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## **Deformation Monitoring of Reinforcement Bars with a Distributed Fiber Optic Sensor for the SHM of Reinforced Concrete Structures**

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### **ABSTRACT**

This paper is concerned with the implementation of FO sensors in reinforcement bars (rebars) for strain measurement in reinforced concrete (RC) structures made of Ultra High Performance Fiber Reinforced Concrete. In the proposed technique, the FO sensor is embedded into a drilled cavity in the rebar using suitable adhesive. The measurement chain consists of an OBR interrogation unit (Optical Backscatter Reflectometer, based on relative Rayleigh measurements) paired with FO sensors.

The validation of the proposed technique has been performed successfully through a series of experiments. In a first validation step, uniaxial tensile tests were carried out on steel rods instrumented with FO sensors. The second validation step was to demonstrate the feasibility of embedding FO sensors in RC structures (embedded into the groove of rebars or bonded on the rebars surface) without damaging them during pouring of the concrete. For this purpose, pullout samples were fabricated by partially embedding instrumented rebars in concrete blocks. Results obtained so far indicate that the sensors perform adequately for the strain measurement of rebars tested in tension and for the strain measurement of rebars embedded in a loaded RC structure.

### **INTRODUCTION**

Fiber Optic (FO) smart structure is an attractive cost effective concept that will allow optimizing maintenance policies of large civil structures such as bridges or nuclear power plants. However, further development of this technology is needed. A major issue is to properly protect the FO during concreting and compacting and in the same time to ensure an accurate stress transfer from the structure to the sensing region.

Regions of interest in a reinforced concrete (RC) structure are generally zones under tension because crack opening has to be controlled in order to limit the penetration of water and aggressive chemical ions and also to guarantee a good durability of the RC structure. However reinforced concrete cracks at very low level of tensile load. The crack opening leads to a strain field discontinuity that can induce a break of FO providing this latter is not protected enough. Moreover, optical fibers are subjected to breakage during transportation and installation to the host structures. Bare fiber optic sensors are then not suitable for being directly embedded in concrete and need some kind of protective encapsulation or/and packaging [1]-[5]. However, the existence of a protective encapsulation of embedded fiber optic sensor or coating on an optical fiber results in a difference between the strain of the concrete matrix and the strain sensed by embedded fiber optic [6]-[7].

To overcome, or at least reduce, problems listed above, authors have tested FO sensors bonded to reinforcing bars (rebars). With such installation method, firstly, the tensile loading of the FO sensor stays limited when surrounding concrete cracks. It was then possible to use FO with very thin coating that ensure a good strain transfer between the sensor and the host material in which it is embedded.

Secondly, the adhesive layer acts as a second coating that protect the silica fibers from the alkaline environment of portland cement based concrete and against any aggressive chemical or mechanical environments.

Bonding FO sensors to rebars was ever successfully experimented by several authors (for example [8] and [9]). Moreover, the interrogation unit for optical sensors used in this study is a commercially available one, previously tested for Structural Health Monitoring (SHM) of concrete structure (see for example [11]-[12]).

Although every component of the sensing chain used in this study has been ever applied for SHM purpose, the originality of the proposed chain is to connect them all together: a thin coated FO bonded into the groove of rebars and interrogated using an optoelectronic device, named Optical Backscatter Reflectometer (OBR). In addition, it has to be noted that the studied application case is the SHM of reinforced Ultra High Performance Fiber Reinforced Concrete (UHPFRC) structures, which to the author's knowledge is a novel field application for optical fiber-based sensors. The concrete mix used in this research derives from one used in cross flow air cooling towers of Cattenom nuclear power plant ([13]). Hence, the study reported here is aimed at demonstrating the applicability of the proposed sensing chain in monitoring such kind of structure. Resolution of FO sensors appears as noticeably attractive in this case where small rebars to UHPFRC transfer lengths are expected.

This structural monitoring capability was evaluated through experiments carried out on steel rods instrumented with FO sensors and submitted to direct tensile tests and on deformed rebars, instrumented with FO sensors, embedded into a concrete block and submitted to direct pullout tests. Tested parameters of the sensing chain were the installation method (FO bonded on the rebar surface or mounted into a groove), the geometry of the groove and the type of optical fiber (mainly influenced by its external diameter and its coating material).

