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Application study of embedded Rayleigh based Distributed Optical Fiber Sensors in concrete beams

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Abstract

In this work, an experiment on two small concrete beams is described where Rayleigh based distributed optical fiber sensors (DOFS) are implemented together with traditional electrical strain gauges for the monitoring of these elements during a three-point load test. Part of the DOF sensor is embedded without protective coating directly in the rebar inside the concrete, being the remaining fiber glued to the surface of the element after the concrete hardening. This allows the direct comparison between the developed strains on the surface of concrete and the rebar with the use of a single sensor. Moreover, two types of adhesives are studied and then compared. From all the possible distributed sensing techniques, the Rayleigh based Optical Frequency Domain Reflectometer (OFDR) is the one which enables the better spatial resolution without the need of post-processing algorithms. In this way, in this experiment, this is going to be the used sensing technique.

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Keywords: fiber optics, structural health monitoring, distributed fiber sensing, Rayleigh scattering, OFDR

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1. Introduction

Civil engineering structures are subjected to several changes during its lifetime due to various phenomena, which can compromise their structural integrity and therefore the safety of the users. In this way, the control and monitoring

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of the aging process of these structures is of paramount importance. Not only does well maintained civil engineering structures increase a country's competitiveness in a global economy, enhancing reliance in adverse circumstances, but they are also coherent with more sustainable and environmental protecting policies.

The practice of structural health monitoring (SHM) has been used in this sense as a way to employ damage identification strategies in order to assure a better control of the service and aging state of civil engineering infrastructures. Notwithstanding, SHM hasn't yet been applied in a systematic manner to these structures mostly due to the lack of reliable and affordable generic monitoring solutions [1].

1.1. Distributed Fiber Optics in SHM

Optical fiber sensors have been one of the most researched and promising areas as a way of enhancing the accuracy and effectiveness in SHM practices due to its inherent advantages such as durability, small size, stability and insensitivity to external electromagnetic interferences.

These sensors have been presenting excellent and auspicious results in their discrete form. Nevertheless, in several situations such as the monitoring of large scale structures, the number of required discrete sensors needed to generate a complete strain information can be impractically high. Furthermore, taking into consideration the case of concrete structures, is nearly impossible to predict with certainty the exact location where cracks are going to appear before the instrumentation of the structural element. By using point sensors, important information might be neglected due to the fact of being in a location that wasn't instrumented. It is in this case that distributed optical fiber sensors (DOFS) present a unique advantage since virtually every cross-section becomes instrumented with the use of a single sensor.

1.2. Rayleigh Optical Frequency Domain Reflectometry (OFDR)

Scattering is at the origin of DOFS measurements and is basically defined as the interaction between the emitting light and the optical medium. There are three different scattering processes that may occur in a DOFS, namely: Raman, Brillouin and Rayleigh scattering [2].

Brillouin based DOFS offer an extended measurement range potential which makes them very useful for obtaining a global strain behavior of the monitored structure but at the same time it does not provide measurements with sufficient spatial resolution in order to detect damage such as cracks. On the other hand, Rayleigh based DOFS present a relative shorter range of measurements, normally limited to the hundreds of meters but provide the capacity of acquiring data with high spatial resolution in a cost-effective way [3].

In this way, this last technique was the one chosen to carry out the work described in this document.

2. Laboratory Experiment

In order to further explore the capabilities of distributed optical fiber sensors when applied to reinforced concrete structures, a laboratory experiment was conducted at UPC-BarcelonaTech. In this experiment, two small single reinforced concrete beams were instrumented with a single 5 m DOFS each, during the conduction of a three-point load test.

2.1. Motivation

When using DOFS it is important to have in mind the compromise between the strain accuracy and the coating used around the optical sensor for its protection. It is easy to understand that the use of a relatively thick coating assures an easier process of implementation of the sensor and decreases the probability of rupturing. Notwithstanding, it implies that a full and accurate stress and strain transfer between the monitored structural element and the sensor is not achieved.

