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Bond behavior of steel bar embedded in Engineered Cementitious Composites under pullout load

Mingke Deng *, Jiaojiao Pan, Hongzhe Sun

School of Civil Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, China

HIGHLIGHTS

- Bond mechanism and failure mode of steel bar embedded in ECC were investigated by direct pullout test.
- Influence laws of various parameters on bond behavior were evaluated.
- Ultimate bond strength of the plain bar embedded in ECC increased 1.71 times that in concrete.
- An accurate bond slip relationship was built based on the distribution of bond stress along the anchorage length.

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ABSTRACT

Composite action of steel bar and Engineered Cementitious Composites (ECC) plays an important role in reinforced ECC structures, which depends on the bond performance of two materials. To evaluate the bond behavior of steel bar embedded in ECC, direct pullout tests were conducted on 10 groups of ECC specimens and 2 groups of control specimens in this paper. The parameters investigated were bar shape, bar diameter, cover thickness, ECC strength and fiber volume content. Experimental results indicated that the ultimate bond strength of the plain bar embedded in ECC increased 1.71 times than that in concrete. For the deformed bar, the bond failure mode of ECC specimens exhibited an obvious ductility due to fiber bridging effect preventing the opening and propagation of internal cracks, whereas the brittle splitting failure occurred for concrete specimens. Furthermore, the ultimate bond strength increased 2.14 times as ECC strength increased from 27.7 to 57.2 MPa. Besides, a critical relative cover thickness was confirmed as 3.41. Finally, based on the distribution of bond stress along the embedded length, the anchorage position function was ascertained and then an accurate bond slip relationship was built, which was significant in structural design and numerical simulation.

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1. Introduction

Engineered Cementitious Composites (ECC) [1–3] exhibits high strength, excellent ductility and damage resistance capacity, which is a new structural material consisting primarily of fibers, fine aggregates, cement and admixture. ECC is manufactured based on the designed theory of micromechanics and fracture mechanics [4]. It can be characterized by the pseudo-strain hardening and multiple cracking behaviors when subjected to tensile load [5,6]. Recently, ECC has been widely utilized in civil engineering due to the remarkable mechanical properties, especially in flexural and shear-dominated members, such as coupling beams, low-rise walls, as well as beam-column joints [7–9]. Findings suggested that ECC can effectively enhance the shear strength, energy dissipation and damage tolerance of members, and consequently improve the performance of reinforced ECC structures.

Combined action between ECC and reinforcing bar is on the basis of the bond behavior, which has an important effect on bearing capacity and deformability of reinforced ECC structures [10,11]. Existing researches indicated that the tensile strength and strain capacity of matrix were dominant factors affecting bond performance [12,13]. It should be stressed that the ultimate tensile strain of ECC was enhanced greatly due to the pseudo-strain hardening behavior with remarkable multiple cracks. In this situation, the good strain compatibility between ECC and steel reinforcement was achieved. Thus, the bond behavior of steel bar in ECC has a great difference with that in traditional brittle materials such as concrete and fiber reinforced concrete (FRC) [12]. And it is essential to investigate the bond mechanism and failure mode of reinforcing bar in ECC for reinforced ECC structures.

* Corresponding author.
E-mail address: dengmingke@126.com (M. Deng).

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In recent years, some studies on bond behavior of steel bar in ECC had been carried out. From the experimental results of pullout specimens, Chao [14] observed that fiber type played a vital role in bond behavior of reinforced HPFRCCs. Due to the excellent crack resistance, the polyvinyl alcohol (PVA) fibers had been widely used in ECC [3,4]. Wang [15] based on the pullout test of basalt fiber reinforced polymer (BFRP) bar embedded in ECC, pointed out that adding PVA fiber can enhance the damage tolerance of matrix and thus improve the bond behavior. Kim [16] investigated the bond behavior between glass fiber reinforced polymer (GFRP) bar and PVA-ECC. Test results showed that energy absorption capacity of specimens was enhanced due to the addition of PVA fiber and the ductility of bond stress-slip curves significantly increased as fiber volume content increased from 1% to 2%. Li [17] observed that the bond strength decreased as the diameter and embedded length of steel bars increased. Bandelt [18] investigated the bond behavior of ECC under monotonic and cyclic loads by beam-end flexural specimens. Results indicated that material toughness of ECC effectively restrained the splitting cracks. Toshiyuki [19] found that the bar spacing of the main bars in ECC elements was reduced due to the improvement of bond performance. Liu [20] put forward the design suggestions of anchorage length of steel reinforcement in ECC members by simulating the loading characteristic of beam-column joints. In the above studies, the effects of cover thickness, ECC strength on characteristic points of bond stress-slip curves such as ultimate bond strength and residual bond strength are not analyzed systematically for steel bar embedded in ECC. Besides, incorporating an accurate bond slip relationship in a numerical simulation will lead to more accurate predictions of structural response to severe loading conditions. Under the assumption of uniform distribution of bond stress along the embedded length, some average bond stress-slip models have been proposed based on the test results of pullout specimens [21] or beam specimens with lap splices in four-point bending [22]. However, the bond stress along anchorage length was varying in practical engineering [23]. Thus, this difference should be taken into account in an accurate bond slip relationship.

