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Novel fiber optic transducers embedded into concrete mass applied to the New Alto Ceira Dam

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Abstract

The New Alto Ceira Dam is a concrete arch dam, 41 m high and 133 m long at the crest, located in the middle region of Portugal. Its objective is the replacement of the existing dam located about 200 m upstream, which is highly deteriorated due to swelling phenomena.

The dam is actually under construction and its monitoring safety plan is in accordance with the Portuguese Safety Regulations on Dams. The instrumentation embedded into the concrete is based on traditional electrical devices developed several decades ago and with proved durability characteristics.

Considering the recent improvements in fiber optic based instruments for structural monitoring, benefiting of multiplexing technique, great reliability and accuracy, it was decided, in an experimental frame, to develop and to install in the New Alto Ceira Dam a set of fiber optic devices.

Assuming the instruments embedded into the concrete mass as those exposed to the most aggressiveness of the construction methodologies, strain meters, thermometers and joint meters were selected to the development and implementation of fiber Bragg grating based transducers in order to appraise their performance, reliability, and installation requirements. After laboratory testing and validation, a limited number of these type of transducers were installed in the New Alto Ceira Dam.

In this paper, the results from calibration tests are presented, and then a comparison of performance between new fiber optic sensors and the traditional electric sensors is made under controlled conditions, in laboratory. Some preliminary results of the experimental monitoring of the dam are also illustrated.

keyword: arch concrete dam, fiber optic sensor, embedded transducers, monitoring results

1 Description and objectives of the New Alto Ceira Dam

The existing Alto Ceira dam is located in the central region of Portugal, and has been built in 1949 to derivate the water of the Ceira River and of its tributaries to the reservoir of Santa Luzia dam. The deviated water is turbinated not only in the Santa Luzia powerhouse but also in Cabril, Bouçã and Castelo de Bode hydro-plants located in the Zezere River.

The Alto Ceira dam is a thin arch defined by circular arches of constant thickness, with a maximum height of 37 m. The thickness of the central cantilever varies between 4.5 m in the base and 1.5 m at the crest, and the dam crest has a development of 120 m. The dam is provided of a surface spillway with a maximum capacity of 200 m^3/s in the right bank, and the diversion tunnel to the Santa Luzia reservoir is located on the left bank and has a maximum capacity of 9.0 m^3/s.

The first evidences of structural anomalies of Alto Ceira dam were observed during the first filling of the reservoir, which have increased since then. The anomalous dam behaviour is characterized by progressive horizontal upstream displacements, progressive upward vertical displacements and intensive cracking. Many studies and tests have been carried out in order to get a better knowledge of the causes of the structural problems. Alkali aggregate reactions (AAR) in the concrete have been identified as the main cause of the intensive cracking of the thin arch dam structure.

In 1994, after having assumed the dam ownership and due to the severe structural problems of the dam, Energias de Portugal (EDP) decided to study, not only its rehabilitation but also the construction of a new dam, close to the existing one.

Later on, in 2006, several additional solutions were studied envisaging in a first stage the dam rehabilitation and, in a second stage, the conception of alternative scenarios for the scheme configuration. However, the conclusion in terms of reliability, economical and environmental aspects, was similar to the one reached in 1994, consisting in the substitution of the existing dam by a new one, located about 200 m downstream. So the 1994 dam design was carefully reviewed according to Portuguese Regulations for Dam Safety and for Dam Design. In Figure 1 a scheme with the location of the new and the existing dams is presented.

The new Alto Ceira dam is a concrete arch dam with gravity abutments. It has a 133 m crest length at elevation 668.50 a.s.l. and a 41 m maximum height above the foundation level. The arch zone of the dam comprises six blocks separated by vertical construction joints, 16.0 m apart between the three central blocks and 17.0 m on the other joints. Its shape definition is based on parabolic arches, with increase in thickness towards the abutments; the central cantilever theoretical thickness is 2.0 m at the crest and 5.5 m at the base; the dam's maximum thickness is about 6.5 m in each bank. The right bank gravity abutment is 20.0 m and has a maximum height of 10.1 m. The correspondent dimensions of the left abutment are 13.0 m and 11.0 m, respectively. The total concrete volume of the dam is about 18 500 m3.

