Experimental study on flexural behavior of GFRP reinforced concrete slabs

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Abstract: Remarkable performance of glass fiber-reinforced polymer (FRP) bars make it an ideal candidate for prolonging the life of concrete structure. Although analytical and experimental research of concrete beams strengthened by FRP have flourished in recent decades, it is still in lack of research in comparison with traditional reinforced concrete structures, especially in case of the flexural behavior. In this paper, two groups of GFRP reinforced concrete slabs with different strength grades and reinforcement ratios were experimentally tested, and theoretical calculation method on their bearing capacities was explored. By comparing the deformation and bearing capacity characteristics, the test results were discussed in detail. The calculation formula of flexural capacity of GFRP reinforced concrete slab was derived and then verified against the experimental data. The test results show that the load deflection curve presents obvious double straight lines, and the reinforcement ratio is not closely related to the initial crack load. The cross section still obeys the plane section assumption and the crack distribution is sparse with large width. The flexural bearing capacity coefficient changes from 1.02 to 1.36. Therefore, the limitation of 1.4 times balanced reinforcement ratio in ACI is verified, which could apply a valuable reference for durability design of GFRP reinforced concrete slabs.

1. Introduction
In order to decline the corrosion deterioration of concrete structures (such as bridge decks, water treatment facilities, marine engineering and chemical plants), more and more attentions have been taken to used Glass Fiber Reinforced Polymer rebar (GFRP rebar), instead of traditional steel bar, as the enhancement materials [1]. Due to their relatively low cost and unique performance (including high tensile strength, good insulation, light weight, easy cutting and non-corrosive characteristics), GFRP bars are popular in various literatures. [2-4]. Recently, GFRP bars have been extensively applied in civil engineering structures, and tremendous scientific endeavors were devoted to investigating their influence on concrete durability [5-8]. However, it has been reported that the GFRP bars have no obvious yield point as compared with reinforcing rebar, which brings a challenge that the calculation theory in existing code [9] is no longer suitable for concrete structures reinforced with...
GFRP bars [9]. Consequently, experimental study and new theoretical system are both necessary for further understanding the enhancement mechanism.

In recent years, a series of experimental tests have been carried out on GFRP reinforced concrete beams so as to explore the flexural bearing capacity of the normal section. Gao and Brahim [10], who firstly focused on the normal section capacity calculation of GFRP reinforced concrete beams, have predicted the deformation and crack growth. Xuhong Li [11] has detailed the shear capacity analysis and proposed several suggestions for designing fiber-reinforced polymer concrete beams. Hong Zhu et al. [12] have investigated the stiffness of FRP reinforced concrete beams from experimental and theoretical perspectives and proposed the modified stiffness calculation formula based on GB 50608-2010. Da Chen [13] analyzed the deformation, failure characteristics and mechanical properties of FRP reinforced concrete beams as contrasted to the reference samples by means of three-point bending and shear mechanical properties tests. For foreign researchers, the flexural bearing capacity of concrete beams enhanced by FRP bars has been studied by Edward [14], and the deformation characteristics of beams have been described. In addition, the corresponding design codes have been quickly developed in the United States, Canada, Japan [14-16] and other countries.

It is known that the experimental research about the mechanical properties of FRP reinforced concrete beams and tendons have been extensively investigated. Many existing works have been devoted to understanding the mechanical properties (flexural behavior, bond characteristics and fracture performance) and durability of GFRP-reinforced concrete beams [17-23]. However, to the best of per author’s knowledge, the effect of GFRP bars on the flexural properties of concrete slabs remains unknown, which is actually very important in the design of engineering structures. In this paper, the effect of reinforcement ratio and structural strength on crack width, deflection and flexural behavior of GFRP reinforced concrete slab is analyzed according to the experimental data of 8 GFRP reinforced concrete one-way slabs. The calculation method on flexural bearing capacity of GFRP reinforced concrete slab is raised for predicting the structural durability characteristics. Meanwhile, the applicability of the 1.4 times balanced reinforcement ratio in the design code is verified.

