Bond Performance between Magnetized Rebar and Self-Compacting Steel Fiber Reinforced Concrete

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Received 9 June 2019, accepted 4 December 2019 doi:10.3151/jact.17.686

Abstract

A new method aiming to improve bond performance between rebar and concrete is proposed in present paper. In this method, the rebar embedded in self-compacting steel fiber reinforced concrete (SSFRC) was magnetized to attract surrounding steel fibers. The special combination of rebar and the attracted steel fiber was expected to improve bond strength of rebar and concrete. Six groups of specimens were made to investigate the effect of rebar magnetization, steel fiber volume fraction and compacting method on bond strength between rebar and concrete. Results show that magnetization of rebar can greatly improve bond strength with the highest increase of 52%. The steel fiber volume fraction can be largely reduced under rebar magnetization condition and the highest bond strength 23.78 MPa was found on specimen with rebar magnetization of 30 mT and 0.25% steel fiber. Moreover, SSFRC was better than vibrated steel fiber reinforced concrete (VSFRC) when using this new method. A bond stress-slip model reflecting the effect of rebar magnetization and steel fiber volume fraction was also developed and verified by experimental results.

1. Introduction

Bond performance between rebar and concrete is a key factor affecting functions of reinforced concrete (RC) structures. Hence, a high construction quality is required especially for the area where operation space is limited such as cast-in-situ beam-column connections of prefabricated concrete frame structure (Wu and Feng 2018). Construction defects often appear due to the intensive layout of longitudinal bars and stirrups in core area of connections (Wang et al. 2019).

To solve the construction defects and weak beam-column connection problem, the idea replacing ordinary concrete of beam-column connections with steel fiber reinforced concrete (SFRC) was proposed by some researchers (Chen 1982; Vasconez et al. 1998). Experimental results show that the bond performance between rebar and SFRC is better than that between rebar and ordinary concrete. In addition, stirrups could be reduced by a large margin or even exempted when steel fiber reinforced concrete was applied.

However, the recent studies (Huang 2016; Garcia-Taengua et al. 2016) indicate that the effect of steel fiber on improving bond strength between rebar and concrete is very limited. The experimental results from Gao et al. (2004) also implies that the addition of steel fibers will impact the bond performance between rebar and concrete to some degree, but the increase of bond strength is no more than 11% and no clear effect rule can be found.

Moreover, construction defects cannot be avoided due to the limited space for concrete vibrators within narrow structure connections where intensive stirrups are usually arranged to guarantee reliable bonding of each structural part (Kumar et al. 1991). On the contrary, self-compacting concrete (SCC) has good fluidity and workability, which can reduce construction defects when constructing the narrow structure connections (Nguyen et al. 2018; Chalioris et al. 2014).

Therefore, a new method utilizing self-compacting steel fiber reinforced concrete (SSFRC) to improve bond performance between rebar and concrete is proposed in this study. In this method, the rebar embedded in SSFRC is magnetized before casting. Then some steel fibers will be attracted around rebar after casting SSFRC. Such special combination of rebar and steel fiber may greatly increase bond strength between rebar and SSFRC. In addition, the SSFRC can also reduce construction defects since no vibrating process is needed.

The purpose of the present paper is to investigate the effectiveness of this new method using magnetized rebar to improve bond strength between rebar and SSFRC. Furthermore, the influence of magnetic field strength of rebar, steel fiber volume fraction and compacting method on bond strength is clarified. Finally, a bond stress-slip model reflecting the effect of rebar magnetization and steel fiber volume fraction is developed to provide basic reference concerning this new construction method.

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2. Experimental program

2.1 Magnetization of steel rebar

It should be noted that steel is a kind of soft magnetic material, which can be quickly magnetized by magnetic source such as magnetizing machine or permanent magnet. For practical application, the magnetization strength and the magnetic hysteresis (ability to preserve the magnetization strength) of steel can be controlled by adjusting the magnetic field strength of magnetic source and the chemical composition of steel rebar. The present study was performed mainly to investigate the feasibility of the new method and the influencing factors. Therefore, just a simple method was employed for the magnetization of steel rebar to obtain a relatively stable magnetic field.