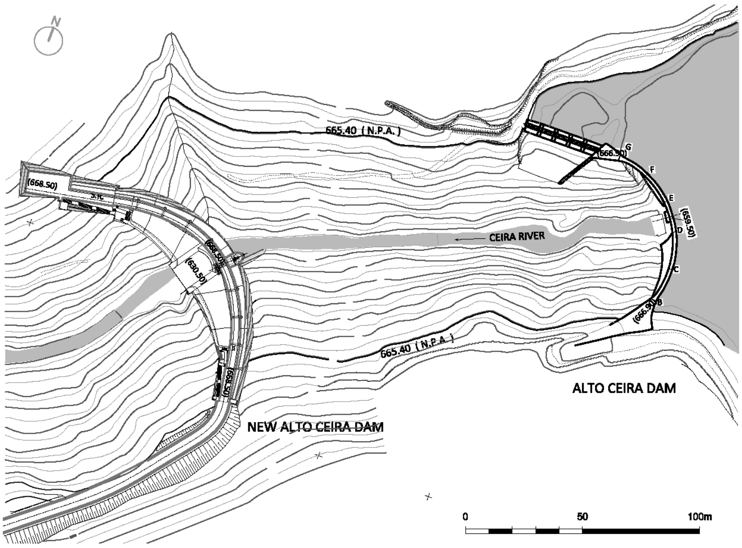

Figure 1 – The new Alto Ceira dam (left) and the upstream existing one (right).

The dam is provided of a surface uncontrolled spillway, almost over the whole crest of the dam and of a downstream stilling basin. Its maximum discharge capacity is of about 200 m^3/s.

The prevention of AAR was a main issue of the dam design. In addition of a careful selection of the quarries that will provide the concrete aggregates, based on the execution of reactivity tests, a high percentage of fly ash was defined to be used in the concrete mixes.

The construction of the new dam, previewed in Figure 2, started in 2009 and will be completed in the end of 2012.

Figure 2 – Preview of the new Alto Ceira dam.

2 The dam monitoring plan

According to the Portuguese dam safety regulation (RSB, 2007), the new Alto Ceira dam is classified as a high hazard structure (Class I), due to the potential loss of life in case of dam failure. This classification requires the design and implementation of a complete monitoring system, which shall be able to provide important data about the dam's structural behaviour and safety conditions throughout its lifetime, including the construction period, the first filling of the reservoir and the operation phase (EDP, 2007; LNEC, 2007). To achieve these objectives the following tasks must be considered: i) monitoring the main loads and the structural responses; ii) accomplishment of periodic visual inspections in the dam accessible zones, the surrounding rock mass and the reservoir; iii) characterization of the rheological properties of both the rock mass and the concrete; iv) development and maintenance of adequate models which shall be able to simulate the dam/foundation behaviour, in order to validate the monitoring data.

The monitoring of the main loads may be classified in three different groups, briefly described below.

The first group concerns the physical and chemical effects of the reservoir water, and includes: i) the measurement of the water level in the reservoir, ii) the measurement of uplift pressures in the foundation; and iii) periodic chemical and physical analyses of the reservoir water, of the drained water and of the water infiltrated through the dam concrete. The water level in the reservoir is measured with a depth gauge and with an automatic water level indicator. The uplift pressures beneath the dam are evaluated in a set of hydraulic piezometers distributed along the base of the dam, one per dam block. The positioning and length of these piezometers will be defined after analyzing all the information obtained during the excavations and the foundation treatment. Chemical and physical analyses of the water and of the suspended products are carried out in order to evaluate the possible deterioration of the rock mass conditions and of the grouted curtains, through the deposition or erosion of materials.

The second group concerns current environmental actions and temperature variations within the dam body. Both the air temperature and humidity are measured in an automated meteorological station. The temperature in the concrete, mainly due to environmental actions and to the dissipation of the concrete hydration heat, is measured in a set of 29 embedded resistance thermometers, distributed in such a way that it allows the evaluation of the thermal field in the dam body, including the temperature close to the dam faces and along several representative radial sections. The concrete temperature is also measured with the embedded electric devices used to measure deformations, stresses and joint movements.

Finally, the third group concerns the seismic loads. Although the dam is located in a zone of moderate to low seismic risk, two three-dimensional seismometers will be installed at the base and close to the top of the central block, in order to evaluate the effects of seismic events.

