Smart Monitoring by Fiber-Optic Sensors of Strain and Temperature of a Concrete Double Arch Dam

Lorenzo Brezzi[1](✉), Luca Schenato[2,3], Simonetta Cola[1], Nicola Fabbian[1],
Paolo Chemello[4], and Paolo Simonini[1]

[1] DICEA, University of Padua, Padua, Italy
lorenzo.brezzi@unipd.it
[2] Research Institute for Geo-Hydrological Protection, CNR, Padova, Italy
[3] Department of Information Engineering, University of Padua, Padua, Italy
[4] ENEL Green Power, Rome, Italy

Abstract. Concrete arch dams are large constructions aimed at producing hydroelectricity, providing water for irrigation and controlling flooding. Since concrete dams in Italy are quite old-fashioned structures, it is a challenge to properly evaluate their conditions, manage maintenance interventions and optimize energy production for a more sustainable development. Traditional field monitoring carried out through visual inspections, topographical measurements and point sensors is complex and gives only discontinued spatial information. Recently, numerous innovative techniques have progressed greatly, and, among these, the use of Distributed Optical Fiber Sensors (DFOS) as detector of strain and temperature can be considered an attractive option, as it allows spatially dense measurements over large distances and with high resolution. To estimate the reliability and potentiality of this innovative system in monitoring the extremely low strains sustained by dams, a concrete double arch dam, namely the Ponte Cola dam in North Italy, was recently instrumented with two different types of DFOS (one for strain and one for temperature measurement) both in the foundation and along the crown of the dam. Several measurement campaigns were carried out and the data collected are briefly presented in this paper and are compared with those obtained through traditional monitoring techniques.

Keywords: Distributed Optical Fiber Sensor · Smart monitoring · Low strain · Structural monitoring

1 Introduction

1.1 Dam Monitoring

In Italy, dams play a central role in electrical power production, temporal and spatial management of water resources, as well as in the mitigation of river floods. The exercise conditions of a dam must be constantly adapted to the environmental conditions (rainfall,

A. Ferrari et al. (Eds.): CNRIG 2023, SSGG, pp. 161–168, 2023.
https://doi.org/10.1007/978-3-031-34761-0_20

local temperatures and upstream water inflow) [1] and monitoring is a priority for real-time assessment of the structure's health state and safety conditions, also in relation to exposure to unexpected dangers. Commonly, monitoring is realized with many punctual sensors of different types and the large amount of collected data are then analyzed with methods that allow a reliable interpretation of dam body deformation [2–4]. In this stage the spatial interpolation of information is fundamental not only to obtain a complete vision of the over-all dam strain behavior but also to evidence local anomalies. To overcome limitations related to punctual measurements, the use of new advanced sensors based on optical fiber technology and, in particular, Distributed Fiber Optic Sensors (DFOSs) is now increasing [5]. They provide measurements of strain and/or temperature with high spatial resolution over long distances. The operating principle of DFOSs is based on the injection of a light wave into an optical fiber and on the analysis of the retroreflected light signal generated by the scattering effects in the silica which constitutes the fiber core. When the fiber cable is connected to a structure which deforms over time, the fiber develops axial strain which proportionally changes the backscattering signals. Analyzing the variation of the optical signal, the axial strain and temperature profiles along the fiber are obtained [6, 7].

This paper presents the preliminary results of a monitoring activity carried out on an Italian concrete dam using two types of DFOSs, one for strain and one for temperature measurements. The research is finalized to estimate the reliability and potentiality of such innovative sensors in monitoring the very low strains developed by dams in their exercise. To this aim, the DFOS data are compared with those collected using other, more traditional systems.

