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A Review of Research on the Stress Performance of Concrete Beams with FRP Bars Instead of Steel Bars

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Abstract

In view of the advantages of fiber reinforced composite (FRP) bars such as high strength, corrosion resistance, light weight, etc., they have now become an important supplement to the construction materials and are being more and more widely used in the field of civil engineering and road and bridge engineering. In recent years, the research on the combined use of FRP tendons and concrete beams has been a hot issue in the field of civil engineering. The research scope of FRP reinforced concrete beams is very wide, involving materials, flexural capacity, shear capacity, bonding performance and influencing factors, etc. This paper traces the research results of FRP reinforced concrete beams at home and abroad, and summarizes them in terms of materials, flexural, shear, bonding, etc., and obtains a more systematic and comprehensive research conclusions, which can provide good references for the design and research of FRP reinforced concrete beams.

Keywords

FRP; Concrete Beams; Bond; Bearing Capacity; Strength.

1. Introduction

At present, the level of engineering construction is constantly improving, people have higher requirements for the economy, safety and durability of building structures. In recent years, the problem of easy corrosion of reinforced concrete structures has been gradually exposed to the corrosion of reinforcing steel leading to a reduction in bearing capacity as a representative of the offshore project, especially in the seawater, chloride salts in the seawater destroy the passivation film of steel reinforcement, accelerated corrosion of steel reinforcement, which reduces the service life of the components and safety performance, resulting in a lot of architectural structures in the design of the baseline period due to corrosion of reinforcement have to spend a lot of manpower and material resources for the repair and maintenance of the later stage. As a result, many building structures have to spend a lot of labor and material resources on repair and maintenance during the design base period due to corrosion of reinforcement, which causes a lot of economic losses. As the country continues to pay attention to the rights and interests of the sea, infrastructure projects in the ocean, such as the construction of artificial islands and reefs will be more and more frequent, the concrete structure of the reinforcement is more susceptible to seawater erosion, and may even lead to safety accidents.

FRP (fiber composite) materials are widely used in the engineering field due to the advantages of high tensile strength, corrosion resistance, good durability and fatigue resistance, and designability [1]. Studies have shown that material replacement is an effective way to solve the corrosion of steel reinforcement. It has been found that FRP reinforcement instead of steel or combined with steel reinforcement is a reasonable way to lay reinforcement. In concrete structures, concrete beams are

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the most common components, but in use, the beams are often in the working condition with cracks, because it is most likely to cause the problem of corrosion of steel reinforcement in the beams. Because of this, a wide range of scholars have conducted extensive and in-depth research on the application of FRP bars in concrete beams. Regarding the application of FRP reinforcement in concrete beams, this paper will systematically elaborate from several aspects.

2. Classification of FRP Reinforcement

FRP tendon (fiber reinforced plastic tendon) is a multi-strand continuous fibers (such as glass fibers, carbon fibers, etc.) through the matrix material (such as polyamide resin, polyethylene resin, epoxy resin, etc.) glued together by a special mold extrusion and drawing molding of a new type of material, see Figure 1. it is an anisotropic linear elastic material, with high tensile strength along the direction of the fibers, corrosion resistance, insulation, lightweight and so on, according to the different fibers can be divided into four types: GFRP tendon, BFRP tendon to, CFRP tendon and AFRP tendon. According to its different fibers, it can be divided into four types: GFRP bar, BFRP bar, CFRP bar and AFRP bar. GFRP bar's fiber material is glass fiber, BFRP bar's fiber material is basalt fiber, CFRP bar's fiber material is carbon fiber fiber, and AFRP bar's fiber material is aramid fiber. From the research situation, the application of GFRP bar and BFRP bar is more widely than CFRP bar and AFRP bar. The disadvantages of these fiber materials are mainly low modulus of elasticity and brittle damage, among which, the modulus of elasticity of CFRP reinforcement is a little higher than the other three [2,3].

Figure 1. BFRP

3. Types of Concrete Beams where FRP Bars are Applied

At present, FRP bars are mainly applied in reinforced concrete girders, but the application of FRP bars in prestressed concrete girders has also appeared. From the length of the girder is divided into long and short girders, with long girders predominating and short girders being rare. In terms of concrete, normal strength concrete is more common and high strength concrete is less. Among them, Ahmed Hussein et al. have studied the ultimate load carrying capacity of high strength concrete [4].

