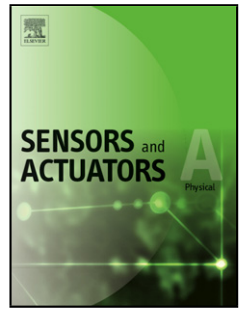

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Optical sensors for bond-slip characterization and monitoring of RC structures

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Highlights

- Optical fiber sensors applicability demonstration to monitor infrastructural interactions, more specifically between reinforcing rebar and concrete, which of the upmost importance in RC constructions.
- Two optical fiber sensors are presented, based on silica and polymer fiber Bragg gratings, which were implanted inside a concrete block specimen and subjected to a pull-out test
- The results confirm the viability and advantages of the optical sensors, evidenced by their higher resolution and far lower dimensions (allowing them to be embedded into the concrete) when compared with their electronic counterparts.
- The straightforward implementation and use of the optical sensors show very promising results when used in civil engineering structures.
- The strain sensitivity of the gratings that measure the bond-slip are 1.20 ± 0.01 pm/με and 1.47 ± 0.03 pm/με, for silica fiber and POF, respectively.
- The optical sensors proved to be a suitable way to detect very small slides in the steel-concrete connection, which is of extreme importance in the field of civil engineering, and currently there are very few solutions that detect such small displacements.
- Additionally, the structure surrounding the gratings was developed to be less intrusive as possible, making this sensor easy and practical to apply in RC constructions.

Abstract

Bond-slip is an important interaction between steel and concrete in reinforced concrete (RC) structures and other civil engineering constructions. It is essential to understand and to characterize, at local level, this stress transference mechanism. In particular its behavior for monotonic and cyclic demands, the parameters that influence this mechanism, and how it is affected by different deterioration factors. Therefore, characterizing and monitoring the bond-slip mechanism is essential for the safety assessment of RC structures, more specifically determining the reinforcing bars slippage inside the concrete, and therefore the stress and strain distribution in RC members. In this work, two optical fiber sensors are presented, based on silica and polymer fiber Bragg gratings (FBGs), which were implanted inside a concrete block specimen and subjected to a pull-out test. After 6 days of curing, the pull-out test was recorded and the displacement incurred during the test was also monitored with a traditional electric sensor; for comparison with the data acquired with the two optical sensors. The results obtained confirm the viability and advantages of the optical sensors, evidenced by their higher resolution and far lower dimensions (allowing them to be embedded into the concrete) when compared with their electronic counterparts. The straightforward implementation and use of the optical sensors show very promising results when used in civil engineering structures.

Keywords: Bond-slip, optical fiber sensor; FBG; RC structures; pull-out test.

1. Introduction

Certain features such as workability, durability and low cost of production have resulted in reinforced concrete (RC) being one of the most consumed building materials in the world [1]. In emerging economies, RC structures correspond to a large part of the existing buildings and infrastructure. Therefore, the development of studies related with safety assessment and maintenance of RC structures are particularly relevant, and this present work is devoted to the development of optical sensors for the characterization and monitoring of bond-slip mechanisms in RC structural systems.

The adherence between concrete and reinforcing bars (rebars) is an essential mechanism controlling the performance of RC structures, for monotonic and cyclic demands. Nonetheless, this adherence is not only a mechanical phenomenon, but can be understood and described, in general terms, by chemical, mechanical and friction adhesions that in tension zones are related to two aspects of bond control, namely the mechanism of stress transference between the rebar and concrete, and the RC resistance to pull-out demands [2]. For Daoud *et al* [3], the bond between the rebar and the surrounding concrete is a fundamental factor for RC performance, its behavior being conditioned by factors such as the steel rebar properties, the concrete strength, and the stress transfer process between the rebars and the surrounding concrete.

An alternative way to study the adherence between the reinforcing rebar and the concrete is through crack analysis, based on the opening and spacing of cracks. This analysis can predict the bond condition between the rebars and the concrete [4]. The crack pattern and its evolution is influenced by the stress distribution in the surrounding area of the rebars, and analysis of the steel-concrete adhesion during the pull-out test offer information regarding the bond stress-slip evolution. Nevertheless, in this kind of test, many cracks develop in the specimen, their presence is influenced by pulling of the rebars and they may not be visible on the surface of the specimen. The results of the pull-out test also show the bond strength between the reinforcing rebar and the surrounding concrete. The maximum bond strength is computed approximately by dividing the imposed force when rebar slippage occurs, by the lateral surface area of the rebars in contact with the concrete [5]. Examples of this testing application can be found in [4]–[6].

The use of optical fiber sensors (OFS) in RC structures for strain monitoring began in the 1980s [7], with several different implementations. Davis *et al* [8] reported a fiber Bragg grating (FBG) sensor tailored to RC strain measures in beams and decks, as they were loaded up to failure. The results show that FBG sensors can be used to measure the strain level inside concrete. However, this technique is limited to RC failure analysis because it only considers the concrete strain level for failure monitoring, and does not include the essential property of RC structures, which is the rebar-concrete adherence.