The present research concerns the conduction of direct pullout tests of 12 groups of specimens, discussing the failure mode and bond mechanism of reinforcing bar embedded in ECC. In addition, it includes an investigation on the influence laws of bar shape, bar diameter, cover thickness, ECC strength and fiber volume content. Besides, the distribution of bond stress along the embedded length was investigated by testing the specimens attached six strain gauges. Finally, considering the effect of anchorage position an accurate bond slip relationship was built, which played a significant role in structural design and finite element analysis of reinforced ECC structures.

2. Experimental program

2.1. Materials

Three ECC mixtures and an ordinary concrete were prepared in this paper. The ECC contained ordinary Portland cement (P.O 42.5R), Class F fly-ash, fine river sand with a 1.18 mm maximum aggregate size, PVA fiber and high range water reducing admixture (HRWR). The performance indicators of PVA fiber are given in Table 1. The ordinary concrete included cement, fine river sand, coarse aggregate with a 20 mm maximum aggregate size and water. Fig. 1 gives the tensile stress-strain curves of ECC. As shown in Fig. 1, the specimen E1 exhibits a tensile strain-hardening behavior up to approximately 2.1% strain with a tensile strength close to 5.1 MPa. It should be noted that the tensile strength of E2 is lower than that of E1 whereas the opposite rule is observed for the ultimate tensile strain. Besides, both tensile strength and strain capacity of E3 are inferior to those of E1 as the fiber volume content decreased to 1% from 2%. The 56-day compressive strength was acquired by testing three 100 mm × 100 mm×100 mm cubes. The proportion and average compressive strength for each mixture are list in Table 2. Table 3 shows the mechanical properties of deformed bar and plain bar used in this paper.

2.2. Specimen design

Due to their simplicity of manufacture and test, pullout specimens are widely used to investigate the bond behavior. As shown in Fig. 2, direct pullout specimen is a concrete prism with a single steel reinforcement embedded horizontally along a central axis. The length of all prisms is 150 mm, and the cross sectional size is changed to accomplish varying covers. The bonded region is in the middle of specimen and its length is 5 times bar diameter (i.e., the embedded length). The bars at the ends of the specimen are sheathed in PVC pipes to prevent the bonding between steel and concrete, which can avoid the local failure of ends resulted from the stress concentration. All specimens were cast in plywood molds and covered with a polyethylene sheet to avoid loss of water. After 24 h, the specimens were demoulded and then cured outdoors for 56 days. The test parameters in this paper included bar shape (the plain bar, the deformed bar), bar diameter (12 mm, 16 mm, 20 mm), cover thickness (22 mm, 32 mm, 42 mm, 54.5 mm, 65 mm), ECC strength (E1, E2) and fiber volume content (1%, 2%). In addition, two control specimens (C1R20, C1P12) were designed to evaluate the differences of bond mechanism and failure mode between ECC and ordinary concrete. As listed in Table 4, three identical specimens of each group and a total of 36 speci-

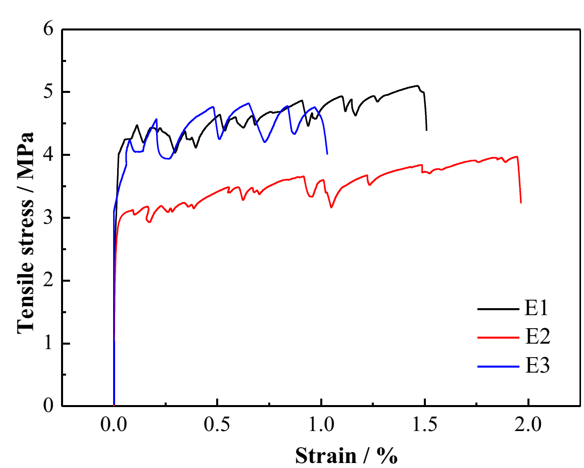

Fig. 1. Tensile stress-strain curves of ECC.

Table 1
Performance Indicators of PVA.

Fiber	Length /mm	Diameter /μm	Tension strength /MPa	Elastic modulus /GPa	Elongation /%	Density /g·cm^{-3}
PVA	12	35	1500	36	7	1.29

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