4. Research on Flexural Load Bearing Performance of FRP Reinforced Concrete Beams

Scholars at home and abroad FRP reinforced concrete beams bending performance carried out conventional tests, theoretical analysis, mostly focused on the concrete strength and beam reinforcement rate on the impact of BFRP reinforced concrete beams bending bearing capacity, and for the anchoring method of the impact of the study is a little insufficient [5].

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4.1 Calculation Formula of Flexural Load Capacity

In order to verify the feasibility of BFRP bars replacing steel bars as tensile reinforcement, Prof. Chen Wanxiang of Tongji University carried out a study on the stiffness changes and damage modes of BFRP-reinforced concrete beams under the influence of many factors by means of a four-point bending test (see Figure 2), and formed a flexural capacity calculation formula based on the experimental data, which was comparatively analyzed with the current codes of China, and compared with the calculation formulae in the current Chinese codes [5]. The calculation formula in the Chinese code is compared and analyzed to verify the reliability and accuracy of the prediction formula, which puts forward an important reference value for the subsequent amendment of the relevant codes [6].

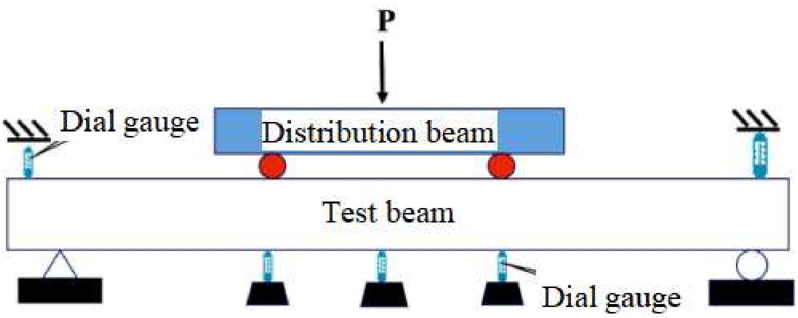

Figure 2. BFRP Four-point bending test arrangement

Its study concluded that the bearing capacity equations of FRP beams in the event of compression damage are divided into two cases, (1) when $\sigma_s^{'} \geq f_y^{'}$, the upper compression zone reinforcement reaches yielding, the BFRP-reinforced beam bending bearing capacity is [7]:

$$M_u = A_s^{'} f_y^{'} \left(h_0 - a_s^{'}\right) + \alpha_1 f_c b x \left(h_0 - 0.5x\right) \tag{1}$$

When $\sigma_s^{'} \prec f_y^{'}$, the reinforcement in the upper compression zone does not reach yield and the bending capacity of the BFRP-reinforced beam is:

$$M_u = \frac{A_s^{'}\left(h_0 - a_s^{'}\right) E_s \left(x - \beta_1 a_s^{'}\right) + \alpha_1 f_c b x \left(h_0 - 0.5x\right) \varepsilon_{cu}}{x} \tag{2}$$

4.2 Calculation of Maximum Crack Width of FRP Reinforced Beam

K.K. Cheng obtained the formula for predicting the maximum crack width of FRP-reinforced beams based on the establishment of a reliability analysis model with a certain range of equilibrium reinforcement rates, see the following formula (3).

$$Z = w_{\mathrm{lim}} - \eta \frac{2.1}{E_{\mathrm{f}}} \left(1.1 \frac{M_G + M_Q}{0.9 A_{\mathrm{f}} h_{0\mathrm{f}}} - 0.65 \frac{f_{\mathrm{t}}}{\rho_{\mathrm{te}}}\right) \cdot \left(1.9c + 0.08 \frac{d_{\mathrm{eq}}}{\rho_{\mathrm{te}}}\right) \tag{3}$$

The reliability index control of the maximum crack width of FRP reinforcement calculated according to the current specification is conservative, so it is necessary to adjust the reliability control level of

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FRP reinforcement so that it is in the range of 0 to 1.5, otherwise it will cause unnecessary waste. It is suggested that it is necessary to use the load quasi-permanent combination when analyzing the maximum cracks of FRP-reinforced beams [8].

