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# Experimental investigations on the bond behavior between concrete and FRP reinforcing bars

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## HIGHLIGHTS

- Bond properties between FRP rebars and concrete were investigated by pull-out tests.
- Optical fiber instrumentation provided strain profiles along concrete/rebar interfaces.
- Bond-slip behaviors and effective development lengths of rebars were determined.
- Effects of various parameters were evaluated (diameter of rebars, sand coating...).
- Intrusive effect of DOFS instrumentation was limited except for few specimens.

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## ABSTRACT

This study focuses on the experimental characterization of the bond behavior between concrete and Fiber Reinforced Polymer (FRP) reinforcing bars (rebars). Pull-out tests were performed on glass, carbon, and aramid FRP rebars, as well as on deformed steel rebars. The influence of various parameters on the bond behavior was studied, such as the type of fibers, the diameter of the FRP bars and their surface geometry. Scanning-Electron-Microscope (SEM) observations were performed to precisely study the sand coating characteristics of these rebars. A main originality of the proposed approach relied on the instrumentation of pull-out samples using Distributed Optical Fiber Sensing (DOFS) instrumentation. Such a distributed measurement system provided access to the longitudinal strain distribution along the rebar near the rebar-concrete interface, and then made it possible to determine the effective development length of the various types of rebars considered in this study. As the introduction of DOFS instrumentation may be intrusive, its influence on the interface behavior was also discussed.



## 1. Introduction

Corrosion of steel reinforcing bars (rebars) is the main cause of degradation of Reinforced Concrete (RC) structures, and has large incidence on maintenance/repair expenses. To prevent such degradations of new infrastructures, the use of corrosion-free reinforcements, such as Fiber-Reinforced Polymer (FRP) rebars is gaining interest. The main products available on the market are made from Glass (GFRP), Carbon (CFRP), Aramid (AFRP) or Basalt (BFRP) fiber reinforced polymers. In these materials, polymer matrices are usually based on thermosetting resins, such as vinylester or epoxy systems. Compared to steel reinforcement, FRP rebars have the advantage of being lighter, stronger in tension, corrosion resistant, and electromagnetically neutral (with the exception of CFRP bars).

A key point controlling the performances of FRP reinforced structures is the bond behavior between the rebar and concrete. Indeed, interfacial properties are critical with respect to the load transfer mechanism between concrete and its reinforcement. In current design practices, bond properties govern serviceability, ductility and ultimate capacity of RC structures. Eurocode 2 [1] states that "the ultimate bond strength shall be sufficient to prevent bond failure". However, designing FRP RC structures is not trivial as the bond behavior of FRP rebars with concrete is affected by many factors, such as concrete strength, rebar stiffness (depending upon constitutive materials, especially the type and volume ratio of

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fibers), surface geometry and coating, adherence between the surface coating and the core of the FRP bar, the type of polymer matrix, and the fiber/matrix interface properties as well [2–5].

At the structural scale, FRP/concrete bond properties play a very important role with respect to in-service deformations (deflections), but also to cracking of the concrete cover.

The most common methods used to assess the bond behavior of FRP rebars with concrete are the direct pull-out test and the bond beam test. Described in ACI 440.3R-04 [6], Rilem recommendations [7] and EN 10080 [8], the direct pull-out test is the simplest test to conduct, and has been applied in many previous studies dedicated to the bond performance of FRP bars [2–5,9–11] embedded in concrete.

During bond tests, measured quantities are typically the maximum applied load and the overall slippage of the FRP reinforcement. However, these measures cannot provide local information regarding the interfacial behavior, and are thus unable to assess the effective development length.

Besides, DOFS technologies are gaining interest in civil engineering applications [12]. They allow continuous strain measurement along the optical fiber attached to the host structures, with a subcentimeter spatial resolution, while being only little intrusive. Such an instrumentation method has already been implemented for pull-out tests in previous studies devoted to the bond behavior between reinforcing steel rebars and Ultra-High Performance Fiber-Reinforced Concrete [13–15], but to the authors' knowledge, it has never been explored in the case of FRP reinforced concrete.

The present study investigates the local bond behavior between FRP rebars and concrete. The interfacial load transfer mechanism was characterized by pull-out tests carried out on RC specimens equipped with a DOFS instrumentation. Such an approach was applied to a selection of various FRP bars available on the market.

