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Experimental study on the enhancement of additional ribs to the bond performance of FRP bars in concrete

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HIGHLIGHTS

- A new anchorage system using additional ribs was proposed to enhance the bond properties of FRP bars.
- The effects of parameters on the bond properties of the bars with additional ribs in concrete were investigated.
- The bonding force transferring mechanism of FRP bars with additional ribs in concrete was analyzed.

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ABSTRACT

The deficient bond performance of Fiber-reinforced polymer (FRP) bars has impeded their application in concrete structures. To enhance this weak characteristic of FRP bars, the additional ribs as a new anchorage system applied on the bars was proposed in this paper. Its effect on the bond performance of the FRP bars was experimentally investigated through 36 pull-out tests with a centric FRP bar placement in concrete blocks. After the tests, the failure mode and bonding mechanism were discussed. The effects of the types of FRP bar, the anchorage length and the number of additional ribs on the bond properties of bars in concrete were also evaluated. Based on the results, it can be concluded that the additional ribs with radial force contributed greatly to the anchoring force. The utilization of additional ribs also changed the bonding force transferring mechanism between the FRP bars and the concrete. The end bearing that arose from the additional ribs reduced the occurrence of concrete splitting, and thus, the tensile strength of the FRP bars can be fully utilized. The test results also indicated that the additional ribs significantly improved the anchorage performance of the FRP bars in concrete. This improvement would continue with the increase in the number of additional ribs.

1. Introduction

In traditional concrete structures, steel bars are widely utilized as reinforcing materials. However, they are prone to corrosion when the corresponding structures are subjected to severe environments. This characteristic will cause degradation of the bond properties and thus lead to deterioration of the structural elements. Fiber-reinforced polymer (FRP) bars, as an advanced composite material, have attracted increasing attention. Compared with steel reinforcement, this material presents obvious advantages, such as light weight, high strength, superior corrosion resistance, fine anti-fatigue, electromagnetic insulation, etc. [1]. It can also be a promising substitute for steel reinforcement.

However, a concern about FRP bars in recent years has been their insufficient bond behaviors in concrete. It has been reported that the FRP bars show a relatively lower bond strength than steel bars under similar conditions [2–7]. This is mainly due to some negative properties of FRP bars, such as anisotropy, low elastic modulus and especially the weak transverse shear strength. For the FRP-reinforced concrete members, the bond properties of FRP bars are the basis of the co-operation of the bars and concrete. This is a key factor that affects the mechanical properties, failure modes, bearing capacity, crack width and deformation ability of structural elements. Thus, it is necessary to further understand the bond behavior of FRP bars and adopt appropriate measures to improve their bond resistance.

Previous studies [8–10] have demonstrated that the bonding mechanism of FRP bars mainly consists of chemical adhesion, friction and mechanical interlocking. Among these, the action of chemical adhesion, which depends on the nature of the cement

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and the roughness of the bar surfaces, may be the weakest. Thus, once a tiny slip occurs, the bond will break. The friction is related to the shrinkage and the elastic modulus of concrete, as well as the roughness of the contact surface. The mechanical interlocking is achieved from the wedge effect between the deformation of the bars and the concrete. The latter two mechanisms reported in the literature play a significant role in the bond slip process and are greatly associated with the surface configurations (e.g., sand coating, deep dents, helical wrapping, etc.) [3,4,11–17]. However, the mechanical interaction was the primary mode, especially for the ribbed FRP bars. Malvar [18] found in tests that the height of the ribs on the surface of the FRP bars is an important factor that affects the bond performance. Hao Q [19] investigated the effects of rib height and rib spacing of the FRP bars on the bond behaviors and proposed the optimal rib geometries by which a superior bond performance can be obtained. In most cases, the bond failure between the ribbed FRP bars and concrete was generally caused by the peeling of the ribs or even a thin layer (including resin and fiber) [7] on the surface of the bars. The bond failures of the steel bars are commonly attributed to the shear off and crush of the concrete. The main reasons for this difference are that the ribs of the FRP bars exhibit a much lower shear strength and rigidity than that of steel bar deformations [2], which leads to the poor mechanical interlocking of the ribs on the FRP bars. Although other measures (known as anchorage systems) [20,21] have been used to enhance these weak characteristics of ribbed FRP bars, the relevant research and productions are still deficient.