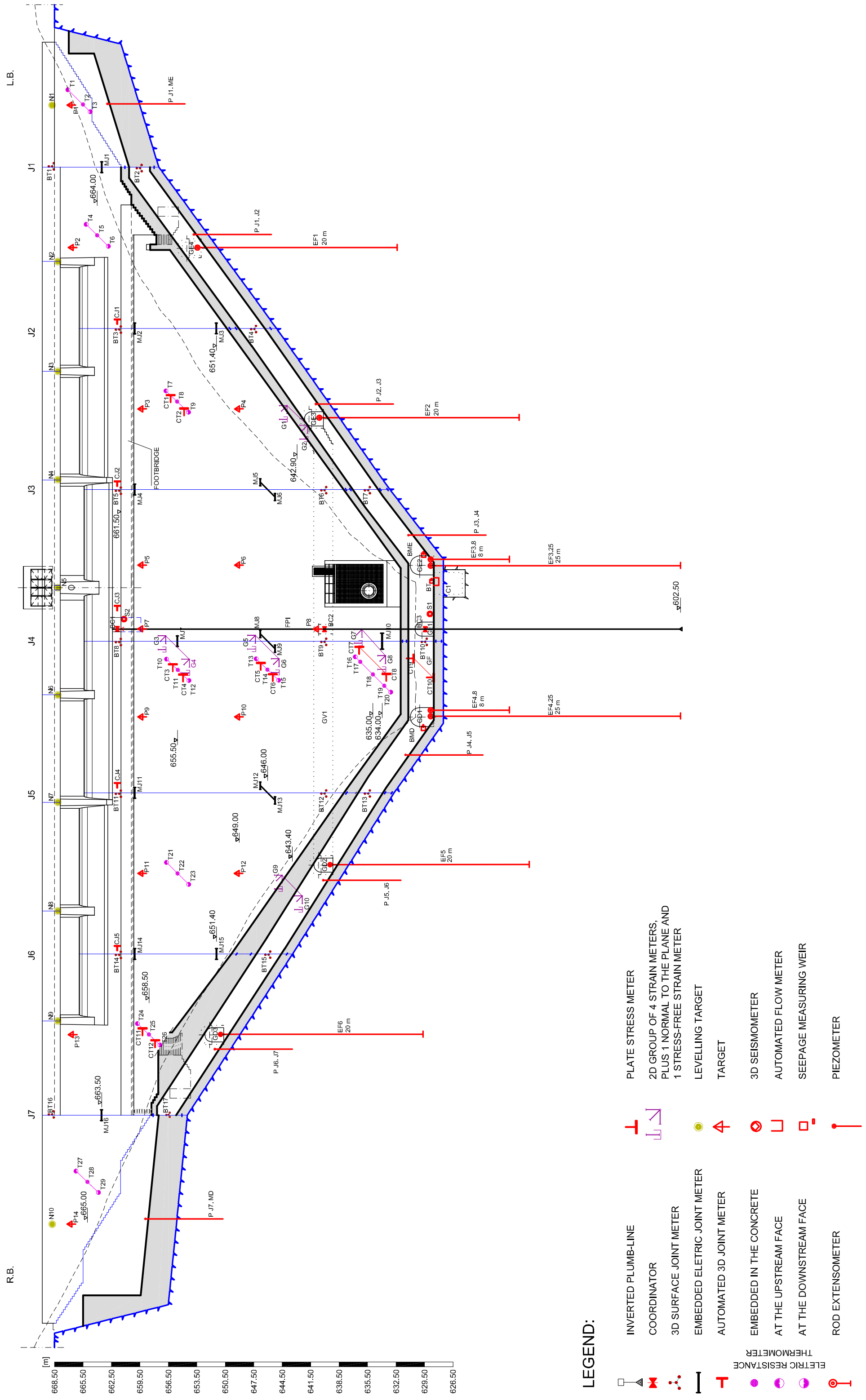

Figure 3 – New Alto Ceira monitoring plan.

The observation of the structural responses due to static loads includes the measurement of absolute and relative displacements, both in the dam body and in the foundation, deformations and stresses in the dam concrete and water flows in the foundation. The above-mentioned seismometers also allow the measurement of accelerations in the case of seismic events.

Absolute horizontal displacements in the dam body are measured using two different and independent methodologies. The first includes an inverted plumb-line located in the central block, sealed in the rock mass at a depth of about 25 m below the dam/foundation interface, which allows measurement of displacements at three different levels. The second method involves the measurement of the horizontal displacements at 14 points of the downstream face of the dam using geodetic methods. The results obtained by the two different methodologies may be compared, because two of the target points used in the geodetic monitoring are placed close to the measurement points of the plumb-line.

Vertical displacements at 10 points along the crest of the dam are measured by precision geometric leveling. Rod extensometers will be installed in 6 boreholes drilled at the base of some dam blocks in order to measure relative displacements. At the bottom of the valley, in blocks J3/J4 and J4/J5, two-point rod extensometers will be installed, sealed at the depths of 8 m and 25 m below the dam/foundation interface, so as to measure displacements at both shallow and deep depths. In the other dam blocks, both on the right and left banks, simple rod extensometers will be installed, sealed at a depth of 20 m below the dam/foundation interface.

Relative displacements between the concrete blocks are measured not only inside the concrete, with 16 embedded electric joint meters, but also in accessible surfaces, such as gallery walls and the area of the downstream face of the dam close to the pathway, with specific devices that allow measurement along three perpendicular directions. The embedded joint meters are located in the middle of the blocks, at mid-thickness of the dam, in the thinnest arches, and 1 m away from both the upstream and downstream faces of the dam, in the thickest arches.

The state of deformation is evaluated with 10 2D groups of strain meters embedded in the dam concrete 1 m far from the upstream and downstream faces of the dam. Each one of these groups includes 5 active strain meters and one no stress strain meter, allowing the evaluation of the state of deformation in a plane parallel to the nearest face of the dam. During the placement of these groups, specimens of the surrounding concrete are prepared, in order to determine the evolution in the concrete’s deformability, and thus the state of stress may be evaluated. The stresses within the dam concrete are directly measured with 12 embedded plate stress meters, located close to the upstream and downstream faces of the dam in 6 different sections. The stress meters located at the bottom of the valley are placed in such a way that they allow measurement of vertical stresses, while the others allow measurement of stresses along the dam arches.

