strain distribution of beam section, then a design method for FRP reinforced concrete structure members in bending was proposed according to test results, which will be of great significance to provide a theoretical basis for the design of concrete structures reinforced with FRP bars and promote their application in practical engineering.

2. Specimen details

Two groups of specimens were tested in total, group A and group B. Group A contained two beams (No. PGB-1 and PGB-2) with a 180×250 mm rectangular cross section and a total length of 1900 mm, and group B comprised two beams (No. SGB-1 and SGB-2) with a 150×200 mm rectangular cross section and a total length of 1300 mm. The upper longitudinal bars of two specimens in group A were both two steel bars with a 14mm diameter, and the lower longitudinal bars were two plain GFRP bars and three plain GFRP bars, respectively. Similarly, the upper longitudinal bars of two beams in group B were two steel bars with a 12mm diameter, and the lower longitudinal bars were two ribbed surfaced

GFRP bars and three ribbed surface GFRP bars, respectively. The stirrups of two groups were steel bars with a 10mm diameter and 100mm space.

According to test results of basic mechanical properties of raw materials, the compressive strength of cubic concrete specimen was measured to be 31.5 MPa, and the yield strength of HPB235 and HRB335 used in the experimental program was 308 MPa and 380 MPa, respectively.

3. Test results and discussion

3.1. Failure mode

As shown in figure 1 and figure 2, there were few cracks on the side surface of specimen PGB-1 and PGB-2, and bond failure and slip occurred between the plain GFRP bars and the surrounding concrete with the GFRP bars pulled out while collapsing, indicating that plain GFRP bars were not able to strengthen concrete structure owing to their poor bond capacity. As for specimen SGB-1 and SGB-2, it could be judged from considerable quantity and uniform distribution of cracks that the member possessed good energy dissipation capacity. Eventually, specimen SGB-1 presented a fracture failure mode due to diagonal cracks traversing deeply into the compression zone making it fail to resist the shear force, while SGB-2 failed as a result of the crushing of the confined concrete on the top of the beam inside the pure bending zone.

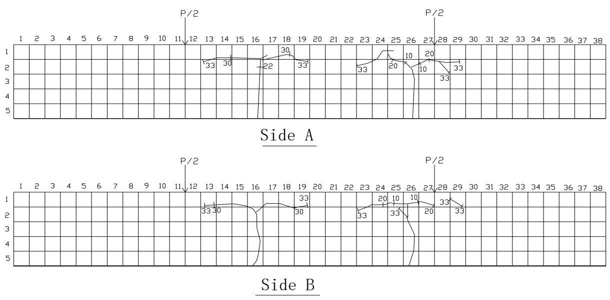

Figure 1. Crack patterns of PGB-1.

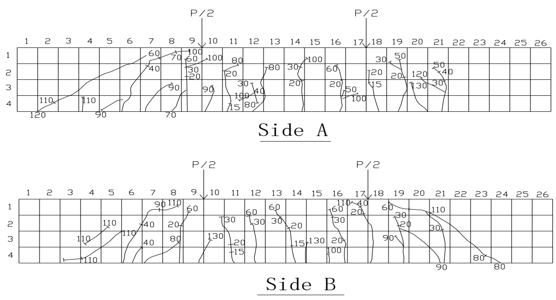

Figure 2. Crack patterns of SGB-2.

3.2. Cross section strain distribution

In this section, cross section strain distribution of GFRP reinforced concrete beam under different load was measured and illustrated in figure 3 for specimen SGB-1 and in figure 4 for SGB-2. It can be figured out that the strain distribution meets with the plane section assumption.

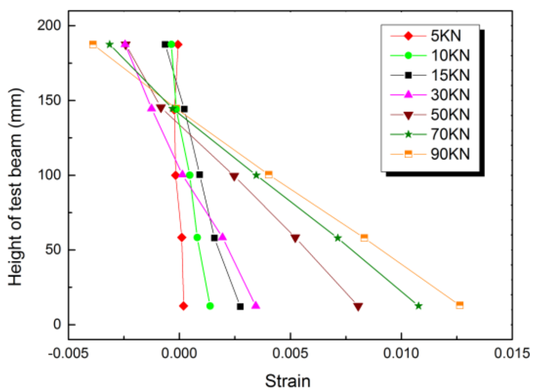

Figure 3. Strain distribution of SGB-1.

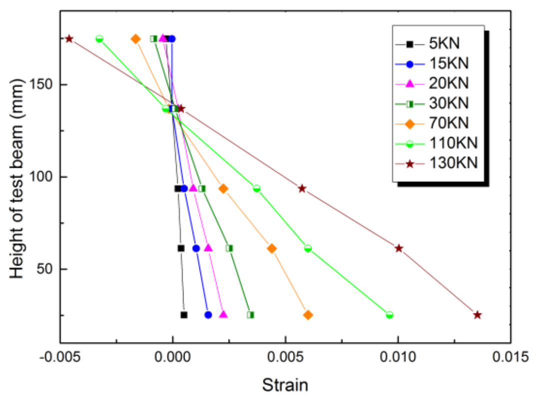

Figure 4. Strain distribution of SGB-2.