Recent advances in sensors have provided alternative techniques for RC bond-slip monitoring. Feng et al [9] developed an electromagnetic (EM) imaging technique based on the reflection analysis of a continuous EM wave sent out and reflected from the layered glass fiber reinforced polymer-wrapped concrete structures. Tsuyuki et al [10] used laser ultra-sonic waves to detect delamination between concrete and steel plate, based on velocity dispersion analysis of ultra-sonic waves. Finite-element analyses by Cheng et al [11] demonstrated that Lamb waves could be used to evaluate the bond condition of steel plate strengthened concrete. On the other hand, piezoceramic-based smart aggregates (PSAs) are widely applicable in the structural health monitoring due to advantages such as the low cost, the quick response, the high reliability, etc. [12,13]. Using a pitch-catch mode, piezoelectric sensors and actuators, embedded in RC, Wu et al [14] detected the debonding between concrete and rebar. Xu et al [15] used pressure sensitive adhesives and wavelet packet analysis to detect concrete filled steel tube columns debonding. Qin *et al* [16] reported the development of smart aggregates composed of a fragile piezo-ceramic patch for RC bond-slip monitoring. The results demonstrated that the PSAs can be used for monitoring the initiation and development of the bond-slip, providing an early warning regarding the bond-slip between the steel plate and the concrete before structural failure occurs. Nonetheless, the smart aggregates sensor measurements are affected by electromagnetic interferences due to the piezoelectric properties, and consequently the data accuracy is compromised.

The present work details two OFS for RC bond-slip characterization and monitoring, one is incorporated into a silica optical fiber (SOF) and the other a polymer optical fiber (POF). These low intrusive sensors are based on FBGs and the experimental results are discussed and compared to an electronic external sensor. The main advantages of the optical sensors are their high sensitivity and resolution, immunity to electromagnetic fields, passiveness (without electricity at the measuring point), small size and weight, resistance to harsh (basic or acidic) environments, and the possibility of real-time, bond-slip monitoring in RC structures.

This paper is organized as follows: following the introduction, the theoretical aspects related to FBGs and the description of the developed optical sensors are presented in section 2. The system calibration and characterization are presented in section 3. Section 4 details the experimental set up of the pull-out test, and the bond-slip results are shown in section 5. Finally, the main conclusions are drawn in section 6.

2. Sensors description and manufacturing

A FBG is a passive wavelength reflecting optical component, based on the modulation of the refractive index along the core of an optical fiber. Usually, the refractive index modulation is periodic, and can be obtained by exposing the photosensitive optical fiber to a periodic ultraviolet light pattern. From the optical signal guided along the core, a specific spectral band centered at the Bragg wavelength (λ_B) is filtered and reflected, with the remaining spectrum transmitted through the fiber. For sensing applications, FBGs are very interesting since it is possible to identify any changes in temperature and strain by analyzing the spectral shift of the reflected Bragg wavelength. The FBG offers high sensitivity and multiplexing capabilities due to its wavelength-encoded information (immune to the optical source power oscillations). These characteristics have contributed to the popularity of this optical technology, particularly industrial applications [17]. A FBG is sensitive both to strain and temperature changes, and the λ_B shifts according to:

$$\Delta\lambda_B = 2\left(\Lambda\frac{\partial n_{eff}}{\partial l} + n_{eff}\frac{\partial\Lambda}{\partial l}\right)\Delta S + 2\left(\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial\Lambda}{\partial T}\right)\Delta T, \quad (1)$$

where n_{eff} is the effective refractive index of the guided mode, Λ is the period of the grating, ΔS and ΔT are strain and temperature changes, respectively. The first part of the equation represents the effects of strain on both period and refractive index of the grating, while the second part represents the thermal effects.

Two prototypes of FBG optical sensors for bond-slip characterization of RC elements were developed and assigned as SOFBG (silica optical fiber Bragg grating) and POFBG (polymer optical fiber Bragg grating). Each completed sensor unit is comprised of two metallic copper components (Fig. 1), with height of 32 mm, 5 mm thickness and 41 mm of total length. The superior component has an “L” shape with a hook placed at the center of the total length, whereas the inferior component has an “F” shape and a curvature (R= 5 mm) on the bottom surface. Along the total sensor length, the superior and inferior surfaces are not in direct contact, and the minimum spacing between them is about 1 mm in the extremities. A transparent polyurethane resin (PU) layer was employed to fill the space between the two metallic surfaces and to embed the optical fiber sensor. Fig. 1(a) shows the details of the spacing between the two surfaces of the sensor, and the characteristics of the sensor following the PU filling process. Each sensor contains two FBGs, one of the gratings, FBG-S, will measure the strain (the displacement of the reinforcing rebar) and temperature effects, whereas FBG-T will be used only for temperature measurements, in order to analyze and compensate the temperature response of FBG-S.

The inferior metallic component was designed to be fixed along of the reinforcement rebar, whereas the superior component was designed to be hooked onto the concrete. Thus, any movement of the reinforcement rebar will cause deformation (by strain) on the FBG-S, and consequently will change the reflected Bragg wavelength. On the other hand, FBG-T is shielded from strain, and will be affected only by temperature variations. For short duration characterization tests, the temperature effect may not be significant, nonetheless, for long duration measurements, the temperature influence is crucial, especially when considering seasonal winter/summer temperature changes.

To manufacture the SOFBG bond-slip sensor, a step index single-mode glass fiber (GF1 from Thorlabs) was used, with core and cladding diameters of 10 µm and 125 µm, respectively [18]. Two FBGs, separated with a 10 mm gap, each of length 3 mm and spectrally separated by 5 nm, were inscribed in the same fiber using the phase mask method. A KrF excimer laser system (Coherent Bragg Star Industrial-LN) was used, emitting light at 248 nm, with 15 ns pulses of 5 mJ energy and 500 Hz repetition rate.