The foundation treatment includes both drainage and grout curtains in order to ensure seepage control under the dam. The characterization of the foundation hydraulic behaviour is based on the measurement of the drains discharges and on the uplift pressures in the piezometers. In addition, the drainage network includes three measuring weirs. The difference between discharges recorded in these devices and those recorded in the drainage boreholes allows the evaluation of the leakage through the dam body.

Some of the above-mentioned measurements will be redundant, because part of the monitoring data is going to be also collected by an automated data acquisition system.

Since the beginning of the construction, the new Alto Ceira dam is included in an information system, called gestBarragens, developed with the aim of supporting the management and analysis of all the data concerning the safety control of Portuguese dams during their lifetime, mainly readings and results of the monitoring systems (Portela et al., 2005). The main objective of this system is to enable a continuous diagnosis of the dams' performance, in order to detect possible changes in their safety or functionality conditions. With this system the relevant data is permanently available to the entities with responsibilities in the dam safety control.

3 The experimental fiber optic sensors installed in the dam

Traditionally, the dams monitoring systems have been based on a set of mechanic and/or electric instruments. These systems have been improved over decades being well proved in terms of metrological performance, stability and durability. However, fiber optic technology can offer a number of advantages when compared with conventional solutions. The fiber optic monitoring systems can benefit from high sensitivity, small size, immunity to electromagnetic interference, high acquisition frequencies, and ability to support serial multiplexing schemes inherent to fiber optic sensors (Udd, 1995). Thus, fiber optic sensors are coming out for measuring a variety of relevant parameters for civil engineering structures (Measures, 2001). Due to their metrological features, Fiber Bragg Gratings (FBG) sensors have reached the greatest success whenever strain or temperature measurement is required (Majumder et al. 2008).

3.1 Fiber Bragg sensors principle

The FBG sensors consist of periodic alterations in the index of refraction of a narrow length of the core of the optical fiber. This periodic modulation acts like a selective mirror for the light wavelength that satisfies the Bragg condition as schematically illustrated in Figure 4. All other wavelengths pass through the grating without any interference (Kersey et al. 1997).

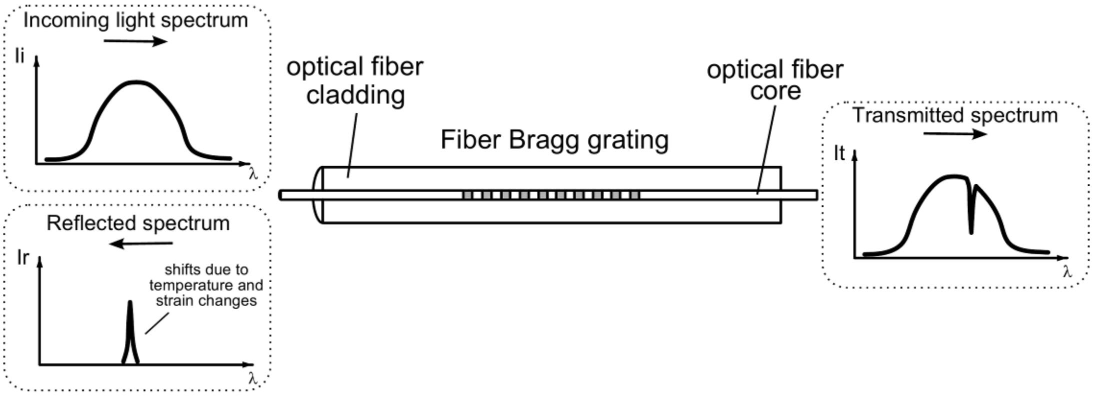

Figure 4 – Schematic diagram of the functional principle of FBG sensors: Fiber Bragg Grating (center); input light spectrum (left-above); transmitted light spectrum (right); reflected light spectrum (left-under).

Strain and temperature variations acting on the optical fiber will change both the effective refractive index and the grating period. The FBG sensing potentialities are the result of the high sensitivity of the reflected light wavelength to both deformation and temperature variations.

3.2 Novel transducers development for concrete dams monitoring

Aiming at the practical and effective application of the FBG sensors in civil engineering structures, transducers with adequate characteristics and performance are mandatory. The primary objective of these transducers should be to transform, with maximum reliability and accuracy, a physical parameter into an optical nature signal, such as the wavelength associated to the FBG. Furthermore, aspects related with the durability, installation facility, robustness and the network integration in field applications are also attributes to consider on the transducers conception.

3.2.1 Concrete strain

Taking into account the specificity exhibited by concrete dams, a novel strain transducer to be embedded into concrete was developed. The target of the developed transducer is to measure the average strain in concrete mass over a suitable length. This average strain should represent the strain of the structure, attenuating all the local effects of the concrete aggregates and other small discontinuities. The capability of installation strain FBG sensors during the construction phase, involving the concrete casting process, with proper robustness, it is another important concern in the transducer design.