2 Case Study: Ponte Cola Dam

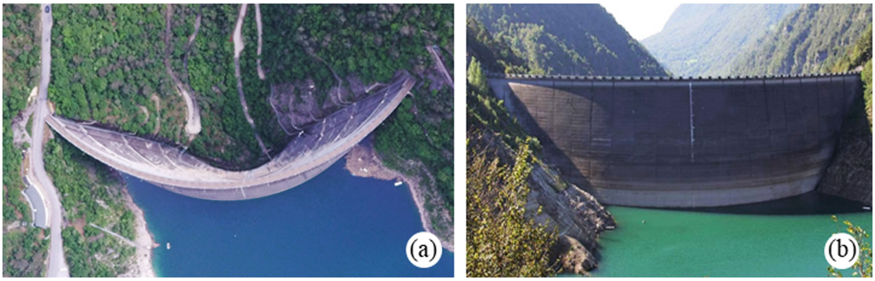

Fig. 1. **a.** Aerial view and **b.** upstream facing of Ponte Cola dam

The case study is Ponte Cola dam, a concrete dam located close to Garda Lake in the Valvestino valley (Brescia). The dam has a double curvature arch shape (Fig. 1) and is built on the rock formation of Upper Trias dolomite. The transition from the double arches to the rock is formed by a massive buffer, almost 24 m wide and 26 m high, which deeply fits into the rocky foundation. Laterally and below it, a waterproof screen is obtained through cement injections executed beyond 60 m of depth. The dam body, made up of 21 ashlars, is 122 m high (crowning height 505 m a.s.l.), has a development at the crest of 286.27 m and a total volume of 239′300 m^3. It was built between July 1960 and October 1962, with the purpose of storing water from the Toscolano and S. Michele streams in a reservoir, providing an energy reserve of about $45x10^6$ kWh.

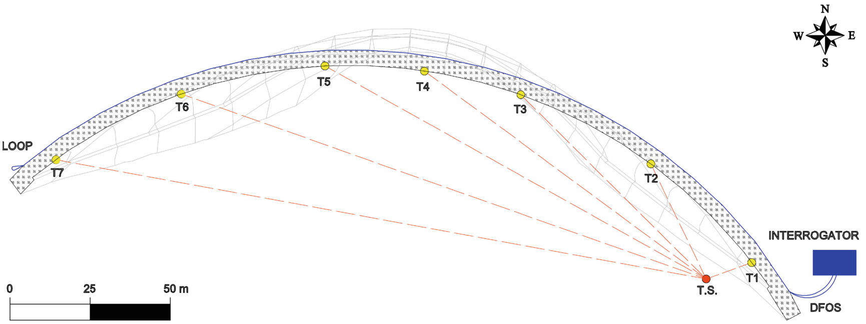

Fig. 2. Positioning scheme of the topographic targets (T1–T7), of the total station (T.S.) and of the DFOS (blue line) on the crown of the dam.

Since its construction, Ponte Cola dam has always been monitored with several instruments. In particular, at the beginning, within the dam body 22 thermocouples (10 thermocouples on the downstream face, 4 on the upstream one and 18 in the concrete casting) were installed, along with 65 removable strain gauges, 29 distance dilatometers and 124 thermo-extensometers. Despite the fact that only some of them are still functional, maintenances and upgrades of the system have been made periodically. The last important upgrade was realized in March 2021, when a topographic survey system capable of automatically detecting the position of about 30 targets on the downstream face was installed. Seven of these targets are distributed symmetrically at the top of the concrete body (Fig. 2). The system provides measurements with a fixed frequency and millimeter precision. In the same spring, an 80 m deep borehole, crossing about 40 m of concrete and 40 m of calcareous rock, was executed starting from a niche, specifically created in the dam body at the base of the central ashlar. Inside the borehole, 5 rod extensometers, aimed at measuring the displacements of the dam foundation and of the underlying soil layers, were installed in April 2021.

2.1 DFOS Installation

Between January and February 2021, two pairs of DFOSs were installed at the dam: one pair was positioned in a small groove created along the dam crown (Figs. 2 and 3a); the other was inserted in a borehole parallel to the borehole hosting the rod extensometers (Fig. 3b). The groove and borehole hosting the fiber cables were filled with mortar to ensure an efficient coupling between the fiber and the structure. To stay within the requirements of length, this paper presents only the measures related to the crown.

The installed DFOS are of two types: one is an armored corrugated optical fiber cable for strain measurement (BruSens® V9, Solifos), while the other is a cable for temperature measurement (BRUSens® DTS STL PA, Solifos) placed parallel to the first. The length of the cables is approximatively 200 m and 600 m for those installed in the dam foundation and at the crown, respectively. Temperature measurement is crucial for understanding the thermo-mechanical behavior, but is also the key for evaluating the thermal-optical effects on the cable strain. In fact, since the optical cable can deform due to traction or temperature variations, the cable's temperature must be known in order to estimate its thermal strain; this value can then be detracted from the total measured strain, therefore providing the mechanical component. This aspect is even more relevant in applications such as the one here described, where the expected strain ranges are modest (below 10^{-4}) but the temperature variations are relevant. In fact, the dam body is a massive structure that does not exhibit large deformations, despite the fact that the outside temperature can vary by more than 30 °C from summer to winter.

