Study on Bonding Properties of GFRP Bars and Concrete Interface in Erosion Solution

Zepeng Song, Chunhua Lu* and Liyuan He
Faculty of Civil Engineering and Mechanics, Jiang Su University, Zhen Jiang City, Jiang Su Province, 212013, China
Corresponding author’s e-mail: lch79@mail.ujs.edu.cn

Abstract: In order to study the degradation of bonding performance between GFRP bars and concrete under erosive solutions, 36 drawn specimens were prepared from 3 different diameter GFRP bars for solution immersion test. The test used three kinds of erosion environments of water, salt and alkali solutions. After immersion for 270 days, the specimen was subjected to static tensile test. The test results show that the bond strength of GFRP bars and concrete decreases greatly in the salt environment. The bond strength of specimens decreased by an average of 24.01% in the salt solution, by 19.35% in the clear water solution, and by 17.36% in the alkaline solution. Based on elastic mechanics, the theoretical calculation formula of bond strength is proposed using the thick-walled cylinder model. The theoretical value agrees well with the measured value and has good applicability, which can provide a certain reference for engineering design.

1. Introduction
Because the steel bars inside the reinforced concrete structure is easy to be affected by the erosion of the environment, the problem of insufficient durability of the structure is very prominent. Glass-Fiber Reinforced Polymer (referred to as GFRP) have the advantages of light weight, high strength, corrosion resistance and so on, and become an ideal material to replace ordinary steel bars serving in various erosion environments, and have broad application prospects in Civil Engineering [1]. However, studies have shown that GFRP tends to degrade in salt and alkali environments [2,3]. Considering that corrosion begins on the surface of the fascia, this may have a greater impact on its bonding properties with the concrete interface. Therefore, it is necessary to systematically analyze the bond strength of GFRP bars and concrete under different erosive environments.

In this paper, the experimental research on 36 GFRP-concrete drawn specimens was carried out. The bond failure mode, bond strength retention rate and failure mode of GFRP bars and concrete under different erosion environments were analyzed. At the same time, based on the thick-walled cylinder model of elastic mechanics, the formula for calculating the bond strength is proposed. The theoretical value agrees well with the measured value, and the accuracy of the formula derived in this paper is verified. The relevant content can provide a theoretical basis for ensuring the effective cooperation of GFRP reinforced materials and concrete, and meeting the requirements of such structures in an erosive environment.

2. Test scenarios

2.1 Test materials
In this paper, three kinds of GFRP bar with different diameters are produced by Nanjing Feng Hui Composites Co., Ltd., which is composed of vinyl ester resin and fiberglass, and its surface is constructed as a full thread. The physical and mechanical properties of the reinforced material are shown in Table 1.

| Fiber content/% | Diameter/mm | Elastic modulus/GPa | Shear Strength/MPa | Tensile strength/MPa |
|-----------------|-------------|---------------------|--------------------|---------------------|
| 64              | 8           | 50.00               | --                 | 1409.52             |
|                 | 12          | 38.22               | 13.67              | 864.36              |
|                 | 16          | 45.73               | 23.21              | 958.23              |

The concrete mix ratio of the drawing specimen is 1:2.838:1.274:0.4 for the mix ratio of cement, stone, sand and water. The average compressive strength of the measured 28d concrete cube test block is 36.94MPa.

2.2 Erosion Environment Design
In this paper, the following three erosive solution environments are designed: (1) salt environment: design according to ASTM d665-06 specification [4]. (2) alkali environment: design according to ACI 440.3R-04 specification [5]. (3) clear water environment: Use urban tap water. The soaking time is 270d. Regularly check the pH value of the solution and replenish moisture to ensure stable environment. In order to facilitate the comparison, a fourth set of laboratory environment (not immersed) was designed, and the corresponding test piece was the reference test piece.

2.3 Pull-out test scheme
Referring to the provisions of the Standard for test method of concrete structures (GBT50152-2012) [6], using the central pull test method for bond strength test. A 150 mm × 150 mm × 150 mm drawn test specimens was selected for casting, and the effective length of the bonding section was set to 5 d (d is the diameter of the bar). Using the test method of Class fiber reinforced polymer rebar for civil engineering (JG/T406-2013) [7], the drawing test was completed on a UTM5305 electronic universal testing machine with a test loading rate of 1.2 mm/min and continuous uniform loading.

3. Analysis of test results

3.1 Forms of Destruction
According to the test, the following three types of damage occurred in this pull-out test: (1) casing slippage damage. (2) reinforced material pull out damage. (3) concrete splitting damage. The form of damage is shown in Figure 1.

