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Factors Influencing the Bond Strength Between FRP Bars and Concrete and the Calculation Methods for Anchorage Length

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Abstract: Since the 21st century, developed countries such as Japan, the United States, and Europe have designated Fiber Reinforced Polymer (FRP) as a key industry for development. Currently, FRP sheets, represented by carbon fiber fabric, have become an important material for structural reinforcement and are widely used in the renovation and reinforcement of various civil and industrial buildings. For example, in the early 1960s, the American company Marshall-Vega produced Glass Fiber Reinforced Polymer (GFRP) bars to address the issue of salt corrosion in reinforced concrete structures in coastal and cold regions. In the design of the ArtScience Museum in Singapore, to ensure the integrity and smoothness of the architectural form, facilitate prefabrication and assembly of components, and meet structural, fire safety, and security requirements, the designers evaluated various materials and ultimately selected polyethylene resin-based GFRP panels. This paper employs a literature review methodology, first analyzing the factors that affect the bond strength between FRP bars and concrete, then reviewing standards to understand the calculation methods for anchorage length in different countries, collecting relevant experimental data, and finally analyzing the advantages and disadvantages of various anchorage length calculation methods.

Keywords: FRP reinforcement, bond strength, anchorage length, pull-out test, beam test.

1. Introduction

In recent years, FRP (Fiber Reinforced Polymer) bars have demonstrated significant technical advantages and growth potential in new construction due to their unique physical and mechanical properties compared to traditional building materials. FRP bars offer superior corrosion resistance, greater design flexibility, and can significantly reduce the weight of structures while providing 20 to 50 times the strength of conventional steel. Additionally, they possess other advantages such as being non-magnetic, insulating (excluding Glass Fiber Reinforced Polymer), and having a low coefficient of thermal expansion, which allows FRP materials to perform better in certain specialized structures. Common reinforcing fibers include carbon fiber, aramid fiber, glass fiber, and basalt fiber. However, the development of FRP as a building material is still in its early stages, especially in new constructions where its application has not yet been fully realized. Therefore, interdisciplinary research that bridges material science and civil engineering is becoming increasingly critical [1].

In China, research on FRP bars started relatively late, with preliminary studies beginning only after 1990. Wei Wei and colleagues have pointed out in their research that while there is substantial research on the bond strength between FRP bars and concrete both domestically and internationally, studies on the anchorage length of FRP bars are relatively insufficient.

This paper employs literature review and case analysis methodologies to analyze the factors affecting the bond strength between FRP bars and concrete. It summarizes why and how these factors influence bond strength based on the research results provided by scholars from various countries. Additionally, the paper collects common formulas for calculating the anchorage length of FRP bars and gathers relevant data to analyze the differences between these calculation methods.

2. Factors affecting the bond strength of FRP reinforcement to concrete

Researchers generally agree that as the strength of concrete increases, the bond strength between the FRP bars and the concrete also improves to some extent. This is primarily due to two reasons. First, higher concrete strength typically corresponds to a lower water-cement ratio, which creates greater hydrostatic pressure around the FRP bars, thereby enhancing bond strength. Second, the steel fibers added to the concrete to increase its strength provide additional confinement [2].

Both domestic and international research consistently indicate that the diameter of FRP bars negatively impacts bond performance; specifically, as the diameter of the FRP bars increases, bond performance decreases. There are three main explanations for this phenomenon.

The first explanation is that as the diameter of the FRP bars increases, the bond length also increases, leading to an uneven distribution of bond stress. Additionally, the increased bond area raises the bleeding rate of the concrete, resulting in more water accumulating beneath the FRP bars, which lowers the bond strength between the FRP bars and the concrete. Secondly, as the diameter of the FRP bars increases, the Poisson effect also becomes more pronounced. As the load increases, the cross-sectional reduction of the larger diameter FRP bars becomes more significant, weakening the interfacial contact. This results in a greater reduction in the friction and interlock between the FRP bars and the concrete, leading to a decrease in bond strength. Finally, the increase in FRP bar diameter makes the shear lag effect more noticeable, further reducing the bond strength between the FRP bars and the concrete [3].

Research has shown that the surface texture of FRP bars is a crucial factor affecting bond strength [4]. Generally, FRP bars with a rougher surface exhibit stronger frictional resistance and mechanical interlock, which leads to an increase in bond strength.