The FBGs of the POFBG sensor were inscribed at the *Cyprus University of Technology*, in a gradient index, multimode, cyclic transparent optical polymer (CYTOP) fiber with core diameter of 62.5 μm, a 20 μm cladding layer and an additional polyester and polycarbonate over-cladding structure to protect the fiber, for a total diameter of 490 μm [19]. Two gratings, spectrally located in the 1550 nm region, were inscribed in the same fiber with a 10 mm gap between them, using the direct-write, plane-by-plane femtosecond laser inscription method [20]. The inscription setup consisted of a femtosecond laser system (HighQ laser femtoREGEN) operating at 517 nm producing pulses of 220 fs duration [21]. The inscriptions were performed without removing the outer protective polymer, and the fiber samples were immersed in matching oil between two thin glass slides. The pulse energy was about 80 nJ at the exit of the laser and the repetition rate was controlled using a pulse picker and set at 5 kHz for these particular inscriptions. The length of the gratings was about 1.2 mm and the plane width was set at 15 μm in the center of the core to minimize the coupling between the higher order modes of the fiber and the grating. More details can be found in [22]. To guarantee a stable connection and monitoring of the POFBG array, the polymer fiber was UV-glued with a silica multimode (62.5/125 μm fiber from Corning) fiber (MMF) for easier coupling and then a silica single mode fiber (SMF) was spliced to the MMF in order to be compatible with our interrogation system.

3. Data acquisition system and sensor characterization

Before installing the bond-slip sensors in the RC samples, their sensitivity to strain and temperature were characterized. The spectral response of each FBG to strain and temperature changes was monitored using an optical interrogator (Micron Optics, model SM 125-500), with a resolution of 1 pm.

Regarding the strain characterization, a simple system was set up, as illustrated in Fig. 2. A translational stage with a precision of 5 μm was used to apply controlled strain to the sensor, and the FBG response was recorded. The experimental set up consisted of fixing the final sensor structure to two supports (Fig. 2), one support was fixed and the other was attached to the translational stage. The longitudinal strain applied to the fibers was controlled by the translational stage, and reached up to 500 με, in 125 με steps. This test was performed at room temperature (21.0 ºC). The FBGs response is depicted in Fig. 3(a), where the FBGs-S show a positive Bragg wavelength shift as the longitudinal strain increases.

Regarding the sensors' response to temperature changes, the SOFBG and POFBG were placed in a climatic chamber (Angelantoni Industrie, model CH 340), with 60% of controlled relative humidity. The chamber's temperature and relative humidity precision is 0.1 ºC and 0.1%, respectively. The temperature was increased from 20.0 ºC to 40.0 ºC, in 5.0 ºC steps, and at each step the stabilization time was 30 minutes. The FBGs response is shown in Fig. 3(b), where the SOFBGs show a positive Bragg wavelength shift when the temperature increases, as expected. The thermal sensitivity of the CYTOP POFBGs is also positive, which is in agreement with [23]. ~~Regarding the humidity sensitivity, many times problematic in POF fibers, CYTOP cladding is hydrophobic and the humidity level does not affect the performance of the sensor. The behavior of CYTOP fiber can be considered~~

similar to the silica fiber, since we did not remove the polycarbonate jacket. Also, the CYTOP fiber (containing the FBG sensors) was embedded into the resin also working as an extra protective barrier for humidity. Regarding the humidity sensitivity, although the POFBGs are in some way protected inside the resin, some perturbation may still occur, humidity may interfere on the collected data. Therefore, CYTOP fiber behavior needs further characterizing, including in the coupling to silica fiber region.

After analyzing the Bragg wavelength changes and adjusting a linear fit to the experimental data, the sensitivity values of the SOFBG and POFBG to strain and temperature were estimated and summarized in Table 1. $S_{T_{FBG-S}}$ and $S_{T_{FBG-T}}$ are the thermal sensitivity values for FBG-S and FBG-T, respectively, $S_{S_{FBG-S}}$ and $S_{S_{FBG-T}}$ are the strain sensitivity values for FBG-S and FBG-T respectively.

The sensitivity of both silica and polymer FBG-T to strain is almost insignificant, since these FBGs are confined by the copper structure, and will not be affected by the displacement of the reinforcing rebar. In the FBGs-S case, as already mentioned, they are affected by both strain and temperature, hence these data must be analyzed and numerical compensation is necessary to obtain only the strain sensitivity values. The equations that describe the λ_B variation for both FBG-S and FBG-T are:

$$\begin{cases} \Delta\lambda_{B_{FBG-S}} = S_{S_{FBG-S}}.\Delta s_{FBG-S} + S_{T_{FBG-S}}.\Delta T_{FBG-S}\,, & for\ FBG-S \\ \Delta\lambda_{B_{FBG-T}} = S_{S_{FBG-T}}.\Delta s_{FBG-T} + S_{T_{FBG-T}}.\Delta T_{FBG-T}\,, & for\ FBG-T \end{cases} \quad (2)$$

where $\Delta\lambda_{B_{FBG-S}}$ and $\Delta\lambda_{B_{FBG-T}}$ are the Bragg wavelength changes measured on FBG-S and FBG-T, respectively. Since the FBG-T is only affected by temperature ($\Delta S_{FBG-T} = 0$), the $\Delta\lambda_{B_{FBG-T}}$ is given by:

$$\Delta\lambda_{B_{FBG-T}} = S_{T_{FBG-T}}.\Delta T_{FBG-T} \quad (3)$$

Considering that both sensors (FBG-S and FBG-T) are exposed to the same temperature ($\Delta T = \Delta T_{FBG-S} = \Delta T_{FBG-T}$) then:

$$\begin{cases} \Delta T = \frac{\Delta\lambda_{B_{FBG-S}} - S_{S_{FBG-S}}.\Delta s_{FBG-S}}{S_{T_{FBG-S}}} \\ \Delta T = \frac{\Delta\lambda_{B_{FBG-T}}}{S_{T_{FBG-T}}} \end{cases} \quad (4)$$

The strain measured by the FBG-S will be given by:

$$\Delta S_{FBG-S} = \frac{1}{S_{S_{FBG-S}}}\left(\Delta\lambda_{B_{FBG-S}} - \Delta\lambda_{B_{FBG-T}}.\frac{S_{T_{FBG-S}}}{S_{T_{FBG-T}}}\right) \quad (\mu\varepsilon) \quad (5)$$

Equation 5 can be equally applied to SOFBG and POFBG sensors, considering the sensitivities for each, presented in Table 1.

