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# Resistance of interfacial debonding failure of GFRP bars embedded in concrete reinforced with structural fibers under cycling loads

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ABSTRACT

GFRP rebars with different surface treatments such as helical wrapping and sand coating were evaluated under cyclic loads. The pull-out specimens were made from the addition of structural fibers (hooked end steel, PP, PVA fibers) with 1% of fiber volume fraction in a concrete matrix with expected change in interfacial bonding property as well as ductility improvement after first cracking. The experimental results were analyzed in terms of bond stress-slip curve, bond strength ratio, and energy dissipation. Severe failures in the interfacial layers of the GFRP rebars at the resin-bar fiber interface was observed as cycling loads increased. The addition of structural fibers to concrete generally showed significant changes for debonding failure mechanism since the strong bonding resulted in reduced energy dissipation as well as a sharp increase of load in the bond stress-slip curve. For the GFRP rebars, wedge effects from crushed or cracked particles due to repeated damage in the interfacial debonding zone affected the low dissipated energy. Abrupt pull-out bar failure was represented. The effect of fibers in the interfacial bonding layer confirmed that resistance of steel rebar to cycling debonding failures from rebar types showed the best performance. In particular, the addition of hooked steel fibers indicated the best performance regardless of rebar types.

## 1. Introduction

Internal reinforcing steel rebar corrosion problems associated with harsh environments have been an issue for many researchers and consist one of the chief causes of failure of concrete structures. For a long period, fiber reinforced concrete (FRP) as alternative materials have been studied in terms of their bond behaviors for either various FRP bars or plate types and application to concrete structures mostly exposed to corrosive environments [1–5]. The main properties required for steel rebar replacement involve interfacial bonding ability to transfer continuous interfacial loads from the rebar to the concrete matrix as well as good failure of ductility which is a slow decrease of applied loads during pullout failure [2,4,6]. The interfacial bond strength of the steel rebar, homogenous isotropic material, mostly result in strong debonding resistance from the ribs. The multiple kinds of surface treatments for pultruded FRP rebars, heterogeneous anisotropic material, can offer solutions for achieving good interfacial bond strength. It can be treated by wrapping a helical yarn on rebar surface before resin polymerization to make corrugated rebar type and sand particles. Rebar deformation and deep dents with resin can be applied [7–11].

The failure mechanism for modified FRP rebars on the surface has been reported to depend on various parameters such as concrete strength, interface properties, and different surface treatments [12–16]. Lee et al. [12–14] used two types of GFRP rebars to investigate the interfacial bond properties and found that the reinforced GFRP bar fiber surface with either sand coated or helically wrapped resin showed totally different failure mechanisms compared to steel rebar from the pull-out test. The failure modes in either concrete-resin layer or resin-bar fiber layer were largely affected by the compressive strength of concrete. For high concrete strength, debonding failure normally happened in the interface of resin-bar fiber. Achillides [15] suggested that the increase of bond strength can be obtained when concrete strength should be close up to an asymptotic value of 50 MPa. The bond strength of GFRP rebars with compressive strength in the range 25–40 MPa was not significantly influenced, while for the specimens within a compressive strength range of 40–65 MPa, the interfacial bond strength was significantly improved by changing the time of onset cracking and the condition of crack advancement [16].

The resistance of cyclic loads for FRP rebars treated by surface modification such as helical wrapping and embedding sand particles were significantly reduced since the delamination and crack of this

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layer were affected by the different mechanical and physical properties of the core bar fiber [17]. The increase in cycling load amplitude and numbers resulted in the increase in debonding slip as well as bond strength after cycling loads for GFRP rebars increased [18]. The right application of short fibers to FRP rebars can be used to improve interfacial bonding property and increase ductile performance during the pullout failure process. The homogenous distribution of fibers with high tensile strength and effective fiber bridge effect onset of concrete cracking affects the delayed crack growth as well as increases toughness [21]. The addition of short fibers to concrete matrix for GFRP & CFRP rebars affected the response of pullout failure in that a moderate improvement of ductility was found, but no significant improvement on interfacial bond strength was noted [20]. The addition of hooked steel fibers instead of synthetic fibers to the interfacial bonding layer improved the bond strength as well as ductile ability for FRP reinforcing bars [21–23].

Research data for the behaviors of FRP rebars to cyclic loading during interfacial bonding failure are currently limited. Furthermore, research works for the interfacial performance change from cyclic FRP rebars movement with the application of structural fibers are unprecedented during a few decades of FRP development history. To understand the nature of FRP rebars for safety usage in the construction industry, the behaviors of FRP rebars suffering from both static and cyclic loads need to be investigated. In this study, the most common types of GFRP rebars were used to evaluate the performance ability of cycling behaviors with the addition of structural fibers. The experimental results from direct pull-out tests are shown and analyzed with the aim of elucidating the failure mechanism of interfacial debonding process, suggesting the possible failure modes for rebar types.

