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Research on the Preparation and Properties of HFRP Bars in Civil Engineering

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In order to study the preparation and properties of HFRP bars for civil engineering, this paper, through experiments on the tensile and fatigue properties and fracture analysis, analyzed the tensile and anti-fatigue properties and preparatory processes of HFRP bars. Results showed that the HFRP bars specifically for civil engineering integrate the pultrusion and winding processes, concluding that high-strength GFRP bars have high fatigue resistance, and the fatigue damage of high-strength 4# GFRP bar is less at the maximum stress of 33.8% and the stress amplitude of 7.5%.

1. Introduction

Non-prestress and prestress are generally used in the traditional concrete structure. Although the concrete itself resists corrosion to a certain degree, under the influence of the humidity, temperature and other factors, the concrete alkaline will be continuously reducing, resulting in steel corrosion. With the continuous development of composite materials, some experts and scholars began to study FRP bars and other composite materials to analyze whether FRP bars can be used in concrete structures as a replacement of steel bars.

In this experiment, the tensile and fatigue properties of HFRP bars were tested, and then the theoretical model of tension strength was established to find improvements for the tensile property of FRP bars.

2. Literature review

At present, the durability of reinforced concrete has become an urgent problem to be solved. According to the many years of engineering practice and application in developed countries, the cost of solving this problem is also high. For example, the UK is spending nearly 25 billion pounds a year to solve the corrosion and protection of reinforced concrete structures caused by the marine environment and the reinforcement of damaged concrete structures. Nearly 15 years after Japan Shinkansen operation, its concrete has also undergone extensive erosion and cracking. When examining the 100 reinforced concrete port terminals, it was found that most of these port terminals had a large number of cracks along the way after they were used for 20 years. In 1985, Saudi Arabia investigated 40 coastal concrete frame structures. The corrosion of the steel bars in the structure of the 30 buildings is serious. Its proportion accounts for 75%. In 1993, the United States spent more than 70 billion US dollars to reinforce and repair buildings caused by corrosion. About 45% of these buildings are structural failures due to corrosion of steel bars. Among the 580,000 reinforced concrete bridges, 300,000 have been corroded. 43% of the bridges have insufficient carrying capacity and must be repaired and reinforced. The main cause of corrosion damage of these reinforced concrete structures is the corrosion of rebar by chloride salts and chloride ions in the marine environment. The cost of repairing these bridge structures will spend 156 billion U.S. dollars.

Ping et al. proposed fiber bundle theory and suppress crack propagation theory. The theory of fiber bundles suggests that when the HFRP composites under normal stress conditions, the low-elongation carbon fibers or fiber bundles first break down. However, they are closely surrounded by glass fibers and the matrix. Although the carbon fibers have been discontinuously broken, the carbon fibers can continue to bear the shear load and still contribute to the stiffness. It causes the carbon fiber to have a much greater strain strain than a single carbon fiber. Inhibition of crack propagation theory holds that in HFRP composites, glass fibers act to suppress crack propagation, thereby reducing the probability of catastrophic crack propagation (Ping et al., 2017). Hu et al. used the shear lag theory to study the stress redistribution of HFRP composites caused by the failure of each monolayer. A modified shear lag model is proposed. It considers the effect of interfacial interfacial failure on stress redistribution. Then, a random critical nuclear theory was used to study the final tensile failure process of inter-layer hybrid composites (Hu et al., 2017). Jong-Myeong et al. first studied the dynamic characteristics of reinforced concrete columns reinforced with FRP. It was found that FRP can change the brittle shear failure morphology of the column into ductile bending failure (Jong-Myeong et al., 2017). Wang et al. studied CFRP-reinforced concrete bridges. The plastic hinge area is reinforced with a unidirectional CFRP cloth. CFRP reinforcement can significantly increase the strength and ductility of the bridge (Wang et al., 2017). Gao et al. studied the seismic performance of CFRP reinforced inverted T-shaped columns. The main parameters are the number of carbon fiber sheets, the shear span ratio, and the axial compression ratio. It was found that CFRP was used to reinforce concrete columns, which prevented the occurrence of oblique cracks or restricted the development of diagonal cracks. It significantly improves the shear capacity of the column. At the same time, with the increase of the amount of carbon fiber reinforcement, the test specimens gradually change from a ductile brittle failure mode to a ductile failure zone with normal cross-section. Based on the experimental data, the relationship between the hysteretic energy coefficient and the target ductility coefficient of reinforced concrete columns reinforced with carbon fiber sheets was obtained. Based on the concept of energy, the calculation formula of the target ductility coefficient is proposed. The amount of carbon fiber cloth to be reinforced can be determined (Gao et al., 2018). Through experiments, Pan et al. found that FRP pipe confined concrete columns can also significantly improve the ductility of the columns without significantly increasing the column stiffness, and the constrained members eventually undergo bending failure. In addition, they also found that the lack of reinforcement column ferrule rate can be compensated by FRP constraints (Pan et al., 2017). Elchalakani et al. studied the seismic behavior of concrete columns reinforced with prefabricated GFRP casing. The FRP sleeve is not damaged. When the displacement is large, the bonding of the overlapping longitudinal bars is destroyed, which leads to a significant reduction in the seismic performance of the column. The results show that the prefabricated FRP casing is very effective in preventing shear failure of the bridge columns and breakage of the reinforcements of the steel bars and improving the ductility of the columns (Elchalakani et al., 2017). Based on the test results of FRP outsourcing test specimens, the stress-strain curve of FRP-confined concrete is generally bilinear. Therefore, a bilinear FRP confined concrete stress-strain model was proposed. It only requires two fixed points. Although this method evades iteration deficiencies, the accuracy is not very high (Vincent and Ozbakkaloglu, 2017).