## I. FIBER OPTIC SENSING CHAIN FOR REBARS MONITORING IN RC STRUCTURES

### I.1 Types of Fiber Optic Sensors and Installation Methods

Two types of single-mode commercially available FO were used in this study. The structure of both FOs, hereafter referred to as FO-P and FO-A, is shown in Figure 1. The former uses a polyimide primary coating (approximately 190  $\mu\text{m}$  dia.), while the latter is an acrylate coated fiber (approximately 250  $\mu\text{m}$  dia.).

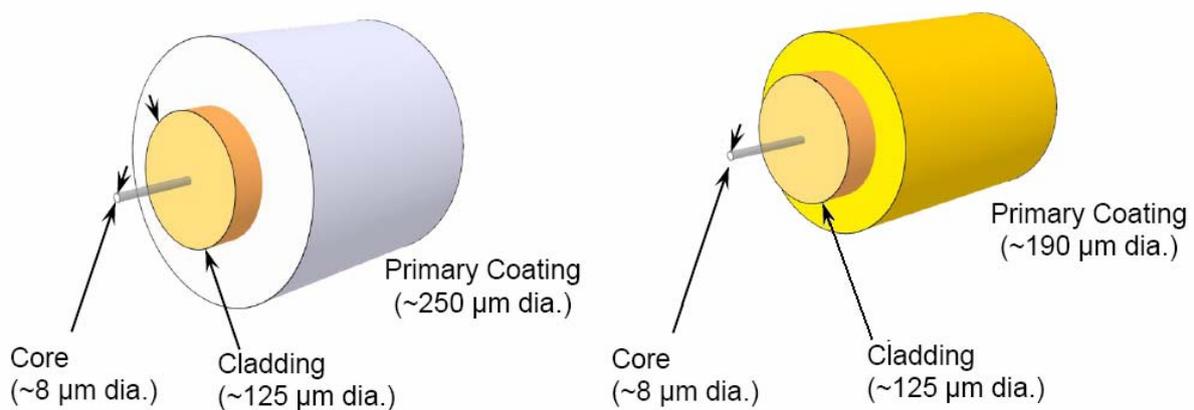


Figure 1. Structure of the single mode optical fibers used in the study.

To integrate monitoring systems based on FO technology in RC structures, it was decided in this research to bond the FOs to reinforcing bars. Two techniques were used:

- FO bonded on the surface of the rebars,
- FO embedded into a groove (owing to the small dimension of the FO) that was previously cut along the rib of rebars (see Figure 2).

This second technique was already successfully tested in previous work [14].

A two component epoxy paste (Araldite 2012) was used as adhesive for surface bonding and as groove-filling material (and consequently adhesive) for embedded FOs.

The groove has a depth of 1.0mm ( $d$  in Figure 2-a) but two different widths ( $L = 1.0\text{mm}$  or  $L = 0.5\text{mm}$ , see Figure 2-b) were tested. Input/output leads of the FO (unbonded parts) were protected by a fiber jacket (Figure 3).