4.3 Influence of Elastic Modulus of FRP Reinforcement on Beam Damage Mode

In 2023, Jin Gao Ming et al. conducted an experimental study on the bending performance of FRP-reinforced recycled concrete beams, analyzed the damage modes of FRP-reinforced recycled concrete beams at the bounded reinforcement ratio by choosing GFRP bars and BFRP bars with different elastic modulus and compared the results with those of other countries [9].

The results of the study were: one GFRP-reinforced concrete beam with 50% RA replacement rate experienced concrete crushing damage in the compression zone, and the other one experienced diagonal tensile damage, indicating that this state is close to the critical state of diagonal tensile damage and concrete crushing damage in the compression zone [10]. Given that the modulus of elasticity of BFRP reinforcement is 20% higher than that of GFRP reinforcement, under the same load, the elongation of BFRP reinforcement is smaller, the deflection of the beam develops slower during the loading process, and the height of the concrete compression zone is higher compared with that of the GFRP-RAC beams, which improves the bearing capacity of the beams' normal section; the bearing capacity of the beams' diagonal section is determined by the hoop reinforcement and the concrete strength, and the longitudinal reinforcement only plays the role of bolster dissipation, and the longitudinal reinforcement only plays the role of bolster dissipation. The diagonal section capacity of the beam is mainly determined by the hoop reinforcement and the concrete strength, and the longitudinal reinforcement only plays the role of bolting, so the increase of the modulus of elasticity of the FRP reinforcement has a small effect on the diagonal section capacity of the beam, so the two BFRP-reinforced concrete beams are damaged by diagonal tensile damage when the other conditions remain unchanged. It can be seen that when the modulus of elasticity of FRP reinforcement is increased, the hoop ratio of the beam should be increased, so as to prevent the diagonal tensile damage of FRP-reinforced concrete beams and make full use of the tensile strength of FRP reinforcement.

5. Study on the Shear Performance of FRP-Reinforced Concrete Beams

5.1 Factors Affecting the Shear Performance of FRP-reinforced Concrete Beams

Several columns of scholars have carried out studies on the effect of FRP reinforcement ratio, effective height of beam section, size effect, shear span ratio and other factors on the shear of beams [10].

In 2002, Yost J R et al. investigated the effect of GFRP reinforcement ratio on the shear strength of concrete beams by loading a group of GFRP reinforced beams at four points. It was found that the shear strength of GFRP-reinforced beams was less than that of RC beams with equal reinforcement ratio for the size, while the effect of longitudinal reinforcement ratio on the shear strength of GFRP-reinforced beams was very insignificant.

In 2012, Alam M carried out four-point bending tests on eight groups of GFRP-reinforced, CFRP-reinforced and RC beams, mainly investigating the effects of effective height of the beam section and longitudinal reinforcement ratio on the shear strength of FRP-reinforced beams without web. The results show that, when the effective height of the section is more than 300mm, the shear strength of the beam increases with the reinforcement ratio, and the normalized shear strength increases linearly with the cube root of the axial stiffness of the FRP reinforcement.

Specific studies have been carried out in numerical simulation for some difficult problems.2022 Shoeib A E et al simulated the shear strength, load-deflection relationship and crack development pattern of 14 sets of GFRP reinforced concrete beams with mixed reinforcement of GFRP bars and steel reinforcement by using finite element analysis software ANSYS. The simulation results are in good agreement with the experimental results and are able to reflect the effects of each parameter.

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In 2024, Lijia Zhang from Jiangnan University investigated the effect of shear-span ratio on shear by fabricating two sets of beam specimens with shear-span ratios of 1.5 and 3.0, as shown in Figure 3.

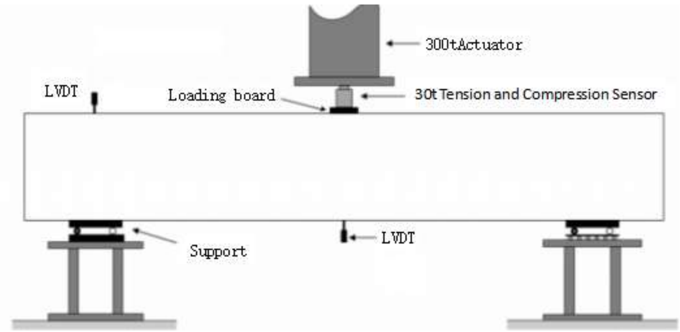

Figure 3. Schematic diagram of the test setup

The conclusion drawn from the experiment is:

(1) When the shear span ratio is 3, all specimens undergo diagonal tensile failure. The reinforcement ratio of FRP bars and steel bars has no significant effect on the shear bearing capacity and initial stiffness. However, an increase in the amount of FRP bars significantly reduces the secondary stiffness, which may lead to an increase in cracks; The larger the proportion of FRP reinforcement cross-sectional area, the greater the ultimate deflection and ductility of the beam.

