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Local bond performance of rebar embedded in steel-polypropylene hybrid fiber reinforced concrete under monotonic and cyclic loading

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HIGHLIGHTS

- The effects of hybrid fibers on the local bond performance were investigated.
- Improvements in bond strength, slip and energy dissipation capacity were observed.
- Empirical laws for monotonic and cyclic bond stress–slip relations were developed.

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ABSTRACT

The performance of the bond between reinforcing bars and fiber reinforced concrete (FRC) plays an important role in determining the mechanical behavior of FRC structures when they are subjected to static or dynamic loadings. This paper presents an experimental study on the local bond performance of rebar embedded in steel-polypropylene hybrid fiber reinforced concrete (HFRC). A total of 102 specimens under monotonic and cyclic loading are investigated by means of pull-out tests. The main variables include fiber volume fraction and aspect ratio, concrete strength and stirrup confinement. The results show that the introduction of hybrid fibers had a synergetic effect on improving the bond performance in terms of peak bond strength and corresponding slip, resulting in a more ductile bond behavior. The improvement becomes more pronounced as the fibers content and concrete strength increase. With respect to the energy dissipation capacity, the hybrid fibers also exhibit a great influence. Specimens with higher fibers content always demonstrate a better energy dissipation capacity, while the opposite is true for increasing the aspect ratio of both fibers. Furthermore, two phenomenological models were proposed to predict the monotonic and cyclic bond behavior of well-confined HFRC specimens, in which the benefits of hybrid fibers were taken into account. The models, as well as involved equations, were verified by independent experimental results.

1. Introduction

The performance of the bond between steel rebar and surrounding concrete matrix has a significant influence on the mechanical behavior of reinforced concrete (RC) structures [1]. It is generally agreed that an intact bond can eliminate the potential risk of localized failure at the contact interface, which consequently ensures adequate bearing capacity of structures as subjected to complex loadings. Unfortunately, for some RC structures in practice, the normal serviceability can hardly be maintained due to insufficient bond strength, particularly in the regions where cracks are more prone to initiate and propagate [2,3]. To tackle this problem, considerable research efforts have been made to investigate the bond performance for specimens failed in either a splitting mode or a pullout mode [4–6]. Among these, the notable study conducted by Eligehausen et al. [6] is worth quoting, in which the reinforcing bars were embedded in confined concrete to simulate the confined region of a beam-column joint. This work revealed the nature of bond failure in certain practical applications, and inspired by it, numerous analytical models were derived subsequently. Moreover, these studies indicated that, for a deformed rebar, the bond mainly consists of three components, i.e. chemical adhesion, friction resistance and mechanical interlocking. Therein, the mechanical interlocking dominates the overall response, which is closely linked to the inherent properties of concrete, especially the tensile strength and energy dissipation capacity [7]. Hence, any improvement in mechanical properties of concrete matrix is expected to yield a preferable bond performance.

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With the rapid development in concrete technology, fiber reinforced concrete (FRC) has been widely appreciated for its superior performance in tension, energy dissipation, and the resistance to cracking [8,9]. Using FRC as an alternative in the critical regions of a structure (e.g. beam-column joints, base of columns, and mid-span of beams, etc.) has been regarded as a promising approach to prevent premature bonding failure [10]. In this respect, a number of investigations have been carried out and many desirable results have been obtained [11–16]. For example, the experimental results from Güneyisi et al. [12] indicated that using steel fiber could significantly enhance the bond strength. A rise in slip at the peak bond strength was also found upon addition of fibers [14–16]. However, some others reported divergent viewpoint on the contrary. [17–21]. Harajli et al. [18] demonstrated that only a marginal increase could be attributed to the addition of steel fiber, and the improvement was considered as a by-product of the increase in concrete strength. Dancygier et al. [20] reported even a worse bonding produced by inclusion of fibers that an obvious reduction of up to 30% in bond strength was observed because of the local disturbance of matrix in vicinity to the embedded rebar, and no positive correlation was found between bond strength and concrete strength.

From the above literature review, it is recognized that the conclusions made from respective investigation have not come to a unanimous agreement, which can consequently lead to the hesitancy in design of structural elements within civil infrastructure when different fibers are involved. The arguments with respect to individual scenario remain to be further evidenced due to the limited experimental results. In addition, it is noticed that the majority of existing investigations were dedicated to single fiber (with steel fiber in particular) that, however, was thought to contribute only partial improvement on the homogenized properties [22–25]. In consideration of the progressive fracture and multiscale nature of cracks in concrete, introducing two or more types of fibers to form a hybrid fiber system seems to be more promising in resistance of bonding failure. Therefore, a few attempts have been made to use hybrid fibers with varying constitutive properties, geometric sizes and practical functions. Hameed et al. [26] carried out a pull-out test of RC containing two different metallic fibers, and Ganesan et al. [27] adopted a blend of metallic and synthetic fibers more recently. The results showed that both hybrid systems exhibited an appreciable synergetic effect on bond performance when compared to that with single fibers. Of the limited researches, the bond behavior of rebar embedded in hybrid fiber reinforced concrete (HFRC) has not been systematically investigated to the authors' knowledge, especially for the cases subjected to different loadings, where significant bond degradation can be observed [28–30].

