Experimental study of flexural behavior and serviceability of hybrid concrete beams reinforced by steel and G/BFRP bars

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Abstract. In this paper, the flexural behavior and serviceability performance of concrete beams reinforced with hybrid glass/basalt fiber-reinforced polymer (G/BFRP) bars and steel bars were investigated. From the viewpoint of reducing the risk of steel corrosion, two kinds of hybrid reinforced beams were designed, eleven concrete beams including 3 steel-reinforced beams and 8 hybrid-reinforced beams were tested. The effect of the hybrid reinforcement ratio on the flexural performance was analyzed and the applicability of replacing steel bars with GFRP or BFRP bars in concrete beams was discussed. The results show that the ultimate bending moment of hybrid-reinforced concrete beam was about 91-97% of that of steel-reinforced concrete beam with the same reinforcement ratio. Since the reduction of the bearing capacity of hybrid-reinforced beam was small, it can be proved that it is feasible to replace the corner steel bar of concrete members with G/BFRP bars. For the serviceability performance of beams hybrid-reinforced with G/BFRP bars and steel bars, however, their deflection and maximum crack width were 20%-60% higher than that of steel-reinforced beams under the same load levels within the limit state of serviceability. It showed that the stiffness and crack resistance of hybrid beams weakened greatly. Finally, it was found that the FRP-to-steel ratio of bar areas had great influence on the flexural behavior and serviceability performance of concrete beams hybrid-reinforced with FRP and steel bars.

1. Introduction

The steel corrosion in concrete has been regarded as a main problem related to the durability of reinforced concrete (RC) structures in last decades. In order to overcome this serious problem, los of efforts have been made for these corroded or possibly corroded RC structures in recent years, including using galvanized or epoxy-coated steel rebar and adding corrosion inhibitor in concrete [1]. Currently, fiber reinforced polymer (FRP) bars are believed as to be another possible material to displace steel bars embedded in concrete [2]. Compared with the common hot rolled bars, FRP bars have some advantages of chemical resistance, superior tensile strength and better manufacturability [3]. However, for some types of FRP bars, their elastic moduli are lower than those of steel bars, and their bonding strength in concrete is low. Finally, the FRP-reinforced concrete structures often show large crack width and deflection [4] and their design is controlled by the requirements of serviceability limit state [5]. Therefore, the wide use of FRP bars in concrete structures is still restricted to a certain extent.

To improve the properties of FRP bars and expand their applications, new types of FRP bars and their application systems have been explored in some investigations. Harris et al. [6] proposed that for the hybrid FRP bars made of various types of fibers, their stress-strain properties can simulate that of steel bars. They also found that the ductility of the concrete beams reinforced with hybrid FRP bars was...
approximately equal to that of RC beams reinforce with steel bars. Qu et al. [7] reported a new hybrid reinforcing system which was made up of steel bars and FRP bars together. They indicated that the hybrid concrete beams reinforced with FRP and steel bars showed good serviceability and ductility and believed that the hybrid reinforcing system was an effective way to improve the performance of FRP-reinforced concrete beams in flexure. However, for these hybrid reinforced concrete elements with FRP and steel bars, the corrosion of steel bars still remains a key problem to be solved. Currently, some investigations showed that the deflection and crack width shown in the FRP-reinforced concrete beams could be controlled by adding the randomly distributed fibers and that the corresponding ductility of these beams could also be improved [8,9]. It is known that hybrid concrete beams are superior to the RC ones in bearing capacity, but because of the use of FRP bars, the crack width and deflection of the hybrid concrete beams are larger than those of RC beams. It should be noted that the research on serviceability performance of FRP-steel reinforced concrete beams is not sufficient.

This study is concerned with the flexural behavior of G/BFRP-steel reinforced concrete beams (hereinafter referred to as ‘hybrid concrete beams’). Some flexural characteristics including the ultimate bending moment, deflection, crack development and width of all tested beams were discussed and compared between theoretical calculations and test values.