In the present study, a Nd-Fe-B permanent magnet with strong magnetic field and a ferrite permanent magnet with relatively weaker magnetic field were chosen for the convenience of magnetizing the rebar quickly and controlling the magnetization strength. The average magnetic field strengths of Nd-Fe-B and ferrite permanent magnet are 200 mT and 100 mT, respectively. Rebar was magnetized when it met permanent magnet. Some iron powder was laid evenly beneath the rebar to reveal the magnetic field distribution. The magnetic field strength along rebar was measured by gauss meter. The result shows that the average magnetic field strength along rebars magnetized by Nd-Fe-B permanent magnet is 30 mT, while that of rebars magnetized by ferrite permanent magnet is 15 mT. Figure 1 shows the magnetization of rebar and detection of magnetic field along it. Moreover, it was observed that the steel rebar can be uniformly magnetized and that the magnetization strength near the surface of rebar was barely influenced by the distance from the magnet, which means that the magnet can magnetize the long rebars. However, the attractive force of magnetized rebar to the steel fibers varied with the distance between steel fiber and rebar. The attractive forces to the steel fibers at different distance from magnetized steel rebar were tested by a testing set-up, as shown in Fig. 2(a). To visualize the attractive force, it is normalized by dividing it by the gravity of a steel fiber. Figure 2(b) shows the relationship of normalized attractive force and distance between magnetized rebar and steel fiber. The attractive force decreased with the increase of distance. The effective attraction scope was $3d_s$ and $1.5d_s$ around rebar for magnetization of 30 mT and 15 mT, respectively, where $d_s$ is the nominal diameter of the rebar.

2.2 Specimen design

The geometry of specimens in this experiment is shown in Fig. 3(a). The nominal diameter $d_s$ of the rebar is 10 mm. According to recommendation of the Chinese standard for testing concrete structures (China GB/T 50152-2012 2012), the pull-out test specimens should be cubic with side length of $10d_s$. The embedment length $l_e$ of pull-out test is recommended as $5d_s$ by the above standard. However, according to research of Yoo et al. (2018) and Gao et al. (2004), the embedment length can be shorter when the prospective bond strength may be much higher than that between rebar and ordinary concrete. The embedment length $l_e$ was taken as $3d_s$ (i.e., 30 mm) in the present experiment. The steel rebar was magnetized before casting concrete, the distance of bonding region from magnet was 120 mm as shown in Fig. 3(b). Five minutes after the magnetization of rebar, concrete was vertically cast into molds from the upper open surface of molds, as shown in Fig. 3(c). A vibrating needle was used to compact concrete for VSFRC. The molds were removed 24±1 hours after casting, and a
A corrosion inhibitor was sprayed onto the both ends of rebar. The specimens were cured in an environmental chamber, which had a temperature of 20±2°C and relative humidity (RH) of 90±5%. Six concrete cubes with edge length of 150 mm were reserved and cured in the chamber for each mixture batch. After 28 days of curing, the specimens were subjected to pull-out test and the reserved concrete cubes were tested for mechanical properties of concrete.

2.3 Material properties

Six types of concrete were designed, classified by the volume fraction of steel fiber. The steel fiber volume fraction was designed to be 0%, 0.1%, 0.25%, 0.5%, 0.75% and 1%. The selection of steel fiber was in line with China’s specification for application of fiber reinforced concrete (China JGJ/T 221-2010 2010). Corrugated steel fiber was selected in this study, as shown in Fig. 4(a). The aspect ratio of the steel fiber is 43.7 and the ultimate tensile strength is 450 MPa. Rebar was deformed steel bar with lugs distance of 7 mm, as shown in Fig. 4(b). The yield strength of rebar is 335 MPa.