4. Specimen detailing and experimental setup

On completion of the sensor manufacture, both bond-slip sensors (SOFBG and POFBG) were glued to a 16 mm diameter rebar on opposite sides using epoxy (Fig. 4). The rebar was placed at the center of a formwork structure with dimensions of 0.2x0.2x0.4 m that was to be embedded in the concrete (Fig. 5). The distance between the sensors' and the box´s wall was about 0.10 m. The rebar (the part inside the box) was about 20 cm inside a tube, and the remaining 20 cm outside, in contact with the concrete, as shown in Fig. 5(b); this allowed for a reduction in the contact area, decreasing the force required to beak adhesion.

The box was filled with N35 concrete ("N35" is a parameter referring to the concrete curing type ("N" - normal) and its resistance to compression) and the cure process time was approximately 6 days. There is a relationship between the waiting time and the curing rate of the concrete, and since the curing rate on the test date is important, it was not necessary to wait for the traditional 28 days to complete the process [24].

The pull-out test was performed according to the methods described in the directive EN 10080 [25], and details of the equipment used are shown in Fig. 6. For this test, the RC specimen was centrally positioned and its movements were restricted by employing two metallic plates, fixed in the inferior part of the steel frame. A conventional electronic sensor, linear variable differential transformer (LVDT), was also placed at the bottom of the block to monitor the rebar displacement; this enabled comparisons between the different types of sensors. To perform the pull-out test, the reinforcing rebar was pulled vertically by a claw, with a displacement speed of 0.15 mm/s.

5. Results

The sensors' response was studied by displacing the reinforcing rebar from the RC sample and monitoring the grating reflection spectra. The Bragg wavelength measurements, acquired at 1 sample per second, were converted to rebar-concrete relative displacement values using Equation 5 and the sensitivity values from the sensors characterization (Table 1). Fig. 7 shows the relative displacement between the steel rebar and concrete, measured with the SOFBG, POFBG and LVDT sensors during the pull-out test. The pull-out machine, servo actuators and load cells, also provide a digital signal of the displacement and load force, which can be used to compare with the optical sensors measurements. This data is also presented in Fig. 7.

The SOFBG and POFBG measured rebar-concrete slides lower than 0.1 μm with an excellent signal-to-noise ratio, unlike the LVDT, which (in the region between the first two vertical dashed lines, where the displacement began) only registered a small displacement difference, practically at the noise level.

Regarding the data acquisition, the end of the measurements for the SOFBG sensor was about 175 seconds after the pull-out test began, and for the POFBG was about 75 seconds, once the fibers yielded to the tension and broke. In the case of the POFBG, it most likely failed at the connection from POF to silica (splice location), otherwise, it was expected to withstand higher deformations than the silica sensor. The CYTOP fiber coupling to the silica fiber was made using UV glue. The connection was optimized using the butt-coupling procedure and the UV-glue applied while the grating spectrum was monitored, however, the amount of UV-glue employed, combined with the vibrations during pull-out test may have caused the failure of the connection. Regardless, the aim was to test the viability of CYTOP for this kind of research and application, and we are planning to carry out some non-destructive and more controllable tests soon. In a real scenario, we never have a

destructive situation. Please, note that we wanted to show the viability of using different fiber material and compare the performance with silica fiber.
The induced displacement was constant over time (0.15 mm/s), so the force on the rebar increased in the beginning until it detached from the concrete (approximately at 50 s). After that point, as the rebar moves (relative to the concrete) the required force is almost constant. It would be expected that the rebar distorts longitudinally first on its free area (between the claws and the start of the concrete specimen), afterwards, it will gradually deform along and inside the concrete, until the collapse of the adherence zone between the rebar and the concrete. Therefore, it is anticipated that the deformation measured at the claws position (by the pull-out machine) will be much higher than the real deformation inside the concrete sample. On the other hand, it is expected that the relative movement at the LVDT position is insignificant until the adherence zone collapse. The LVDT is a high resolution advice, however, several drawbacks can be pointed to its use embedded into a concrete structure, such as: being a electromechanical device with relative motion between parts is very sensitive to the concrete and humidity corrosion effects, especially for long time monitoring (such as the one intended in this work), also it's not possible to multiplex several sensors into one cable (significantly increasing the cabling if several sensors are necessary), electrical power is needed at the measuring point (or even close), oscillations due to the external electromagnetic interference may occur in the measurement data in important structures like hydroelectric dams. Optical sensors do not have these problems, and allied to the other characteristics of these sensors, expressed in section 1, they are more suitable for high resolution displacement measurement, especially when embedded. As shown in Fig. 7, the FBG-S sensors have a sharp slope, while the FBG-T sensors remain almost stable, without significant changes, which means that the pull-out process did not involve significant temperature variations.

Both SOFBG and POFBG sensors show a suitable performance when the displacement begins at 50 seconds. From 50 seconds to 70 seconds, the measurements from both sensors show a displacement of around 0.07 mm, at 90 seconds, the maximum relative displacement measured by SOFBG is about 0.15 mm.