A transducer with geometry and mechanical attributes capable of characterizing with accuracy the average concrete strain over a given length is depicted in Figure 5. This is constituted by a smooth stainless steel bar with two anchoring heads in each extremity. One FBG sensor aligned lengthwise with the bar is glued at the central position for the measurement of the representative deformation.

Figure 5 – Schematic representation of the optical based strain transducer to be embedded into concrete.

Laboratory tests were performed, aiming at the assessment and calibration of the transducer behavior. In this context, uniaxial tension tests were carried out to evaluate the transducer response in terms of strain sensitivity and to perform the consequent calibration (see Figure 6 (left)).

Cyclic load compression tests, with the transducer embedded in an instrumented concrete prism, were carried out, and the measurements obtained with the novel transducer compared with the data coming from the additional instrumentation (see Figure 6 (center)). An embedded Carlson extensometer, a vibrating wire strain gage and a pair of clip gages were used for comparison. The strain evolution during the test is plotted in Figure 7 (left) confronting the different gages. Figure 7 (right) depicts also the relation observed between the external clip gages (reference) and the embedded fiber optic transducer. A deviation less than 1% was observed when comparing the results of the different transducers assessing the concrete strain under compression cycles.

This novel transducer was also submitted to thermal cyclic tests in a climatic chamber aiming at evaluating its behavior and stability under temperature variations (see Figure 6 (right)). The compensation of the temperature effects in the transducer is mandatory in order to obtain the true mechanical strain component. This effect is particularly important in long term applications often involving large temperature changes with a strong impact in the sensors readings. The temperature compensation can still be made on a linear regime by means of a complementary measurement of the temperature.

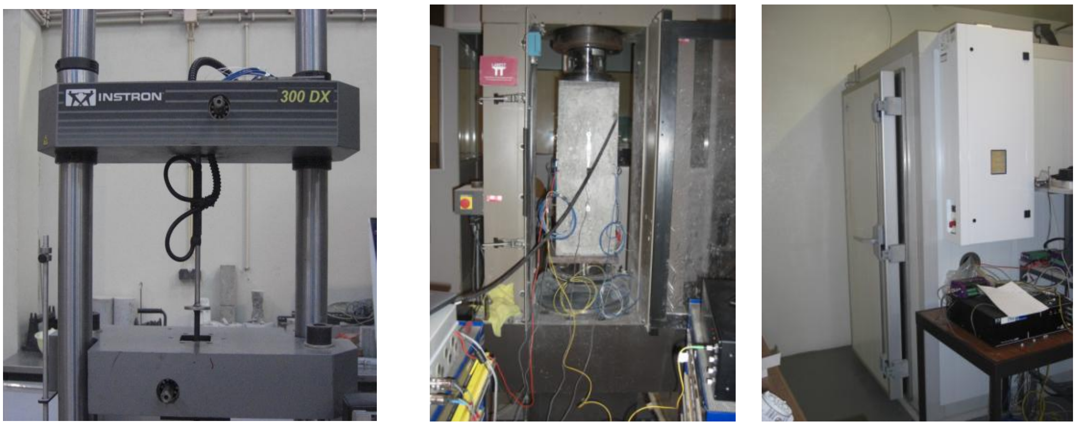

Figure 6 – Laboratory tests for transducer performance assessment: uniaxial tension tests (left); concrete prism compression cycles (center); temperature cycles (right).

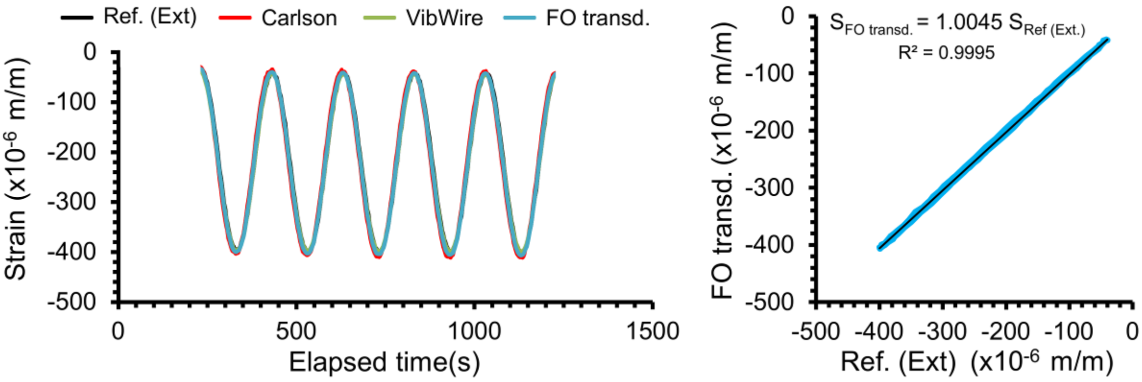

Figure 7 – Results of the uniaxial tension test: strain history (left); correlation between the reference strain obtained with the external clip gages and the strain measured with the novel transducer (right).