(2) When the shear span ratio is 1.5, all specimens undergo shear compression failure. The smaller the reinforcement ratio of FRP bars and steel bars, the weaker the shear bearing capacity; The ductility of FSRC beams is weaker than that of RC beams and FRP reinforced concrete beams, and gradually decreases with the increase of the steel to FRP reinforcement ratio [11].

5.2 Calculation Formula for Shear Capacity of FRP-reinforced Concrete Beams

In 2023, Professor Qu Wenjun of Tongji University, through the study of the damage mode of reinforced concrete beams, taking into account the strain coordination conditions, stress balance conditions, concrete and reinforcing materials, and many other factors under the conditions of the constitutive relationship, the FRP reinforcement concrete beam shear load capacity calculation to mention a unified formula to facilitate the application of engineering, see the following formula.

$$V = \sigma_{c1} b_w h_0 \cot\theta + \frac{A_{sv}\sigma_{sv} + A_{fv}\sigma_{fv}}{s} h_0 \cot\theta \tag{4}$$

Where: A_{sv} is the area of steel hoop; A_{fv} is the area of FRP hoop; σ_{sv} is the stress of steel hoop; σ_{fv} is the stress of FRP hoop; b_w is the width of beam section; and s is the spacing of hoop [12].

This formula is rare in that it is not only suitable for the shear calculation of BFRP-reinforced concrete beams, but also suitable for the shear calculation of other three kinds of FRP-reinforced concrete beams, which can be said to be a universal formula for the shear calculation of FRP reinforcement.

5.3 Calculation Method of Shear Capacity of Short FRP-reinforced Concrete Beams

In 2024, Song Bo et al. from Beijing Institute of Technology (BIT) conducted shear tests on 10 short BFRP-reinforced concrete beams, and analyzed the effects of beam height, shear-to-span ratio, and horizontal and vertical web reinforcement rates on the shear damage mode, the mid-span displacement curves of the loaded beams, and the shear load capacity. After comparing with the calculation results of European and American codes, the reasonableness of the calculation method of

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shear capacity of FRP-reinforced concrete short girders based on the tensile arch model is verified [13,14].

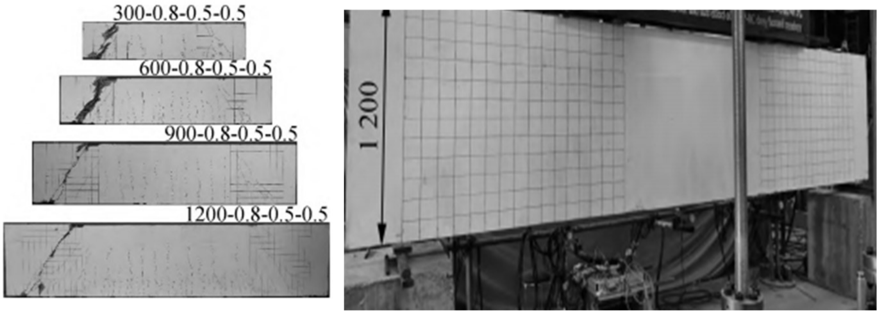

Figure 4. Experimental components and on-site testing

6. Bonding Performance of FRP Bars to Concrete

6.1 Numerical Simulation Analysis of Bond-slip between FRP Bars and Concrete

Bakis used IDeas software to establish a finite element model of FRP reinforcement and concrete pullout, which considered tangential stiffness, normal stiffness and parameters that have an effect on bond performance, and the simulated load-slip curves and bond stress-slip curves were more consistent with the test results [15,16].

Based on her own experimental bond-slip curve and the proposed bond-slip constitutive model, Haixia Zhang performed numerical calculations on 12 pullout specimens using ANSYS software, and the interface between the FRP bars and the concrete was connected by a nonlinear spring unit. The calculation results show that the average value of the ratio of the test value to the calculated value of the peak bond stress is 1.04, and the average value of the corresponding slip is 0.97, which can generally realize the nonlinear numerical calculation of the pullout specimens more accurately [17].

