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Experimental research on the anti-cracking capacity of concrete beams reinforced with glass fiber-reinforced polymer bars

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Abstract: The cracking moment of concrete beams reinforced with glass fiber-reinforced polymer (GFRP) bars is an important index for measuring the anti-cracking capacity, and which is also an important parameter to calculate the crack width, deflection and mechanical properties of concrete beams reinforced with GFRP bars. Based on the calculation method for cracking moment of RC beams, combined with tensile strain relationship of concrete, the method of calculating the cracking moment of concrete beam reinforced with GFRP bars which is connected with the calculation method of cracking moment of reinforced concrete beam is deduced. To study the influence rule of reinforcement ratio of GFRP bars and the concrete strength on cracking moment, the experiments on flexural capacity of 14 concrete beams reinforced with GFRP bars were carried out. The accuracy of the proposed calculation method has been verified by comparing the predictions with the experimental results. The results show that the design method can be used to calculate the cracking moment of GFRP RC double reinforcement section beams.

Keywords: GFRP bar, concrete beams, cracking moment, experimental research

1 Introduction

Fiber-reinforced polymer (FRP) bars have good corrosion resistance, high tensile strength, lighter weight, lower elastic modulus, lower shear strength and non-magnetic properties compared to steel. At present, commercially available FRP can be divided into glass FRP (GFRP), carbon FRP (CFRP), aramid FRP (AFRP) and basalt FRP (BFRP) by the type of fibers used [1]. In the last three decades, FRP bars have emerged as an alternative solution of steel reinforcement to overcome the corrosion in extreme environments [2]. In addition to improve the durability of reinforced concrete, FRP bars have been used in concrete structure where magnetic neutrality or easy cutting requirement is required [3].

The cracking moment of concrete beams reinforced with FRP bars is an important index for measuring the anti-cracking capacity. Which is also an important parameter to calculate the crack width, deflection and mechanical properties of concrete beams reinforced with FRP bars [4], therefore, it is necessary to research the anti-cracking capacity of concrete beams reinforced with FRP bars. Presently the research on the cracking moment of FRP RC beams is mostly confined to concrete beams reinforced with single FRP bar [5-6]. There are few studies on the cracking moment of concrete beams reinforced with double FRP bars and the calculation methods to the cracking moment of FRP reinforced concrete flexural members [7-8]. When calculating the cracking moment of concrete beams, the elastic moment of inertial of the section is adopted directly by the US specification AC1440, without consideration of the plastic deformation of concrete in tension zone [3]. Therefore, in this paper, the crack resistance of concrete beam with GFRP bars is studied by the bending test results of 14 concrete beams reinforced with GFRP bars and the calculation method of the cracking moment of concrete beams reinforced with double GFRP bars is given. Lastly, the design equation of cracking moment of rectangular section of concrete beam with FRP bars is presented.

2 Design equations for cracking moment

2.1 Basic assumption

Referring to ACI 440.1R-06 [3], the following assumptions are made in calculating the cracking moment of RC beams reinforced with GFRP bars:

1) A plane section before loading remains plane after loading;
2) The stress-strain curve of GFRP reinforcement is idealized as linear elastic to failure;
3) There is a perfect bond between the GFRP reinforcement and the concrete; and
4) The stresses in the concrete can be computed from the strains by using stress-strain curves for concrete; according to GB50010-2010 [9], the stress-strain relationship of concrete in compressive is as follows:

$$\sigma_c = f_{cd}\left[\frac{2\varepsilon_c}{\varepsilon_0} - \left(\frac{\varepsilon_c}{\varepsilon_0}\right)^2\right], \quad \text{when} \quad 0 \le \varepsilon_c \le \varepsilon_0 \tag{1}$$

$$\sigma_c = f_{cd}, \quad \text{when} \quad \varepsilon_0 \le \varepsilon_c \le \varepsilon_{cu} \tag{2}$$

where σ_c and f_{cd} are the stress and the design compressive strength of concrete, respectively; ε_c and ε_{cu} are the concrete strain and the concrete ultimate compressive strain, respectively; ε_0 is the peak compressive strain of concrete.

According to the literature [4, 10], the simplification stress-strain relationship of concrete in tensile is as follows:

$$\sigma = f_t \frac{\varepsilon}{\varepsilon_{t0}}, \quad \text{when} \quad 0 \le \varepsilon \le \varepsilon_{t0} \tag{3}$$

$$\sigma = f_t \left(1 - \alpha \frac{\varepsilon - \varepsilon_{t0}}{\varepsilon_{tu} - \varepsilon_{t0}}\right), \quad \text{when} \quad \varepsilon_{t0} \le \varepsilon \le \varepsilon_{tu} \tag{4}$$

where f_t is the design tensile strength of concrete, $f_t = E_c \varepsilon_{t0}$, $f_t = 0.26 f_{cu}{}^{2/3}$; ε_{tu} is the concrete ultimate tensile strain; ε_{t0} is the peak tensile strain of concrete; α is a coefficient.