6. Conclusion

In this work, we demonstrated the ability of using optical fiber sensors to monitor infrastructural interactions, more specifically between reinforcing rebar and concrete, which of the upmost importance in RC constructions. Two sensors were implemented and tested, both based in FBGs, one in silica fiber and the other in POF. Each sensor contains two FBGs, one measuring strain and temperature, and the other measuring just temperature, being able to compensate thermal effects in real field application, over long time periods. The strain sensitivity of the gratings that measure the bond-slip (FBG-S) are 1.20 ± 0.01 pm/$\mu\varepsilon$ and 1.47 ± 0.03 pm/$\mu\varepsilon$ for SOFBG and POFBG, respectively. Although the FBGs presented high sensitivity, the measurement range was low, since the sensors stopped monitoring reliable data for displacement values of 0.07 mm (POFBG) and 0.15 mm (SOFBG). In the case of POFBG sensors, due to their higher elasticity compared to SOFBG sensors, a larger measuring range would be expected, so it is suspected that there may have been a failure in the spliced area between the POF and the pigtail. Despite CYTOP failed to measure the displacement during the pull-test earlier than the silica fiber, this kind of fiber has high potential to be used in future tests. The strain sensitive is higher for CYTOP fiber, which translates in higher resolution as a bond-slip sensor. Also, like other polymer fibers, it can stand up to higher strain values than the silica fiber without yielding. Considering these key points, the CYTOP fiber is more suitable as bond-slip sensor than the silica fiber, and in the future, more tests can be made to analyze the full potential of the CYTOP and/or other polymer fibers as bond-slip sensors. Nevertheless, the optical sensors proved to be a suitable way to detect very small slides in the steel-concrete connection, which is of extreme importance in the field of civil engineering, and currently there are very few solutions that detect such small displacements. Additionally, the structure surrounding the gratings was developed to be less intrusive as possible, making this sensor easy and practical to apply in RC constructions.

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References

[1] K. Mehta, P. Monteiro, Concreto: microestrutura, propriedades e materiais., 3 ed. São Paulo: Pini, 2008.

[2] Z. Dahou, Z. Sbartaï, A. Castel, F. Ghomari, Artificial neural network model for steel–concrete bond prediction, Eng. Struct. 31 (2009) 1724–1733.

[3] A. Daoud, O. Maurel, C. Laborderie, 2D mesoscopic modelling of bar–concrete bond, Eng. Struct. 49 (2013) 696–706.

[4] A. Torre-Casanova, L. Jason, L. Davenne, X. Pinelli, Confinement effects on the steel–concrete bond strength and pull-out failure, Eng. Fract. Mech. 97 (2013) 92–104.

[5] O. Hill, B. Malo, F. Bilodeau, D. Johnson, J. Albert, Bragg grating fabricated in monomode photosensitive optical fiber by UV exposure through a phase mask, Appl. Phys. Lett. 62 (1993) 1035–1037.

[6] B. Silva, M. Barbosa, L. Filho, M. Lorrain, Experimental investigation on the use of steel-concrete bond tests for estimating axial compressive strength of concrete: Part 1, Ibracon Struct. Mater. J. 6 (2013) 715–725.

[7] B. Wang et al., Strain monitoring of RC members strengthened with smart NSM FRP bars, Constr. Build. Mater. 23 (2009) 1698–1711.

[8] M. Davis, D. Bellemoreb, A. Kersey, Distributed fiber Bragg grating strain sensing in reinforced concrete structural components, Cem. Concr. Compos. 19 (1997) 45–57.

[9] M. Q. Feng, F. De Flaviis and Y. J. Kim, Use of microwaves for damage detection of fiber reinforced polymer-wrapped concrete structures, J. Eng. Mech., 128 (2002) 172–83.

[10] K. Tsuyuki, R. Katamura, S. Miura and H. Asanuma, Non-destructive testing of concrete based on analysis of velocity dispersion of laser ultrasonics, European Conf. Non-Destructive Testing (2006).

[11] C. C. Cheng, Y. T. Ke and K. T. Hsu, Using lamb waves to evaluate debonding of steel plate strengthened concrete, Mater. Trans., 53 (2012) 274–8.

[12] G. Song, H. Gu, Y. Mo, T. Hsu and H. Dhonde, Concrete structural health monitoring using embedded piezoceramic transducers, Smart Mater. Struct., 16 (2007) 959–68.

[13] Q. Kong, S. Hou, Q. Ji, Y. Mo and G. Song, Very early age concrete hydration characterization monitoring using piezoceramic based smart aggregates, Smart Mater. Struct., 22 (2013) 085025.

[14] F. Wu and F. K. Chang, Debond detection using embedded piezoelectric elements in reinforced concrete structures - Part I: Experiment, Struct. Health Monit., 5 (2006) 5–15.

[15] B. Xu, T. Zhang, G. Song and H. Gu, Active interface debonding detection of a concrete-filled steel tube with piezoelectric technologies using wavelet packet analysis, Mech. Syst. Signal Process., 36 (2013) 7–17.

[16] F. Qin, Q. Kong, M. Li, Y. Mo, G. Song, F. Fan, Bond slip detection of steel plate and concrete beams using smart aggregates, Smart Mater. Struct. 24 (2015) 115039.

[17] P. Antunes et al., Optical fiber accelerometer system for structural dynamic monitoring, IEEE Sens. J. 9 (2009) 1347–1354.

[18] THORLABS, Graded-index polymer optical fiber (GI-POF) [Online]. Available: https://www.thorlabs.com/catalogPages/1100.pdf. [Accessed: 19-Jun-2017].