2. Experimental investigation

2.1. Materials
The design strength grade of concrete is C30, and its mix proportion is given in table 1. The cement used here is an ordinary Portland cement of Grade 42.5. The coarse aggregate is the stone with size of 2.4~16 mm. The fine aggregate is the sand with a modulus of fineness of 2.4. The water used here is the tap water. The 150-mm cubic compressive strength \( f_{cu} \) measured after 28 days curing was 37.9 MPa (table 1).

| Table 1. Mix proportion of concrete and its compressive strength. |
|----------------------|--------|--------|--------|--------|--------|
| W/C ratio | Cement (kgm\(^{-3}\)) | Water (kgm\(^{-3}\)) | Sand (kgm\(^{-3}\)) | Gravel (kgm\(^{-3}\)) | \( f_{cu} \) (MPa) |
| 0.49 | 449 | 220 | 615 | 1116 | 37.9 |

| Table 2. Properties of HRB steel bars. |
|----------------------|--------|--------|--------|
| Types | Diameter (mm) | Elongation rate (%) | \( f_y \) (MPa) | \( f_u \) (MPa) | \( E_s \) (GPa) |
| HRB400 | 12 | 15.6 | 517.2 | 630.8 | 200 |
| HRB400 | 16 | 15.8 | 540.3 | 642.6 | 200 |

Note: \( f_y \) and \( f_u \) are the yield and ultimate tensile strength of HRB steel bar, respectively; \( E_s \) is the elastic modulus of HRB steel bar.

| Table 3. FRP bars used here and their mechanical properties. |
|----------------------|--------|--------|
| Types | Nominal diameter (mm) | \( f_u \) (MPa) | \( E_s \) (GPa) |
| BFRP | 8 | 1299.6 | 42.0 |
| GFRP | 12 | 868.2 | 40.1 |
| GFRP | 16 | 958.2 | 45.7 |

Note: \( f_u \) and \( E_s \) are the ultimate tensile strength and elasticity modulus of FRP bars, respectively.

The steel bar used here is a steel type of HRB400 with the nominal diameters of 12 and 16 mm. The notation HRB400 presents a hot-rolled ribbed rebar (HRB) with a standard yield strength of 400 MPa. Their properties are indicated in table 2. Two types of FRP bars, GFRP (glass FRP) and BFRP (basalt
FRP) produced by a company in Nanjing, China, are also embedded in the tension zone of the beams. In order to enhance the bonding strength between FRP bar and concrete, the surface of FRP bars was ribbed during pultrusion. The mechanical properties of two types of FRP bars used here are given in table 3.

2.2. Specimens
Figure 1 gives the sectional parameters of the prepared specimens. The designed cross-sectional dimension is 180 mm × 300 mm and the total length is 1800 mm. There are two types of reinforcement: single-layer reinforcement (see figure 1(b)) and double-layer reinforcement (see figure 1(c)). The stirrups with the diameter of 8 mm were placed at two sides of the beam with 100 mm spacing. The cover thickness of concrete is 30 mm and the reinforcements of all specimens are listed in table 4.

![Figure 1. Schematic diagrams of hybrid reinforced beams: (a) reinforcements of beams; (b) single-layer reinforcement; (c) double-layer reinforcement.](image)

| Type                  | No. of specimen | Tensile bar | A_s (mm²) | A_f (mm²) | Reinforcement ratio ρ_h,s (%) |
|-----------------------|-----------------|-------------|-----------|-----------|------------------------------|
| Single-layer reinforcement | S-1             | 4S12        | 452       | 0         | 0.98                         |
| Single-layer reinforcement | GS-1            | 2G12+2S12   | 226       | 226       | 0.87                         |
| Single-layer reinforcement | GS-2            | 2G16+2S12   | 226       | 402       | 1.26                         |
| Single-layer reinforcement | BS-1            | 2B8+2S12    | 226       | 101       | 0.67                         |
| Double-layer reinforcement | S-2             | 3S16        | 603       | 0         | 1.31                         |
| Double-layer reinforcement | GS-3            | 2G12+1S16   | 201       | 226       | 0.80                         |
| Double-layer reinforcement | GS-4            | 2G16+1S16   | 201       | 402       | 1.17                         |
| Double-layer reinforcement | S-3             | 4S12        | 452       | 0         | 1.06                         |
| Double-layer reinforcement | GS-5            | 2G12+2S12   | 226       | 226       | 0.94                         |
| Double-layer reinforcement | GS-6            | 2G16+2S12   | 226       | 402       | 1.36                         |
| Double-layer reinforcement | BS-2            | 3B8+2S12    | 226       | 151       | 0.82                         |

Note: S means steel bar, while G and B mean GFRP bar and BFRP bar, respectively.