Currently, theoretical research on the relationship between anchorage length and bond strength is still insufficient. It is generally observed that as the anchorage length of FRP bars increases, the bond strength between the FRP bars and the concrete decreases. Bonding experiments have shown that the distribution of bond stress along the entire embedment length is uneven. Furthermore, the greater the embedment length, the more uneven the bond stress distribution becomes. Additionally, when the embedment length is between 5d and 10d, and the relative cover thickness is between $c/d = 4.5$ and $c/d = 7$, bond strength varies significantly with changes in embedment length. However, when the embedment length is between 10d and 15d, and the relative cover thickness is between $c/d = 7$ and $c/d = 9$, bond strength decreases as embedment length increases.

B. Benmokrane's pull-out tests revealed that bond stress is not linearly distributed along the bonded length of FRP bars, and the degree of uneven bond stress distribution increases with longer anchorage lengths, leading to a reduction in bond strength [4]. Additionally, research by Refai, Hossain, and Zhai Keyi indicates that, regardless of whether GFRP bars or BFRP bars are used, and whether traditional high-strength concrete or ultra-high-strength concrete is employed, the findings consistently show that the longer the bond length, the lower the bond strength [4].

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Current experimental data and research indicate that as the temperature increases, the bond strength between FRP bars and concrete gradually decreases. Specifically, when the temperature ranges between 120°Cand 220°C, the bond strength of FRP-concrete specimens remains relatively stable, with only a slight decrease. However, when the temperature exceeds 350°C, the bond strength experiences a sharp decline [5].

The reason for these results can be attributed to the behavior of the bonding resin in the FRP bars as the temperature rises. As the temperature increases, the bonding resin within the FRP bars undergoes decomposition and carbonization, leading to a reduction in bond strength between the FRP bars and the concrete. However, if the temperature exposure is below 220°C and the specimen is then returned to room temperature, the bonding resin in the FRP bars can partially recover its bonding properties, resulting in a relatively stable overall bond strength. On the other hand, when the temperature exceeds 350°C, the bonding resin in the FRP bars undergoes complete carbonization, causing a drastic reduction in the bond strength of the FRP-concrete specimens.

The thickness of the concrete cover, which is the minimum distance from the surface of the bar to the surface of the concrete component, also affects bond strength. Increasing the thickness of the concrete cover enhances the bonding performance and splitting resistance of the surrounding concrete. When the concrete cover thickness reaches a certain level, it can prevent splitting failure. Li Mingli's beam test results showed that increasing the concrete cover thickness can improve the failure load of beam specimens. Li Mingli believes that the increased concrete cover thickness inhibits the development of cracks in the concrete, which benefits the bond between the FRP bars and the concrete interface [6].

Different types of FRP bars can have varying impacts on bond strength, with the differences between BFRP (Basalt Fiber Reinforced Polymer) and GFRP (Glass Fiber Reinforced Polymer) being particularly notable.

The deformation of FRP bars mainly results from the interaction between surface deformations and the surrounding concrete, generating diagonal pressure. The radial component of this force acts on the surrounding concrete, putting the concrete in a circumferential tensile state. When the concrete cover is thicker, or when there is transverse reinforcement, the development of cracks within the concrete is restricted. This restriction may weaken or shear off the deformed ribs on the surface of the FRP bars, leading to pull-out failure. If the embedment length is sufficiently long and the bond strength between the FRP bars and the concrete is strong enough, it is possible for the FRP bars to break outside the concrete specimen. Therefore, the failure mode depends on the relative position of the FRP bars within the concrete.

3. Calculation of anchorage length

3.1. ACI4401R 2023

The ACI code considers the bond mechanism between FRP reinforcement and concrete to be similar to that between reinforced concrete and is related to the type of FRP reinforcement, modulus of elasticity, surface shape [7].

According to the ACI code, the bar tension and surface bond stresses areμ_f equilibrium, expressed as follows:

$$l_{bf}\pi d\mu_f = A_{f,bar}f_{fu} \tag{1}$$

Where $A_{f,bar}$ demonstrates Cross-sectional area of a single bar.