Each type of concrete was designed to be SSFRC, and a group of vibrated steel fiber reinforced concrete (VSFRC) was also designed for comparison. The mix proportions of six types of concrete are given in Table 1. All the concrete was made of the same kind of cement. The chemical composition of cement and fly ash is listed in Table 2. The particle size distribution of the SSFRC aggregate was the same as its corresponding VSFRC aggregate, as shown in Fig. 5. As mentioned previously, rebar was magnetized before casting concrete. According to the results of magnetization test, the shaping of SSFRC would be affected due to too many steel fibers attracted onto rebar if the magnetic field strength along rebar is too strong. Therefore, the average magnetic field strength along rebar is designed to be 30 mT, 15 mT and 0 mT, respectively. After magnetization of rebar, all specimens were cast in direction perpendicular to the rebar. For VSFRC, a vibrating needle was used to help with compacting. In addition, six cubes of 150 mm side length were reserved for compressive and splitting ten-

| No. | Cement (kg/m³) | Fly ash (kg/m³) | Sand (kg/m³) | Gravel (kg/m³) | Superplasticizer (kg/m³) | Steel fiber (%) | w/c | Slump-flow / Slump (mm) | T500 (s) |
|-----|----------------|----------------|--------------|----------------|--------------------------|----------------|-----|------------------------|---------|
| I-1 | 385            | 165            | 742          | 907            | 4.95                     | 0              | 0.53| 768                    | 1.8     |
| I-2 | 385            | 165            | 742          | 907            | 0                        | 0              | 0.53| 87                     | /       |
| II-1| 385            | 165            | 742          | 907            | 4.95                     | 0.1            | 0.53| 723                    | 2.1     |
| II-2| 385            | 165            | 742          | 907            | 0                        | 0.1            | 0.53| 85                     | /       |
| III-1| 385           | 165            | 742          | 907            | 4.95                     | 0.25           | 0.53| 669                    | 2.8     |
| III-2| 385           | 165            | 742          | 907            | 0                        | 0.25           | 0.53| 80                     | /       |
| IV-1| 385            | 165            | 742          | 907            | 4.95                     | 0.5            | 0.53| 634                    | 3.5     |
| IV-2| 385            | 165            | 742          | 907            | 0                        | 0.5            | 0.53| 76                     | /       |
| V-1 | 385            | 165            | 742          | 907            | 4.95                     | 0.75           | 0.53| 587                    | 4.2     |
| V-2 | 385            | 165            | 742          | 907            | 0                        | 0.75           | 0.53| 70                     | /       |
| VI-1| 385            | 165            | 742          | 907            | 4.95                     | 1              | 0.53| 555                    | 5.4     |
| VI-2| 385            | 165            | 742          | 907            | 0                        | 1              | 0.53| 64                     | /       |

Note: Slump-flow was measured for SSFRC while slump was measured for VSFRC. 

$T_{500}$ = time when slump-flow reaches 500 mm.
sile strength for each group. All experiment procedures complied with the Chinese standard for testing concrete structures (China GB/T 50152-2012 2012) and the specification for application of self-compacting concrete (China JGJ/T 283-2012 2012). The parameters of all specimens are listed in Table 3.

### 2.4 Test system

The pull-out test was carried out on an MTS 809 Axial test system, which has maximum axial force output of 100 kN. A stiff and concise test frame, which consisted of two high-strength steel plates and four steel bolts, was manufactured for quick installation as well as accurate measurement. The schematic diagram of test setup is shown in Fig. 6. First, the bottom end of test frame was strongly clamped by bottom wedge grip. Then the upper wedge grip clamped rebar of specimen after it placed in the right position and a magnetic pedestal was adjusted to ensure placement of a displacement gauge in the center position before test started.

The whole pull-out test was set on displacement con-
trolled condition, and performed monotonically with rate of 0.5 mm/min. The frequency of data collection was 4 datum every second. Testing continued until the residual stress started to become invariant or the end slip reached the value of 8 mm.

The slip of the free end of rebar was measured by the displacement gauge. The real slip of rebar could be rectified by comparison of displacement between the free end of rebar and displacement of the grip. The bond stress can be calculated as follows since the embedment length is relatively short. The bond stress along embedment length can be assumed to be distributed uniformly.

\[
\tau = \frac{F}{\pi d_s l_e}
\]

where \(\tau\) is the bond stress (MPa), \(F\) represents the applied force (N), \(d_s\) is the rebar diameter and \(l_e\) is the embedment length.