3.2.2 Joint-displacements

The joint-displacement transducer is identical in terms of functional principle when compared to the previous strain transducer. Figure 8 represents the transducer architecture. This device consists in a thin high strength steel rebar with two anchoring heads at the extremities. A FBG sensor is installed in the middle section for measuring the representative strain variation.

Particularly in this case, a rubber coating along the transducer body eliminates completely the residual bonding transference between concrete and transducer. Thus, the deformation transfer occurs exclusively at the anchoring elements. One transducer extremity is bonded into the previous cast concrete block and the other is embedded in the new concrete phase.

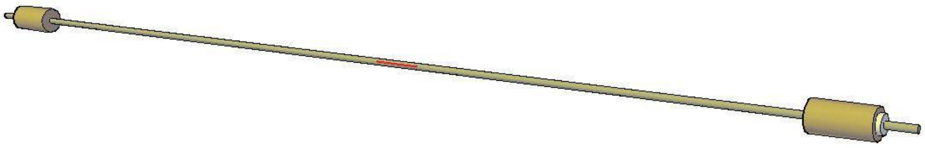

Figure 8 – Schematic representation of the optical based joint-displacement transducer.

Since the non-bonding characteristics of the transducer body, it is effective to assume the strain measured by the FBG sensor as the average strain over the bar length. For the same reason, it is also valid to assume that the integration of this average strain along the transducer length (1.00 m) represents the relative displacement between anchors.

Also for this transducer a set of laboratory tests were carried out to assess its performance. Uniaxial load test were carried out to calibrate the sensor and to assess the maximum deformation range. Anchoring pulling tests allowed validating the force anchoring transference to concrete. Finally temperature cycles certified the temperature compensation process.

3.2.3 Temperature

The adopted temperature sensors are based on the measurement of the total strain of a stainless steel cantilever beam free of mechanical stresses. This simple principle is presented in Figure 9 showing the internal architecture of the transducer.

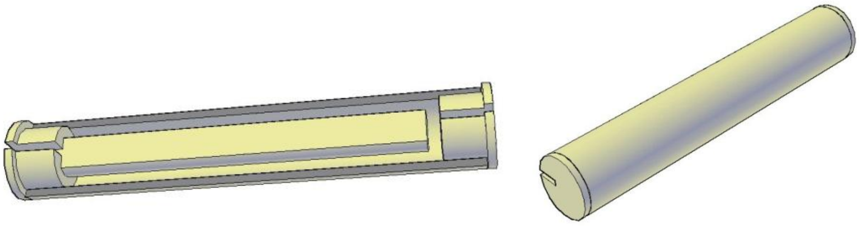

Figure 9 – Schematic representation of the optical based temperature transducer.

As depicted in figure, the external stainless tube comprises internally the small cantilever beam. This configuration allows keeping the internal body with perfect and constant boundary conditions and totally free of mechanical stresses. The gap at the free cantilever extremity makes possible the free thermal deformation of the internal body, enabling the applied FBG sensor to measure the temperature variation.

Taking into account the standard and linear response of the stainless steel face to temperature variations, the strain measured by the FBG sensor can be directly correlated with the temperature magnitude. Laboratory tests allowed to calibrate the effective temperature sensitivity of each transducer.

3.3 Field installation

The monitoring plan based on fiber optic technology applied to the new Alto Ceira dam is focused on the measurement of representative parameters at selected points of the structure. The previously presented transducers were used for measuring the strain variations in the concrete mass, the joints displacements (relative opening or closing movements between adjacent concrete blocks) and the temperature changes. The fiber optic instruments location is shown in Figure 10. Two separated zones of the structure were selected, both at the center part at level 646.00, comprising two different concrete cast blocks (B4 and B5).

In concrete block B5, two 2D-strain groups were installed 1 m away from the upstream (GO5) and downstream (GO6) faces of the dam. These two groups are in correspondence with the position of two alternative groups of conventional gages (G5 and G6). The Figure 11 presents a general view with the sensors installation (left), and shows the arrangement of the spatial pre-aligned fiber optic strain transducers (right). The groups of extensometers were involved with concrete whose aggregates have a maximum dimension of 62 mm.

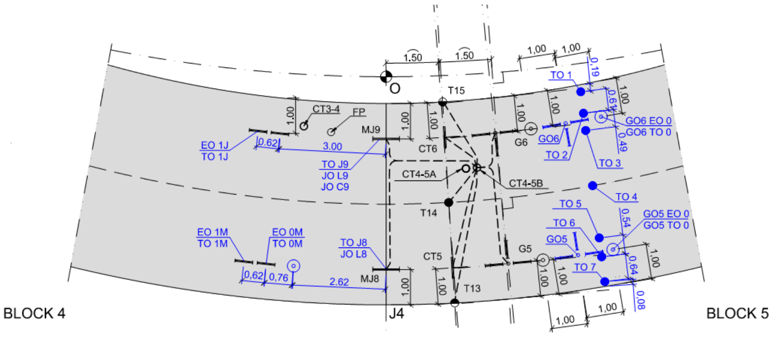

Figure 10 – Fiber optic instruments location and respective nomenclature.