The following variants are obtained from the above equation:

$$l_{bf} = \frac{A_{f,bar}f_{fu}}{\pi d\mu_f} \tag{2}$$

or

$$l_{bf} = \frac{d_b f_{fu}}{4\mu_f} \tag{3}$$

Experiments by Orangun, Jirsa and Breen have shown that the bond stress of the reinforcement as a function of the concrete strength, the diameter of the reinforcement, is expressed as follows:

$$\mu = \frac{K_1\sqrt{f_c'}}{d_b} \tag{4}$$

The formula (3) gives.

$$l_{bf} = K_2 \frac{d_b^2 f_{fu}}{\sqrt{f_c'}} \tag{5}$$

Where K_2 is an empirical constant. Based on previous studies, the bond length of the FRP reinforcement for pull-off damage control is conservatively estimated as:

$$l_{bf} = \frac{d_b f_{fu}}{18.5} \tag{6}$$

3.2. JSCE Code

The anchorage length of FRP reinforcement in the Japanese code is determined based on proper testing, and the basic unfolding length of a tensile reinforced type that undergoes bond fracture failure can be calculated by the following equation, under the condition that $l_d > 20\emptyset$

$$l_d = \frac{\alpha_1 f_d \emptyset}{4 f_{bod}} \tag{7}$$

Where $\emptyset$ is the diameter of rebar, f_d is the design tensile strength, and f_{bod} is the design bond strength

Particularly, during concrete pouring, if the rebar to be anchored is more than 30 centimeters away from the final concrete surface and is positioned at an angle of less than 45° to the horizontal plane, the basic development length should be 1.3 times the l_d value obtained from the formula.

3.3. Eurocode

In the codes given in Europe, the anchorage length consists of two parts, the transmission length and the bending bond length. The transmission length can be derived from the equilibrium equation of the axial stress in the prestressing reinforcement and the bond on the surface of the reinforcement [7].

$$f_{pi} * A_p = L_t * \tau * \pi * \phi$$

$$L_t = \frac{f_{pi} * A_p}{\tau * \pi * \phi} \tag{8}$$

Where A_p is the reinforcement cross-section area, $\emptyset$ is the diameter of rebar, f_{pi} is the initial stress, and τ is the constant between reinforcement and concrete.

The flexural bond length is the length required to ensure sufficient bonding between the rebar and the concrete under the influence of the stress difference between the maximum stress (F_{PS}) and the effective stress (F_{PE}) within the rebar.

$$L_{fb} = \frac{\alpha_2 \phi (f_{ps} - f_{pe})}{f_{bpd}} \tag{9}$$

And the anchorage length is the sum of the transmission length and the bending bond length:

$$L_a = L_t + L_{fb} \tag{10}$$

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3.4. Chinese norms

According to the Technical Standard for Fibre Reinforced Composite Reinforced Concrete Bridges (CJJ/T280-2018), when calculating the pre-tensioned prestressed FRP tendons, the prestressing anchorage length of the prestressed FRP tendonsl_a should be taken according to the following formula [7]:

$$l_a = \frac{f_{fpd}}{8f_{td}} d \geq 65d \tag{11}$$

Where f_{fpd} is the tensile strength values of FRP bars, f_{td} is the design value of axial tensile strength of concrete, and d is the diameter of FRP bars.

3.5. Research results of anchorage length by renowned scholars in China and abroad

3.5.1. Pleimann

Pleimann conducted GFRP bar pull-out tests in 1987 and gave a more conservative formula for the anchorage length of GFRP bars based on the experimental data [5].
For GFRP bars:

$$l_d = \frac{f_u A_b}{42\sqrt{f_c'}} \tag{12}$$

For e-glass:

$$l_d = \frac{f_u A_b}{38\sqrt{f_c'}} \tag{13}$$

Among them, l_d is the anchorage length of FRP bars, f_u is the ultimate strength of FRP bars, A_b is the FRP bar section, and f_c' is the compressive strength of concrete

3.5.2. Faza and Gangkao

In 1990, Faza and Gangkao gave the formulae about the basic anchorage length of FRP bars by cantilever beam test and pull-out test [5].

$$l_{db} = \frac{0.028 A_b f_{yf}}{\sqrt{f_c'}} \tag{14}$$

Among them:
l_{db} is the basic anchoring length, f_{yf} is the effective yield strength, 80% of the ultimate tensile strength of FRP bars; f_c' is the compressive strength of concrete, not exceeding 69 MPa; and A_b is the FRP reinforcement cross section area

3.5.3. Ehsani, H. Saadatmanesh.

In 1996, M.R. Ehsani, H. Saadatmanesh and S. Tao obtained the basic anchorage length of GFRP straight bars from 48 beam specimens, 18 pull-out specimens, and 36 bending bar specimens of GFRP reinforced concrete bond tests [5]:

$$l_{db} = \frac{0.022 f_y A_b}{\sqrt{f_c'}} \tag{15}$$

$$l_{db} = 0.0508 d_b f_y$$
$$l_{db} \geq 381$$

In addition, other corrections are given by M.R. Ehsani for some special cases. For example, when the FRP bars are located on the top, the correction factor is 1.25; when the protective layer of concrete is less than or equal to the diameter of the doubled bars, the correction factor is 1.5.