3. Experimental results and discussion

3.1 Experimental observations

The pull-out failure mode occurred in all specimens. Lin et al. (2019) concluded that pull-out failure mode tends to happen when concrete cover to steel rebar diameter ratio \(c/d_s\) \(\geq\) 4.5 to 5. The failure phenomenon agreed well with previous conclusions since \(c/d_s = 4.5\) in the present experiment. Moreover, no obvious cracks appeared on the surface of specimens after testing as shown in Fig. 7.

A group of specimens were split by hydraulic press machine after pull-out testing for the convenience of direct observation of embedded rebar and its surrounding concrete, and red arrows were used to mark the steel fibers to better understand the steel fiber distribution, as shown in Fig. 8.

Specimen I-1-0 was SCC without steel fiber. Specimen VI-1-0 was SCC with 1\% steel fiber while rebar was unmagnetized when casting concrete. Specimen VI-1-30 was SCC with 1\% steel fiber and rebar was magnetized when casting concrete. Specimen VI-2-30 was vibrated concrete with 1\% steel fiber and rebar was magnetized when casting concrete. The steel fibers were randomly distributed in concrete when the rebar was unmagnetized while many steel fibers were attracted around the rebar when it was magnetized, as shown in Figs. 8(b) and (c). However, the concentrated distribution of steel fibers was disrupted in the VSFRC specimen and the steel fibers were distributed uniformly throughout the specimen.

![Fig. 6 Test setup: (a) test frame, (b) loading apparatus.](image)

![Fig. 7 Surface of specimens after testing: (a) front surface, (b) rear surface.](image)
fibers tended to distribute horizontally toward one side preferentially as shown in Fig. 8(d).

Moreover, much concrete powder was also found between lugs of embedded rebar as shown in Fig. 9, which was typical phenomenon of pull-out failure mode. Concrete was gradually crushed into powder when the rebar was pulled out and pull-out failure happened after concrete keys were sheared off.

### 3.2 Pull-out test results

The main test results are listed in Table 4. The bond strength was defined by the maximum bond stress of the ascending stage. The peak slip was defined by the corresponding slip of the maximum bond stress and the residual strength was defined by the minimum bond stress of the descending stage.

| No. | Specimens | Bond strength $\tau_{\text{max}}$ (MPa) | Peak slip $s_1$ (mm) | Residual strength $\tau_f$ (MPa) |
|-----|-----------|----------------------------------------|----------------------|-------------------------------|
| 1   | I-1-0     | 16.59                                  | 2.27                 | 5.9                           |
| 2   | I-2-0     | 16.60                                  | 2.27                 | 6.37                          |
| 3   | II-1-0    | 16.35                                  | 2.16                 | 9.52                          |
| 4   | II-1-15   | 17.04                                  | 2.28                 | 4.17                          |
| 5   | II-1-30   | 17.94                                  | 2.85                 | 6.42                          |
| 6   | II-2-30   | 16.55                                  | 2.74                 | 7.11                          |
| 7   | III-1-0   | 15.97                                  | 2.15                 | 5.06                          |
| 8   | III-1-15  | 18.52                                  | 2.46                 | 6.12                          |
| 9   | III-1-30  | 23.78                                  | 3.13                 | 7.98                          |
| 10  | III-2-30  | 16.66                                  | 2.47                 | 5.56                          |
| 11  | IV-1-0    | 14.33                                  | 1.76                 | 4.09                          |
| 12  | IV-1-15   | 19.00                                  | 2.48                 | 4.70                          |
| 13  | IV-1-30   | 20.81                                  | 2.89                 | 6.36                          |
| 14  | IV-2-30   | 16.87                                  | 2.40                 | 4.16                          |
| 15  | V-1-0     | 13.6                                   | 2.10                 | 3.83                          |
| 16  | V-1-15    | 17.83                                  | 2.43                 | 5.25                          |
| 17  | V-1-30    | 23.56                                  | 2.52                 | 6.51                          |
| 18  | V-2-30    | 16.57                                  | 2.03                 | 5.73                          |
| 19  | VI-1-0    | 15.91                                  | 2.06                 | 4.50                          |
| 20  | VI-1-15   | 19.37                                  | 2.51                 | 4.70                          |
| 21  | VI-1-30   | 21.44                                  | 2.81                 | 6.91                          |
| 22  | VI-2-30   | 16.81                                  | 2.80                 | 5.22                          |

Fig. 8 Embedded rebar and surrounding concrete: (a) specimen without steel fiber, (b) specimen without rebar magnetization, (c) specimen with rebar magnetization, (d) vibrated concrete specimen with rebar magnetization.

