Study on the Comprehensive Experimental Teaching Design for the Course of Basic Principles of Concrete Structures

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Abstract: The course "Fundamental Principles of Concrete Structures" is a core professional course that encompasses the mechanical properties and design theories of concrete materials and various structural components. It involves a substantial amount of theory and experimentation. Comprehensive experimental teaching serves to deepen students' understanding of professional theories and enhance the effectiveness of instruction. This study explores the design of a comprehensive experiment on the bond behavior between steel reinforcement and concrete. It integrates experiments on the basic mechanical properties of concrete with those on the bonding behavior between steel reinforcement and concrete. Additionally, it incorporates elements such as analysis of influencing factors and measurement of steel reinforcement slippage. This experiment exhibits features of both verification, design-oriented, and comprehensive experiments. Educational practice results demonstrate that this comprehensive experimental approach enhances students' learning enthusiasm, providing robust support for the mastery of professional knowledge and the cultivation of practical innovation capabilities.

Keywords: Concrete structure; Comprehensive experiment; Teaching; Bond behavior

1 Introduction

Amidst the swift advancement of the civil engineering sector in recent times, new materials and technologies have been continuously applied, and new concepts and requirements have emerged [1-2]. Consequently, cultivating highly qualified and versatile civil engineering professionals has become a crucial mission in higher education for civil engineering majors [3-4]. The course 'Basic Principles of Concrete Structures' holds a significant position in the core curriculum of civil engineering, playing a crucial role in supporting talent development and achieving graduation requirements [5]. As this course encompasses the mechanical properties and design theories of various components, which are derived from experimental analysis, conducting practical experiments on typical structural components is essential for students to deepen their understanding of structural design theories. Moreover, through well-designed experiments, students' practical skills, engineering application abilities, and innovative capabilities can be effectively enhanced. In the current context, many universities offer predominantly demonstrative and verificative experiments for the course "Basic Principles of Concrete Structures," with fewer opportunities for comprehensive, design-oriented, and research-oriented experiments. This approach does not fully reflect the

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"student-centered" educational concept, leading to reduced student interest and engagement in experiments. Furthermore, the current experimental teaching lacks sufficient support for fostering students' practical and innovative abilities. Therefore, there is an urgent need to reform and explore the experimental teaching of this course.

2 Experimental design concept

The experimental design should be based on the objectives of talent cultivation and course teaching objectives. The goal of Wuhan University of Science and Technology's Civil Engineering program is to nurture proficient, practical-oriented professionals. The teaching objectives of the "Fundamental Principles of Concrete Structures" course are to enable students to grasp the basic theoretical system of concrete structures and the design methods of components, and to foster students' innovative consciousness and engineering practical ability. Therefore, the experimental design should reflect its role in cultivating students' theoretical knowledge, practical skills, and innovative capabilities.

The effective collaboration of steel reinforcement and concrete relies on their strong bond behavior, and it significantly influences the mechanical performance of reinforced concrete structures. Therefore, mastering the bond behavior is fundamental to understanding the structural mechanics and design principles. However, the comprehension of bond behavior has remained a focal point and a challenging aspect in the course "Basic Principles of Concrete Structures." Therefore, we designed a comprehensive experimental project: the bond behavior test between steel reinforcement and concrete. By combining verification, comprehensive, and design-oriented experiments, we aim to reinforce students' professional knowledge and enhance their practical and innovative abilities.

3 Experimental design for bond behavior between steel reinforcement and concrete

3.1 Objective of the experiment

To learn the testing and theoretical analysis methods of the basic mechanical properties of concrete materials; to study the experimental method of directly measuring the bond behavior of reinforcement and concrete using the pull-out test; to investigate the bond behavior under the influence of different factors; to design a strain gauge measurement plan to measure the slip between reinforcement and the concrete matrix, and to comprehend the basic principles and analysis methods for studying the bond stress-slip relationship.