A special attention was paid to the influence of various features of the FRP rebars, such as the nature of the fibers, the internal microstructure (presence of flaws, fiber arrangement), the surface characteristics (geometry and sand coating), or the rebar diameter, on the interfacial mechanical behavior. In addition, an analysis of the strain profiles recorded by the DOFS system made it possible to evaluate the effective development lengths for the various FRP bars under consideration. Moreover a comparison of pull-out tests performed on RC specimens equipped with DOF sensors and non-instrumented specimens, gave information regarding the intrusiveness of the proposed DOFS methodology.

## 2. Experimental program

### 2.1. Materials

Various rebars available on the international market were selected for this study, based on glass, aramid or carbon fibers. Corresponding series are named GLASS, CARBO and ARA, respectively. These FRPs are manufactured by pultrusion process, with the exception of ARA rebars, which are produced from Kevlar braided ropes. Table 1 gathers information regarding the manufacturers, commercial brands, nature and volume contents of fiber and polymer matrix constituents, and type of manufacturing process for all series of FRP rebars.

For each series, the FRP materials were supplied with different surface finishes, either sand coated or plain (smooth, without additional surface coating). Corresponding sub-series are labeled xxx-S and xxx-NS respectively. Note that in practice, only sand-coated rebars of the GLASS type and CARBO type are commercialized on the market for construction applications. However, GLASS-NS and CARBO-NS have been studied in order to evaluate the effect of the sand-coating on the bond behavior of these rebars.

Various rebar diameters were considered, which are also specified in the samples designation.

For the sake of comparison, conventional deformed steel rebars (named STEEL-D-12) were also considered in this work.

The main characteristics of all rebars under study are detailed in Table 2. Typical aspects of these rebars are shown in Fig. 1. It is to note that ARA rebars present a specific surface geometry made of concavo-convex shapes due to the braiding process, which is supposed to improve their bond capacity with concrete. With regard to CARBO series, one can notice the presence of a white multifilament yarn helically wrapped around the bar which creates an additional surface relief. This feature is observed both on uncoated (CARBO-NS) and sand coated (CARBO-S) rebars.

Elastic moduli and tensile strengths of the various series of rebars were evaluated by tensile tests, according to ASTM D7205/D7205M-06 standard [16]. Further details regarding the experimental procedure adopted for tensile tests (especially the anchorage system used for preventing bar breakage in the grips of the testing machine) can be found in [17,18]. These tests were conducted for a single diameter value of each series, although many studies have reported a size dependence of the longitudinal strength for FRP rebars [19,20]. The main objective here, is to check that the supplied FRP materials fulfill the properties claimed by the manufacturers. Mean values of the tensile properties based on five repeated tests, together with the corresponding guaranteed properties, are listed in Table 3 for the various series of rebars.

Globally, test results are found in agreement with values of tensile strength and modulus announced by the various FRP suppliers, with the exception of samples from the ARA series, for which significantly higher values can be noted compared to those reported by the manufacturer.

### 2.2. Test setup for characterizing concrete/rebar interface behavior

The bond behavior between the rebars and concrete has been characterized by direct pull-out tests, according to ACI 440.3R-04 standard [6]. The test setup and loading conditions are depicted in Fig. 2. RC specimens consist of a 1.20 m-long straight rebar partially embedded, with centric placement, in a normal strength concrete cylinder (16 cm-diameter and 20 cm-height). Concrete was cast, while the rebar was set in the vertical position. A plastic tube, called bond breaker, is placed between the rebar and concrete near the loaded side of the concrete block, in order to prevent edge effects induced by the reaction support. For each RC specimen, the length of the bond breaker is chosen so that the embedment length of the bar in concrete is equal to six bar diameter (Fig. 2.b). Such a condition is supposed to favor a preferential failure by slippage of the rebar [10].

All the pull-out specimens were made from the same batch of a normal strength concrete, formulated with aggregates with a maximum size of 22 mm. Compressive strength of the concrete was evaluated on three cylindrical specimens (16 cm diameter and 32 cm height) after 37 days of cure out of water (the testing machine was not available at 28 days of cure). The tests resulted on a mean compressive strength of 28.1 ± 0.4 MPa. More details of the compressive tests are available in [17].

Pull-out tests were conducted five month after the casting of the specimens, using a 350 kN universal testing machine. The RC specimens were put on the drilled horizontal crosshead beam of the machine, with the rebar passing through the beam hole (Fig. 2.a). The test is controlled by the grip displacement at a constant speed of 1.2 mm/min. During the test, the free end slip of the rebar is monitored with a non-contact laser displacement sensor located at an initial distance of 40 mm from the end of the bar. This sensor allows measurement on a range of 20 mm with a precision less than 10 μm.