Refer to the principle of “equal strength replacement”, the hybrid reinforcement ratio, ρ_h,s, designed based on the tensile strength of bars can be expressed as equation (1) [10]. The calculations of all test beams were given in table 4.

\[
ρ_{h,s} = \frac{A_s}{bh_0} + \frac{f_{sd}}{f_{yd}} = ρ_s + \frac{f_{sd}}{f_{yd}} ρ_t
\]  

where, \(A_s\) and \(A_f\) are the bar areas of steel and FRP specimens in the tension zone, respectively; \(b\) and \(h_0\) are the width and effective height of the section; \(f_{sd}\) is the design strength of FRP bars, \(f_{yd}=0.8f_{ys}\).

2.3. Flexural test
All specimens were tested in a four-point bending mode using a 50-ton self-balancing structure with the vertical loading reaction force system. During the test, the external loads were added step by step based on the Chinese national standard [11] and all experimental data were automatically recorded by the
After nearly ten minutes loading, the displacements and the crack widths of the test specimen were measured and recorded.

3. Results and discussion

3.1. Testing process

Figure 2 plots the load-deflection curve of some test beams. It can be concluded from figure 2 that the bending process of the hybrid concrete beams can be divided into the following three stages: (1) Pre-cracking stage; (2) Cracking to the yielding stage of steel bars; and (3) Post-yield stage of steel bars. Figure 3 depicts the crack distribution of the GS-4 beam.

3.2. Verification of plane cross-section assumption

Figure 4. Strain distribution of GS-1 beam at mid-span.
From the measured data, the strains of the cross-section at middle span of the test specimens were used to testify the assumption of plane cross-section. Figure 4 indicates the strain diagram of the GS-1 beam. It can be found from figure 4 that as the load increases and the crack develops, the neutral axis gradually moves upward, but the strain of the concrete still conforms to the plane section assumption.

3.3. Bearing capacity of beams in flexure

Four basic assumptions were adopted as follows: (1) Plane section assumption; (2) FRP bars and steel bars have the same strain at the same position; (3) The tensile strength of concrete is not considered; and (4) A simplified model is adopted for the stress-strain property of each constituent material.

According to the simplified material constitutive model and the basic assumptions, the ultimate bending moment of the cross section of the hybrid concrete beam $M_{u,e}$ could be calculated according to equations (2)–(4) [12], and the results are given in Table 5.

$$\alpha f_y b x = f_y A_y + E_y \varepsilon_y A_y$$

(2)

$$\varepsilon = \frac{(A-B) + \sqrt{(A-B)^2 + 4\alpha B}}{2\alpha}$$

(3)

$$M_u = \alpha f_y b h_0 \varepsilon \left(1 - \frac{\varepsilon}{\varepsilon_{uc}}\right)$$

(4)

where $A = f_y \rho f_c$, $B = \varepsilon_{uc} E \rho f_c$, $\varepsilon = \varepsilon_{uc}(f/f - 1)$ and $\varepsilon_{uc}$ is the ultimate compressive strain of concrete.

Table 5. The bearing capacity analysis of test beam.

| No. of specimen | $M_{uc}$ (kN·m) | $M_{ue}$ (kN·m) | $M_{u}/M_{ue}$ |
|-----------------|-----------------|-----------------|-----------------|
| S-1             | 53.80           | 59.12           | 0.910           |
| GS-1            | 50.19           | 57.5            | 0.873           |
| GS-2            | 60.04           | 63.30           | 0.958           |
| BS-1            | 41.87           | 52.00           | 0.805           |
| S-2             | 69.22           | 60.25           | 1.149           |
| GS-3            | 49.25           | 56.37           | 0.874           |
| GS-4            | 59.84           | 66.70           | 0.897           |
| S-3             | 51.97           | 60.77           | 0.855           |
| GS-5            | 45.14           | 53.79           | 0.839           |
| GS-6            | 54.20           | 50.56           | 1.072           |
| BS-2            | 41.31           | 50.01           | 0.826           |

It can be observed from Table 5 that the theoretical calculated values $M_{u,e}$ of the hybrid reinforced concrete beam are in good agreement with the experimental values $M_{u,e}$. The mean ratio of the two values is 0.893 and the variation coefficient is 0.09, which means that the equation for calculating the ultimate bending moment of the hybrid concrete beam is reliable. From the comparison of the ultimate moment values, it can be found that the hybrid reinforcement ratio $\rho_{he}$ has a great effect on the beam’s bearing capacity. For example, the ratios of S-1, GS-1 and GS-5 beams are 0.98%, 0.87% and 0.94%, respectively, which are close to each other. The ultimate bending moments of GS-1 and GS-5 beams are 0.97 and 0.91 times of that of S-1 beam respectively. It can be seen that the limit bending moment decreases slightly, which indicates that it is feasible to replace the corner steel bar with FRP bars.