2.2 Design equations

When the concrete beam reinforced with GFRP bars is about to crack, the strain of concrete in compression zone is small, the relationship between stress and strain presents a linear feature. The strain and the stress distribution in the cross section is shown in Fig. 1, the cracking moment can be calculated by internal force balanced method. The cracking moment M_{cr} of GFRP RC beams is calculated by the following equation:

$$M_{cr} = M_c + M_f = f_t W_s \tag{5}$$

where M_c is the moment of concrete, including the moment caused by concrete in compression zone, elastic part and plastic part of concrete in tension zone; M_f is the moment of GFRP bars, including the moment caused by GFRP bars in compression and tension zone; W_s is the elastic plastic resistance moment of GFRP RC beam section considering the plastic deformation of concrete in the tensile region.

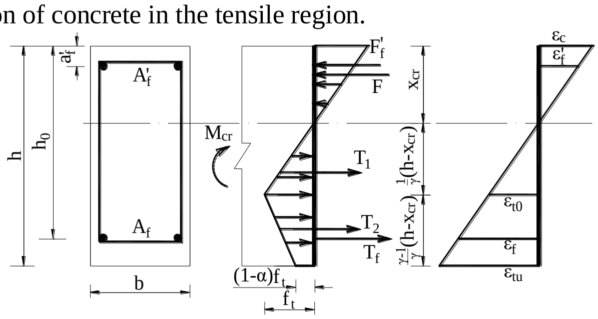

Figure 1. Distribution of stress-strain relationship

For the convenience of calculation, assuming linear relationship between the stress and the strain of concrete, the concrete edge strain ε_c in compression zone is calculated

$$\varepsilon_c = \frac{x_{cr}}{(h - x_{cr})/\gamma} \varepsilon_{t0} \tag{6}$$

where $\gamma = \varepsilon_{tu}/\varepsilon_{t0}$; x_{cr} is the depth of neutral axis; h is the height of beam.

The concrete resultant force D in compression zone can be expressed as Eq. (7):

$$D = \frac{\gamma f_t b x_{cr}{}^2}{2(h - x_{cr})} \tag{7}$$

The tensile force T_1 of the concrete elastic part in tension zone can be expressed as Eq. (8):

$$T_1 = \frac{f_t b}{2\gamma}(h - x_{cr}) \tag{8}$$

The tensile force T_2 of the concrete plastic part in tension zone can be expressed as Eq. (9):

$$T_2 = \frac{(\gamma - 1)(2 - \alpha) f_t b (h - x_{cr})}{2\gamma} \tag{9}$$

The tensile strain ε_f of GFRP bars in tension zone which is shown in Eq. (10):

$$\varepsilon_f = \frac{h_0 - x_{cr}}{h - x_{cr}} \varepsilon_{tu} \tag{10}$$

The tensile force T_f of GFRP bars in tension zone can be expressed as Eq. (11):

$$T_f = E_f \varepsilon_f A_f = n_f \gamma f_t A_f \frac{h_0 - x_{cr}}{h - x_{cr}} \tag{11}$$

where $n_f = E_f / E_c$; E_f is the tensile modulus of elasticity of GFRP bars; h_0 is the effective height of beam; A_f is the cross section area of GFRP bars in tension zone.

The compressive strain ε_f' of GFRP bars in compression zone which is shown below:

$$\varepsilon_f{}' = \frac{x_{cr} - a_f{}'}{(h - x_{cr})/\gamma} \varepsilon_{t0} \tag{12}$$

The compressive force T_f' of GFRP bars in compression zone can be calculated by Eq. (13):

$$D_f = E_f'\varepsilon_f' A_f' = n_f'\gamma f_t A_f' \frac{x_{cr} - a_f'}{h - x_{cr}} \tag{13}$$

where $n_f' = E_f'/E_c$; E_f' is the compressive modulus of elasticity of GFRP bars; a_f' is the depth of GFRP bars in compression zone; A_f' is the cross section area of GFRP bars in compression zone.