Figure 11 – General view with the strain group relative location (left), and detail five strain transducers group arrangement (right).

Complementary, in concrete block B4, a pair of single strain transducers was installed 1 meter apart to the dam faces. A direct comparison with conventional Carlson strain gages will be here possible due to sensors proximity as shown in Figure 12 (left). Both sensors have identical alignments in a regular strain field.

Figure 12 – Double-wall bucket for no stress concrete monitoring (left), and single strain transducer (right).

Beside the strain gages, also embedded in concrete mass, double-wall buckets were installed allowing the characterization of the deformation evolution in no stressed specimens. In Figure 12 (left) it is presented the respective bucket near the strain gages. The Figure 12 (right) depicts the bucket with the internal optic strain transducer in detail.

An array of seven fiber optic thermometers was installed for assessing the temperature profile along a transversal dam alignment. This set of sensors is connected in a single string which is encapsulated in a flexible corrugated tube. Temperature sensors were positioned at the mid-point, and 0.1 m, 0.7 m, and 1.2 m away from each face of the dam (Figure 13 (left)). A second set of temperature sensors was placed coupled to the strain transducers allowing the temperature compensation.

Figure 13 (right) depicts the fiber optic joint meters installation. It is possible to observe the fiber optic joint transducer at position with one end anchored in the casted block and the other one ready to be embedded in the new concrete phase. A conventional Carlson joint-meter is placed close to the novel transducer for comparison.

Figure 13 – Detail of the embedded temperature array (left), set up for joint meter gage (right).

Additional details of the installation scenario are shown in Figure 14.

Figure 14 – Details of field installation: contrast between electrical cables and optical fiber conduct (left); concrete cast around sensors (center); fiber optic instrumentation acquisition point and respective equipment (right).

It is patent the difference in terms of complexity and economy concerning the cable conduction in Figure 14 (left). The signal of a similar number of sensors is transmitted in three optical fibers, here inside a corrugated tube, instead of 16 electrical cables. The concrete cast works around the sensors is illustrated in Figure 14 (center) being important to refer the integrity and serviceability of all the devices after concrete placement. Last, Figure 14 (right) shows the central fiber optic acquisition point composed of a UPS unit, a compact PC and the 8-channel BraggMeter unit (FiberSensing FS2200).

4 Results

Along this section the main results obtained since the installation of the experimental fiber optic monitoring system are presented and briefly discussed. Strain variations and temperatures over a period of about 3 months are plotted on next figures. Joint displacements are also illustrated for a period of about one month. It should be mentioned that the optic signal interrogation unit became operational in November 26th, 2011.

4.1 Concrete strains

Figure 15 plots the strain evolution on a 2-D strain group. Six different strain transducers are represented together relating to the indicated schematic orientation. The coupled temperature is also presented. Concerning the plotted strains it is important to refer that these results represent the total deformation state combining the thermal, the shrinkage and the mechanical components of the concrete deformation. The concreting of the instrumented zone occurred at November, 4th and the readings started 20 days after.

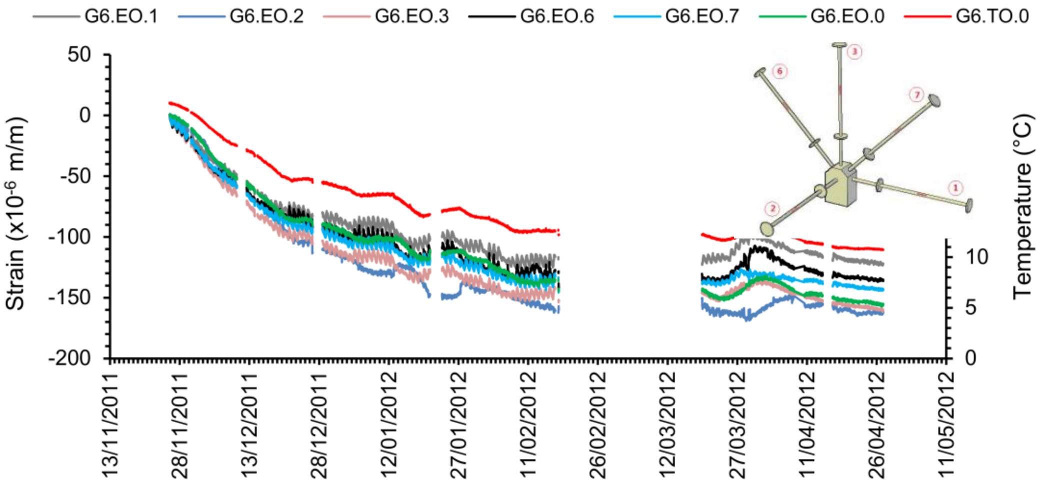

Figure 15 – Strain evolution at the G6 2D strain meters group (refer to Figure 10 for sensors location).