The comparison of the ultimate bending moments of the two groups of hybrid concrete beams of GS-1, GS-2, BS-1, GS-3 and GS-4 shows that under the condition that the tension zone is provided with the same area of FRP and steel bars, the form of single layer is better. The ultimate bending moment of hybrid concrete beams enhances with the hybrid reinforcement ratio, which is consistent with the test results given in [13].
3.4. Calculation of crack width

The formula proposed in ACI specification [14] is applied to calculate the maximum crack width of the hybrid reinforced concrete beam under short-term load, as given in equation (5).

\[ w_{s,\text{max}}^c = k_g e_1 \beta \frac{1}{d_c} A \]  

(5)

where \( d_c \) is the distance between the center of the longitudinal reinforcement at the bottom of the beam and the edge of the concrete in the tension zone; \( A \) is the average effective area of the tensile concrete around each longitudinal reinforcement; \( \beta \) is the distance from the edge of the tension zone to the neutral axis; \( e_1 \) is the ratio of the spacing from the center of the longitudinal reinforcement to the neutral axis; \( k_g \) is a function reflecting the influence of the bond strength of the tensile bars in the hybrid-reinforced concrete beam on the crack width.

The relationship between the calculations of short-term maximum crack width \( w_{s,\text{max},c} \) by equation (5) and the measured value \( w_{s,\text{max},e} \) is shown in figure 5. The comparison showed that the theoretical values of the short-term maximum crack width agree well with the measured values. The mean value of the ratio \( w_{s,\text{max},c}/w_{s,\text{max},e} \) is 0.996, and the variation coefficient is 0.112. The results indicated that the crack width in flexure of the hybrid concrete beam can be predicted using equation (5).

![Figure 5. Comparison of short-term maximum crack width.](image)

3.5. Inter-span deflection calculation

For the prediction of the stiffness of hybrid concrete beams, the method given in the code of ACI440.1R-06 is adopted to determine the effective moment of inertia, \( I_e \) [15]. The product \( E_c I_e \) of the concrete elastic modulus and the effective moment of inertia is regarded as the short-term stiffness \( B_s \) of the hybrid concrete beam.

According to the method of structural mechanics, the calculation formula of short-term deflection of the hybrid concrete beams in a four-point bending system (see figure 3) is given as:

\[ f_m' = 110.08 \frac{M l_0^2}{B_s} \]

(6)

where \( f_m' \) is the calculated value of the mid-span deflection (mm); \( M \) is the bending moment at mid-span (N m); \( B_s \) is the short-term stiffness of the beam (N m²); \( l_0 \) is the calculated span of the test beam (\( l_0 = 1.6 \) m, in this study).
Figure 6. Comparison of short-term deflection at mid-span.

The measured value of $f_{m,e}$ of the hybrid concrete beam is compared with the theoretical value $f_{m,c}$ calculated by the equation (6), as plotted in figure 6. From figure 6, it can be observed that the calculated deflection $f_{m,c}$ is in good agreement with the measured deflection $f_{m,e}$, and the average value of the ratio $f_{m,c}/f_{m,e}$ is 1.002, and the coefficient of variation is 0.023. It can be concluded that the short-term deflection in flexure of hybrid concrete beams is the most accurately described by equation (6).

4. Conclusions
The following conclusions can be made from this study:

- For the hybrid concrete beams reinforced with steel bars and G/BFRP bars, the sectional strains still conform to the plane cross-section assumption. The crack development process is basically similar to that of the common RC beam. The load-deflection curve can be divided into three parts, and the inflection points are related with the cracking load and the yielding load of the steel bar.
- Theoretical and experimental analysis results show that the calculated value of the ultimate bending moment of the hybrid-reinforced concrete beam derived from the basic assumption was in good agreement with the experimental value. For the hybrid concrete beams with the ratio $\rho_{hs}$ in the range of 0.67%-1.26%, their ultimate bending moments were about 95% of that of common RC beam and the ultimate bending moment increased with increasing the hybrid reinforcement ratio.
- The calculated values of the short-term maximum crack width and the deflection in flexure of the hybrid concrete beams agreed well with the experimental values. Their deflection and largest crack width were 20-60% higher than those of traditional RC beams with the approximate load values within the limit state of serviceability.

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