For the anchorage length of hooked bending bars the formula is then:

$$l_{db} = \frac{152 d_b}{\sqrt{f_c'}} \tag{16}$$

In addition, the calculation of the anchorage length should not be less than 8 times the diameter of the FRP bar and 152 mm.

3.5.4. Gao Danying and B. Brahim

In 2000, Danying Gao and B. Brahim obtained the test results of the bonding properties of fibre polymer reinforcement to concrete using pull-out and beam tests, and proposed a formula for calculating the anchorage length of fibre polymer reinforcement, and gave different formulas for different damage modes [5].

For splitting damage:

$$l_{db} = \frac{(0.022 \sim 0.026) f_y A_b}{\sqrt{f_c'}} \tag{17}$$

For pullout damage:

$$l_{db} = 0.015 d_b f_u \tag{18}$$

Zheng Qiaowen. In 2006, based on the data obtained from his pull-out test and beam test, and referring to the specifications given in China at that time, Zheng Qiaowen boldly assumed that the bond strength and tensile strength between FRP reinforcement and concrete are proportional to each other, and took into account the diameter of the FRP reinforcement, the surface form, the bond length, and the concrete strength's influence on the bond strength, and introduced the surface form of the GFRP reinforcement. Influence coefficientα The influence coefficient of the surface form of GFRP bar, the influence coefficient of the actual bond lengthϕ and the influence coefficient of concrete strengthβ The formula for calculating the anchorage length of GFRP bars is [5]:

$$l_a = \frac{\lambda f_u d_b}{4\alpha\beta(8 - 0.17d) f_t} \tag{19}$$

Where λ is the safety reserve factor for anchorage lenght.

3.6. Calculations and analyses

In order to compare the advantages and disadvantages of the commonly used specification algorithms given in the United States, Japan and Europe, the experimental data selected in this paper are shown in Table 1 below. three different algorithms are used for checking the calculations, and the results obtained from the three algorithms are finally compared. The anchorage lengths calculated by each formula are shown in Table 2 below.

Table 1. Experimental data

Types of FRP bars	s_0	τ_0	s_u	τ_u
G-56-8	0.163	14.010	13.611	5.169
G-70-10	0.271	10.540	12.421	3.781
G-84-12	0.159	9.156	11.937	3.650

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Table 2. Calculation results of common basic anchorage length formulas

formulas	Basic anchorage lengths for different diameters		
	8mm	10mm	12mm
ACI440	352.1	440.2	528.1
JSCE	146.1	244.3	337.2

It can be seen that the empirical coefficients used in the US code for calculating the anchorage length of FRP bars will have a higher safety margin.

4. Conclusion

This paper summarizes and analyzes the factors influencing the bond strength between FRP bars and high-strength concrete. The following conclusions have been drawn: Among the numerous factors affecting the bond strength between FRP bars and high-strength concrete, the impact of many is not fixed; they vary depending on factors such as temperature and bar diameter. Factors like the compressive strength of concrete, the thickness of the concrete cover, and the surface texture of the FRP bars have relatively consistent effects on bond strength. However, factors like the diameter of the FRP bars and their anchorage length do not lend themselves easily to general conclusions. This is partly because research on these aspects is not as extensive as on others, and partly because international standards on these factors are not fully unified.

Furthermore, this paper places particular emphasis on the impact of anchorage length on bond strength, an area where research is relatively scarce. A review of relevant literature was conducted, and standards such as the American ACI4401R 2023, European standards, Japanese standards, Chinese standards, as well as research findings on anchorage length by renowned scholars since the 1980s were collected. These calculation methods were compared and analyzed. The analysis shows that most calculation methods agree that the anchorage length of FRP bars is related to the ratio of the cross-sectional area of the FRP bars to the compressive strength of the concrete. The basic anchorage length is then adjusted based on factors such as surface texture, effective bond length, concrete cover thickness, and the position of the FRP bars, resulting in anchorage length formulas intended to provide safer, more economical, and applicable results.

Due to limitations in literature review capabilities and the inability to conduct relevant pull-out and beam tests to obtain experimental data on anchorage length, this paper lacks sufficient data for comparative analysis. It is hoped that future studies and research will help identify more general trends in the factors influencing bond strength and develop safer, more economical, and applicable anchorage length calculation standards.

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