Yan etal established the interfacial slip damage evolution equation based on the strain equivalence principle of damage mechanics, and proposed a method to evaluate the bond damage at the GFRP bar-concrete interface. The degree of interface slip deterioration is evaluated by the change of the modulus of the cut line of the interfacial slip curve. The results show that the damage evolution model strictly follows the lognormal distribution, where the minimum value of the lognormal distribution R2 is 0.9851 [18].

6.2 Bond-slip Test Study of FRP Reinforcement and Concrete

Zhili Yu from Dalian University of Technology conducted tensile tests on three types of FRP reinforcement, see Figure 4. The actual engineering environment was simulated by immersing the FRP reinforcement in a seawater lake, and the tests were conducted in groups according to different temperatures and immersion times. The bond-slip curve formation process was objectively analyzed.

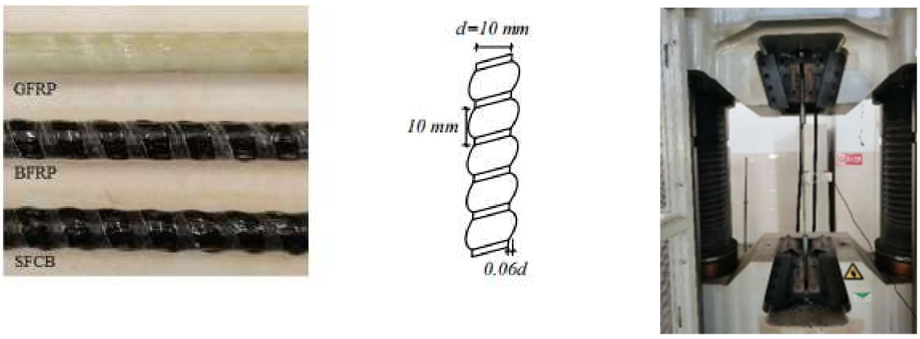

Figure 5. Material parameters and field test

It is analyzed that: the initial curve of the three kinds of reinforcement is close to a straight line in the upward section in general, and with the gradual increase of slip, the slope of the curve in the upward section begins to decrease, and the curve enters into the downward section, the concrete between the ribs in the bond zone is damaged by the shear extrusion and the concrete debris is attached to the surface of the reinforcement, which results in the occlusal and frictional forces decreasing and the bond stress decreasing rapidly, and then the slip increases, and the slip in the downward stage is larger than that in the upward stage in general. The degradation of mechanical properties of FRP tendons is the main reason for the degradation of ultimate bond strength [19,20].

7. Conclusion

In view of the lightweight, high strength and corrosion-resistant characteristics of fiber compliant materials, they can be widely used in civil engineering structures, including road and bridge engineering and tunnel engineering. This paper takes a holistic view and summarizes the conclusions and results of FRP reinforcement research from various research levels involved in FRP reinforcement.

(1) The types of FRP reinforcement materials and their advantages and disadvantages, and the types of FRP reinforcement applied in concrete beams are pointed out.

(2) The rules and related formulas of FRP reinforcement in terms of flexural load bearing and properties are summarized. Including the effect of the modulus of elasticity of FRP reinforcement on the damage mode of beams, the calculation of the maximum crack width of FRP-reinforced beams, and the formula for calculating the flexural load capacity.

(3) The results of the research on the shear performance of FRP-reinforced concrete beams are summarized, including the formula for calculating the shear capacity of FRP-reinforced concrete beams, the influencing factors of the shear performance of FRP-reinforced concrete beams, and the method of calculating the shear capacity of FRP-reinforced concrete short beams.

(4) The conclusions of the research on the bonding performance between FRP bars and concrete are summarized. It includes numerical simulation analysis of bond-slip between FRP reinforcement and concrete, and research results of bond-slip test between FRP reinforcement and concrete.

(5) The vast majority of existing research has focused on concrete beams with a mixture of FRP bars and steel bars. There are few studies on FRP bars replacing all tension zone beams. Based on comprehensive research on FRP reinforced concrete beams, we will conduct specific and effective research and analysis on the replacement of tension zone steel bars with FRP bars, focusing on issues such as bearing performance, crack propagation, and deflection. We hope to make substantial progress.

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