3.2 Concrete compressive strength test

3.2.1 Experimental method

In accordance with the relevant provisions of the standard "Standard for test method of ordinary fresh concrete" GB/T 50080[6], 150 mm×150 mm×150 mm concrete cube specimens are prepared. The specimens are kept in an indoor environment with a temperature of 20℃±5℃ and a relative humidity greater than 50% for 1d to 2d after demolding. Subsequently, the specimens are placed into a standard curing chamber set at a temperature of 20℃±2℃ and a relative humidity of over 95% for the curing process.. When the specimens reach the specified test age, they are removed from the curing location, and their dimensions and shapes are checked. The size tolerances should comply with the provisions of Section 3.3 in the standard "Test Methods for Mechanical Properties of Concrete" GB/T 50081-2019[7]. After being taken out, the specimens should be tested as soon as possible. The concrete cube compressive strength test was conducted using a compression testing machine (Figure 1). During the test, a continuous and uniform load was applied, with a loading rate ranging from 0.3 MPa/s to 1.0 MPa/s. The loading process continued until the cube specimen failed, and the failure load was recorded.

Figure 1 Compression Testing Machine

3.2.2 Experimental data analysis

The compressive strength of concrete cubes is calculated using Equation (1):

$$f_{cu} = P / A \tag{1}$$

Where P is the failure load obtained during the test, and A is the cross-sectional area of the concrete cube. The arithmetic average of three measured values is taken as the strength value for that group of specimens, with a precision of 0.1 MPa. The axial compressive strength f_c, axial tensile strength f_t, and elastic modulus of concrete E_c can all be calculated based on the average compressive strength of the measured cubes using Equation (2), (3) and (4):.

$$f_c = 0.79 f_{cu} \tag{2}$$

$$f_t = \tfrac{1}{8} f_{cu} \tag{3}$$

$$E_c = \frac{10^2}{2.2 + \frac{34.7}{f_{cu}}} \tag{4}$$

3.3 Pull-out test for bond strength between steel reinforcement and concrete

3.3.1 Experimental method

The bond strength between steel reinforcement and concrete is measured using a direct pull-out test. Pull-out specimens, as shown in Figure 2, are prepared for the experiment[8]. The concrete base is a 150mm×150mm×150mm cube, and the steel reinforcement is centrally placed along the cube's axis with a loading length of 300mm and a free end length of 50mm. In the concrete cube, bonding and non-bonding regions are defined. The non-bonding regions are separated from the concrete using PVC sleeves to reduce stress concentration phenomena. Three different steel reinforcement diameters (12mm, 14mm, 16mm) and three different bonding lengths (50mm, 70mm, 90mm) are selected for the specimens to analyze the influence of steel reinforcement diameter and bonding length on bond strength. An in-house designed strain measurement method is used to measure the slip of steel reinforcement and analyze the bond stress-slip relationship. When fabricating the specimens, insert the steel reinforcement into the mold(Figure 3) and secure it in place, then pour the concrete and compact it using vibration. After 24 hours of curing at room temperature, demold the specimens and finally cure them for 28 days in a standard environment (temperature of 20±2℃ and relative humidity above 95%) .

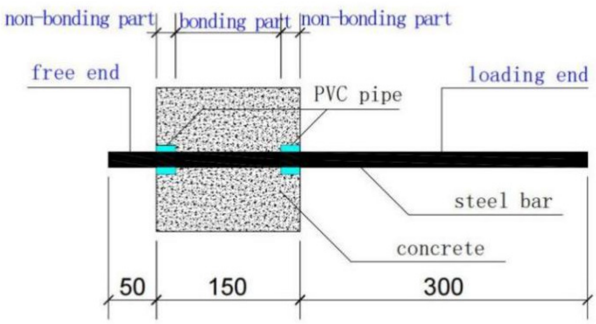

Figure 2 Pull-out Test Specimen Design (Unit: mm)

Figure 3 Specimen mold

The pull-out test devices are shown in Figure 4. The electro-hydraulic servo universal testing machine applies pull-out force to the sample. Loading is displacement-controlled at a rate of 0.2mm/min, and the machine automatically records load data. Loading stops upon concrete substrate failure, steel bar fracture, or steel bar pull-out. Strain gauges are symmetrically positioned at the steel bar loading end to measure steel bar strain, while a dial gauge measures displacement at the steel bar loading end.