(a) Casing slip damage (b) Reinforced material pull out damage (c) Concrete splitting damage

Figure 1 Type of specimen damage

3.2 Theoretical model analysis of bonding strength
The thick-walled cylinder model established in the reference elastic mechanics is used to analyze the force of the drawn specimen [8], the sum of the radial stress is uniform internal pressure \( P \), \( f \) is the compressive stress experienced by the concrete in the cracked part; GFRP reinforcement and concrete
is shown in Figure 2. As shown in Figure 3, the GFRP Reinforcement and concrete Force Analysis Unit is established, \( t \) is the extrusion force of the GFRP bar to the concrete bonding interface; \( \mu \) is the friction coefficient, \( \mu t \) is the interface friction force, and \( t \) and \( \mu t \) are decomposed into radial stress and tangential stress. Among them, the bond strength \( \tau \) is the sum of the tangential stresses.

\[
\tau = t \sin \theta + \mu t \cos \theta \\
P = t \cos \theta - \mu t \sin \theta
\]

(1)

The angle in the upper formula is generally taken as 20°~45°. \( f \) for cracking part of the concrete subjected to compressive stress, we know:

\[
P \pi d = 2 \pi f e
\]

(2)

where \( e \) is the distance from the center of the GFRP to the edge of the cracked concrete; \( d \) is the diameter of the GFRP bar. According to the thick-walled cylinder model, the cyclic tensile stress can be provided by elastic mechanics as:

\[
\sigma_s = \frac{(d/2)(t \cos \theta - \mu t \sin \theta)e^2}{(c + d/2)^2 - e^2}
\]

(3)

where \( r \) is the distance from the center of the specimen to any point (mm); \( c \) is the thickness of the protective layer (mm). The tangential tensile stress at the \( r = e \) reaches the maximum value, and the \( e \) generation into Eq.(3) is achieved:

\[
\sigma_{\text{max}} = \frac{d}{2e}(t \cos \theta - \mu t \sin \theta)(c + d/2)^2 + e^2
\]

(4)

The maximum value of tangential tensile stress is the tensile strength of concrete:

\[
\sigma_{\text{ct max}} = f_{\text{ct}}
\]

(5)

where \( f_{\text{ct}} \) is the compressive strength of the cube, and the \( f_{\text{ct}} \) is the tensile strength of the concrete.

\[
e = 0.486\left(\frac{c + d}{2}\right)
\]

(6)

Simultaneous Eqs. (4)~(6) solution was \( t_{\text{ct max}} \):

\[
t_{\text{ct max}} = 0.395 \frac{(c + d/2)}{1.665d}\left(\cos \theta - \mu \sin \theta\right) f_{\text{cu}}^{0.55}
\]

(7)

When there is a crack development depth exceeding this range, it is considered that the crack penetrates the test piece and the test piece reaches a broken state.

Substituting Eq.(7) into Eq.(1) the theoretical bond strength of GFRP bars and concrete is:

\[
\tau = 0.395 \frac{(c + d/2)(\sin \theta + \mu \cos \theta)}{1.665d}\left(\cos \theta - \mu \sin \theta\right) f_{\text{cu}}^{0.55}
\]

(8)

The difference of bond strength between different diameter GFRP bars is mainly reflected in two aspects: (1) The increase of diameter will increase the angle between GFRP bars and the failure surface of concrete, so when the diameter is less than 10mm, \( \theta \) is 20°, and when the diameter is between 10mm and 14mm, \( \theta \) is 30°; when the diameter is greater than 16mm, \( \theta \) takes 40° ; (2) The rib height and rib width of the surface of the GFRP reinforcement will increase with the increase of the diameter, so the friction coefficient with the concrete will also increase. According to the diameter of the GFRP bars ,
0.35, 0.50 and 0.65 are taken as the friction coefficient with concrete.

4. Test results and analysis

4.1 Comparison of theoretical value and test value
The measured bond strengths $\tau_u$ of the three diameter GFRP bars of 8, 12 and 16mm were 12.81MPa, 16.53MPa and 26.79MPa, respectively. By substituting the model Eq. (8) into various parameters of GFRP bar-concrete, the theoretical value of bond strength $\tau_8$ is 13.25MPa, the error with the measured value is 3.43%; $\tau_{12}$ is 16.35MPa, the error is 1.09%; $\tau_{16}$ is 26.52MPa, the error for the is 1.01%. It can be seen that the theoretical value agrees well with the measured value.

4.2 Analysis of the influence of diameter on bonding performance
It can be seen from Figure 4 that as the diameter of the bars increases, the bond strength between the GFRP bars and the concrete and the increase in the bond strength also increase. The main reasons are: (1) the larger the diameter, the more contact area between the bars and the concrete. The contact area between the GFRP bars and the concrete is proportional to the contact area, which leads to the increase of the bond strength; (2) the increase of the diameter increases the rib height of the bar and the rib width, and further. The mechanical bite force between the bar and the concrete is increased, so the bond strength is increased.