The main argument for the use of a thick coating is connected with the fact of ensuring that the sensor is well protected from external environmental agents. In this way, some authors have experimented the bonding of DOFS directly on the rebars of this concrete elements [4], [5]. In the mentioned studies, coated optical fibers were used and there was also the need of implementing a groove in the rebar in order to better accommodate the installation of the sensors. In this study, the feasibility of implementing an uncoated DOFS on the reinforcement of concrete beams without the need of mechanizing it is assessed. In this way, the deployment procedure becomes easier, diminishing its costs and obtaining the best possible strain transfer accuracy from the concrete to the rebar. Moreover, two different adhesives are used in this study for the bonding between the optical fiber and the rebar: cyanoacrylate and two-component epoxy. This choice is based on the most common used types of adhesives for the implementation of DOFS on reinforced concrete elements, as verified through a literature review.

The fiber was implemented simultaneously embedded at the rebar and on the outside surface of the concrete after its hardening allowing for the direct strain comparison between these two locations and the study of its damage detection capabilities.

2.2. Preparation

Both concrete beams tested on this study presented the same geometric properties. Each beam was 800 mm long, 100 mm wide and 180 mm thick as seen in Figure 2. Moreover, in each beam specimen it was used a single and transversally centered 900 mm long Φ12 S500 rebar with a 40 mm concrete cover.

Two different adhesives were used on the segments of the sensors that were attached to the rebar. For beam1 was used cyanoacrylate and for beam 2 a two-component epoxy as seen in Figure 1. It's important to notice that 5000 mm long DOFS were used and only a segment with 750 mm was attached to each rebar leaving the rest of the optical fiber to be bonded on the concrete surface of the beams.

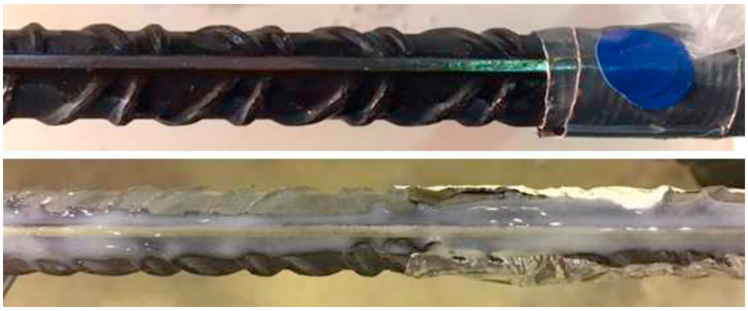


Figure 1. Used cyanoacrylate on beam specimen 1 (top) and two-component epoxy on beam specimen 2 (bottom)

In order to compare the results provided by the optical fibers, three electrical strain gauges were also deployed in each rebar. They were equally spaced with one at the center of the rebar and the other two spaced from this one by 225 mm to each side.

In the process of concrete pouring, samples were also created in order to test them and to, obtain the concrete properties (compressive strength, tensile strength and modulus of elasticity) of the tested beams, as presented in Table 1.

Table 1. Mechanical properties of concrete

Specimen	fcm (MPa)	E (GPa)	fctm (MPa)
Beam 1	38.41	28.366	3.076
Beam 2	44.36	27.353	3.523

After 28 days of the concrete pouring, the remainder of the fiber was glued to the front and bottom surfaces of each beam in a pattern which created five different segments, as seen in Figure 2. Here, in both beams, the chosen adhesive was the same two-component epoxy used on the rebar of beam 2.

This pattern was chosen in order to obtain three different types of strain measurements in the lateral side of the beam (compression on the top, neutral axis in the middle and tension on the bottom) and also to follow the evolution of the possible cracks to be originated during the load test.

