

Optical Fiber Sensor for Prestressed Concrete Structures Bond Behaviors Measurements

L. R. COBO¹, I. A. CARRASCAL², A. QUINTELA¹,
A. POLANCO² and JM LÓPEZ-HIGUERA¹

ABSTRACT

During the slack period of precast concrete structures fabrication, the prestressing force is transferred, by adhesion to concrete being the armor compliant behaviors, up today, a still pending matter. To contribute to a better understanding of the subject, a new quasi-distributed optical fiber sensor system is specifically designed, fabricated and embedded into a prestressed concrete prismatic beam. The experimental results are presented, discussed and finally, conclusions are extracted. The fiber transducer is based on Brag grating technology and a new custom encapsulation..

INTRODUCTION

The prestressed reinforcement is the most used technique in the construction of precast concrete structures, however, the reinforcement bond behavior is something that has not developed according to their importance and use.

In this kind of structures the armor is prestressed prior to concrete structural element and later, the armor is slacked once the concrete is being hardened and gained adequate strength.

During the slack period, the prestressing force initially applied to the armature, is transferred, by adhesion to concrete. The armor compliant behavior is something that, up today, has not been properly studied due to the fact that low reliable and low precision technics are commonly used.

Figure 1 shows an exchange sequence between reinforcement and concrete efforts during the unstressing process. The adherent nature of a prestressed reinforcement is defined through the conventional anchor length defined in Figure 1 as L_s .

¹Photonics Engineering Group, University of Cantabria, Av los Castros S/N, 39005, Santander, Spain

²Dept. of Science and Engineering of Materials, University of Cantabria, Av. Los Castros, s/n. 39005 Santander, Spain

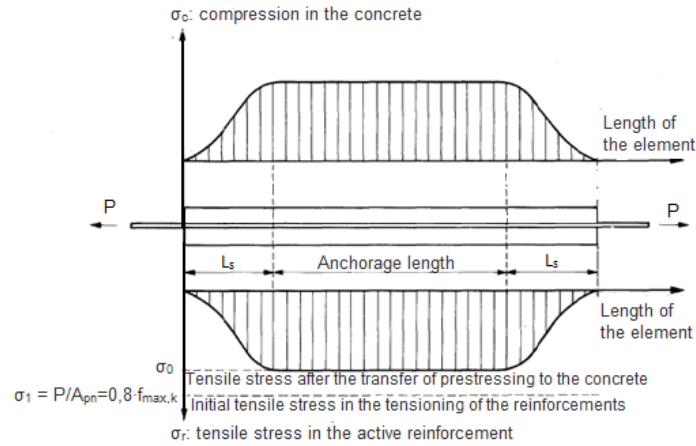


Figure 1. Forces exchange between reinforcement and concrete in the the unstressing process.

The UNE 7-436-82 "Bond test of steels wires for prestressed concrete" [1] indicates the methodology for determining this parameter and the validity criterion.

Conventional anchoring length, L_s , is defined as the length of coating required to ensure the transmission of the maximum prestressing force which occurs on the concrete by releasing the ends of the reinforcement, initially tensioned to 80% of its nominal breaking load, when this force causes on the concrete section a compressive stress of 15 MPa, with the compressive strength of concrete 25 MPa at the time of reinforcement release, in the case of steels of normal bond, and 40 to 50 MPa in the case of a steel of high bond.

The standard does an initial classification of the tests to be performed depending on whether or not the item is subject to fatigue and the type of bonding of the reinforcement, normal or high. This work focuses on items not subject to fatigue steel reinforcement normal bond.

The method proposed in the reference standard for determining the anchorage length consists to the penetration length of each of the reinforcements in the concrete section, δ_i , after releasing the reinforcement stress. This measurement was repeated after 1, 6, 24 and 168 hours. A standard test procedure proposes the deformation measurement of the concrete, ϵ_c , during the test.

In this paper the description of the new quasi-distributed optical fiber sensor system able to measure both the temperature and the strain/elongation along the axial axis (inside the beam) and the obtained experimental results are presented, discussed and finally, very interesting conclusions will be extracted. The fiber transducer is based on Bragg grating technology and a new custom encapsulation specifically designed for this particular investigation.

OPTICAL FIBER TRANSDUCER

The sensor system relies on a quasi-distributed transducer based on Fiber Bragg Gratings (FBG). In a simple way, a FBG is a periodic variation of the refractive index

in the optical fiber core which reflects particular wavelengths. The reflected wavelengths are centered around the Bragg wavelength and is defined by $\lambda_{Bragg} = 2n_{eff}\Lambda$, where n_{eff} is the effective index (constant) in the fiber core and Λ is the period of the variation of the refractive index. By elongating the FBG, Λ is increased and, therefore the central wavelength (λ_{Bragg}). So, by measuring the central wavelength, the strain of the holder structure in which the FBG is attached can be determined [2]. This principle has been widely used for structural health monitoring [3] in very different fields such civil engineering or renewable energies [4].