According to Fig. 1, by considering equilibrium of internal forces, Eq. (14) is obtained

$$\frac{f_t b}{2\gamma}(h - x_{cr}) + \frac{(\gamma-1)(2-\alpha) f_t b(h - x_{cr})}{2\gamma} + n_f \gamma f_t A_f \frac{h_0 - x_{cr}}{h - x_{cr}} = \frac{\gamma f_t b x_{cr}^2}{2(h - x_{cr})} + n_f'\gamma f_t A_f' \frac{x_{cr} - a_f'}{h - x_{cr}} \tag{14}$$

The depth of neutral axis x_{cr} is obtained by solving Eq. (14)

$$x_{cr} = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \tag{15}$$

where $A = \gamma^2 - [1 + (\gamma-1)(2-\alpha)]$; $B = 2h[1 + (\gamma-1)(2-\alpha)] + (2\gamma^2/b)(n_f A_f + n_f' A_f')$;
$C = -h^2[1 + (\gamma-1)(2-\alpha)] - (2\gamma^2/b)(n_f A_f h_0 + n_f' A_f' a_f')$.

Based on equilibrium conditions and compatibility conditions (shown in Fig. 1), the following equations can be obtained:

$$M_c = \frac{\gamma f_t b x_{cr}^3}{3(h - x_{cr})} + \frac{f_t b(h - x_{cr})^2}{3\gamma^2} + \frac{(3\gamma + 3 - 2\alpha\gamma - \alpha)(\gamma - 1) f_t b(h - x_{cr})^2}{6\gamma^2} \tag{16}$$

$$M_f = \frac{\gamma n_f f_t A_f}{h - x_{cr}}(h_0 - x_{cr})^2 + \frac{\gamma n_f' f_t A_f'}{h - x_{cr}}(x_{cr} - a_f')^2 \tag{17}$$

The design equation of cracking moment M_{cr} of GFRP RC beams is obtained from Eq. (5), (16) and (17):

$$M_{cr} = \frac{\gamma f_t b x_{cr}^3}{3(h - x_{cr})} + \frac{f_t b(h - x_{cr})^2}{3\gamma^2} + \frac{(3\gamma + 3 - 2\alpha\gamma - \alpha)(\gamma - 1) f_t b(h - x_{cr})^2}{6\gamma^2} + \frac{\gamma n_f f_t A_f}{h - x_{cr}}(h_0 - x_{cr})^2 + \frac{\gamma n_f' f_t A_f'}{h - x_{cr}}(x_{cr} - a_f')^2 \tag{18}$$

According to the research results of literature [4], when the flexural member cracks, the maximum tensile strain of concrete is close to $2\varepsilon_{t0}$, that is, $\varepsilon_{tu} = 2\varepsilon_{t0}$; The coefficient $\alpha = 0.7 \sim 1.0$. In this article, $\gamma = 2$, $\alpha = 1.0$. The cracking moment of GFRP RC double reinforcement section beams is obtained from Eq. (15) and (18). The elastic plastic resistance moment W_s is obtained from Eq. (5) and (18).

3 Test specimens and material properties

The test specimens consisted of 14 GFRP reinforced concrete beams classified into two groups according to the concrete compressive strength as given in Table 1. All beams had the same length, depth and width of 3000, 300 and 200 mm, respectively. These beams were reinforced completely with GFRP, no steel reinforcement was used. The four-point vertical loading scheme is adopted, and the two concentrated loads are applied to the one third point of the beam respectively. Realization of symmetric and synchronous loading of two loading point is achieved by using distribution beam. Beam geometry and the loading support arrangement are illustrated in Fig. 2.

The cube compressive strength of beams in group 1, obtained from testing three 150mm cubes under 28 days' standard curing condition, was 30.7MPa. whereas, the value of that in group 2 was 44.9Mpa, the modulus of elasticity of concrete were 30.0 GPa and 34.48 GPa, respectively; the tensile strength of concrete were 2.55 MPa and 3.28 MPa, respectively. The mechanical properties of GFRP bars used in the test beams were obtained by carrying out uniaxial tensile or compressive tests on three GFRP specimens. Table 1 shows the main parameters of the test specimens.