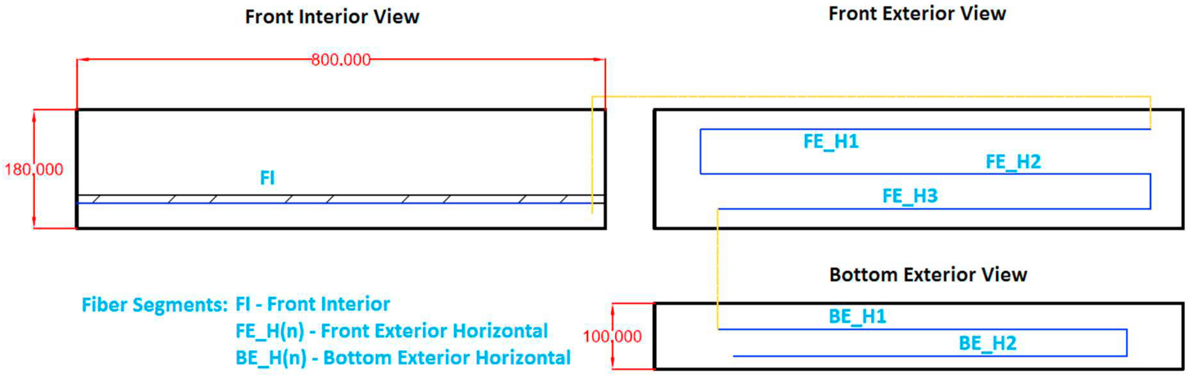


Figure 2. Definition of total number of deployed fiber segments

The load test was conducted on a INSTRON hydraulic actuator with an induced load through a displacement controlling mechanism. The overall scheme of the test is seen in Figure 3. The applied load had an increasing sequence of load until 20 kN, being then unloaded down to 3 kN and finally loaded again up to failure, which was estimated to happen around 45 kN load level.

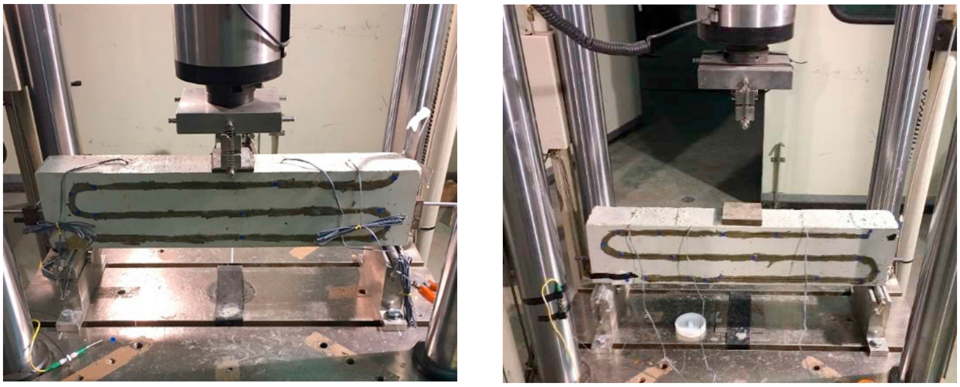
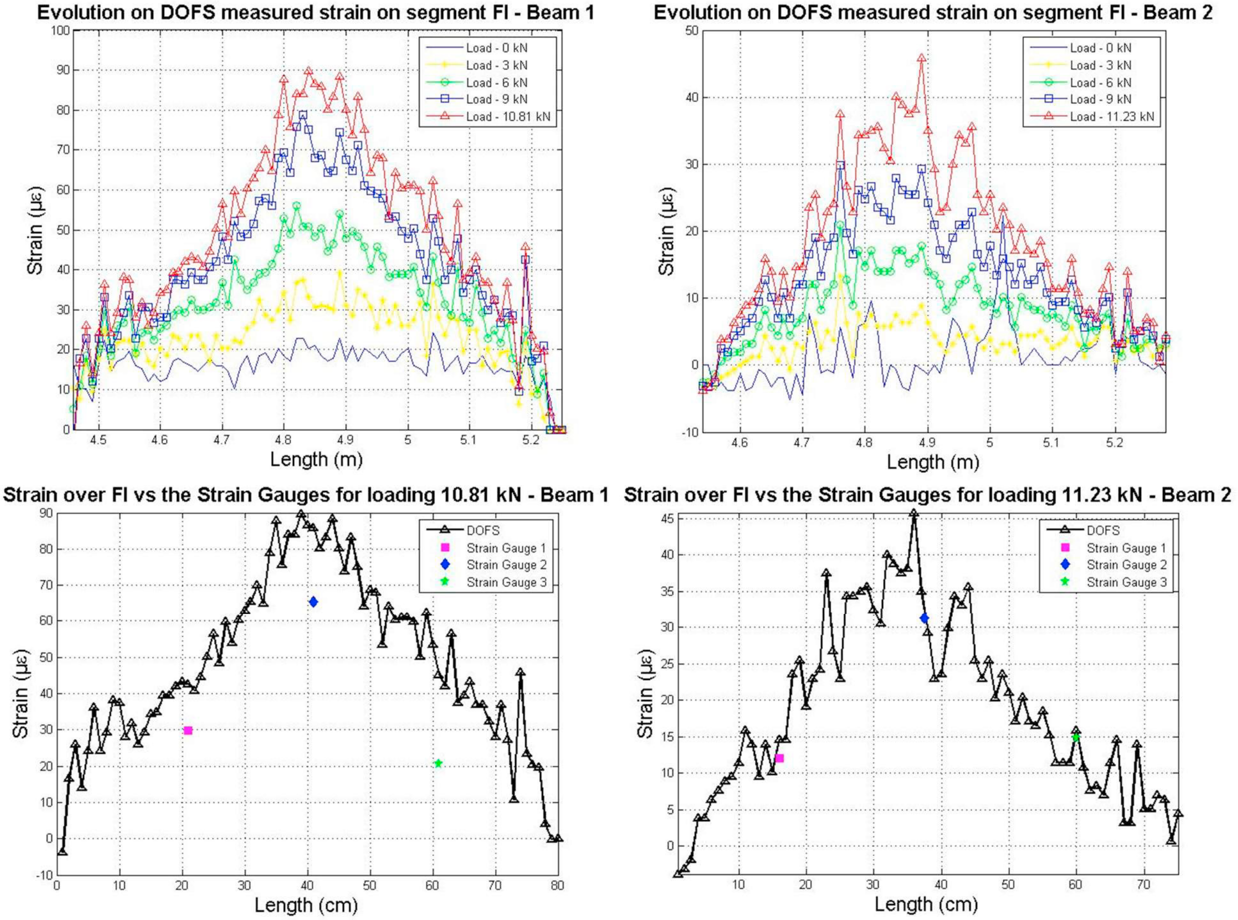