[19] A. Lacraz, M. Polis, A. Theodosiou, C. Koutsides, K. Kalli, Femtosecond laser inscribed Bragg gratings in low loss CYTOP polymer optical fiber, IEEE Photonics Technol. Lett. 27 (2015) 693–696.
[20] A. Theodosiou et al., Modified fs-laser inscribed FBG array for rapid mode shape capture of free-free vibrating beams, IEEE Photonics Technol. Lett. 28 (2016) 1509–1512.
[21] A. Theodosiou, M. Polis, A. Lacraz, K. Kalli, M. Komodromos, A. Stassis, Comparative study of multimode CYTOP graded index and single-mode silica fibre Bragg grating array for the mode shape capturing of a free-free metal beam, Proc. SPIE (2016), 98860.
[22] D. Vilarinho, A. Theodosiou, C. Leitão, A. G. Leal-Junior, M. F. Domingues, K. Kalli, P. André, P. Antunes, C.Marques, POFBG-Embedded Cork Insole for Plantar Pressure Monitoring, Sensors, 17 (2017) 2924.
[23] A. Theodosiou, M. Komodromos, K. Kalli, Carbon cantilever beam health inspection using a polymer fibre Bragg grating array, J. Light. Technol. 36 (2018) 986-992.
[24] M. Shetty, Concrete technology theory and practice, S. Chand & Company Ltd., New Delhi, 2006.
[25] European Standard, EN 10080: Steel for the reinforcement of concrete - Weldable reinforcing steel - General. EN, 2005.

Biography

Esequiel Mesquita was born in Iraucuba, Ceara, Brazil, on April 1989. In 2012 he received the bachelor degree in Civil Engineering by Universidade Estadual Vale do Acarau and the PhD in Civil Engineering in 2017 from Faculty of Engineering of University of Porto, with doctoral fellowship from CAPES Foundation, Ministry of Education of Brazil. He has experience in materials characterization and durability of reinforced concrete structures, and he current research interests include structural health monitoring, optical sensors, structural risk assessment, structural safety maintenance, assessment, strengthening and repair of existing structures and built heritage conservation. Current he is an Adjunct Professor at the Civil Engineering Department and Laboratory of Reabilitation and Buildings Durability – LAREB, at the Federal University of Ceará, Brazil.

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Paulo Sérgio de Brito André was born in Luanda, Angola, in 1971. He received the bachelor's degree in physics engineering, the Ph.D. degree in physics, and the Agregação title (habilitation) degree from the Universidade de Aveiro, Portugal, in 1996, 2002, and 2011, respectively. He joined the Instituto Superior Técnico, University of Lisbon, in 2013, as an Associate Professor, where he lectures on telecommunications.

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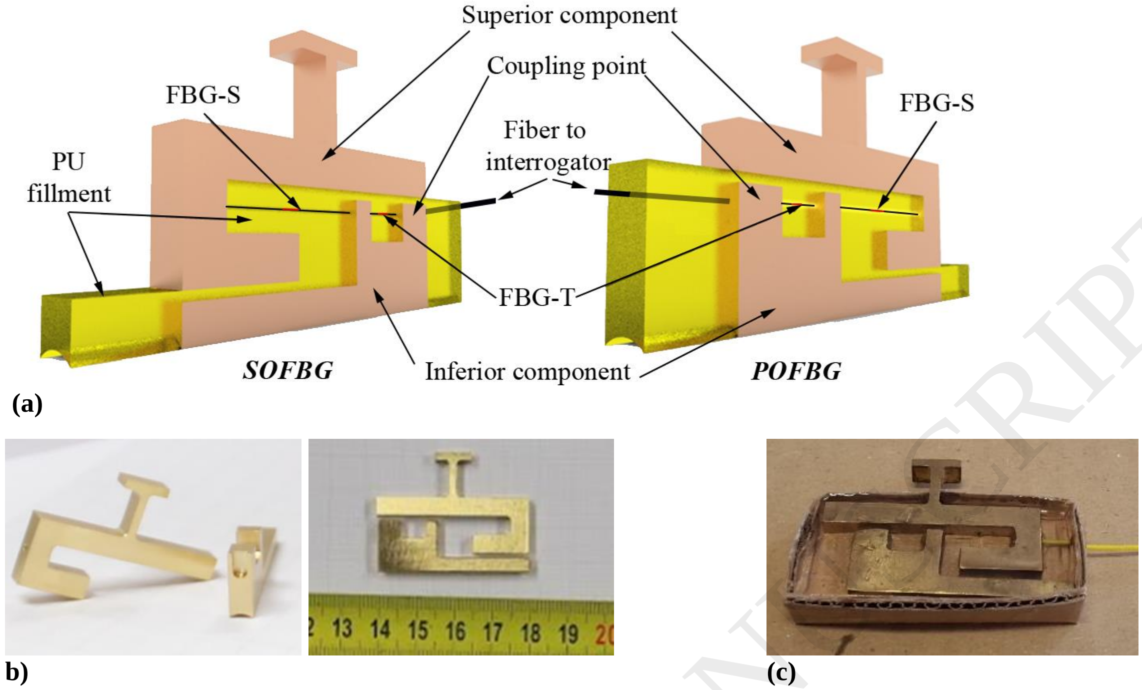


Fig. 1. (a) Details of the bond-slip OFS; (b) image of the two parts (ruler for scale in cm) and c) sensor after PU resin filling, inside a paper mold, without surfaces regularization.

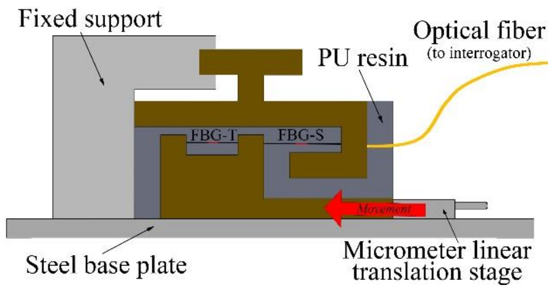


Fig. 2. Set up used for strain characterization.