In summary, the most widely used structural type in civil engineering is reinforced concrete structure. Among them, reinforcing steel and concrete are the most widely used building materials in the structure. However, there are also some problems in its use, such as low tensile strength and large dead weight. According to surveys, durability of civil issues is lower when civilian buildings and public buildings are maintained for more than 50 years. Its outdoor components, such as rain covers, provocations and balconies, have a service life of only 25 to 35 years. 75% of industrial buildings require overhaul after 30 to 35 years of use. The service life of buildings in a hazardous environment is only 20 to 25 years. In addition, due to factors such as physical ageing, functional changes, chemical corrosion, and increased design standards, the service life of civil buildings has also been reduced.

3. Experiment Principle and Method

Based on the pultrusion process, a pultrusion-winding device, a traction device, and an online curing mould were developed to build a bar experimental device for continuous production. At the same time, the sand stress-strain model and the bar tensile strength theoretical model were established. Then, the material test method was determined through the test of bar performance, providing the basic conditions for the property evaluation and improvement of the bars. In addition, the three-dimensional shear lag model of unidirectional HFRP was established. The fiber bundle is defined as a fiber matrix resin system, while HFRP is defined as a combination of two or more fiber bundles. The bond performance between the bar and the concrete was systematically studied by the drawing test and beam test. The bar developed in this paper as the reinforced material was then applied to the concrete sewage treatment pond, and the structure was tested and analyzed.

4. Experimental Results and Analysis

4.1 Experimental Study on Tensile Property of HFRP Bars

Glass fiber is the polymer matrix composite mostly common used for reinforcement. Molten glass can be pulled into continuous filaments that can cluster into roving. In manufacturing, the fiber surface is coated to

improve the wettability of the substrate and provide better binding effect between the components of the composites, and the coupling agent is applied to the glass fiber to provide a flexible layer on its surface, effectively improving the binding strength with the resin.
The core-skin structure and the mixed-layer design of the HFRP bars were adopted. In the core structure, the core material is carbon fiber, and the skin E-glass fiber and S-glass fiber, according to the forming process conditions, suffered the skin and core fiber arrangement, finally generating hybrid bars.
FRP bars are used to enhance the concrete structure and feature high longitudinal strength, corrosion resistance, non-magnetic, fatigue resistance, light weight, low conductivity, and other excellent properties compared with steel. Two kinds of reinforced fibers, carbon and glass, were mixed to produce HFRP bars, HFRP for short, which can make full use of the respective advantages of fibers to improve the modulus, strength and elongation at break of the single material. In this study, the hybrid bars were in the form of sandwich and scattered hybrid. Figure 1 is the cross section shot by a three-dimensional video microscope. Carbon and glass were mixed according to 50% total fiber volume, with the fiber relative volume content of 10%, 20%, 30%, 40%, and 50% respectively. The fiber used were T700, 12k carbon fiber, and ordinary fiberglass, with the fiber properties shown in Table 1.