Figure 4 Test devices

3.3.2 Experimental results analysis

(1) Failure Modes

The specimen failure modes primarily involve pull-out failure and pull-out splitting failure (Figure 5). In the pull-out failure mode, the steel bar is pulled out without significant damage to the concrete substrate. On the other hand, in the pull-out splitting failure mode, when the specimen reaches its ultimate load, cracks appear simultaneously, and the bond strength between the steel bar and the concrete substrate gradually decreases. During the experiment, it is also essential to observe the development of cracks and analyze the failure process in conjunction with the bond stress mechanism.

(a) (b)

Figure 5. Failure mode. (a) Pull-out failure;(b) Pull-out splitting failure.

(2) Bond Strength

The mean bond stress at the junction of the steel bar and the concrete substrate, considering the bonding segment of the steel bar as a simplified cylinder, can be determined using Equation (5) [9]:

$$\tau = \frac{P}{\pi d l_a} \tag{5}$$

where τ is the average bond stress in MPa, P is the applied pull-out load in N, d is the diameter of the steel bar in mm, and l_a is the bond length in mm. When the applied pull-out load reaches its peak load P_u, the corresponding peak bond stress τ_u represents the bond strength. The calculated average bond strength of certain test specimens is displayed in Table 1, derived from Equation (5).

Table 1. Average bond strength of some test specimens.

Specimen	Ultimate Load/N	Bond Strength/MPa
R12-L70	36050.43	13.67
R14-L70	40777.92	13.25
R16-L70	45910.13	13.05
R12-L50	37084.43	16.87
R16-L90	76374.85	19.30

(3) Influencing Factors

① Steel Bar Diameter

Assessing the impact of different steel bar diameters on the bond strength, we employ specimens with bond lengths of 70mm and 90mm for comparation. Figure 6(a) shows a marginal decline in the bond strength between the concrete and steel bar as the steel bar diameter increases. In specimens with a bond length of 70mm, the bond strength decreases by 3.1% (13.25 MPa) for 14mm diameter steel bars and by 4.5% (13.05 MPa) for 16mm diameter steel bars, compared to the 12mm diameter bars (13.67 MPa). For specimens with a bond length of 90mm, the bond strength reduces by 5.5% and 6.2% for 14mm and 16mm diameter steel bars, respectively, compared to the 12mm diameter bars. This trend is primarily attributed to changes in bond force components, particularly the relative decrease in rib height and increase in rib pitch as the steel bar diameter increases (refer to Figure 7). These alterations result in reduced mechanical interlocking force between the steel bar and concrete, consequently leading to a decline in bond strength[10].

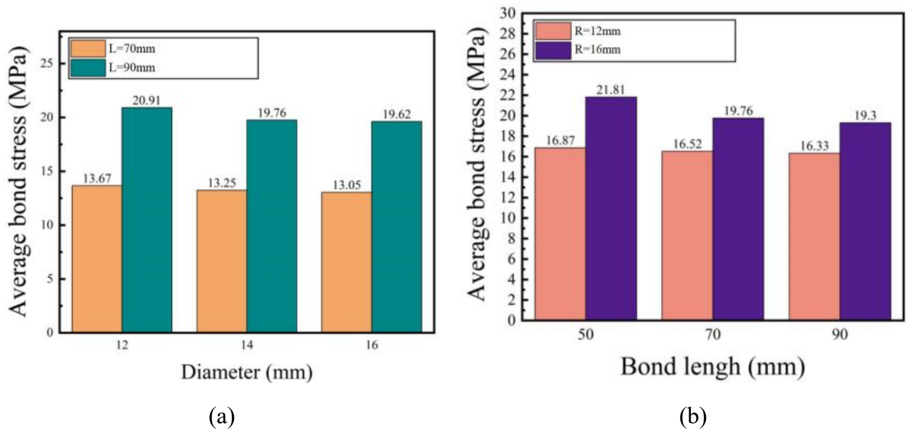

Fig 6 Influencing factors on bond stress. (a) Steel bar diameter;(b) Bond length.