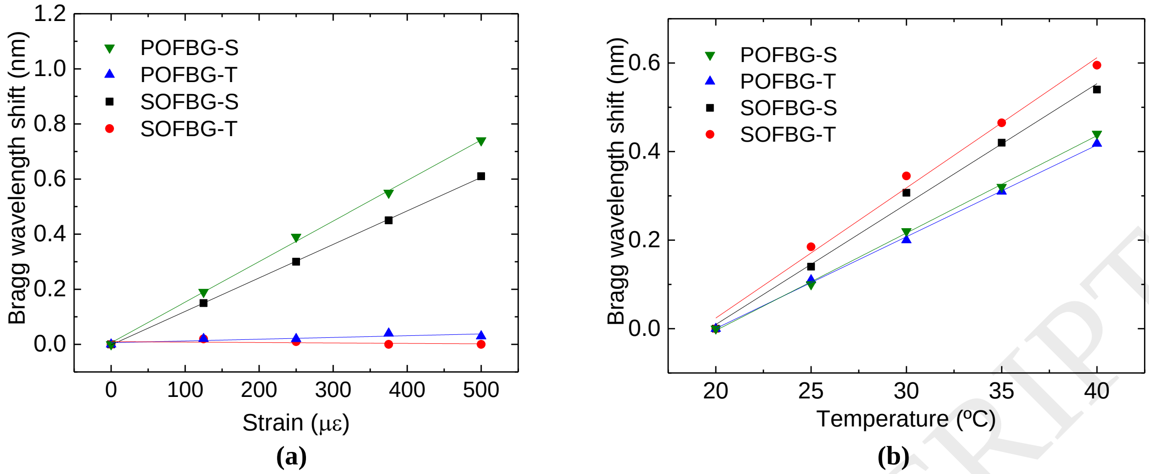
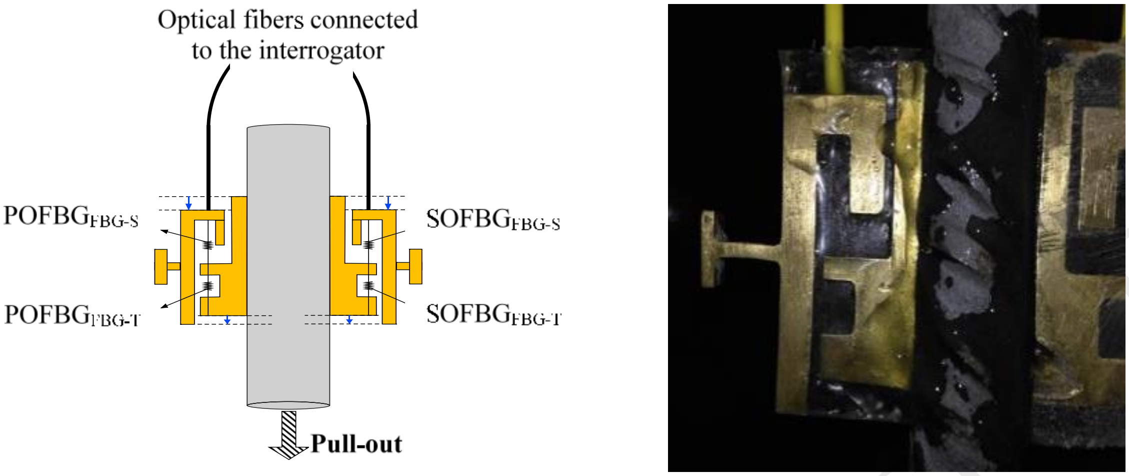
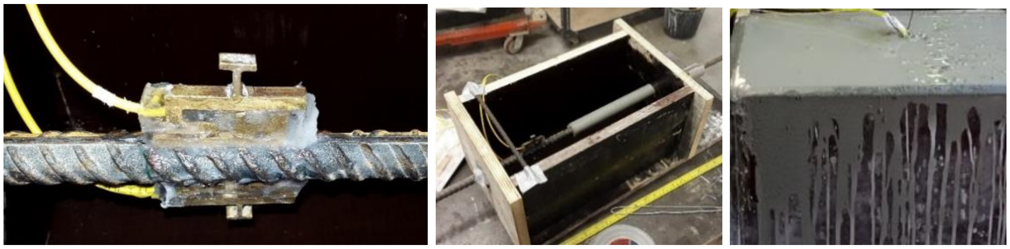


Fig. 3. SOFBG and POFBG gratings response to strain (a) and temperature (b). The symbols are experimental data and the lines are linear fits.



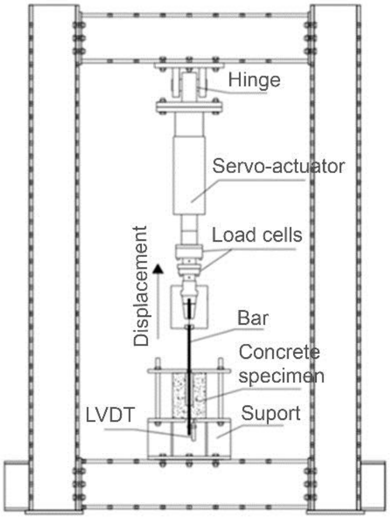
(a) **(b)**

Fig. 4. (a) Schematic of the sensors' position and (b) image of the sensors glued in opposite sides of the rebar.