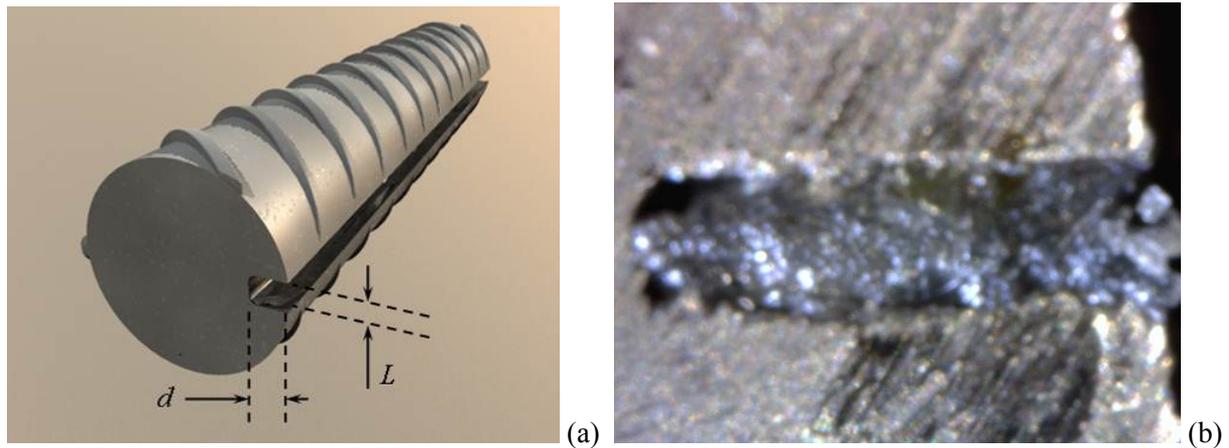


Figure 2. Geometry of the groove (a) and detail view (b).

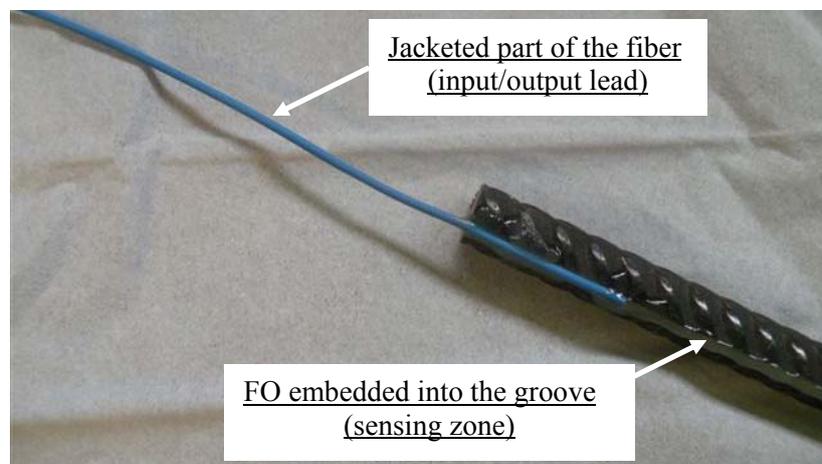


Figure 3. Detail view of the end of the bonded zone.

## I.2 Main Principles of the Distributed Optical Fiber Sensing System used in this Study

The sensing chain consisted to FO connected to a commercially available optoelectronic device, named OBR (Optical Backscatter Reflectometer). This interrogation unit is an Optical Rayleigh Frequency-Domain Reflectometer (OFDR) that provides strain measurement (at a constant temperature). The instrument correlates two OFDR traces then converts the spectral shift into strain assuming a linear dependency of  $-0.1499\text{GHz}/\mu\text{m}/\text{m}$  (value determined experimentally at 1550nm for a standard single mode fiber). The OBR is a portable device that was ever successfully evaluated for the SHM of representative-scale RC structural element equipped with various optical fiber sensing cables [15].

