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Monitoring of ASR/ISR structural effects in Aguieira bridges

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Abstract

The São João das Areias and Criz II bridges were affected by internal swelling reactions of concrete, which particularly affected their piers and foundations. Laboratory tests diagnosed both Alkali-Aggregate Reaction and Internal Sulphate Reaction as the causes of those expansions. This situation motivated important rehabilitation works on these bridges. In the course of these works, a structural health monitoring system was installed in each of these bridges in order to characterize the structural effects of the swelling reactions, both in the loss of rigidity and the temporal evolution of this degradation.

The aim of this paper is to describe the instrumentation performed in these bridges and present the preliminary results achieved.

***Keywords**: ASR/ISR structural effects; concrete bridges; structural monitoring*

1. INTRODUCTION

A set of seven bridges located in the reservoir of Aguieira Dam, in the centre of Portugal, sharing the same structural solution and built between 1976 and 1979, was severely attacked by internal swelling reactions of concrete, which particularly affected bridge piers and foundations. Laboratory tests diagnosed both Alkali-Aggregate Reaction (AAR) and Internal Sulphate Reaction (ISR) due to Delayed Ettringite Formation (DEF) as the causes of those expansions.

The AAR was attributed to the use of alkali reactive aggregates, mainly quartzitic and granitic types. The aggregates will also have been an internal source of alkalis, since the measured levels of soluble alkalis in concrete samples extracted, expressed as Na_2O_{eq}, ranges between 0.93 to 8.13 (3.44 in average) kg/m^3 of concrete.

The ISR in these bridges was attributed to the high cement content employed, associated to the massive structural elements (foundations, piers and crossbeams). No information was obtained about the cement employed in these bridges, but the determinations of cement content in samples extracted confirms high dosages in some parts (higher than 400 kg/m^3), as well as high cement SO_3 contents (values between 1.48 and 4.44 %). These parameters, associated to the high alkalinity and presence of water, are crucial to trigger the ISR [1],[2].

In face of the problem, different approaches were taken by the Portuguese road authorities to overcome the situation and to allow the continued use of the road network [3].

One of the bridges, over the mouth of the Dão River, was replaced, due to the high cost of the rehabilitation works required. In three other bridges, it was decided to mechanically substitute the cylindrical piers by building a new annular cross section independent pier surrounding the old shaft. Micropiles were executed through the existing footings to support the new footings. These new piers were designed to have sufficient strength to support by themselves the deck, as it will be necessary in the case of the total loss of the original piers. The rehabilitation of the three remaining bridges was based on a single structural solution: the construction of six piles with a metallic casing around each pier and the corresponding pile cap. The pile cap has a prestressed connection with the pier in order to support the pier load when the stiffness of the immersed part of the pier decreases due to the swelling reactions. Additionally, a concrete covering was applied in the upper part of the piers, above the pile cap.

In order to monitor the structural effects of these reactions, in two of these bridges, São João das Areias Bridge and Criz II Bridge, a structural health monitoring system was installed. With the main goal of quantifying the transfer of load from the original pier to the new piles, as well the development of that transfer over time, the instrumentation was focused on two piers of each of these bridges. For this effect, a vertical strain gauge was placed inside each of the six piles of each pier. Complementary, some strains are also being measured at the surface of the original pier, as well as inside the additional concrete cover, besides the measurement of the rotation at the top of the piers, the movements of expansion joints and the ambient temperature.

This paper describes the structural health monitoring systems installed in both bridges and presents the preliminary results achieved.

2. THE BRIDGES AND THEIR REHABILITATION PROJECTS

2.1 The structural system

The superstructure of both bridges is a 15,20 m wide continuous pre-stressed reinforced concrete slab supported by 4 beams with variable height (2,0 m to 2,50 m) and width (0,50 m to 0,30 m). The slab has also a variable thickness from 0,16 m to 0,25 m at the connection to the beams. Both decks have crossbeams in the support sections as well as at the third-span sections.

The reinforced concrete piers are composed of a single shaft, with a hollow cross-section, in the shape of a rhombus with sharp bevelled edges, inscribed in a 6,0 m × 3,0 m rectangle, with a wall thickness of 0,20 m (Figure 2.1). The bearings are placed on column heads, whose height varies between 1,00 m and 3,00 m and with a thickness of 0,80 m.

The bridges have direct foundations and the connection to the piers is made through a basement with the same section of the piers but with 0.70 m in width. The footings, 1,50 m height, have an octagonal polygon section, with external dimensions of 8,00 m x 4,00 m (Figure 2.2).