Fig. 9 Remanent concrete powders between lugs.
The bond stress-slip relationships of steel fiber reinforced concrete specimens are also shown in Fig. 10 for convenience of further analysis and discussion. For each group of steel fiber reinforced concrete specimen a specimen without steel fiber was incorporated as comparison.

### 3.3 Effect of rebar magnetization

The bond strength between rebar and steel fiber reinforced concrete is summarized in Fig. 11. As Figs. 10 and 11 reveal, a very positive effect was brought by rebar magnetization when steel fiber volume fraction was above 0.1%. The bond strength between rebar and steel fiber reinforced concrete increased with magnetic field strength of rebar. The highest increase was about 35%.
51%, 45.5% and 49% for specimens with 1%, 0.75%, 0.5% and 0.25% steel fiber, respectively. Moreover, the biggest bond strength 23.78 MPa was found on specimen with 0.25% steel fiber and rebar magnetization of 30 mT. This phenomenon demonstrated the efficiency of rebar magnetization on improving bond strength between rebar and steel fiber reinforced concrete.

A finite element model (FEM) was established to disclose the effect of concentration of steel fibers resulted from rebar magnetization on the steel-concrete bonding. The modeling process is described below.

(1) Material models
A concrete damaged plasticity (CDP) model (Lubliner et al. 1989) was adopted to simulate the behavior of concrete. All parameters of concrete are listed in Tables 5 and 6. Considering the relatively low stress level, steel rebar and steel fiber are set as elastic materials with Young’s modulus 210 GPa and Poisson’s ratio 0.3.

(2) Steel-concrete bonding modeling and elements description
The two-line constitutive model of cohesive elements was adopted to simulate the failure process of bonding between rebar and concrete, and Maxs Damage Law presented below is selected to simulate the initial damage of cohesive element.

\[
\text{Max} \left\{ \frac{t_1}{t_3}, \frac{t_2}{t_3}, \frac{t_1}{t_2} \right\}
\]

(3) FEM results
The modeling results can reasonably reflect the bond stress-slip relationship of pull-out test, as shown in Fig. 12. The peak stress appeared in the conical area around the rebar for the specimen without steel fiber, as shown in Fig. 13. The stress distribution pattern of FEM coincided with typical stress distribution (Xu 1990). However, the lateral element, and the reduced integration with hourglass control is applied in calculation.

![Fig. 12 FEM and experimental bond stress-slip relationships.](image)

![Fig. 13 Stress distribution of III-1-0.](image)
stress was shared by steel fibers that contributed to the impressive improvement of bond strength between rebar and concrete when steel fibers were attracted around magnetized rebar, as Fig. 14 shows. Besides, steel fiber on the one hand reduced origination and development of microcracks due to bridge effect, and on the other hand improved friction between lugs and surrounding concrete (Huang et al. 2016; Tang and Yan 1990).

3.4 Effect of steel fiber volume fraction

Figure 15 is a comparison of bond strength between specimens with the same rebar magnetization. When the field strength of rebar was 0 mT, specimens without steel fiber and specimens with 0.1% of steel fiber had a little bigger bond strength than those with more steel fibers. According to previous research (Huang et al. 2016; Garcia-Taengua et al. 2016; Tang and Yan 1990; Bae et al. 2016), the bond strength between rebar and steel fiber reinforced concrete was higher than that in concrete without steel fiber. The above research was conducted with ordinary concrete. However, the specimens were made of self-compacting steel fiber reinforced concrete in this study. In addition, the fluidity of SCC was reduced with an increase of steel fiber volume fraction as slump-flow test showed. Therefore, the relatively low fluidity of concrete affected the compacting, which caused more voids and microcracks in concrete. The voids and microcracks stopped the increase of bond strength between rebar and surrounding steel fiber reinforced concrete.