## II. PERFORMANCE CHARACTERIZATION OF THE MEASUREMENT CHAIN

### II.1 Uniaxial Tensile Testing of Rebars

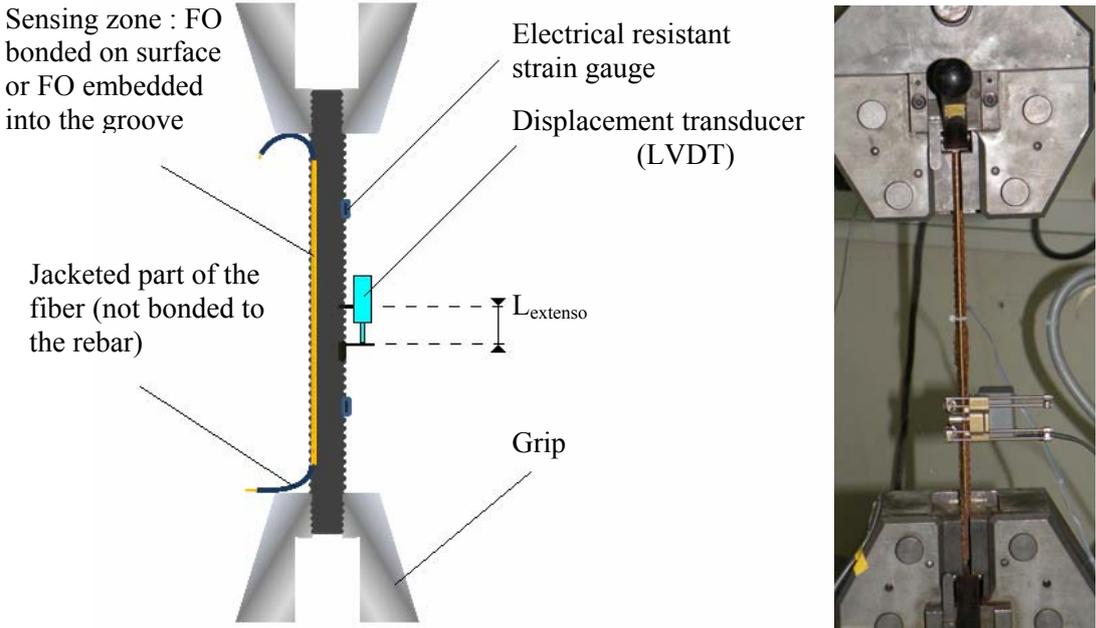
Load-controlled direct tension tests were performed on steel rods specimens with a length of 60 cm and a test zone of 45 cm (i.e. the FO was sensing 45 cm). The test is accomplished on a universal testing machine (Figure 4-b) with a constant applied load rate of 0.5MPa/s until complete failure of samples. The steel rods were instrumented with the optical fiber sensor. Conventional strain gage and a linear variable differential transformer (LVDT) were also employed for comparison of axial strain results. Instrumentation details are presented in (Figure 4-a).

In order to simplify the text of the paper, the term “chain” is used herein as a generic term comprising type of fiber, installation method of the FO (surface bonded or embedded in a groove) and interrogation unit (OBR).

Four different sensing chains, listed on Table 1, were tested. Experimental results are presented in Figure 5-Figure 8. As a first result, and based on the measurement of conventional LVDT and electrical resistance strain gages, it can be concluded that all the tested chains, except A-NG, can measure accurately longitudinal strain. However, from the comparison between Figure 5 (chain A-NG) and Figure 7 (A-WG), and from the comparison of Figure 6 (P-NG) and Figure 8 (P-WG), it appears that the embedded FOs offer a better strain transfer than the surface bonded FO. This conclusion is based on the capability of the considered sensing chain to monitor the strain gradient generated by transition from a bonded zone (and consequently loaded zone) to unbonded zone (unloaded zone) of the FO. In Figure 5 and Figure 6 the reproduction of this transition is very smooth while a faster change in the strain profile is furnished by sensing chains A-WG (Figure 7) and P-WG (Figure 8).

However, with reference to the strain profiles recorded by A-WG (Figure 7) and P-WG (Figure 8), and particularly to the form of the transition zone, it was found that the acrylate coating leads to a larger absorption of the host material strain than the polyimide coating. To verify this assumption, and check the ability of these two chains to survive the concreting process and acquired quantitative strain information from RC structures, RC elements made of UHPFRC and equipped with such sensors were tested.

Experimental measurements recorded by A-WG and P-WG did not exhibit sensible difference when considering results obtained with a 0.5 or 1.0mm widths of the groove.



**Figure 4.** Instrumentation details and test setup for uniaxial tensile testing of rebars.

**Table 1:** List of the sensing chains

Sensing chain	Type of FO	Installation method	Width of the groove	Interrogation Unit
A-NG	FO-A	Bonded on the surface	-	OBR
P-NG	FO-P	Embedded into a groove	Half: 0.5 mm Half: 1.0 mm	OBR
A-WG	FO-A	Bonded on the surface	-	OBR
P-WG	FO-P	Embedded into a groove	Half: 0.5 mm Half: 1.0 mm	OBR