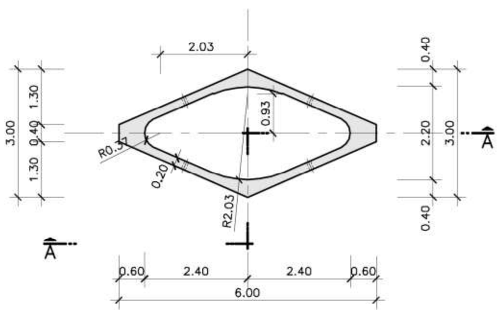

Figure 2.1: Current cross section of the piers

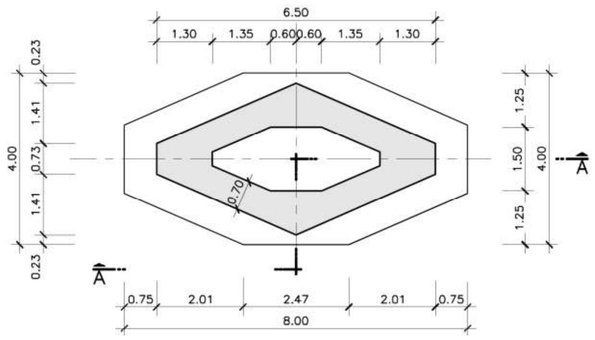

Figure 2.2: Basement and footing of the piers

2.2 Criz II Bridge

The bridge over the river Criz, located at the National Road EN 234, usually called Criz II Bridge, has a total length of 300 m with six intermediate spans of 40,0 m and two extreme spans of 30,0 m.

The height of the piers varies between 27 m and 70 m. The piers P2 to P6 are founded inside the reservoir (Figure 2.3), with a maximum foundation depth of about 35 m.

The first rehabilitation works were carried out between 2007 and 2010, involving the abutments and the deck, including the application of external prestressing in the deck, due to the poor performance of the original prestress system, as well the replacement of the bearing devices and the installation of damping devices in one abutment to improve seismic (pier P3).

Figure 2.3: Criz II Bridge before the before the piers and foundations rehabilitation

Later, in 2016 and 2017, the rehabilitation works of the piers and foundations took place, required due to ASR/ISR. It consisted in the execution of six piles around each pier, headed by a pre-stressed reinforced concrete pile cap (Figure 2.4), in order to ensure, if necessary, the load transfer to the new foundations [4]. The piles, with 1,50 m diameter, have a lost metallic jacketing.

Figure 2.4: Criz II Bridge at the end of the rehabilitation works

The shaft of piers P2, P3 and P4, which have total heights of around 60 m, were also reinforced by means of reinforced concrete jacketing from the top of the piles cap up to the top of the pier (level of 145,5 m). The interior of each of these piers was concreted with simple concrete, between the levels of 120,00 and 126,5, in order to avoid the additional pressure in the shaft, caused by the concreting of the pile cap.

2.3 São João das Areias Bridge

The São João das Areias Bridge over the Mondego River is located on the national road EN 234-6. It has a total length of 260 m, with five intermediate spans of 40,0 m and two extreme spans of 30,0 m (Figure 2.5). The height of the bridge piers varies between 17,2 m and 50,6 m.

Figure 2.5: São João das Areias Bridge before the rehabilitation of the piers and foundations

The deck and the abutments were rehabilitated between 2011 and 2012. The works carried out included the application of external prestressing in the deck, the replacement of all the bearing devices and the installation of four viscous dampers at the left abutment (E1).

The design for the rehabilitation of piers and foundations was mainly focused on the piers P2 to P5 [5], which are in the riverbed and were damaged by swelling reactions. Six piles with a diameter of 1,20 m were executed around the existing footing of piers P2 to P4 and connected to the pier through a pre-stressed pile cap, with a solution similar to that used in the Criz II bridge (Figure 2.6). The pier P5 was reinforced through the execution of micropiles, connected to the pier through a 1,50 m thick prestressed reinforced concrete pile cap.

A reinforced concrete jacketing was also applied around the shaft of these four piers from the top of the pile cap up to 0,5 m above the most frequent water level (126,30 m). In addition, the interior of these shafts was filled up to the top level of the jacketing with simple concrete.