For the specimens with rebar magnetization, on the contrary, the steel fibers attracted by rebar not only alleviated the congestion of surrounding concrete but also improved the bond strength as above section analyzed. However, no obvious improvement of bond strength was found even in 30 mT of rebar magnetization condition when steel fiber volume fraction was 0.1% as Fig. 15 shows. Because little steel fibers were available to be attracted around rebar which limited the effect of magnetic field.

3.5 Effect of compacting method

As mentioned before, a group of VSFRC specimens was cast as comparison for each group of SSFRC specimens. The compressive strength and splitting tensile strength of SCC and vibrated concrete were almost the same as Table 3 shows. The bond stress-slip relationships of self-compacting and vibrated steel fiber reinforced concrete specimens with rebar magnetization of 30 mT are shown in Fig. 16.

The bond strength of self-compacting and vibrated specimens without steel fiber was almost the same. The bond strength of vibrated specimens with 0.1% steel fiber was a little reduced compared with the self-compacting one. However, when it comes to specimens with higher steel fiber volume fraction, the reduction of bond strength was 43%, 23%, 42% and 27% for specimens with 0.25%, 0.5%, 0.75% and 1%, respectively. As observed in Fig. 8, the vibration disrupted the concentrated distribution of the steel fibers, making steel fibers distribute horizontally toward one side preferentially, which phenomenon has also been observed by many other researchers (Edgington and Hannant 1972; Gettu et al. 2005). The relatively parallel and preferential distribution of steel fibers damaged the positive effect of rebar magnetization. In addition, above phenomena also...
demonstrated the importance of fluidity of concrete when applied magnetized rebar to improve bond strength between rebar and concrete because low fluidity and vibration can weaken the attracting ability of magnetized rebar.

4. Bond stress-slip model

In this section, a phenomenological analysis is conducted to develop a bond stress-slip model of between magnetized rebar and SSFRC based on the experimental results and previous conclusions.

The piecewise model was adopted in this study. This type of model has been described by many researchers (Elgiehausen et al. 1983; Xu 1990) and recommended by many design standards (fib 2010; China GB 50010-2010 2010) because it is simple and can reflect the bond state related to concrete cracking and crushing on each stage.

According to Xu (1990), the bond state of pulling-out failure included the stages of concrete cracking, concrete crushing and concrete key shearing-off. Each stage coincided with the interaction mechanism between rebar and concrete. On the concrete cracking stage, rebar bonded with concrete going through elastic and partially cracked state of concrete. In this stage, the final bond stress and corresponding slip was described as splitting

![Graphs showing bond stress-slip relationships](image)

Fig. 16 Comparisons of bond stress-slip relationships between SSFRC and VSFRC specimens.
stress $\tau_{cr}$ and $\delta_{cr}$, respectively. On the second stage, cracks around lugs continued growing and concrete between lugs was gradually crushed into powders, then the direct confinement on the surface of rebar was removed. In this stage, the bond stress stopped increasing due to lack of direct confinement near rebar, which led to a peak bond stress $\tau_{max}$ and corresponding slip $\delta_{u}$. On the final stage, bond stress declined and concrete keys was sheared off due to the further increase of rebar slip, then, a fracture surface along lugs of rebar formed and the bond stress stayed which was described as residual stress $\tau_f$ and the corresponding slip was $\delta_f$. The whole pulling-out failure process is shown in Fig. 17.

According to above description, the main task is to determine several parameters - i.e., splitting stress $\tau_{cr}$ and ultimate bond stress $\tau_{max}$ and its corresponding slip $\delta_{cr}$, residual bond stress $\tau_f$ and its corresponding slip $\delta_f$. In addition, the influence of steel fiber and rebar magnetization should also be taken into consideration based on experimental results in this study.