4.2 Joint-displacements

The two displacements between concrete blocks are shown in Figure 16. Each measurement point is 1m away from the downstream and upstream dam face, respectively. The joint-meters readings have started at the beginning of the concrete hydration of the corresponding concrete pouring phase of Block 4.

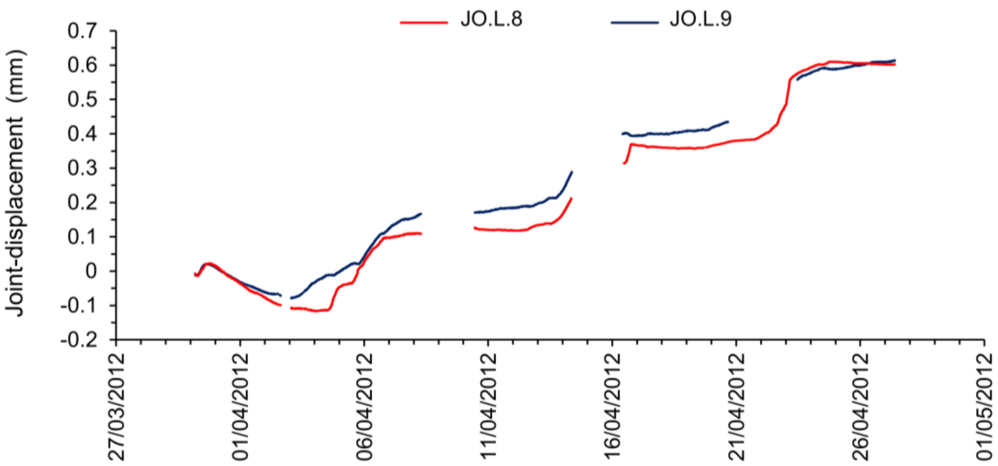

Figure 16 – Joint-displacement evolution in the interface between concrete block B5 and B6 (refer to Figure 10 for sensors location).

4.3 Temperature

The results of the temperature array, comprising seven measurement points are plotted in Figure 17.

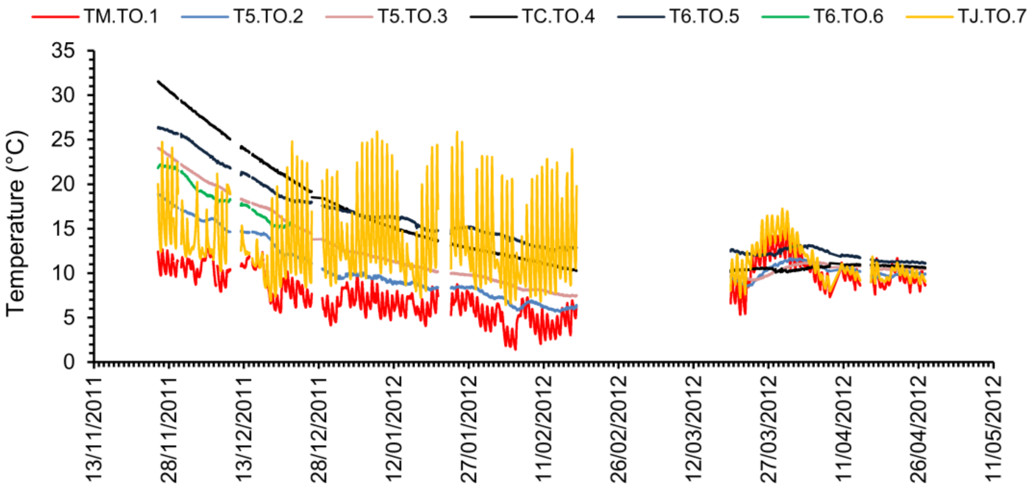

Figure 17 – Temperature evolution (refer to Figure 10 for sensors location).

The temperature data illustrated in Figure 17 corresponds to the same concreting phase of the strain group shown in Figure 15, that was carried out in November, 4th, being the readings available 20 days after the beginning of concrete hydration.

5 Conclusions

In this paper, the development and implementation of fiber Bragg grating based transducers for the measurement of strain, joint-displacements and temperatures is presented. After laboratory testing and validation, the transducers were installed in the New Alto Ceira Dam leading already to the achievement of some promising preliminary results.

The main goal of this work is the enabling and validation of new competitive alternatives for dam instrumentation to the conventional monitoring devices, using fiber optic technology.

In addition to the current validation of the presented transducers performance, it is also foreseen the development of other new transducers that will allow the evaluation of important parameters such as displacements, rotations, uplift pressures, foundation strains and water infiltration.

6 Acknowledgments

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