Figure 3. Scheme of load test for beam 1 (left) and beam 2 (right)

2.3. Results

As referred before, one of the main advantages of the use of DOFS is the possibility of simultaneously measure strain on a high number of points. In this experiment, by using a 5 m length optical fiber with a predetermined spatial resolution of 1 cm, it was possible to obtain 500 measuring points of strain in each beam. The measurement of the DOFS sensor was made with a 5 second interval.

During the execution of the load test on beam 1, it was observed that an initial crack was formed for a load of 10.81 kN. In the same way, for beam 2 it was observed that a crack was originated for a load of 11.23 kN. The expected cracking load was of 8.86 kN for beam 1 and 10.15 for beam 2. By analysing Figure 4, it is possible to observe that the optical fiber sensor correctly measures the evolution of the strains as it presents a fairly good agreement with the measurements of the strain gauges.


Evolution on DOFS measured strain on segment FI - Beam 1

Evolution on DOFS measured strain on segment FI - Beam 2

Strain over FI vs the Strain Gauges for loading 10.81 kN - Beam 1

Strain over FI vs the Strain Gauges for loading 11.23 kN - Beam 2

Figure 4. Strains measured by the DOFS on the segment embedded on the concrete for Beam 1(up-left) and Beam 2 (up-right) and comparison with Strain Gauges for Beam 1 (down-left) and Beam 2 (down-right)

At this stage, the cracking is not yet detected by the sensors on the rebar in opposition to what happens with segments of the fiber attached on the surface of the concrete (see Figure 5), that are at a lower level of the beam cross-section, where the red line represents each beam tensile strain capacity. This detection is made at the sensors in the rebar a couple of measurements later (Figure 5). Here, it is possible to observe that although the embedded fiber detects the damage (cracking), the identification of its location presents some challenges, especially on beam 1.

Furthermore, it was observed that with the continuation of the load test, in beam 1 the fiber broke for a load of 23.45 kN completing a cycle of load and unloading of the beam but the same was not observed in beam 2 since here the fiber broke before the unloading cycle for a load of only 17.72 kN.

3. Conclusions

In this experiment, it was possible to observe the feasibility of implementing uncoated DOFS directly on the rebar of a reinforced concrete beam without the need of mechanizing it since it was possible to measure the evolution of strains and detect damage with the DOFS' segments instrumented at the rebar. Some further analysis has to be made to assess the behavior of these measurements after the occurrence of damage (cracking)

Finally, it was possibly to conclude that DOFS with both adhesives presented a fairly good agreement with the strain gauges but the use of cyanoacrylate allowed for the measurement of strains for a longer experiment time.