Figure 1 : (a) Sandwich (b) Scattered and mixed

Table 1: Fiber performance parameters table

material	Linear density	Body density	Tensile Strength	Tensile modulus	Elongation at break
T700s	800	1.82	4800	230	1.4
S2 glass	1200	2.53	4020	82	5.3
S1 glass	1200	2.53	4600	86	5.4
E glass	1200	2.54	2760	79	3.3

The specimens were made by the drawing-wrapping forming process, that is, the combination of pultrusion and winding. The ring winding for the outer layer can make the unidirectional fiber bond more tightly and improve the circumferential strength. The bar, with the diameter of 9.5mm, had its two ends reinforced with FRP. The specimens were divided into pure ordinary E-glass fiber (G), pure high-strength S2 glass fiber, pure high-strength S4 glass fiber, pure T700 carbon fiber (C), intra-layer and inter-layer hybrid FRP bars of different fiberglass and carbon fibers, with the C/G mixing ratio in accordance with the 50% fiber volume content. The fiber volume content of real test pieces changed slightly, but the C/G mixing proportion was considered unchanged.
The microcomputer controlled electronic universal testing machine (Figure 2) were adopted in the experiment, whose maximum tensile force can reach 200KN, with the maximum stretching stroke of 400mm, the maximum compression stroke of 400mm, the effective test width of 575mm, and the displacement resolution of 0.01mm, enabling a high test accuracy. The extensometer of the universal testing machine was used to measure the elongation at break, with the gauge length of 50mm.
The shear strength and compressive strength of the FRP bar are very low, usually no more than 10% of its tensile strength. In this sense, in the tensile property test, if both ends of the specimen are directly clamped, they may be easily damaged due to large force of the test machine's chuck, which will lead to failure in

correctly characterizing the tensile properties of the bar. So special fixtures was made. Before the experiment, the specimen was held in the upper and lower fixtures.

Figure 2: Computer controlled electronic universal testing machine

The tensile strength σt (MPa) was calculated by the following formula: $\sigma_t = \frac{P_b}{S}$
In the formula, Pb --fracture load, MPa;
S—specimen area, mm2.
The tensile failure elongation was calculated according to the following formula: $\varepsilon_t = \frac{\Delta l_b}{l}$
In the formula, the tensile failure elongation is εt, and the total elongation of the guage length of the specimen at failure is Δlb, with the unit of mm.
As the elongation of carbon fiber is less than that of glass fiber, the longitudinal tensile strain of unidirectional hybrid bars is controlled by carbon fiber which will break when the composite material is stretched to the limit strain of carbon fiber. When the relative content of carbon fiber is less than the critical value, the load of the carbon fiber is transferred to the glass fiber, and the load can continue to increase, bringing the secondary damage. When the relative volume content of carbon fiber exceeds the critical value, primary damage will occur. The critical volume content can be obtained by the following formula. $V_{cr} = \frac{1}{\frac{1+X_{fc}}{X_{fg}-kX_{fc}}}$
In the formula, Xfc and Xfg refer to the tensile strength of carbon fiber and glass fiber respectively, $\mathrm{k} = \frac{E_g}{E_c}$.
However, even in a single fiber composite, the calculated value of the strength theory deviates from the measured value due to the influence of the fiber-matrix matching, interface, and the composite process. In order to eliminate the influence of these factors, we can multiply the strength of S and C, the two fiber bundles, by a deviation coefficient Sc and Sg respectively. It is also the ratio of measured value and calculated value of single fiber reinforced bars. When the tensile strength of C and G hybrid bars is predicted, the predicted value of primary and secondary failure strength is multiplied by Sc and Sg respectively for modification.
The results show that there are two failure modes, and the elongation at break presents a hybrid effect. The mixed effect of the sandwich hybrid is higher than that of the scattered hybrid. Based on the above research results, the stiffness, strength and elongation at break of single fiber reinforced bars can be improved by rational collocation of C and G hybrid fibers, which satisfies the practical engineering needs. In addition, based on the experimental data of single fiber reinforced bar and considering the influence of molding process, a modified tensile strength prediction method was proposed in this paper, which can be used in the preliminary design of the bar.