Table 1. Parameters and Cracking Moment of GFRP Reinforced Concrete Beams

Specimen	b /mm	h_0 /mm	f_t /MPa	E_c /GPa	A_f /mm^2	f_{fu} /MPa	E_f /GPa	A_f' /mm^2	E_f' /GPa	$M_{cr,ex}$ /kN·m	$M_{cr,th}$ /kN·m	$M_{cr,th}/M_{cr,ex}$
G30-0.4-1	200	269	2.55	30.0	226.2	660	44.25	226.2	44.0	7.20	7.96	1.11
G30-0.6-1	200	269	2.55	30.0	339.3	660	44.25	226.2	44.0	7.38	8.10	1.10
G30-0.8-1	200	267	2.55	30.0	402.1	578	40.69	226.2	44.0	7.61	8.13	1.07
G30-1.1-1	200	267	2.55	30.0	603.2	578	40.69	226.2	44.0	8.55	8.35	0.98
G30-1.5-1	200	267	2.55	30.0	804.2	578	40.69	226.2	44.0	8.73	8.57	0.98
G30-2.0-1	200	247	2.55	30.0	1005.	578	40.69	226.2	44.0	8.82	8.54	0.97
G30-1.1-2	200	251	2.55	30.0	565.5	660	44.25	226.2	44.0	7.88	8.24	1.05
G30-1.1-3	200	251	2.55	30.0	565.5	660	44.25	226.2	44.0	8.15	8.24	1.01
G50-0.4-1	200	269	3.28	34.48	226.2	660	44.25	226.2	44.0	9.00	10.19	1.13
G50-0.6-1	200	269	3.28	34.48	339.3	660	44.25	226.2	44.0	9.27	10.35	1.12
G50-0.8-1	200	267	3.28	34.48	402.1	578	40.69	226.2	44.0	9.45	10.38	1.10
G50-1.1-1	200	267	3.28	34.48	603.2	578	40.69	226.2	44.0	9.68	10.62	1.10
G50-1.5-1	200	267	3.28	34.48	804.2	578	40.69	226.2	44.0	10.08	10.87	1.08
G50-2.0-1	200	247	3.28	34.48	1005.	578	40.69	226.2	44.0	9.90	10.83	1.09

Note. b, the width of test specimen; h_0, the effective depth of test specimen; f_t, the tensile strength of concrete; E_c, the modulus of elasticity of concrete; A_f and A_f', the area of GFRP bars in tension zone and in compression zone; E_f and E_f', the tensile and compressive modulus of elasticity of GFRP bars; f_{fu}, the tensile rupture of GFRP bars; $M_{cr,ex}$, the experimental value of cracking moment; $M_{cr,th}$, the theoretical value of cracking moment.

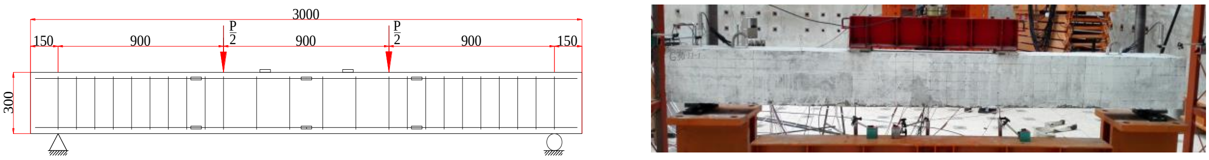

Figure 2. Test specimen details and test set-up

4 Comparison between calculated values and experimental values

Table 1 presents the experimental values of cracking moment of 14 GFRP RC double reinforcement section beams. The proposed calculation method was used to calculate the cracking moment of 14 specimens, and the experimental results were compared with the theoretical calculated results.

The results showed that the ratio between theoretical and experimental cracking moments is in the range of 0.97~1.13; the average, standard deviation and coefficient of variation of the ratio are 1.064, 0.056 and 0.053, respectively. The calculated results obtained from the current analysis agree well with the experimental results. Among the calculation results, the ratio of the cracking moment and the actual test value of the 8 beams in group 1 are varied in the range of 0.97~1.11; the average, standard deviation and coefficient of variation of the ratio are 1.034, 0.056 and 0.054, respectively. The ratio of the cracking moment and the actual test value of the 6 beams in group 2 are varied in the range of 1.08~1.13; the average, standard deviation and coefficient of variation of the ratio are 1.103, 0.019 and 0.017, respectively. The deviation of the 6 beams in group 2 is larger, this may be due to the lower strength of the concrete which result to a lower value of the test results. With the increase of the longitudinal GFRP reinforcement ratio, the cracking moment of GFRP RC beams increases gradually. GFRP bars have a certain influence on the cracking moment of beams, but the effect is small. With the increase of concrete strength, the cracking moment of GFRP RC beams increases obviously, the cracking moment is mainly determined by the tensile strength of concrete and section size.

5 Conclusion

This paper presents an experimental research on the anti-cracking capacity of 14 concrete beams reinforced with GFRP bars. The following conclusions can be drawn from the studies made:

1) The design equations of cracking moment of GFRP reinforced concrete beams double reinforcement section is presented. The ratio between theoretical and experimental cracking moments is in the range of 0.97~1.13; the average, standard deviation and coefficient of variation of the ratio are 1.064, 0.056 and 0.053, respectively. The calculated results obtained from the current design method are in good agreement with the experimental results. The design method can be used to calculate the cracking moment of GFRP RC double reinforcement section beams.

2) With the increase of the longitudinal GFRP reinforcement ratio, the cracking moment of GFRP RC beams increases gradually, GFRP bars have a certain influence on the cracking moment of beams, but the effect is small.

3) With the increase of concrete strength, the cracking moment of GFRP RC beams increases obviously, the cracking moment is mainly determined by the tensile strength of concrete and section size.

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