2. Experimental program

2.1. Material characteristics

Considering the mechanical characteristics of one-way slab and the limitation of test site and equipment, the rectangular section for the test slab is adopted. Eight concrete beams in total were prepared with addition of different types of GFRP bars in this experiment. After curing for 28 days, the beams with the size of 1000 mm × 150 mm cross-section and 2400 mm clear span were simply supported and subjected to two concentrated static loads. The number of beams, reinforcement situation and basic properties of the materials are detailed in Table 1. GFRP steel bars are produced by Nanjing Woao Technology Development Co., Ltd, and the concrete is commercial concrete.

| Group | Specimen | Concrete grade | Bars | $\rho$ (%) | $\rho_{fb}$ (%) | $\rho_{fb}/\rho$ | Ultimate strength (MPa) | Modulus of elasticity (GPa) |
|-------|----------|----------------|------|------------|----------------|----------------|-------------------------|---------------------------|
| I     | GF-1     | C30            | φ12  | 0.45       | 0.52           | 0.87           | 828.3                   | 42.3                      |
|       | GF-2     | C30            | φ12  | 0.60       | 0.52           | 1.15           | 828.3                   | 42.3                      |
|       | GF-3     | C30            | φ12  | 0.75       | 0.52           | 1.44           | 828.3                   | 42.3                      |
|       | GF-4     | C30            | φ12  | 0.90       | 0.52           | 1.73           | 828.3                   | 42.3                      |
| II    | GFII-1   | C40            | φ12  | 0.45       | 0.52           | 0.87           | 828.3                   | 42.3                      |
|       | GFII-2   | C40            | φ12  | 0.60       | 0.52           | 1.15           | 828.3                   | 42.3                      |
|       | GFII-3   | C40            | φ12  | 0.75       | 0.52           | 1.44           | 828.3                   | 42.3                      |
|       | GFII-4   | C40            | φ12  | 0.90       | 0.52           | 1.73           | 828.3                   | 42.3                      |

\[ \rho = \text{area of reinforcement}/bh; \ \rho_{fb} = \text{balanced reinforcement ratio}. \]
2.2. Experiment setup and instrumentation
The 30t Hydraulic jack with digital display instrument is used to load the reaction frame by 3-point loading method. In the loading process, the loading speed is 5kN per level before the crack, and the loading speed is reduced to the 3kN per level after the crack. DASP strain meter is used to obtain the strain. After each stage of loading, the deflection of the slab is obtained and the distribution of the crack is observed. During the loading process, the development of the crack is described. When the concrete is crushed or GFRP bar is broken, the experiment must be stopped, and then the limit value of the bearing capacity is recorded. Fig. 1 displays diagram of test loading device and sensor distributions.

For obtaining the deflection of the tested slabs, thirteen transducers are performed, in which, three are located at each cross section of one third of the span and mid-span, and two are located at each cross section of the supports. Additionally, the slabs were equipped with four steel strain gauges on the surface of the middle GFRP bars, five concrete strain gauges on each side surface of the mid-span section, and three concrete strain gauges on the bottom surface of one third and middle of the span.

Fig. 1 Diagram of loading device and sensor distributions (unit: mm).

3. Test results, data analysis and discussions
Based on the test results, remarkable experimental data are highlighted and compared with each other in this section. The test results show that similar trends happen on the flexural behaviors of conventional and GFRP reinforced concrete beams in many aspects the initial crack which is caused by bending moment always appears in the vertical crack near the middle of the span, and its direction is perpendicular to that of tensile stress, which is thus so called the bending crack. With the increase of load, the crack extends vertically. Moreover, more bending cracks appear in the pure bending section while inclined cracks appear in the shear-bending section, which extends in the bottom surface from the support of the beam to the loading point. It is noted that the bearing capacity is gradually weakened with the increase of load time, and meanwhile the cracks in the middle section of the span almost run through the whole section.

3.1. Load-deflection
For each slab, the relationships between load force and deflection are displayed in Figs. 2 and 3.
It can be seen from the both two figures, all load-deflection curves are approximately bilinear, and the slope changes once cracks appear. The slope of the curve is relatively large until the slabs are broken, which is different from the horizontal or fall segments of the reinforced concrete member.

The curves can be divided into two stages based on their different slopes. The first stage refers to the initial loading stage, in which, the deformation as well as the initial strain in the tension and compression zones is very small. The slab is in elastic state, and the concrete works together with GFRP tendons. There is no crack in this stage. At the second stage, when the concrete in pure flexural section reaches the ultimate strength of concrete crack strength, the first crack appears at the weakest position of pure bending section, and the deflection increases suddenly once cracks begin to propagate. For this case, the slope of load-deflection curve becomes smaller and the increase speed of deflection is accelerated.

