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Study on crack development of concrete beams in bending reinforced with FRP bars

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Abstract. The comparatively high tensile strength and low elastic modulus of fiber reinforced polymer (FRP) bars result in deflection and crack width requirements controlling the design of concrete beams reinforced with FRP bars. Consequently, when it comes to the design of such members, the deflection and crack width are first calculated at serviceability limit state, and then are checked at ultimate limit state. In this paper, five concrete beams reinforced with different FRP reinforcement ratios were tested and the crack development and pattern as well as the effect of reinforcement ratio on crack width and spacing were analyzed. The experimental results were compared with the calculation results using design guidelines recommended by Japan JSCE code, American ACI440.1R-03 code and China GB50608-2010 code. Several design suggestions were proposed for bending concrete beams reinforced with FRP bars.

1. Introduction

FRP bars are linear elastic materials with no discernible yield point, and the relatively low elastic modulus, high tensile strength and quite different bond characteristics from steel bars all lead to greater deflection and crack width. Researches have found that serviceability requirements should be as critical as the ultimate limit states in the design of concrete beams reinforced with FRP bars, especially when considering the deflection and crack width requirements [1-2]. In this paper, CFRP and GFRP reinforced concrete beams were tested in bending so as to investigate the flexural behavior in terms of crack pattern and deflection behavior. According to experimental results, several crack-width calculation formulas recommended by design codes home and abroad were verified and compared to experimental results. These studies are discussed hereafter.

2. Experimental program

Tests were conducted on five specimen beams subjected to two-point concentrated static loads. Three beams were 180mm in width, 250mm in depth and 1900mm in length, which were numbered CB-1, CB-2 and CB-3. And the remaining two were numbered GB-1 and GB-2 with a cross-section size of 150×200mm and a length of 1300mm. Two steel bars with a diameter of 16mm were adopted as upper longitudinal reinforcement for specimen CB-1 and CB-2 and their lower longitudinal reinforcement were two CFRP bars and three CFRP bars of 9.5mm diameter, respectively. As for CB-3, the upper and lower longitudinal reinforcement were both two CFRP bars. Steel stirrups of 12 mm diameter were used at 100 mm spacing along the tested length for these three beams. The reinforcement details of specimen beam GB-1 and GB-2 were the same as that of CB-1 and CB-2, the only difference was that the upper steel bars were 12mm diameter and the lower reinforcement were GFRP bars, instead.

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Moreover, the diameter of steel stirrups was 10mm with the same spacing of 100mm. The material properties of FRP rods adopted in this test were shown in table 1.

Table 1. Mechanical properties of FRP bars.

FRP type	Diameter (mm)	Ultimate strength (MPa)	Yield strength (MPa)	Elastic modulus (GPa)	Ultimate elongation rate (%)
CFRP	9.5	1779	1245	136	1.65
GFRP	9.5	993	695	72	2.31

3. Test results

3.1. Crack behaviour

In this section, the crack patterns of CFRP and GFRP reinforced concrete beams under ultimate load were shown in figure 1. The crack patterns of concrete beams reinforced with FRP bars were similar to that of normal RC beams. As can be seen in figure 1, cracks distributed uniformly and densely. Compared with CFRP reinforced concrete beams, GFRP strengthened concrete beams scattered more symmetrical and denser cracks. Based on statistical analysis, the crack spacing of concrete beams reinforced with CFRP and GFRP bars was 88mm and 75mm, respectively.

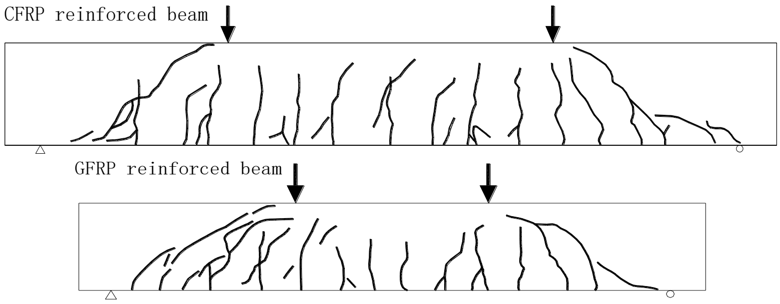


Figure 1. Crack patterns at ultimate state.

3.2. The effect of reinforcement ratio on crack width and spacing

An initial vertical crack along the depth of beam appeared in pure bending section and then, with the increasing of applied load, inclined cracks occurred outside pure bending section owing to the increasing of the shear stress, which narrowed the crack spacing. The experiment found that the decrease of crack spacing was slowing down and tended to be stable when the applied load up to 35 percent of ultimate load. The crack spacing and crack width at different load levels of five test beams were listed in table 2, from which we could know that the crack spacing decreased with the increase of reinforcement ratio.

Table 2. Crack spacing and width of test beams.

Beam No.	Sectional dimension (mm)	Reinforcement ratio (%)	Cracks number	Crack spacing (mm)	Crack width (50KN) (mm)	Crack width (90KN) (mm)	Crack width (35%P_u) (mm)
GB-1	150×200	0.51	15	79	0.96	1.8	0.75
GB-2	150×200	0.76	14	71	0.66	1.17	0.46
CB-1	180×250	0.35	16	93	0.56	0.96	0.60
CB-2	180×250	0.52	18	80	0.37	0.72	0.69
CB-3	180×250	0.34	15	90	0.62	1.02	0.57

As illustrated in table 2, reinforcement ratio had an evidently influence on crack width. A lager reinforcement ratio meant a greater surface area and better bond strength, which could bear a lager crack stress so as to protect the beam from cracking early. Consequently, the crack width decreased as the reinforcement ratio increased.