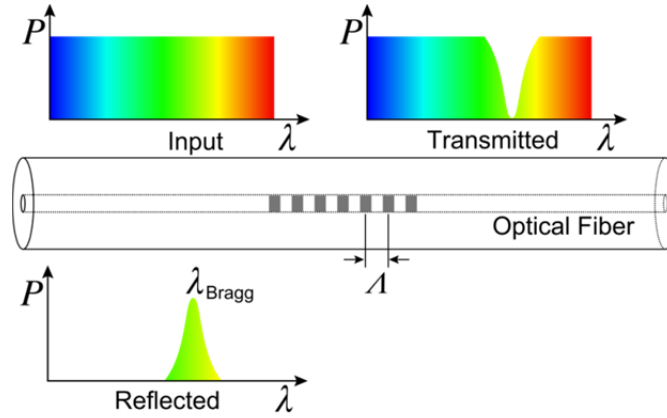


Figure 2. Basis of Fiber Bragg Gratings.

To get the deformation evolution along the concrete beam, some FBGs are glued to a holding piece at a fixed distance. For each position to be measured, a FBG is needed to get the punctual deformation. By combining the response of all the embedded FBGs along the beam, the deformation trend can be obtained.

The holding piece is mechanized in PMMA of a constant thickness of 3 mm with a shape which favors its integration into the concrete. Two fixing areas surround each sensing point to force a better joint with the concrete, causing a homogeneous deformation on the central part of each sensing point. The FBG is glued to the bottom surface of a central groove made in the holding piece. This groove is also used to guide the optical fibers along the transducer, protecting it from possible hits or cracks during the installation.

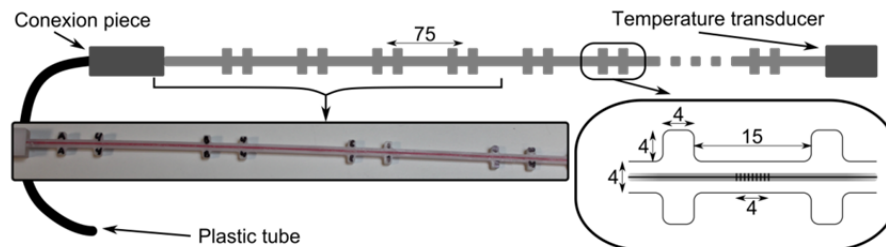


Figure 3. Transducer details. Dimensions are in millimeters.

On the employed transducer (Figure 3), 16 FBG were glued to the holding piece (using cyanoacrylate) allowing 16 deformation measurement points. All the FBGs are connected in 4 different optical fibers using different central wavelengths (λ_{Bragg}). Another FBG transducer is employed to get the temperature evolution and

compensate the deformation measurements. For this purpose, a single FBG is placed loosely on the ending piece of the transducer. The central groove is sealed with thermofusible adhesive. The four optical fibers were protected with a plastic tube to reach the out edge of the beam.

TRANSDUCER INTEGRATION AND BEAM FABRICATION

The proposed transducer is installed in a prestressed prismatic concrete beam of rectangular section (0.2 by 0.15 m²) of 3.55 meters of length. It is produced using a concrete with a minimum value of resistance of 65 MPa at 28 days, f_{cm} . During concrete placing of the beam, three cylindrical test control samples were prepared ($h = 300$ mm and $\varnothing = 150$ mm) for determining the concrete compressive strength.

On each of the reinforcement a strain gage will be placed in order to verify that no loss takes place during the clamping operation. See Figure 4.



Figure 4. Placement of strain gages.

The tensioning of the reinforcement is done separately, element by element, and reinforcement force is reestablished, if necessary, individually also, in reverse order. This operation guarantees the reinforcement force uniformity in all elements.

The tensioning of the reinforcements is performed by steps (at least three); recording the force and deformation of the reinforcement (the deformation is measured by strain gauge strips). These values are compared with those of the typical stress-strain diagram of the steel tested, with the purpose of avoiding any error in the assessment of the initial clamping force.

After reaching the test force ($P_i = 0.8 \cdot f_{pm, G}$) the corresponding value obtained from the strain gauge, $\epsilon_{a,i}$ is recorded. If during the process the force decreases, the hydraulic jack will be applied again until reaching the original value. The stretching is performed 24 hours before the concrete placing.

In order to get the adhesion properties of the prestressing reinforcement, the transducer is placed near one edge of the concrete beam to analyze its response evolution. It is fixed in the middle of the two steel reinforcement wires with nylon wires prior to concreting. The first sensing point is placed at 335 mm from the edge of the beam and the last a 1460 mm. The distance between two consecutive sensing points is 75 mm.