4. Calculation method for flexural capacity

Reinforced Concrete Structure Design Code can be referred to while calculating bending capacity of concrete beams reinforced with FRP bars. There are four essential assumptions as follows: ①Ignore the role of concrete in tension after crack appearing. ②Stress-strain relationship of FRP bars is linear elastic [4]. ③Ultimate compressive strain of concrete is 0.0033 [5]. ④There is no slip between FRP bars and the surrounding concrete before ultimate limit states.

Based on test results, FRP reinforced concrete beams were more likely to fail in two modes: One is tensile fracture of FRP bars anterior to concrete crushing, which is called failure mode I. This failure is unsafe for the design of concrete structure. Another is called failure mode II, and this failure is caused by the crushing of concrete in compression zone, and at this time, the strain of FRP bars doesn't reach or exceed the permissible strain.

The balance relative depth of compression zone of FRP reinforced concrete beam can be calculated by the following Equation (1):

$$\xi_b = \frac{0.8}{1 + \dfrac{f_{fu}}{0.0033E_f}} \tag{1}$$

Where, f_{fu} is design strength of FRP bars, and E_f is elastic modulus of FRP bars, in MPa.

When the relative depth of compression zone ξ_f satisfies with the condition $\xi_f \leq \xi_b$, the FRP reinforced beam will fail in failure mode I. Then ξ_f can be calculated as:

$$\xi_f = \frac{f_{fy}A_f}{\alpha_1 f_c b h_0} \tag{2}$$

Where, f_{fy} is design strength of FRP bars, A_f is area of FRP bars in tension (mm^2), α_1 is a coefficient which can refer to *Reinforced Concrete Structure Design Code* in China, and h_0 is effective depth of section.

When ξ_f meets the condition $\xi_f \geq \xi_b$, the FRP reinforced beam will fail in failure mode II. Then, ξ_f is given by Equation (3):

$$\alpha_1 f_c b \xi_f h_0 = \sigma_f A_f - f_y' A_s' \tag{3}$$

Where, $\sigma_f = \varepsilon_f E_f = 0.0033 \dfrac{0.8 - \xi_f}{\xi_f} E_f$, $\sigma_s' = \varepsilon_s' E_s' = 0.0033 \dfrac{\xi_f - 0.8a_s'(h_0)^{-1}}{\xi_f} E_s'$, σ_f is stress of FRP bars in tension, and σ_s' is stress of steel bars in compression.

Hence, the Equation (3) can be written as the following form,

$$\alpha_1 f_c b \xi_f^2 h_0 + 0.0033(E_f A_f + E_s' A_s')\xi_f - 0.0033 \times 0.8(E_f A_f + \frac{a_s'}{h_0} E_s' A_s') = 0 \tag{4}$$

The relative depth of compression zone ξ_f can be calculated from Equation (4). Finally, the ultimate bending capacity can be calculated by the formula given in Equation (5):

$$M_u = f_c \xi_f (1-0.5\xi_f) b h_0^2 + \sigma_s' A_s' (h_0 - a_s') \tag{5}$$

Table 1. Comparison between test and calculation results.

Number of test beam	SGB-1	SGB-2	PGB-1	PGB-2
①Experimental ultimate load(KN)	100	130	33	58
②Experimental bending capacity (KN·m)	20	26	8.3	14.5
③Calculated bending capacity (KN·m)	18.7	23.5	22.3	29.4
②/③	1.07	1.11	0.37	0.49

Bending capacity of test beams calculated by proposed equation in this research were compared with experimental values as illustrated in table 1. Close agreement was found between values calculated by the formula proposed in this paper and the experimental results.

5. Conclusions

The results of two-point bending tests, which were conducted on beams reinforced with CFRP and steel bars, were presented in this paper. The following conclusions can be summarized:

(1) The plain GFRP bars possess poor bond performance with surrounding concrete, which results in their unable to reinforce concrete structure.

(2) The ribbed surface GFRP bars showed good bond capacity and worked well with concrete before final failure, and the strain distribution of beam cross-section satisfied with the plane section assumption.

(3) FRP reinforced concrete beams presented brittle characteristics while collapsing under loads. The deflection and crack were much larger than that of reinforced concrete beams.

(4) The failure mode II is recommended when designing concrete beam reinforced with FRP bars. Steel bars can be placed in the compression zone and FRP bars can be placed in the tension zone of concrete beam in order to improve the ductility of structure.

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