![Figure 4 The effect of different diameters of GFRP bars on their bond strength](image)

4.3 Effect of erosion environment on bonding performance
The bars are corroded in harsh environments and affect their bonding properties [2,9-12]. It can be seen from Figure 5 that the bond strength between GFRP bars and concrete is significantly reduced under the action of erosion environment, but the influence degree of different erosion environments on the bond strength of the test pieces is different. The test results show that the bond strength of the 8, 12, and 16 mm specimens in the clear water environment decreased by 19.67%, 22.75%, and 15.64%, respectively, and the salt environment decreased by 26.46%, 32.37%, and 13.21%, respectively, and the alkali environment was 13.66%. 26.01%, 12.43%. It can be seen that the salt environment has the greatest influence on the bonding performance of GFRP bars and concrete, followed by the clear water environment, and the influence of alkali environment is small.
5. Conclusions
In this paper, the bonding properties of GFRP bars and concrete are tested firstly. Then the calculation formula of the theoretical model of bond strength between GFRP bars and concrete is established by thick-walled cylinder model. The effects of different erosion environments and diameters on the bond strength are studied. In conclusion:

(1) Establish a theoretical model of the bond strength between GFRP bars and concrete, and propose a calculation formula. By comparing the theoretical values and the test values obtained from the test, the accuracy of the proposed formula is verified.

(2) The bond strength between GFRP bars and concrete increases with the increase of diameter, mainly because the increase of diameter will increase the rib height and rib width of the reinforcement and the contact area with concrete, so the bond strength increases.

(3) The bond strength between GFRP bars and concrete shows a certain degradation trend under the action of three kinds of erosion environments. However, the erosion environment is different, and the degree of influence on the bonding performance is also different. The salt environment has the most obvious influence, the water environment is second, and the alkali environment has a lower degree of influence.

Acknowledgement
This work is funded by the National Natural Science Foundation of P.R. China (Grant Nos. 51578267 and 51878319) and the ‘six talent peaks’ project in Jiangsu Province (Grant No. 2015-JZ-008).

Author:
Zepeng Song (1996-), male, Lianyungang, Jiangsu, master; E-mail: 2263408159@qq.com

References
[1] Sorie Zorislav, Kisecek Tomislav, Galic Josip. Deflections of concrete beams reinforced with FRP bars[J].Materials and Structures, 2010, 43 (1) :73-90.
[2] Hyeong-Yeol Kim, Young-Hwan Park, Young-Jun You et al. Short-term durability test for GFRP rods under various environmental conditions[J]. Composite Structures, 2008, 83(1): 37-47.
[3] Kamal A, Boulfiza M. Durability of GFRP rebars in simulated concrete solutions under accelerated aging conditions[J]. Journal of Composites for Construction, 2011, 15 (4) : 473–481
[4] ASTM D665-03. Standard Test Method for Rust-Preventing Characteristics of Inhibited Mineral Oil in the Presence of Waters [S]. Farmington Hills: American Concrete Institute, 2006.
[5] Jiang Congsheng. Experimental study of FRP bar reinforced cement [J]. Fiber Reinforced Plastics/Composite, 2003(03):17-18.
[6] GB50152-2012. Standard for test method of concrete structures[S]. Beijing: Ministry of Housing
and Urban-Rural Development of the People's Republic of China, 2012.

[7] JG/T406-2013. Class fiber reinforced polymer rebar for civil engineering[S]. Beijing: Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2013.

[8] Yang Boyuan. Engineering Plastoelasticity[M]. Tianjin: Tianjin University Press, 2003.

[9] Wu Gang, Dong Zhiqiang, Xu Bo, Wang Xin. Bond performance and calculation method for the basic anchorage length of BFRP bar with concrete in marine environment[J]. China Civil Engineering Journal, 2016, 49(07): 89-99.

[10] Wu Gang, Zhu Ying, Dong Zhiqiang, Wang Xin, Wu Zhishen. Experimental study on the corrosion resistance performance of BFRP bars in the alkaline environment[J]. China Civil Engineering Journal, 2014, 47(08): 32-41.

[11] Mohamed Hassan, Brahim Benmokrane, Adel El Safty, et al. Durability of basalt-reinforced-polymer (BFRP) bars embedded in concrete in aggressive environments[J]. Composites Part B, 2016 (106): 262-272.

[12] Mathieu Robert, Patrice Cousin, Brahim Benmokrane. Durability of GFRP reinforcing bars embedded in moist concrete[J]. Compos. Constr., 2009, 13 (2): 66-73.