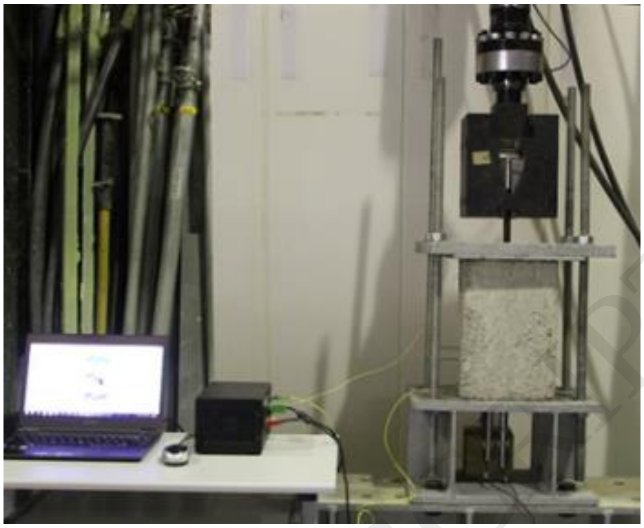


(a) **(b)** **(c)**

Fig. 5. (a) Final aspect of the sensors fixed to the rebar; (b) formwork structure with the rebar and (c) formwork filled with concrete.



(a)



(b)

Fig. 6. Experimental setup of the pull-out testing: (a) details of the pull-out testing equipment and (b) system image.

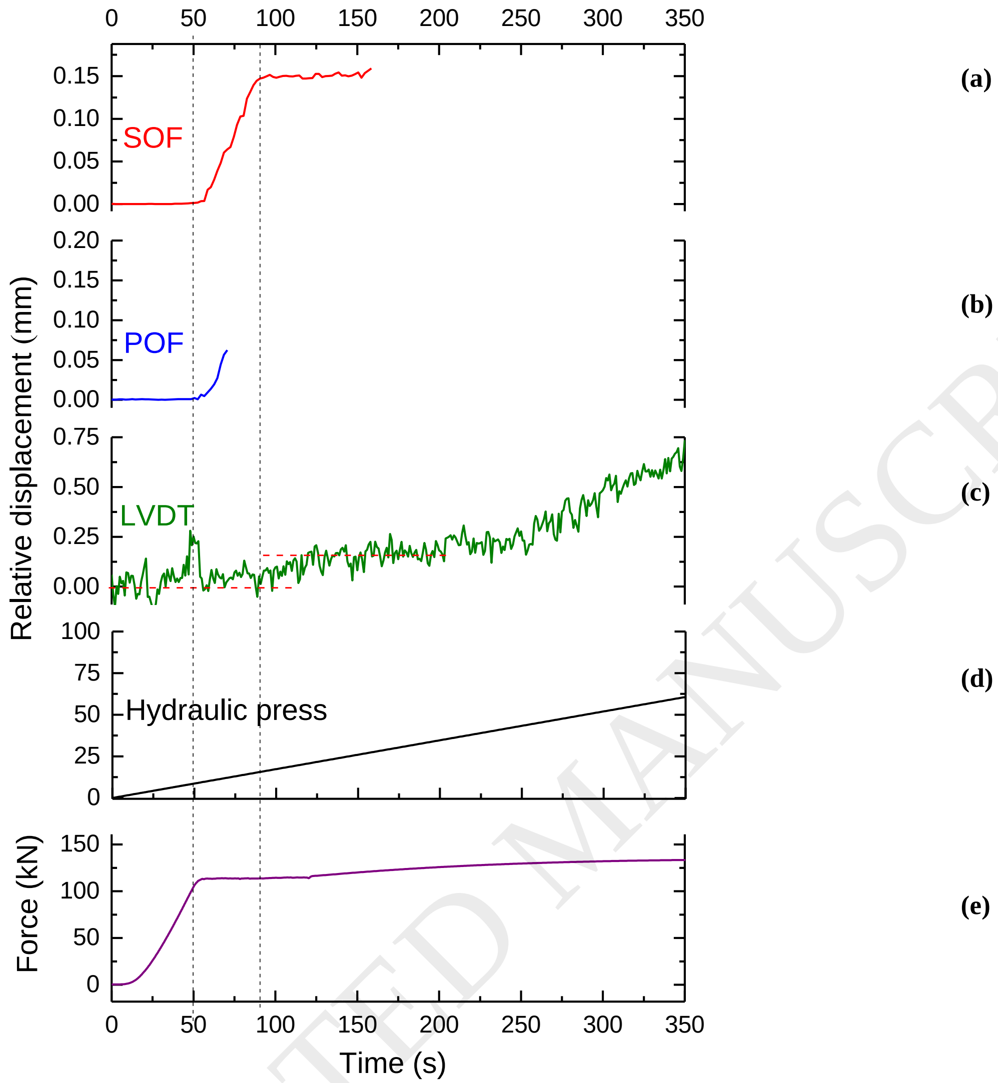


Fig. 7. Reinforcing rebar-concrete relative displacement measured by the (a) SOFBG, (b) POFBG, (c) LVDT and (d) pull-out machine sensors, and (e) load force applied by the machine, during test.

Table 1. Strain and temperature response for SOFBGs and POFBGs

Strain (pm/με)				Temperature (pm/°C)			
SOFBG		POFBG		SOFBG		POFBG	
$S_{S_{FBG-S}}$	$S_{S_{FBG-T}}$	$S_{S_{FBG-S}}$	$S_{S_{FBG-T}}$	$S_{T_{FBG-S}}$	$S_{T_{FBG-T}}$	$S_{T_{FBG-S}}$	$S_{T_{FBG-T}}$
1.20 ± 0.01	-0.02 ± 0.01	1.47 ± 0.03	-0.06 ± 0.02	27.20 ± 1.10	29.40 ± 1.50	22.00 ± 0.40	20.72 ± 0.38