### 4.1 Determination of splitting and bond stresses and corresponding slip amount

Tepfers (1979) proposed a model to calculate the bond stress of three stages - i.e., elastic state, partially cracked state and plastic state. This model was proved to be suitable for pulling-out failure mode by Bea et al. (2016). Therefore, the model proposed by Tepfers (1979) was adopted to calculate splitting stress $\tau_{cr}$ and ultimate bond stress $\tau_{max}$.

According to Tepfers (1979), the bearing force $P_b$ induced by lugs can be decomposed into radial compression force $P$ and friction force $T$, as shown in Fig. 18. The radial stress $p$ corresponds to the radial compression force $P$ and the bond stress $\tau$ corresponds to the friction force $T$. The relationship of $p$ and $\tau$ can be presented as follows.

$$p = \tau \tan \alpha$$  \hspace{1cm} (3)

where $\alpha$ is the angle between the bond force and the embedded rebar.

Then, the splitting stress $\tau_{cr}$ and ultimate bond stress $\tau_{max}$ can be presented as follows according to model proposed by Tepfers (1979).

$$\tau_{cr} = \frac{(c + 0.5d_i)}{1.664d_i} \frac{1}{\tan \alpha} f_i$$  \hspace{1cm} (4)

$$\tau_{max} = \frac{2c}{d_i} \frac{1}{\tan \alpha} f_i$$  \hspace{1cm} (5)

where $c$ is the thickness of concrete cover, $d_i$ the nominal diameter of rebar and $f_i$ the tensile strength of concrete.

In fact, $\alpha$ was assumed to be a constant value 45° in above model by Tepfers (1979) and Bea et al. (2016). However, Ka et al. (2018) found the angle between bond force and embedded rebar was related to friction coefficient $f$ between concrete and steel bar, and that the relationship between $\alpha$ and $f$ can be presented derived as follows.

$$\tan \alpha = \frac{\pi}{4} - \frac{\alpha_c}{f}$$  \hspace{1cm} (6)

where $f$ is the friction coefficient between concrete and steel bar and $\alpha_c$ the surface angle of crushed concrete, as shown in Fig. 17. $f$ was regarded as static friction coefficient, which was 0.6 and $\alpha_c = 25°$ according to Xu (1990) and Ka et al. (2018).

However, the pulling-out test is a dynamic process, and this dynamic behavior was more obvious as concrete...
gradually crushed. Therefore, $f$ was regarded as static friction coefficient on the first stage and dynamic friction coefficient on the second stage in this study. According to Su et al. (2016), $f$ was 0.9 and 0.5 for static and dynamic condition, respectively.

Many studies (Harajli 1995; Zhao and Zhu 2018) have indicated that $s_p$ and $s_u$ were independent of concrete strength and confinement, instead, dependent on the clear distance $c_{\text{clear}}$ between lugs of rebar for pulling-out failure mode. Marcia-Delso et al. (2013) recommended that $s_y$ should be experimentally determined for each case if possible. Elasticity modulus of SCC could be smaller due to smaller volume fraction of coarse aggregate and higher water cement ratio (Yi 2009). Therefore, $s_p$ and $s_u$ should be bigger for SCC. Based on previous conclusions and experimental results, $s_p = 0.25c_{\text{clear}}$ and $s_u = 0.35c_{\text{clear}}$ in this study. The residual bond stress $\tau$ and its corresponding slip $s$ were taken as $0.4\tau_{\text{max}}$ and $c_{\text{clear}}$ according to the 2010 CEB-FIP Model Code (fib 2010).

Then, the piecewise bond stress-slip model of SCC without steel fiber can be described as follows.

$$\tau = \begin{cases} \frac{\tau_u s}{s_p} & 0 \leq s < s_{cr} \\ \frac{\tau_{cr} - \tau_u}{s_p - s_u} (s - s_u) + \tau_u & s_{cr} \leq s < s_u \\ \frac{\tau_{cr} - \tau_u}{s_f - s_u} (s - s_u) + \tau_u & s_u \leq s < s_f \\ 0.4\tau_{\text{max}} & s \geq s_f \end{cases}$$

(7)

4.2 Influence of steel fiber and rebar magnetization

The effect of steel fiber on bond strength can be taken into account by introducing a steel fiber factor $k_f$ according to Harajli et al. (1995) and Huang et al. (2016). The bond strength of SSFRC specimens without rebar magnetization was normalized via dividing it by bond strength of specimens without steel fiber, as shown in Fig. 19. Steel fiber factor $k_f$ can be expressed as follows based on the least-squares analysis.

$$k_f = 0.15 \rho^3 + 0.08 \rho^2 - 0.26 \rho + 1$$

(8)

where $k_f$ is the steel fiber factor (dimensionless parameter) and $\rho$ the steel fiber volume fraction.