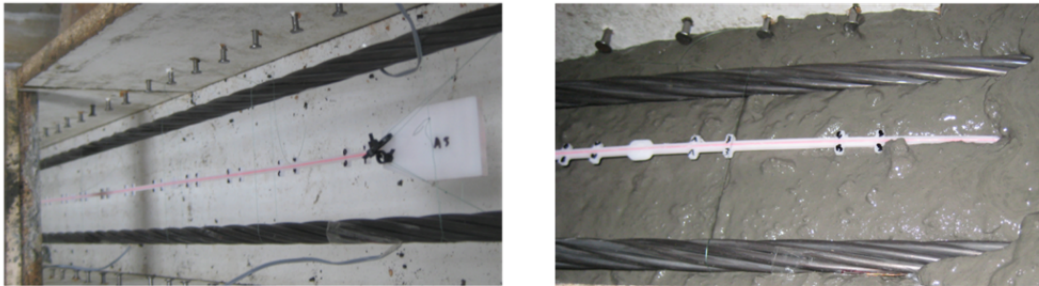
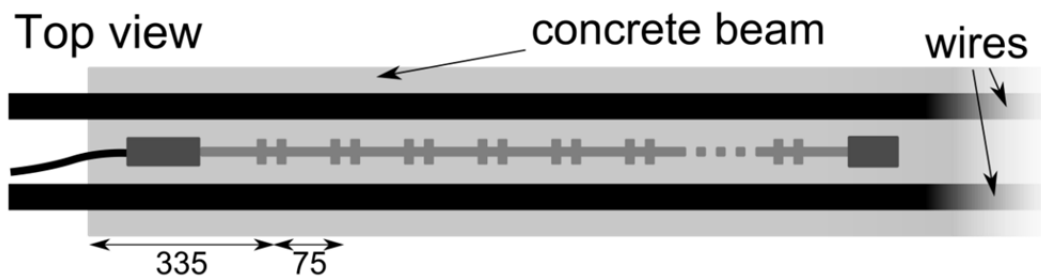


Figure 5. Installation details (up) and fabrication photos (down). Dimensions are in millimeters.

After 24 hours from the tensioning it is proceed to concrete casting. After 5 days, when it was certain that the concrete had acquired an adequate strength, the stored samples were broken in order to confirm that the resistance exceeded the required value. The mean resistance of the three specimens reached 38.5 MPa, which is higher than the 24.5 MPa set by the standard as minimum test requirement.

Once the check is done, proceed to the reinforcement's unstressisng. The first operation consists in carefully removing the formwork and then placing two comparators with their corresponding supplement at each side of the beam, recording the initial values of penetration, $l_{0,i}$. (Figure 6).



Figure 6. Placement of the transducer displacement for measuring penetration δ .

The measurements consist in determining the penetration δ at the ends of the specimens at each of the elements of the active reinforcement, i.e. the relative displacement of the sections of steel and concrete that where, prior to the introduction preload, at the head of the specimen.

RESULTS AND DISCUSSION

The whole process has been monitored since the pouring process. The stress on the reinforcement wires is maintained during the concrete curing process. Once the beam is cured, a release stage of the reinforcement wires is followed and the deformation evolution of the beam is measured during 220 hours.

The first interesting data coming from the installed transducer is the evolution of the temperature during the curing process of the beam. As shown in the Figure 7, from the 20th hour the temperature establishes with a final rise of about 13 °C.

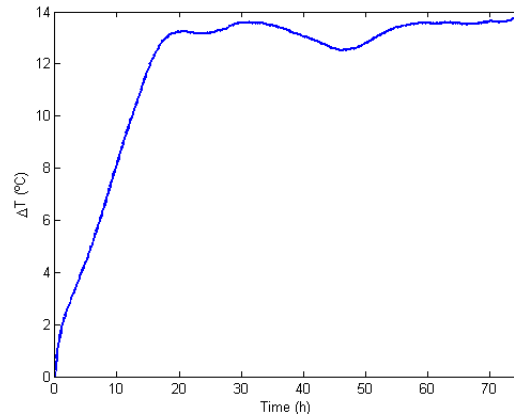


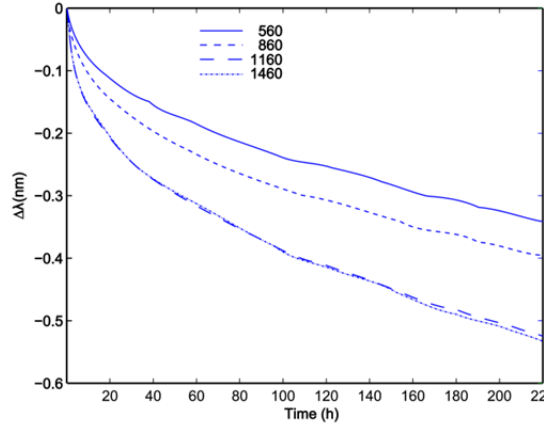
Figure 7. Temperature evolution during the concrete curing process.