4.2 Fatigue Property Research

Reinforced materials for FRP bars in the experiment were fiberglass (produced by Chongqing Polycomp International Corporation), carbon fiber (produced by Japan Toho Company), high-strength glass fiber (produced by Nanjing Fiberglass courtyard), and high-strength glass fiber (produced by Sinoma Nanjing Fiberglass Research and Design Institute). The matrix material was epoxy vinyl acetate resin produced by Ashland Company. Also, the initiator, filler, and other ancillary materials were also used. Then the PLG-200C high frequency tensile and compressive fatigue test machine was applied to study the fatigue properties of ordinary fiberglass bars, high-strength fiberglass bars, and high-strength glass-carbon fiber hybrid bars were studied.

The maximum stress respectively takes 30%, 35%, 40%, and 45% of the ultimate stress (considering the dispersion of the static strength test results, the 90% of the static strength is taken as the ultimate stress), with the stress amplitude as 7.5% and 15% of the limit stress. The test frequency is about 78Hz.

Table 1: Ordinary glass fiber fatigue test results

Maximum stress level	Radiation level	frequency	phenomenon
30	7.5	1206428	fracture
35	7.5	1273839	fracture
40	7.5	360455	fracture
45	7.5	449036	fracture

Table 2: High-strength 2#fiberglass bars fatigue test results

Maximum stress level	Radiation level	frequency	phenomenon
30	7.5	3720000	Not damaged
35	7.5	3000000	Not damaged
40	7.5	3000000	Not damaged
40	15	142637	fracture
56	15	7076	fracture

Through the analysis of the fatigue test results, it can be seen that with the maximum stress as 30%- 45% of the ultimate stress and the stress amplitude of 7.5%, the ordinary fiberglass bar suffered damage in a few cycle times. Under the same maximum stress and stress amplitude, the high-strength 4# fiberglass bar, high-strength 2# fiberglass bar, and the high-strength 2# glass-carbon fiber hybrid bar didn't suffer any damage despite over tens of thousands cycles, concluding that the fatigue performance of ordinary glass E-fiber bars is poor.

When the maximum stress is 35% or 40% and the stress amplitude is 15%, the high-strength 2# glass fiber bar and the high-strength 4# glass fiber bar were destroyed in a few cyclic times, and the fatigue cycles of the high-strength 4# glass fiber is a little more than that of the high-strength 2# fiberglass bar, indicating a slightly better fatigue performance of the high-strength 4# glass fiber.

As for the high-strength 4# fiberglass bar, if we raise the maximum stress to 37.4% and the stress amplitude to 15% from the maximum stress of 33.8% and the stress amplitude of 7.5 % after 2,684,752 times of fatigue tests, the fatigue failure cycles were nearly the same as that directly under the maximum stress of 37.4% and the stress amplitude of 15%, indicating that the fatigue damage of the high-strength 4# fiberglass bar is less under the maximum stress of 33.8% and the stress amplitude of 7.5 %.

The fatigue properties of FRP bars are mainly determined by stress amplitude and the maximum stress. The heat and sticky phenomena of the specimen were not found in the test, so the high-frequency fatigue experiment could be used to test the fatigue properties of FRP bars.

4.3 Fracture Analysis

The hybrid morphology and fracture morphology of hybrid specimens were observed and photographed with a three-dimensional video microscope. It was found that the carbon fibers are unevenly distributed with irregular cross-section shapes, which is more obvious with less carbon fiber volume content. And the interfacial area of interlayer hybrid bars is much smaller than that of intra-layer hybrid bars. Also, the surfaces of carbon fiber and glass fiber are both smooth, which shows that the bonding strength between the fiber and the substrate is low

5. Conclusion

This experiment mainly analyzed the tensile properties and the preparation process of HFRP bars. According to the experimental results, high-strength FRP bars have high fatigue resistance, and the high-strength 4# fiberglass bar suffers less fatigue damage under the maximum stress of 33.8% and the stress amplitude of 7.5%. In addition, the scientific and reasonable configuration of C and G hybrid fibers can improve the stiffness and elongation at break of single fiber reinforced bars for better applications.
The improvement of FRP bars to enhance the concrete quality can further solve the concrete structure failure. At present, there are few researches on FRP bars in China, making it difficult to apply the research results to construction projects. The study of FRP bars shall not only attach importance to the properties of FRP bars, but also needs to consider the production cost.

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