Therefore, a new anchorage system was proposed in this paper to enhance the bond properties of FRP bars. In this method, additional ribs with radial force were applied on the FRP bars to form several new ‘ribs’. A total of 36 pull-out tests with a centric FRP bar placement in concrete were conducted, and the failure mode and bonding mechanism were discussed. The effects of the type of FRP bars, the anchorage length and the number of additional ribs on the bond properties of the bars in the concrete were also investigated. The research carried out in this paper will promote the applications of additional ribs to enhance the bond properties of FRP bars in concrete.

2. Experimental program

Previous experimental studies [22] have indicated that the shear strength between the FRP bars and the additional ribs is much higher than that of the bars and the concrete. Due to extrusion, several obvious deformations occurred on the inner surface of the additional ribs. The use of additional ribs makes it possible to improve the bond and anchorage properties of the FRP bars in concrete. Based on the previous explorations, this concept will be checked using center pull-out tests.

2.1. Materials

Both CFRP (carbon fiber reinforced polymer) bars and BFRP (basalt fiber reinforced polymer) bars with a diameter of 10 mm were used in this test, as shown in Fig. 1. The geometries and mechanical properties of the bars are given in Table 1. For

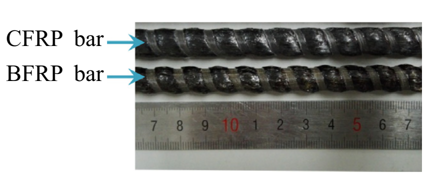

Fig. 1. The FRP bars.

Table 1
Geometry and mechanical properties of the FRP bars.

Bar	d/mm	Rib spacing/mm	Rib height/mm	Tensile strength/MPa	Elastic modulus/GPa
BFRP	10	10	0.7	1035	50
CFRP	10	10	0.5	1365	103

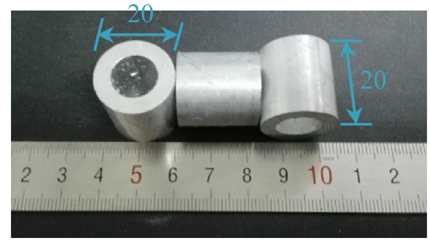

Fig. 2. The aluminum alloy tubes.

the specimens with BFRP and with CFRP bars, the average compressive strengths of the concrete cubes measured in the compressive tests were 35.3 MPa and 30.6 MPa, respectively. Aluminum alloy tubes of type 6061-T6 (Fig. 2) with a length of 20 mm, an inner diameter of 12 mm, and a tube thickness of 4 mm were selected as the materials for the additional ribs. The hardness is 90 HB, and the elongation is 9%. This kind of tube is more commonly used in construction.

2.2. Preparation of specimens

This experimental program consists of 18 groups of pull-out tests, where each group was made of two identical specimens with centric FRP bar placement in the concrete. Among the tests, two types of concrete blocks (Fig. 3), i.e., 150 mm × 150 mm × 150 mm and 150 mm × 150 mm × 300 mm in size, were fabricated. Three parameters for the material type (basalt and carbon FRP), anchorage length, and the number of additional ribs were investigated, as shown in Table 2. For the specimen name given in Table 2, the first symbol shows the type and diameter (10 mm) of the FRP bar (B = BFRP bars and C = CFRP bars), the second symbol stands for the anchorage length (50 mm, 100 mm and 150 mm), and the third symbol indicates the number of additional ribs applied to the FRP bars.

In this experiment, the aluminum alloy tubes were arranged on the FRP bars from one end and were then extruded with the hydraulic-pincers to produce a plastic deformation. Thus, additional ribs with radial force were made, which was different from the helical ribs on the surface of FRP bars. The helical ribs were created by wrapping a thin plastic tape in a helical pattern on the FRP bars before heat curing during manufacturing, thereby eliminating stress. The number of additional ribs applied on the FRP bars was considered as a key factor to be investigated. The additional ribs were designed to be evenly distributed at equal intervals along the anchorage length of the FRP bars, as shown in Fig. 4. Due to extrusion, the length of tubes changed from 20 mm to 25 mm, which was the length of the additional ribs. Based on this length, the anchorage lengths of the FRP bars were set to be 50 mm, 100 mm and 150 mm, respectively. To ensure the accuracy of the anchorage length, PVC pipes with a diameter of 16 mm were provided for the non-adhesive section of the bars inside the concrete blocks as a bond breaker (Fig. 5). In addition, the length of the loaded end of the bars was 500 mm to meet the test requirements. An anchor system, which was achieved using a seamless steel pipe