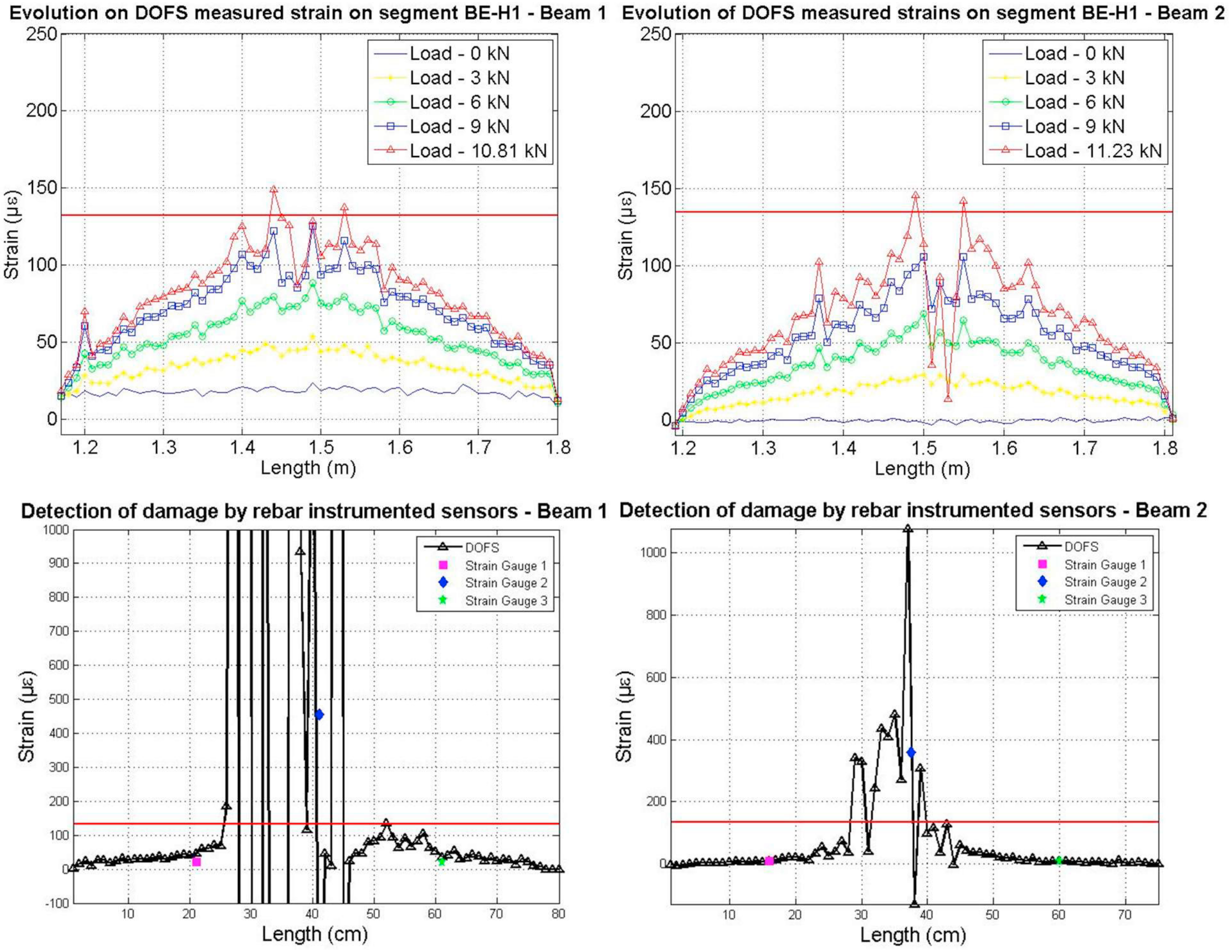


Figure 5. Detection of damage by DOFS at segment BE-H1 on Beam 1 (up-left) and Beam 2 (up-right) and at segment FI on Beam 1 (down-left) and Beam 2 (down-right) – the red line represents the strain tensile capacity of the concrete

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