All the DFOSs are interrogated with a Brillouin Optical Frequency Domain Analyzer (BOFDA) from FibrisTerre (Germany) adopting a double-end configuration: the cable starts at a certain point, runs along the profile and, after a curve of 180°, it returns to the initial point, where the two cable ends are connected to the interrogator. This configuration allows a spatial resolution of 20 cm. The declared accuracies for strain and temperature measurement are of 2 $\mu\varepsilon$ and 0.1 °C, respectively.

Special precautions were followed to avoid any damage to the fibers during installation. Although the fibers are coated with special protective cores, they are unable to withstand excessive concentrated stresses or very small radii of curvature. Since the cables were installed in a loop configuration, they were protected through a specifically made device from developing excessive deformations at the loop point. In any case, even if the fiber breaks at one point, the double-end configuration still allows interrogation of the cable at both ends adopting a single-end configuration, ensuring measurements up to the point of breakage, albeit increasing the spatial resolution.

Fig. 3. Localization of the fibers installed on crown (**a**) and niche (**b**).

2.2 Measurements Campaigns

Some preliminary manual measurement campaigns were carried out after the installation of sensors. In this phase, two calibration tests (here not show for lack of space) were performed on the cables for temperature detection. Subsequently, three long surveys with automatic interrogation of DFOSs were conducted in August 2021 (26 days), in November-December 2021 (27 days) and in July-September 2022 (40 days). In these long surveys, the DFOSs were connected through standard communication cables to the interrogator located in the dam control house. In this way, it is possible to contemporary interrogate all four fibers and automatically record the data to a digital memory, without interruption and without the need for the presence of a technician.

The data obtained by the DFOSs are variations of strain or temperature with respect to an initial reference measurement. Thanks to the loop configuration, all measures are obtained in both "up-down" and "down-up" directions, which generally show high consistency with one another. Four typical temperature and strain profiles determined with fibers at the dam crown are shown in Fig. 4. To make their interpretation easier, they belong to the second and third periods and all vary with respect to the first reference measurement obtained on 02/08/2021 at noon.

It can be immediately noticed in Fig. 4a that for each date the temperature is approximately constant along the entire extension of the fiber. The two profiles recorded at November 2021 show a decrease of about 15 °C and 20 °C with respect to August 2021. In August and September 2022, instead, the temperature trend is again consistent with the reference measurement. Although the measurement is approximately constant, small peaks with an interspace of about 10–12 m are noticeable. Similar peaks are even more evident in the strain profiles. Consistent with the temperature variation, the strain measurements seem to depend on seasonality, emphasizing how the dam deformations are mainly due to variations in air temperature.

Figure 4 also shows high measurement consistency in the two directions, up-down and down-up, confirming the reliability of the measurements.

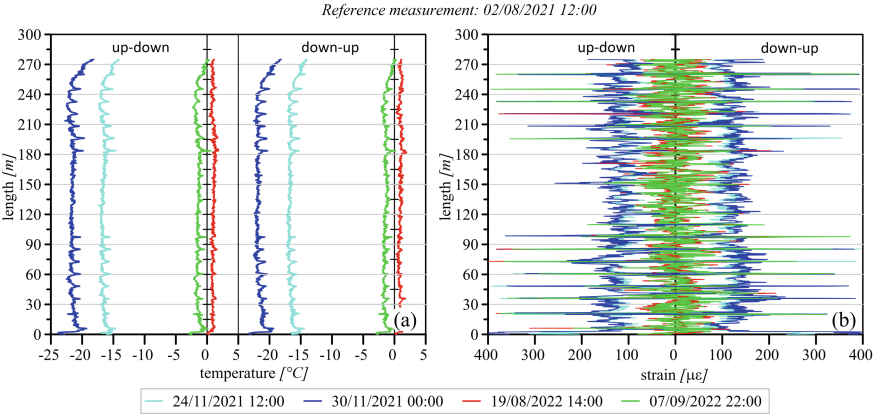

Fig. 4. Temperature (**a**) and strain (**b**) profiles acquired with DFOSs at the dam crown in 4 single measurements. Reference measurement: 02/08/2021 at noon.