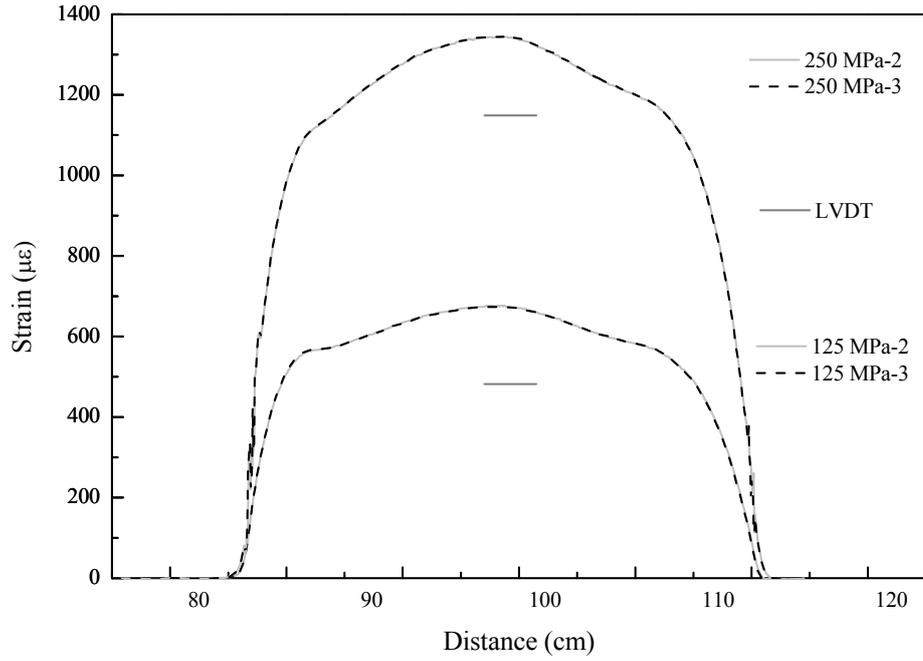


Figure 5. Rebar longitudinal strain distributions under various loadings (from the sensing chain A-NG)

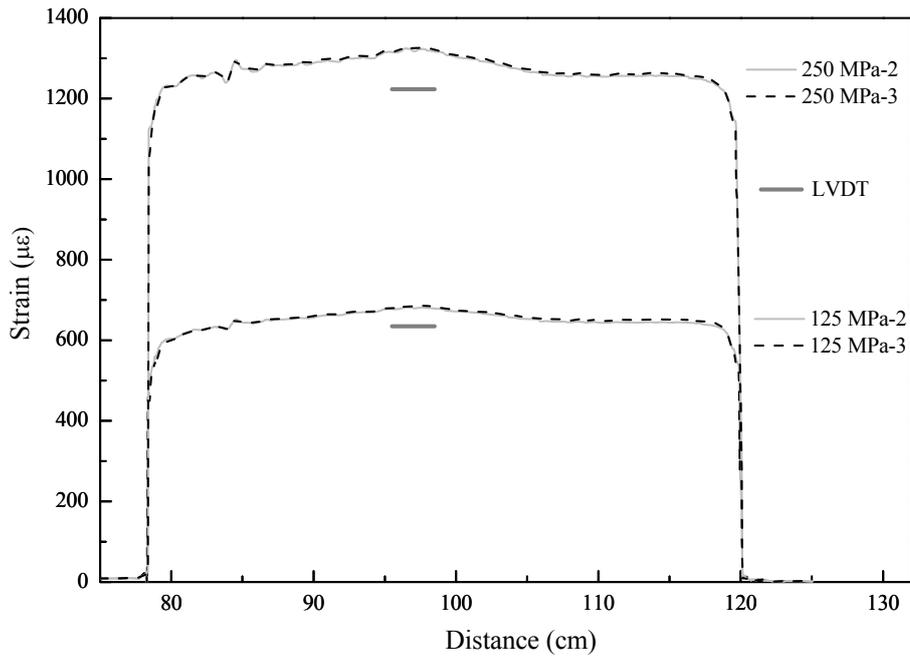


Figure 6. Rebar longitudinal strain distributions under various loadings (from the sensing chain P-NG)

The loading program was cyclic. Each cycle varies from zero to a chosen stress amplitude. Three cycles were performed at the amplitude of 125MPa, and three complementary cycles were performed at the amplitude of 250MPa. In Figure 5-Figure 8., the cycles are denoted by A-n, where A is the stress amplitude and n is the number of the cycle (for ex. 250MPa-2, is the result recorded along the rebars during the second cycle carried-out at the stress amplitude of 250). As shown in Figure 5-Figure 8, the optical fiber did not exhibit any hysteresis.