A magnetization factor $k_m$ was also introduced to include the effect of rebar magnetization when steel fiber volume fraction was above 0.1%. Because the effect of rebar magnetization on bond strength could be ignored according to experimental results. The normalized bond strength increased with magnetic field strength of rebar, as shown in Fig. 20. Magnetization factor $k_m$ can be described as follows according to result of normalization.

$$k_m = 0.2 \frac{H}{15}$$

(9)

where $k_m$ is the magnetization factor (dimensionless parameter) and $H$ the average magnetic field strength along the rebar.

Then the influence of steel fiber and rebar magnetization can be described as $k_f + k_m$. The new piecewise bond stress-slip model after considering the effect of steel fiber and rebar magnetization can be expressed as follows.

$$\tau = \begin{cases} \frac{\tau_u s}{s_p} & 0 \leq s < (k_f + k_m) s_{cr} \\ \frac{\tau_{cr} - \tau_u}{(k_f + k_m)s_u - (k_f + k_m)s_{cr}} (s - (k_f + k_m)s_{cr}) + \tau_u & (k_f + k_m)s_{cr} \leq s < (k_f + k_m)s_u \\ \frac{\tau_{cr} - \tau_u}{(k_f + k_m)s_f - (k_f + k_m)s_u} (s - (k_f + k_m)s_u) + \tau_u & (k_f + k_m)s_u \leq s < (k_f + k_m)s_f \\ 0.4(k_f + k_m)\tau_{\text{max}} & s \geq (k_f + k_m)s_f \end{cases}$$

(10)

4.3 Comparison of experimental results and proposed model.

The comparison of the experimental results and the proposed model is shown in Fig. 21. The results of the comparison show that the proposed model in this study can offer relatively good evaluation on bond stress-slip relationship for SCC specimens, and reasonably reflect the effect of steel fiber and rebar magnetization.
5. Conclusions

The following conclusions can be drawn based on the present study:

(1) Rebar magnetization can bring a very efficient and positive effect on improving bond strength between rebar and SSFRC. The increase of bond strength can reach up to 51% compared with those without magnetization of rebar. The amount of steel fiber can be largely saved in terms of improving bond strength between rebar and concrete when rebar is magnetized. Because magnetization of rebar can attract enough steel fibers attached around rebar, and the attracted steel fibers can share tensile stress, strengthen the bridge effect of steel fiber and increase friction between lugs and surrounding concrete, as demonstrated by the finite element model.

(2) The fluidity of SCC can be reduced due to the adding of steel fiber. Therefore, limited effect on bond strength can be gained when too many steel fibers are added for SCC specimens without rebar magnetization. The effect of rebar magnetization can be limited when steel fiber volume fraction is less than 0.1%. A steel fiber volume fraction of 0.25% is recommended for SSFRC to ensure the fluidity as well as effect of rebar magnetization.

(3) SSFRC is recommended because low fluidity and vibration can weaken the attracting ability of magnetized rebar of vibrated concrete specimens.

(4) A piecewise bond stress-slip model was developed, and a steel fiber factor and magnetization factor were also proposed to consider the effect of steel fiber and rebar magnetization on bond strength. Results show that the proposed model in this study can offer relatively good evaluation on bond stress-slip relationship for SCC specimens, and reasonably reflect the effect of steel fiber and rebar magnetization.

Acknowledgements

This work reported here was conducted with the financial supports from the National Natural Science Foundation of China (Grant No. 51708477, 51678069), and the Project Funded by China Postdoctoral Science Foundation (Grant No. 2018T110837, 2017M620350). The supports are gratefully acknowledged.

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