3 Data Analysis

A first interpretation of measurements is carried out by comparing the temperatures measured by DFOSs with those obtained from thermocouples installed on the dam (Fig. 5). In this regard, three different sensors can be considered significant for comparison: one installed at an elevation of 490 m asl on the upstream side of the dam, measuring air temperature; one located at 440 m asl on the same side and measuring water temperature in the reservoir; one drowned in the concrete at an elevation of 490 m asl, recording temperatures inside the dam. The variability of air temperature is evident, both in the day-night and summer-winter cycles. On the other hand, the daily temperature variations in water and concrete are much less pronounced, underlining the great thermal inertia of these materials compared to that of air. It is important to note that the comparison here discussed is not reported to evaluate the reliability of the data acquired through thermal DFOS, which was already verified using the calibration tests, but only to show the high variability of temperatures in this structure with respect to the external temperature, and to highlight the importance of detecting the temperature in exactly the same position as the strain cable in order to obtain a proper measurement of strain.

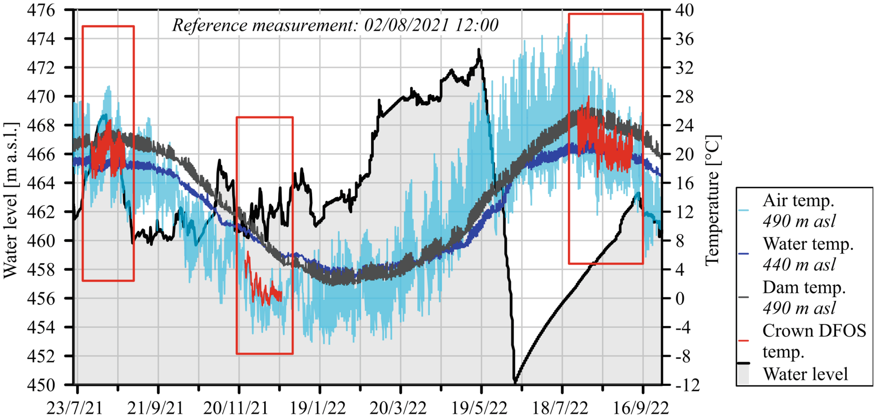

Fig. 5. Mean temperature in time obtained by DFOS in the 3 periods of survey compared with data acquired by some traditional temperature sensors.

Given the evident homogeneity of temperature variation profiles along the crown, it is possible to refer to an average temperature variation obtained for the entire DFOS profile for each recording. To compare its trend over time with that acquired using traditional sensors, the temperature variations obtained by DFOSs are translated by a value equal to the temperature recorded at the reference time (12.00 noon on 02/08/2022) by the concrete sensor. The results, shown in Fig. 5, show high consistency in the temperature trends. At the reference hour, the temperatures recorded in the concrete and air were 21.7 °C and 21.5 °C, respectively, indicating near thermal equilibrium. The data obtained with the DFOSs show greater temperature variability between concrete and water, but this can be explained considering that the fiber is installed on the outside surface of the dam, while the sensor is buried several meters inside the dam body. The measurement obtained from the DFOSs is more consistent with those recorded in air, but with less variability daily, indicating that contact with the dam surface and the thin layer of grout cementing the fiber to the dam allows for some thermal inertia.

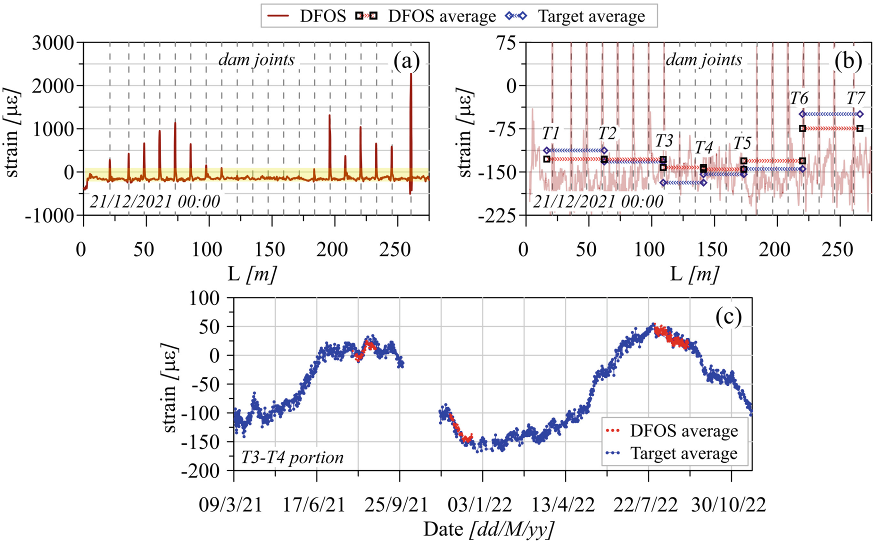

Fig. 6. **a.** Strain measurement obtained by the DFOS along the crown at 21/12/2021 00:00; **b.** zoom of plot a in the range of strain (75 με; + 225 με) with mean strain values in the portion between two nearby targets obtained with DFOS (red segments) and topographic data (blue segments). The position of dilatation joints is indicated by vertical segmented lines. **c.** Average strain of the segment T3–T4 measured with DFOS and topographic survey plotted vs time.