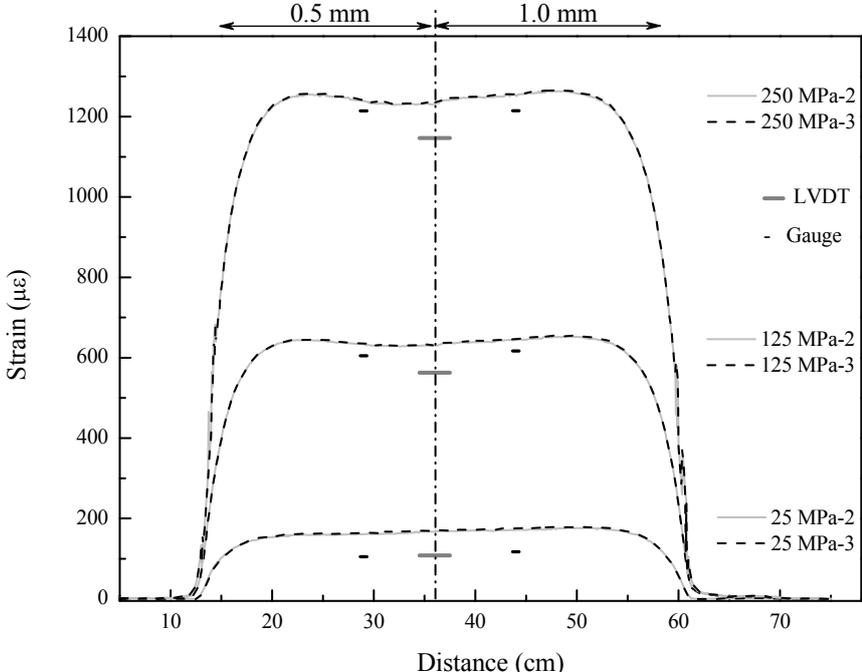


Figure 7. Rebar longitudinal strain distributions under various loadings (from the sensing chain A-WG)

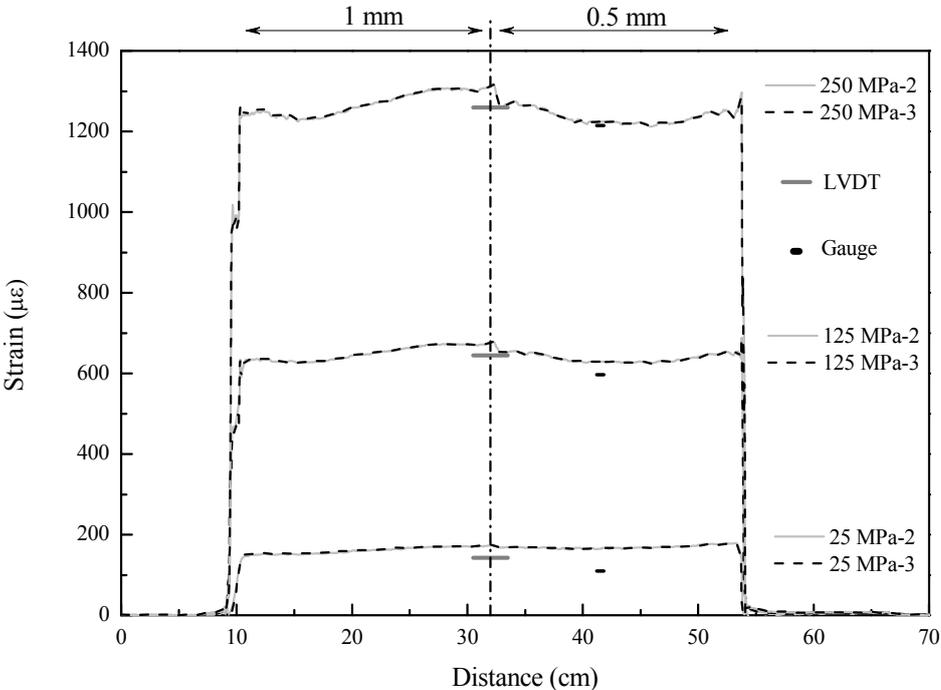


Figure 8. Rebar longitudinal strain distributions under various loadings (from the sensing chain P-WG)