## 2. Experimental program

### 2.1. Materials

The reinforcing bars used were one type of steel bar and two types of GFRP bars obtained from international manufacturers. The GFRP bars made of E-glass fibers and a thermosetting resin were selected. The diameter of the GFRP bars was 12.7 mm (#4). GFRP-A bar was sand-coated on the surface and GFRP-B bar was helically-wrapped to improve interfacial bonding as shown in Fig. 1. The fiber volume fraction and density of both GFRP rebars were about 2.0 g/cm$^3$ and 70%, respectively. The fracture strength of GFRP bars varied from 617 MPa to 690 MPa, and the elastic modulus was 40.8 GPa–42.0 GPa for the GFRP bars and 200 GPa for the steel bar. Both GFRP bars indicated a linear stress-strain property up to fracture. The detailed material properties of the GFRP bars are shown in Table 1. The properties of structural fibers used in this study were hook-end steel fiber, polypropylene (PP) fiber and polyvinyl alcohol (PVA) fiber obtained from K company, Gyeonggi, Korea. Material properties and surface configuration of fibers are represented in Table 2 and Fig. 1.

Table 3 shows the mix designs for application of steel, PP and PVA fibers with different reinforcing bars in composites. The fiber volume fractions of discrete fibers in hardened concrete were 1% for all types of rebars. Each batch was mixed in a shear pan mixer with a maximum capacity of 0.06 m$^3$. The following mixing procedures were used for all types of mixes. First, the cement and sand were dry-mixed for approximately 30 s. Then the water containing superplasticizer was added and the mixtures were continuously mixed for 2 min. Finally, discrete fibers were slowly added to the mixer. Altogether, additional mixing time was continued for another 3 min to confirm uniform fiber distribution and to prevent the effects of fiber segregation as well as fiber balling. The fiber added specimens after testing were cut to confirm the distribution of discrete fibers in concrete and uniformly distributed fibers were found.

### 2.2. Specimens

A total of 36 rectangular specimens were prepared and tested. The specimen size was 190.5 × 102 × 152.4 mm$^3$ modified from the experimental investigation performed by Alavi-Fard et al. [24]. Each specimen was made up of a concrete cube with a single rebar embedded horizontally along a central axis as shown in Fig. 2. The bond length of the embedded rebar was set to 63.5 mm, five times the diameter of the rebar. Furthermore, in order to make an effective measurement of the interfacial bonding behavior on the bonded length, the rebar on the top and bottom sides was sheathed with soft PVC tube to prevent bonding between the bar and the concrete. Concrete was placed in two layers and each layer was rodded 25 times with a 16 mm diameter tamping rod. The concrete was cast horizontally with the rebar inside the steel formwork. After molding, the specimens were instantly covered with a plastic sheet, stopping moisture loss for 24 h. The specimens were then removed from their molds and continuously cured underwater until the time of test at 21 °C. Two parameters were mostly considered in this investigation: the response of surface treatment of rebars as well as the resisting debonding effects of structural fibers to cyclic loading on the interfacial region. Three nominally identical specimens were prepared for each specimen type as shown in Table 4.

### 2.3. Test setup and testing procedure

The specimen was placed on the universal testing machine (UTM) so that the surface of the cube specimen on the side of the long end of the bar was in contact with the bottom of the mold and the end of the bar was gripped by the jaws, with round wedges, of the testing machine as shown in Fig. 2. The pullout behaviors of the steel and GFRP bars were identified using a 2000 kN capacity universal testing machine. A rate of 0.02 mm/s was selected and a continuous pullout load was first applied to the bars up to the failure for comparing repeated load behaviors. The pullout loads from maximum 70% and minimum 10% compared with

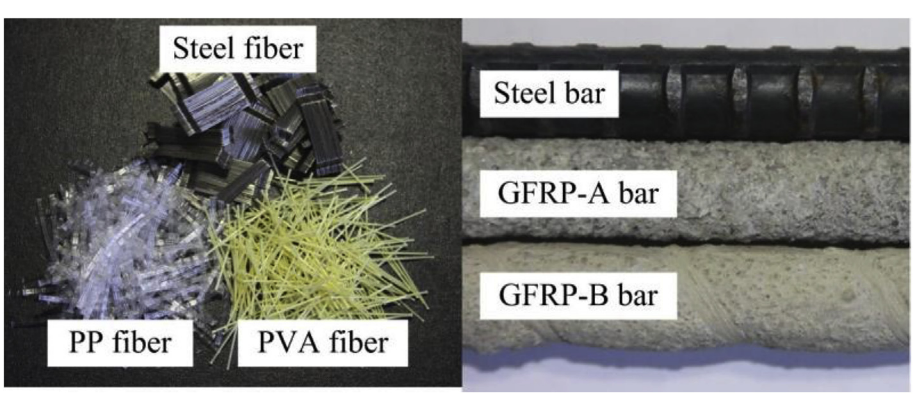


**Fig. 1.** Types of used fibers and bars.