In order to assess the reliability of the strains measured with DFOSs, a comparison with the deformations obtained with topographic survey is attempted. In this regard, the average deformations of the sections between two consecutive targets are calculated based on the displacements measured by the topographic system. Even in this case, the deformations are obtained by assuming as reference configuration the position of targets at noon on 02/08/2022. A translation of the data acquired by topographic system is also applied, since the targets are located on the downstream side, while the DFOSs are glutted on the up-stream side of the dam. The spatially dense measurements provided by DFOSs are then cut into portions between two neighboring targets, and the average strain data in each interval are calculated. To give an example of the strain profiles obtained for each measure, Fig. 6a shows the strain obtained with DFOSs along the crown (ruby red line) on 02/12/2021. For sake of comparison, in Fig. 6b a zoom of the same plot in the range of strain (–75 με; + 225 με) is shown, in which the average strain measured by DFOS in the portion of crown between two nearby targets and the average strain calculated on the base of topographic surveys in the same portion are indicated respectively with red and blue segments. In all the portions the coherence between the data obtained with the two systems is evident, also considering the very small value of the average strains (less than 50 $\mu\varepsilon = 0.5\times10^{-4}$).

Another interesting feature clearly visible in the same figure is the presence of several strain peaks measured with the DFOSs, distributed at fairly regular distances. The strains associated with these peaks reach values exceeding 900 $\mu\varepsilon$, higher on the lateral sides and lower in the central part of the crown. Plotting the location of the expansion joints of the dam, it is evident that each strain peak corresponds to a joint, underlining the ability of the distributed sensor to pick up even such details. Finally, Fig. 6c shows the time trend of the average strain of the stretch T3–T4, located in the center of the dam (Fig. 2), allowing a broader comparison between data obtained over time by DFOSs and topographic measurements. Again, the measurements obtained with optical fibers show high consistency with data from traditional monitoring, and allow expansions and contractions of the dam to be followed in both the short and long term.

4 Final Remarks

The application of sensors based on optical fiber technology for the monitoring of Ponte Cola dam permits evaluation of the reliability of these innovative sensors for the in-site monitoring of modest strain (up to 10 $\mu\varepsilon$). The data demonstrate the ability of DFOSs to obtain strain profiles over a long span with small spatial resolution, an ability that permits detection of even local irregularities in the strain behavior. The paper also underlines the importance of measuring the temperature profile in order to obtain a proper strain measurement.

Acknowledgements. The research was performed with funding of Green Power spa and cofounded by the University of Padova within the program UNI-IMPRESA 2019 (project TITANO).

References

1. Dhandre, N.M., Kamalasekaran, P.D., Pandey, P.: Dam parameters monitoring system. In: 7th India International Conference on Power Electronics - IICPE, pp. 1–5. IEEE (2016)
2. Scaioni, M., Marsella, M., Crosetto, M., Tornatore, V., Wang, J.: Geodetic and remote-sensing sensors for dam deformation monitoring. Sensors **18**(11), 3682 (2018)
3. Su, H., Wen, Z., Sun, X., Yan, X.: Multisource information fusion-based approach diagnosing structural behavior of dam engineering. Struct. Control. Health Monit. **25**(2), e2073 (2018)
4. Lin, P., Li, Q., Fan, Q., Gao, X.: Real-time monitoring system for workers' behaviour analysis on a large-dam construction site. Int. J. Distrib. Sens. Netw. **9**(10), 509423 (2013)
5. Schenato, L.: A review of distributed fibre optic sensors for geo-hydrological applications. Appl. Sci. **7**(9), 896 (2017)
6. Soga, K.: Understanding the real performance of geotechnical structures using an innovative fibre optic distributed strain measurement technology. Riv. Ital. Geotech **4**, 7–48 (2014)
7. Cola, S., Schenato, L., Brezzi, L., Tchamaleu Pangop, F.C., Palmieri, L., Bisson, A.: Composite anchors for slope stabilization: Monitoring of their in-situ behaviour with optical fibre. Geosciences **9**(5), 240 (2019)