The objective of this research is to study the local bond performance of rebar embedded in well-confined steel-polypropylene HFRC under monotonic and cyclic loads, which is of great benefit to analyze the structural response of those confined regions. The influences of volume fraction and aspect ratio of hybrid fibers, concrete strength and stirrup confinement were studied. Two phenomenological bond stress–slip models for evaluating the monotonic and cyclic bond behavior were also developed respectively, in which the effects of hybrid fibers were taken into account.

2. Experimental program

2.1. Materials

Three mixtures of plain concrete were designed and the corresponding mix proportions are given in Table 1. Ordinary Portland cement (P.O. 42.5), fine river sand with a fineness modulus of 2.65 and gravels of sizes between 5 and 15 mm were used. A naphthalene based superplasticizer with a water reducing rate of about 15% was adopted to improve the workability. All these mix proportions are designed according to the code JGJ 55-2011 [31].

Table 1
Designed mix proportions (kg/m^3).

Mixture No.	Cement	Sand	Gravel	Water	Superplasticizer	Water cement ratio
I	398	836	1022	175	4.0	0.44
II	486	743	1026	175	4.9	0.36
III	565	676	1014	175	5.7	0.31

Corrugated steel fiber (SF) and a modified type of monofilament polypropylene fiber (PF) with good hydrophilia were used. The respective features are shown in Fig. 1.

The geometry of the deformed steel bars is schematically shown in Fig. 2 and the specific parameters are listed in Table 2. Plain bar with a nominal diameter of 6 mm was used as the stirrups.

2.2. Specimens preparation

As illustrated in Fig. 3, the specimen consists of a cubic concrete matrix (150 mm × 150 mm × 150 mm) and a steel rebar embedded centrically. According to the recommendations in literature [21,32], only the central part of concrete was bonded to the rebar while both ends were detached by installing two PVC pipes. The embedded length was fixed at 60 mm (3 times the diameter of the rebars) in order to prevent the yielding of rebars during the test.

A total of 102 specimens were tested, including 51 monotonic and 51 cyclic loading tests, i.e. six identical specimens were tested for each of the 17 cases listed in Table 3. The parameters considered in this study are summarized below and the specific values can be found in Table 3:

- Characteristic values of fibers: According to the studies [23,33], a volume fraction of 0.5–2.0% and an aspect ratio of 30–80 were recommended for SF. Hence, the volume fractions of the corrugated SF were selected as 0.5%, 1.0%, and 1.5% and the aspect ratios were 30, 60, and 80, respectively. For PF, to avoid the balling effect due to excessive dosage, three low volume fractions of 0.05%, 0.10% and 0.15% were used, and three aspect ratios of 167, 280, and 396 were selected for the purpose of comparison.
- Concrete strength: Three plain concrete strengths were designed, i.e. 30 MPa, 40 MPa and 50 MPa.
- Stirrup confinement: The cases with or without stirrup confinement were considered. The confined specimens were cast with two stirrups placed in the center (30 mm spacing). The remaining specimens had no stirrup confinement.
- Loading method: Specimens under both monotonic and cyclic loadings were investigated.

All the specimens were cast in the direction perpendicular to the rebar with a small needle vibrator. After 24 h, they were demoulded carefully and stored in the curing room at a constant temperature of 20 °C until 28 days strength was achieved. In addition, for each case, six cubes of 150 mm side length were prepared from the same batch mixture for compressive and splitting tensile strength tests (Table 3). The fabrication of specimen followed the specification in CSCE 38:2004 [34].

2.3. Test setup

The experiments were conducted on a standard testing machine (Instron 1342) which has a 25 tonne load capacity. The schematic diagram of the test setup is shown in Fig. 4. Before mounting onto the test machine, the specimen was positioned into a specially designed steel frame, which was an assembly of three steel plates (45 mm in thickness) and four long stiff rods (20 mm in diameter). In the central zone of each plate, three small holes were preformed to facilitate the installation of rebar and linear variable displacement transducers (LVDTs). Besides, in order to eliminate the unwanted arch-effects caused by compression [35], four steel blocks were inserted into the gaps between the specimen and the steel plates, as recommended by the ACI Committee 408 [11]. Additionally, four LVDTs were fixed at both ends of the rebar to measure the relative displacements with respect to the concrete.

For monotonic loading, the specimen was subjected to a controlled direct tension at a maximum loading rate of 0.1 kN/s. The loading process was terminated when the slip at the free end of the rebar was greater than 10 mm (approximately the length between two adjacent ribs of the rebar).

For cyclic loading, all the tests were carried out using the same loading scheme, as shown in Fig. 5. For each controlled displacement Δ_i, six cycles were performed in order to assess the bond degradation. In the first several cycles when the displacement was smaller than 1 mm, the loading rate was set as 0.05 mm/s. Subsequently, the loading rate was increased to 0.1 mm/s for saving time. The test stopped when the relative slip reached to 4.5 mm (about half length between two adjacent ribs of the rebar).