### 3.2 Crack resistance

The cracking load is shown in Table 2, and the crack load test value is $M_{cr,exp}$. A comparison of cracking loads in different groups is shown in Fig. 4.

| Group | Specimen | $F_{cr}$ | $M_{cr,exp}$ | $\alpha$ |
|-------|----------|----------|--------------|----------|
| I     | GFI-1    | 37.2     | 11.16        | 0.98     |
|       | GFI-2    | 37.8     | 11.34        | 1.00     |
|       | GFI-3    | 37.6     | 11.28        | 0.99     |
|       | GFI-4    | 38.8     | 11.64        | 1.02     |
|       | GFII-1   | 40.9     | 12.27        | 0.97     |
|       | GFII-2   | 39.6     | 11.88        | 0.94     |
|       | GFII-3   | 41.5     | 12.45        | 0.99     |
|       | GFII-4   | 40.3     | 12.09        | 0.96     |

From the experimental results in Fig. 4, it can be concluded that the cracking load is closely related to the strength grade of concrete, and the cracking load increases with the increasing of concrete strength.
In order to understand the relationship between cracking moment and tensile strength of concrete, the influence coefficient $\alpha$ is introduced to reflect the effect of reinforcement ratio against crack moment, which is called the crack moment coefficient of section.

$$\alpha = \frac{M}{W f_{tk}}$$

Where $\alpha$ is crack moment coefficient of section, $W$ is the bending cross-section coefficient and $f_{tk}$ is the design value of concrete tensile strength. When the coefficient $f_{tk}$ is chosen as the concrete tensile strength, the calculation formula is used as $f_{tk} = 0.6\sqrt{f_{ck}}$.

It can be inferred from Table 2 that the crack moment coefficient is close to 1.0, which is similar to that of reinforced concrete. The elasticity modulus of GFRP bar is similar to that of plain concrete, so the effect of reinforcement ratio on cracking moment can be neglected. This is because the stress of longitudinal reinforcement is very small when the load of GFRP reinforced concrete slab reaches cracking load. The ability of inhibiting crack propagation mainly depends on the tensile strength of concrete, a similar factor that can decide the cracking moment of reinforced concrete beams.

### 3.3. Concrete strain

Taking the mid-span strain of GFI-3 and GFII-3 slabs for example, the load-stress curves of slabs with a reinforcement ratio of 0.75% before cracking are shown in figures 5 and 6. It can be seen that the strain is relatively small before concrete cracking. The strain distribution of concrete obeys the plane section assumption, and the stress-strain relationship presents a proportion relation in the elastic stage.
3.4. Cracking behavior
The distribution of crack and crack spacing of all slabs in the ultimate state are shown in Table 3.

| Specimen | Ultimate load (kN) | Crack spacing | Maximum crack width | Number of cracks |
|----------|--------------------|---------------|---------------------|-----------------|
| GF-I1    | 129.8              | 105           | 2.48                | 7               |
| GF-I2    | 139.5              | 108           | 2.28                | 8               |
| GF-I3    | 170.5              | 102           | 2.05                | 7               |
| GF-I4    | 197.2              | 106           | 1.20                | 8               |
| GF-II1   | 131.9              | 103           | 2.32                | 8               |
| GF-II2   | 141.7              | 105           | 3.26                | 8               |
| GF-II3   | 172.0              | 102           | 1.88                | 7               |
| GF-II4   | 180.0              | 107           | 1.43                | 8               |

Unit (Crack spacing, Maximum crack width): mm

Although the strength and the ratio of reinforcement are different for each slab, the average crack spacing of pure bending is close to 100 mm, which is directly related to the bond performance between GFRP bars and concrete as well as the thickness of concrete cover.

The stiffness of the slab is large before cracking. When the bending cracks appear on the pure bending section of the span, the structure in the tensile region no longer works, resulting in a sudden decrease of the stiffness on the whole beam section. After cracking, the stress and strain changes linearly because there is no obvious yield point for GFRP bar. Unlike the steel bar which has a yielding step, the load-deflection curve is similar to straight line. With the increasing of load, the deformation and vertical crack increase gradually, and the inclined crack appears near the supports. The concrete beam with GFRP reinforcement is destroyed by loading, then stopped loading.