② Bond Length

Assessing the effect of varied bond lengths on bond strength using pull-out specimens equipped with steel bars of 12mm and 16mm in diameter, the findings reveal a decline in bond strength between the steel bar and concrete with increased bond length, as depicted in Figure 6(b). In cases involving a 12mm steel bar diameter, in contrast to samples featuring a 50mm bond length (16.87 MPa bond strength), the bond strength diminishes by 2.1% and 3.2% for bond lengths of 70mm and 90mm, respectively. Similarly, for specimens with a 16mm steel bar diameter, compared to those with a bond length of 50mm, the bond strength reduces by 9.4% and 11.5% for bond lengths of 70mm and 90mm, respectively. This trend is explained by the non-uniform distribution of bond stress between the steel bar and substrate along the bond length during the pull-out process. With increasing bond length, the bond stress distribution becomes more irregular, resulting in reduced average bond stress. Furthermore, the elongation in tensile strain at the steel bar loading end increases as the bond length extends, resulting in radial shrinkage within the steel bar due to the impact of Poisson's effect.

This phenomenon lessens the substrate's restraining force on the steel bar, consequently causing a decline in bond strength[11].

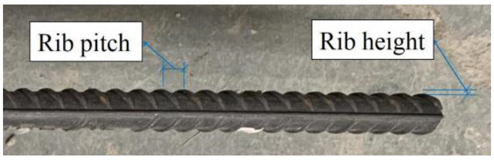

Figure 7. Ribs of the steel bar.

(4) Bond Stress-Slip Relationship

By affixing strain gauges onto the steel bar's loading zone, it becomes possible to gauge the tensile strain experienced by the steel bar. Coupled with the measured displacement of the loading section, this enables the calculation of the steel bar's slippage within the bonded area. Figure 8 depicts the BC segment, representing the real bonded area between the steel bar and the substrate, with the CD segment denoting the non-deforming free section of the steel bar in the loading process..The AB segment indicates the section directly exposed to the pull-out force during loading. Point A denotes the displacement measurement point, and the strain gauges are positioned at the midpoint of the AB segment to test the average strain ε of the steel bar. Consequently, the actual displacement of the loading end during the loading phase can be derived using Equations (6) and (7).

$$S_f = S_m - S_d \tag{6}$$

$$S_d = \varepsilon \times L_{AB} \tag{7}$$

Where: S_f represents the actual slip of the loading end; S_m represents the measured displacement of the loading section; S_d represents the elastic deformation of the steel bar in the *AB* segment; and L_{AB} represents the length of the *AB* segment of the steel bar; the units of these parameters are all measured in mm.

By measuring the actual displacement of the loading end of the steel bar and the corresponding applied loads, the average bond stress and slip of the steel bar can be calculated using Equations (5) , (6) and (7) respectively. Graphing the bond stress against the slip produces the bond stress-slip curve, depicted in Figure 9.

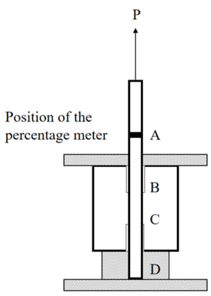

Figure 8 Steel bar slip measurement diagram.

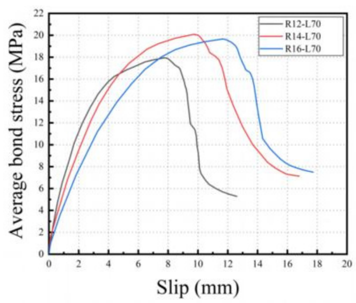

Figure 9 Bond stress-slip relationship curves.

4.Conclusions

Through the experimental teaching of the bonding mechanical behaviors between steel bars and concrete, students have gained a deeper understanding of the professional theories related to bonding. Classroom feedback has indicated a positive reception of the experimental teaching, with a significant increase in students' enthusiasm for learning. In 2022, after the introduction of this experiment, the student evaluation score for the course “Fundamental Principles of Concrete Structures” reached 93.46 points, an increase of 1.63% compared to the score in 2021. The comprehensive experimental teaching has not only equipped students with the basic principles of concrete structures, but has also deepened their understanding of concrete structure design and construction. It has effectively demonstrated its role in fostering students' theoretical knowledge, practical abilities, and innovation skills, providing robust support for the reform of professional course teaching in the context of the new engineering education and the cultivation of high-quality, comprehensive professional talents.

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