Once the beam is cured, the stress from the reinforcement wires is removed. For this process each wire is stressed to release the fixing means and after the load is reduced gradually. The process is repeated for each of both wires.

The main deformation is produced in the first instants of the releasing process but the concrete continue comprising as the time passes. In the figure 8.a is shown the evolution of compression for four points

In order to check the deformation evolution of the concreted beam, some checkpoints are taken at 1, 6, 24, 168 and 220 hours from the releasing stage. This evolution is shown on the Figure 8.b. On this figure is also shown the curve which fits the deformation status at $t=220$ hours after the releasing stage. The value of anchorage length is determined to be 1085 mm, based on the estimate of the point of intersection of the two fit lines

a)



b)

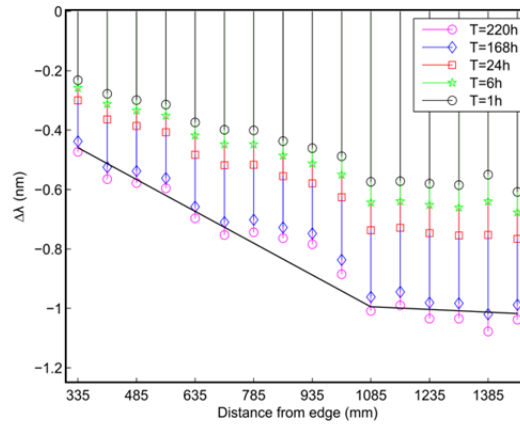


Figure 8. a) Evolution of compression for four points (560, 860, 1160 and 1460 mm from the beam edge) b) Deformation of the 16 sensing points at different times: 1, 6, 24, 168 and 220 hours after releasing.

The anchor length will be determined according to the analyzed standard by calculating the average (δ_m) of the penetrations in all reinforcements after seven days, and considering the anchoring conventional length equal to:

$$L_s = 3,5 \frac{E_s \cdot A_{pn}}{f_{pm,G}} \delta_m$$

where:

- E_s is the modulus of elasticity of the active reinforcement, $E_s = 200 \text{ GPa}$
- A_{pm} is the area of the active reinforcement, $A_{pn} = 140 \text{ mm}^2$
- $f_{pm, G}$ is the guaranteed breaking load of active reinforcement ($f_{pm, G} = A_{pn} \cdot f_{max, k} = 140 \text{ mm}^2 \cdot 1860 \text{ MPa}$)
- δ_m is the average penetration of all reinforcements for three samples after 7 days

To obtain a representative value of the mean, δ_m , the number of test specimens should be at least equal to three, to take into account the dispersion due to the concrete, and the number of the specimen's reinforcements must be such that at least, twelve values of reinforcement penetration are available. In this work we have worked only with a

beam for which the result corresponds to only four reinforcements. The following table shows the values of reinforcement penetration in the concrete.

Table 1. Values of reinforcement penetration in the concrete.

Penetration		
$\bar{\delta}_1 = 3.27 \text{ mm}$	$\bar{\delta}_{\text{active}} = 2.69 \text{ mm}$	$\bar{\delta}_m = 2.80 \text{ mm}$
$\bar{\delta}_2 = 2.11 \text{ mm}$		
$\bar{\delta}_3 = 3.19 \text{ mm}$	$\bar{\delta}_{\text{passive}} = 2.91 \text{ mm}$	
$\bar{\delta}_4 = 2.63 \text{ mm}$		

Results according to standard:

- Anchor length of the passive side: $L_{s, \text{passive}} = 1095 \text{ mm}$
- Average anchor length: $L_{s, m} = 1054 \text{ mm}$

It is found that the results obtained by the transducer are the same with those calculated with the formulation proposed by the reference standard. The difference between the obtained values in the passive side where the fiber optics transducer is placed is 10 mm, ie less than 1%, with a 10% tolerance level in the standard when using an alternative method for determining the anchorage length.

CONCLUSIONS

The fiber optic transducers developed in this work, placed and embedded in the core of the concrete beam, proves to serve as an alternative method for the anchoring length determination of an active reinforcement given by the UNE 7-436-82 standard, based on the registration of the penetration depth of the concrete's reinforcement.

This technology also enables the analysis of the temperature's temporal evolution within the concrete, and can be applied thus to characterize the hardening process of concrete.

The continuous recording of the strain in the beam indicates that, after the 7 days proposed by the standard for measuring the penetration have elapsed, the deformations are not stable and the beam shortening process continues, generated by prestressing thereof.

ACKNOWLEDGEMENTS

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