4. Calculation models for crack width

The crack with of five specimens was calculated and analyzed using the formula suggested by the following guidelines and compared to the test results, and the calculation results of different codes on crack width were discussed.

4.1. Crack-width calculation models

4.1.1. JSCE (1997) [3]. Calculation formula of maximum crack width given by *Recommendation for Design and Construction of Concrete Structure Using Continuous Fiber Reinforcing Materials* is as follows:

$$w = k\left[4c + 0.7(c_{\mathrm{f}} - \varphi)\right]\left(\frac{\sigma_{\mathrm{f}}}{E_{\mathrm{f}}} + \varepsilon'_{\mathrm{csd}}\right) \tag{1}$$

where k is a constant that is related to the bond property and reinforcement, usually takes from 1.0 to 1.3; c is the concrete cover depth, mm; c_{f} is the centroid distance of FRP bar, mm; φ is the diameter of FRP bar, mm; σ_{f} is the stress of FRP bars under design load, MPa; E_{f} is the elastic modulus of FRP bar, MPa; $\varepsilon'_{\mathrm{csd}}$ is compressive strain and can be taken as 150×10^{-6}.

4.1.2. ACI-440.1R-03 [4]. America ACI 440.1R-03 specifications recommend the following formula for the calculation of crack width:

$$w = \frac{2.2}{E_{\mathrm{f}}}\beta k_{\mathrm{b}} f_{\mathrm{f}} \sqrt[3]{d_{\mathrm{c}} A} \tag{2}$$

in which E_{f} is modulus of elasticity of FRP, MPa; β is the ratio of the distance from the neutral axis to extreme tension fiber to the distance from the neutral axis to the center of the tensile reinforcement; k_{b} is a coefficient that accounts for the degree of bond between FRP bar and surrounding concrete and can be taken as 1.2; f_{f} is stress in the FRP bar in tension, MPa; d_{c} is concrete cover depth measured from extreme tension fiber to center of bar, mm; A is the effective tension area of concrete, mm.

4.1.3. China GB50608-2010 [5]. *Technical Code for Infrastructure Application of FRP Composites* of China suggests that maximum crack width should be computed as shown in Equation (3):

$$\omega_{\max} = 2.1\psi\frac{\sigma_{\mathrm{fk}}}{E_{\mathrm{f}}}\left(1.9c + 0.08\frac{d_{\mathrm{eq}}}{\rho_{\mathrm{te}}}\right) \tag{3}$$

with specific parameters in the formula referring to GB 50608-2010.

4.2. Comparison between experimental and calculation results

Based on available data, above three formulas were used to predict crack width of five specimens and the calculation results were compared to test results, as shown in figure 2. From three charts we can see that JSCE equation overestimates crack width when applied to CFRP bar and underestimates crack width when applied to GFRP bar. As for China GB50608 equation, calculation results of GFRP reinforced member agree well with experimental results, but it overestimates crack width when applied to CFRP bar. While crack width values calculated by ACI formula match best with experimental results, indicating that this recommend model can be used to predict crack width of FRP reinforced concrete member.

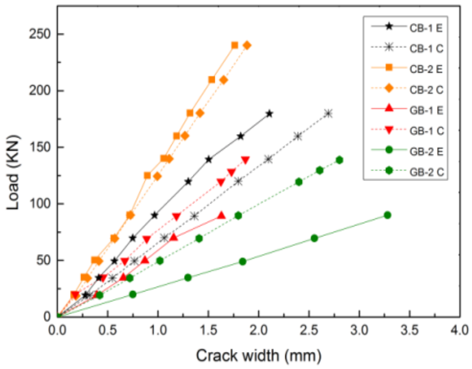
5. Conclusions

This study was carried out by means of static testing and focused on the crack development and crack-width calculation. According to experimental observations and analysis of tests results, the following conclusions can be summarized.

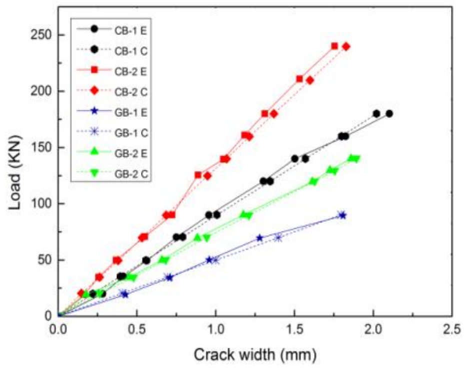
It was evident that good bond capability between CFRP or GFRP bar and surrounding concrete allows concrete member to work efficiently. GFRP strengthened concrete beams scattered more symmetrical and denser cracks as compared to that of CFRP reinforced beams.

A relationship between reinforcement ratio and crack spacing and width was developed. Results showed that as the reinforcement ratio increased, the crack spacing and width decreased. Crack widths in FRP reinforced members were proved to be larger than those in normal steel reinforced members.

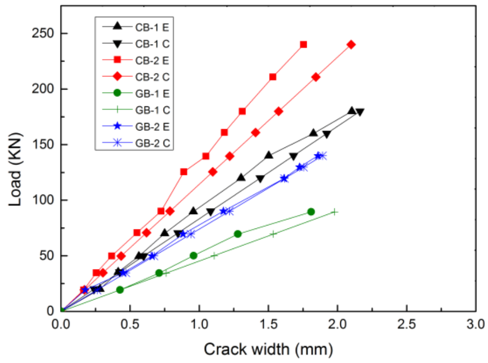
ACI 440.1R-03 code can provide relatively accurate prediction on crack width of FRP reinforced members.



(a) JSCE.



(b) ACI440.



(c) GB50608.

Figure 2. Comparison between experimental and calculation results.
Note: "E" represents experimental results, and "C" represents calculation results.

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