4. Flexural capacity of GFRP reinforced concrete slab

4.1. Basic assumption
The flexural bearing capacity of GFRP reinforced concrete slabs can be theoretically determined by referring to the current design code for concrete structures and relevant codes of FRP tendons at home and abroad. Considering the particularity of the mechanical properties of GFRP tendons, the calculating process for obtaining the bearing capacity of GFRP reinforced concrete slabs will be derived in the following paragraph.

Based on the principal theory of the normal section bearing capacity of the flexural member of the FRP reinforced concrete (GB50608-2010), it should be calculated according to the following basic assumptions.
1) the cross section remains plane after deformation.
2) the tensile strain of concrete is not considered.
3) the stress-strain relation curve of concrete conforms to the specification of concrete structural design code (GB50010-2010);
4) the stress-strain relationship of GFRP tendons follows the linear relationship, which is shown in figure 7.
5) the effect of concrete strain in compression zone is not considered.
Fig. 7 Stress-strain relation diagram of GFRP bar

In Fig. 7, \( \varepsilon_{fd} \) is the design strain of tensile strain and \( f_{fd} \) is the design of tensile stress. The stress of tensile GFRP tendons is equal to the product of strain and elastic modulus and can be expressed as \( f = E_f \varepsilon_f \), where \( f \) is the stress of GFRP tendons and \( E_f \) is the elastic modulus of GFRP tendons, \( \varepsilon_f \) is the strain of GFRP tendons.

4.2. Theoretical Analysis of normal Section bearing capacity

According to the working characteristics and failure characteristics of GFRP reinforced concrete slabs, the failure patterns can be divided into two types: GFRP bars broken and concrete crushed. The failure modes are different depending on the size of reinforcement ratio \( \rho_f \), so the failure modes are divided into three types:

4.2.1 Balanced failure

When the balanced failure occurs, the tensile GFRP bars reach the tensile effective stress limit, and the concrete is subjected to compressive failure, which is the critical state of tensile failure and compressive failure and is an ideal failure mode. The strain relationship at this stage is:

\[
\begin{align*}
\varepsilon_c &= \varepsilon_{cu} \\
\varepsilon_f &= f_{fe}/E_f
\end{align*}
\]

The effective Design stress of FRP under different reinforcement ratio of GFRP tendons \( f_{fe} \) is calculated according to the Formula of Code

\[
f_{fe} = \begin{cases} 
    f_{fd} & \rho_f \leq \rho_{fb} \\
    f_{fd}\left[1-0.211\left(\rho_f/\rho_{fb} - 1\right)^{0.2}\right] & \rho_{fb} < \rho_f < 1.5\rho_{fb} \\
    f_{fd}\left(\rho_f/\rho_{fb}\right)^{-0.5} & \rho_f \geq 1.5\rho_{fb}
\end{cases}
\]

(3)

Where \( \rho_{fb} \) is the balance ratio of the GFRP reinforced concrete, and \( \rho_f = A_f/bh_0/\rho_f \) is the reinforcement ratio of longitudinal reinforcement.

According to the equilibrium condition and deformation coordination condition, we can know that

\[
\alpha_f \beta_1 f_c x_0 = \rho_f b h_0 f_{fe}
\]

\[
\frac{x_0}{\varepsilon_{cu}} = \frac{\varepsilon_{cu} E_f}{\varepsilon_{cu} + f_{fe}/E_f}
\]

Balance ratio \( \rho_{fb} \)

\[
\rho_{fb} = \frac{\alpha_1 \beta_1 f_c}{f_{fe}} \frac{\varepsilon_{cu} E_f}{\varepsilon_{cu} + f_{fe}/E_f}
\]