### II.3 Direct Tension Pullout Bond Test

The second validation step was to demonstrate the feasibility to implement the FO sensors in reinforced UHPFRC structures and particularly to test their capacity to be embedded into concrete without damaging them during pouring operation. For this purpose, pullout samples were fabricated by partially embedding instrumented rebars in UHPFRC blocks (see Figure 9). Considering conclusion of the previous experimental campaign, only two sensing chains were tested (see Table 2). Tensile loading was monotonically applied to the loaded-end of the rebar up to failure.

Measurements were performed meanwhile solicitation was imposed to the deformed rebar, but during measurement, it was necessary to maintain the load to a constant value. Measurement steps were carried-out at the loading stages labeled Fx-n. in Figure 10 and Figure 11 (x corresponds to the type of FO and n refers to the step number).

Results presented on Figure 10 and Figure 11. demonstrate that FO sensors not only can survive the concreting process, but can also acquire strain measurement. However, as previously observed in the direct tensile test, it was found that the polyimide coating ensure a better strain transfer to the core of the FO.

**Table 2:** List of the sensing chains tested during pullout bond test

Sensing chain	Type of FO	Installation method	Width of the groove	Rebar embedded length (Ls)
A-NG	FO-A	Bonded on the surface	-	36 mm
P-NG	FO-P	Embedded into a groove	Half: 0.5 mm Half: 1 mm	48 mm

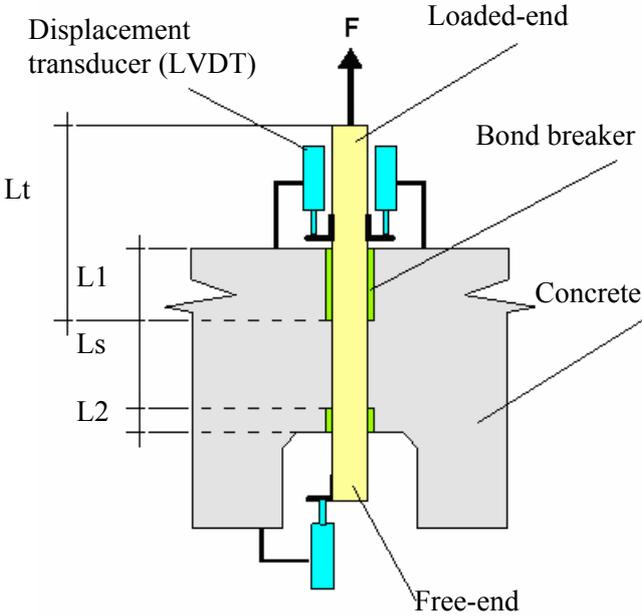


Figure 9. Principle of the direct tension pullout bond test and overall view.