4.2.2 Tensile failure

Because of the small reinforcement ratio, the GFRP tendons appear brittle failure. GFRP tendons in the tensile zone reach the ultimate strain, while the concrete in the compressive zone does not reach the ultimate strain. Before the failure, the slabs have large deformation, and the stress-strain relationship is as follows:
4.2.3 Compressive failure
The above-mentioned conclusion is similar to that of reinforced concrete beams which indicates that concrete in compression zone is crushed during failure even with large reinforcement. The GFRP bar is still in the linear elastic stage, and the plate has a large deflection. The strain relation is:

\[ \varepsilon_c \leq \varepsilon_{cu} \]
\[ \varepsilon_f = \frac{f_{fe}}{E_f} \]  
(7)

\[ \alpha_1 f_e b\beta_1 x_0 = \rho f h_0 f_{fe} \]  
(8)

\[ \frac{h_0 - x_0}{f_{fe}/E_f} \]  
(9)

\[ \alpha_1 f_e b\beta_1 x_0 = A_f f_f \]  
(10)

\[ \frac{h_0 - x_0}{f_f/E_f} \]  
(11)

\[ \frac{h_0 - x_0}{f_f/E_f} \]  
(12)

4.3 Calculation of flexural capacity
On the basis of the existing references, the flexural capacity coefficient can be expressed as

\[ S = \frac{M_{u,exp}}{M_{u,th}} \]  
(13)

where \( F_u \) is the ultimate load of GFRP reinforced concrete slabs. \( M_{u,exp} \) and \( M_{u,th} \) are the experimental and theoretical value of ultimate bearing capacity of GFRP reinforced concrete test slabs, respectively.

| Group | Specimen | \( F_u \) | \( M_{u,exp} \) | \( M_{u,th} \) | \( S \) | Failure |
|-------|----------|----------|----------------|--------------------|-------|----------|
| I     | GFI-1    | 129.8    | 38.94          | 31.78              | 1.23  | T        |
|       | GFI-2    | 139.5    | 41.85          | 38.04              | 1.10  | T        |
|       | GFI-3    | 170.5    | 51.15          | 37.07              | 1.38  | T        |
|       | GFI-4    | 197.2    | 59.16          | 42.62              | 1.39  | C        |
|       | GFII-1   | 131.9    | 39.57          | 31.78              | 1.25  | T        |
|       | GFII-2   | 141.7    | 42.50          | 41.56              | 1.02  | T        |
|       | GFII-3   | 172.0    | 51.60          | 43.78              | 1.18  | T        |
|       | GFII-4   | 180.0    | 54.00          | 44.53              | 1.26  | C        |

T=Tension failure, C=Compressive failure

The experimental results for bearing capacity are listed in Table 4, indicating that six concrete slabs with GFRP bars are subjected to tensile failure and the other two are compression failure. The load-bearing capacity of each slab is calculated by above formulas, and compared with the experimental values, then the flexural bearing capacity coefficient is from 1.02 to 1.36. The flexural bearing capacity coefficient directly reflects the capacity of members to bear unexpected overload. For concrete beams with different strength grades, with increasing reinforcement ratio, the flexural bearing capacity coefficient of group I is increased from 1.10 to 1.39, and that of group II is increased from 1.02 to 1.26. The flexural load-carrying capacity coefficient increase gradually, the flexural bearing capacity increased accordingly. Consequently, the safety storage is increased.

According to the ACI code and the research on GFRP beams by domestic scholars, \( \rho = 1.4\rho_{fb} \) is the guarantee of the compression failure of the members. It is found from the tests of concrete slabs with GFRP bars that tensile failure may also occur when the reinforcement ratio is slightly greater than 1.4. To ensure the compressive capacity of concrete beams, a relatively large reinforcement ratio should be selected in the design process.
5. Conclusion
The flexural capacity of GFRP reinforced concrete slab with different reinforcement ratio and concrete strength is experimentally studied. The following conclusions are obtained:

1. After cracking, the flexural stiffness of GFRP reinforced concrete slab is smaller whereas the deflection is larger. The cracks are sparse with large crack width.

2. Because of the low elastic modulus of FRP bars, the influence of reinforcement ratio on crack strength is very small, so the effect of reinforcement ratio on crack resistance can be neglected in case of the same strength grade.

3. The reinforcement ratio is an important factor affecting the bearing capacity of GFRP concrete. The flexural bearing capacity of the plate increases with the increase of the reinforcement ratio.

4. When the reinforcement ratio is 1.0 - 1.4 times the equilibrium reinforcement ratio, both tensile and compressive failure may occur since the failure of the plate is brittle failure. Therefore, $\rho_f > 1.4\rho_{f\text{eq}}$ is suggested for the durability design of the GFRP reinforced concrete slab.

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