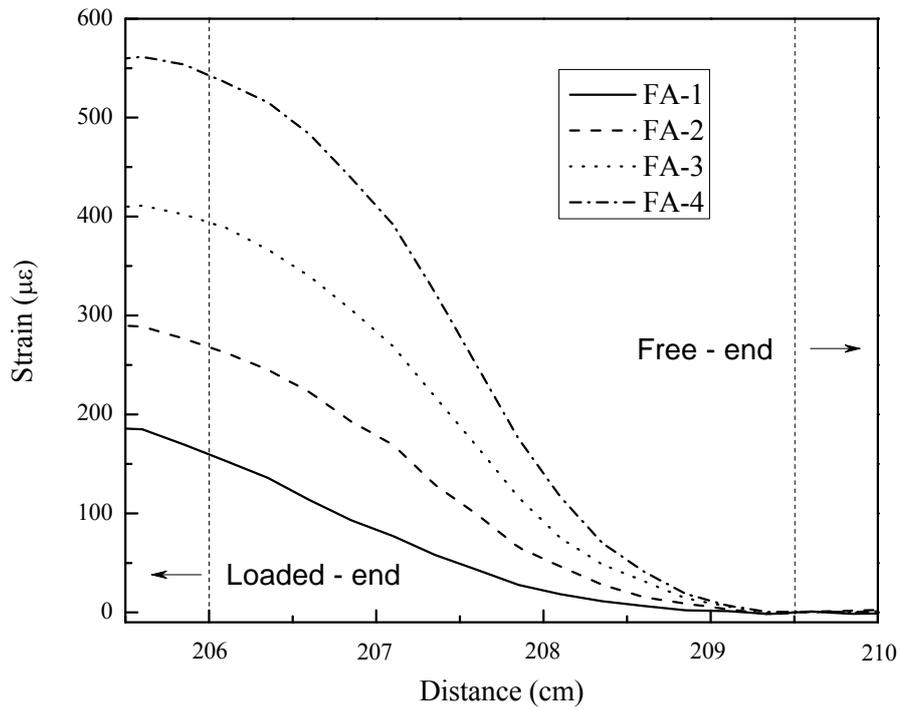


Figure 10. Rebar longitudinal strain distributions under various loadings (from the sensing chain A-Wg)

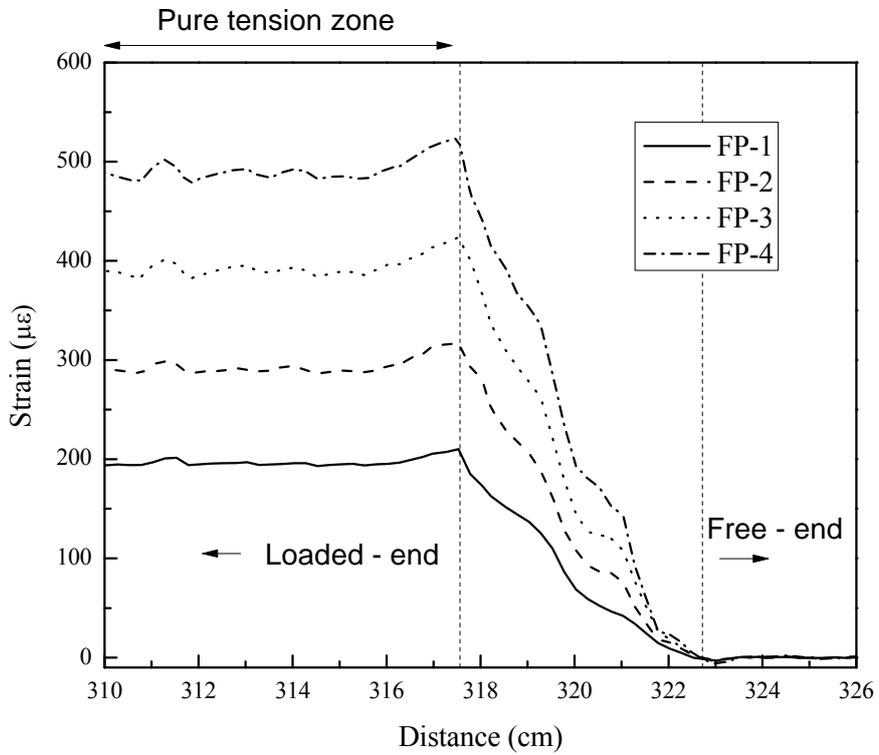


Figure 11. Rebar longitudinal strain distributions under various loadings (from the sensing chain P-Wg)

## CONCLUSIONS

A methodology pertaining to a distributed measurement of the longitudinal strain of rebars of reinforced UHPFRC structures is described. The experimental validation of different sensor chains has been performed. Tested parameters were the installation method of FOs (FO bonded on the rebar surface or mounted into a groove), the geometry of the groove and the type of optical fiber (mainly influenced by its external diameter and its coating material). It was demonstrated that the installation configurations and FO type can lead to a considerable difference in measurement results. Finally, best configuration for the sensing chain was found to be a FO with a polyimide primary coating embedded in a groove cut along the rebar.

Experimental results demonstrate that with adequate parameters, the FO sensing chain not only can survive the concreting process, but can also lead to an accurate strain measurement from RC structures made of UHPFRC.

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