Figure 2.6: São João das Areias Bridge at the end of the rehabilitation works

3. STRUCTURAL HEALTH MONITORING SYSTEM

Before the rehabilitation works a structural health monitoring system was installed in both bridges by NewMensus in order to check the safety of the bridges [6]. These systems were based on the measuring of rotations at the top of the piers and of joints displacements at abutments, besides the environment temperature.

During these works an innovative improvement of both Structural Health Monitoring (SHM) systems was carried out aiming to characterize the structural behaviour associated with the concrete expansion process, in particular the submerged part of the piers. This improvement is briefly presented below.

The development of the swelling reactions of the concrete will decrease, predictably, the stiffness of the concrete, leading to a load transfer from the original piers to the piles. It is intended, on the one hand, to quantify the degradation process of the affected concrete, that is, the loss of column stiffness, and, on the other hand, to measure its evolution over time. For this purpose, vibrating wire strain gauges were installed in the piles of the piers P2 and P3 of both bridges. The location of the sections instrumented in this way (sections S2 and S3) is identical in both bridges, as presented in Figure 3.1, relating to Criz II Bridge, and in Figure 3.2, referring to São João das Areias Bridge.

These strain gauges were installed when the reinforcement bars of the piles were still in the construction site (Figure 3.3). The strain gauges were fixed to two bars positioned for this purpose, which were welded to the main rebars of the piles (Figure 3.4). Then, the rebars were transported in a barge to the respective pier and installed inside the metallic jacket. Figure 3.5 shows a detail of a vibrating wire strain gauge during the installation of the reinforcement bars inside the metallic jacket.

For the same purpose, the original shaft of the instrumented piers was also instrumented. In these piers, at the same level of the sensors installed in the piles, a vertical strain gauge was installed on each face of the original shaft (Figure 3.6). In addition, two horizontal strain gauge were mounted. Figure 3.7 presents the layout of the instrumented sections at the bottom of two piers of each bridge.

In order to better characterize the planned load expected process, a section of the jacketed area of the P2 pier of each bridge was also instrumented (section S1). For this purpose, eight vibrating-wire embedded strain gauges were installed, two on each shaft of the jacketing (Figure 3.8).

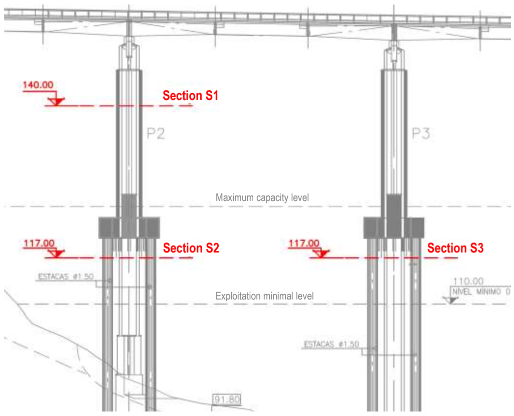

Figure 3.1: location of the instrumented sections at Criz II Bridge

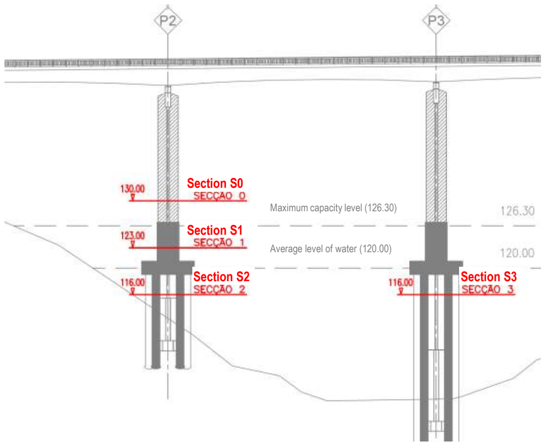

Figure 3.2: location of the instrumented sections at São João das Areias Bridge

Figure 3.3: Rebar instrumentation at the construction site

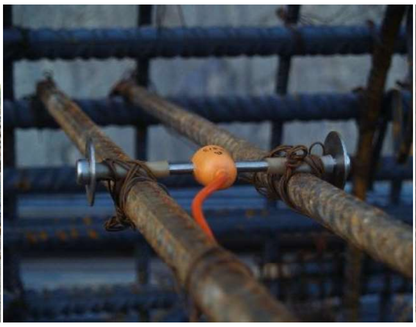

Figure 3.4: Strain gauge installed in the rebar of a pile

Figure 3.5: Strain gauges during concreting of a pile

Figure 3.6: Strain gauges in an original pier

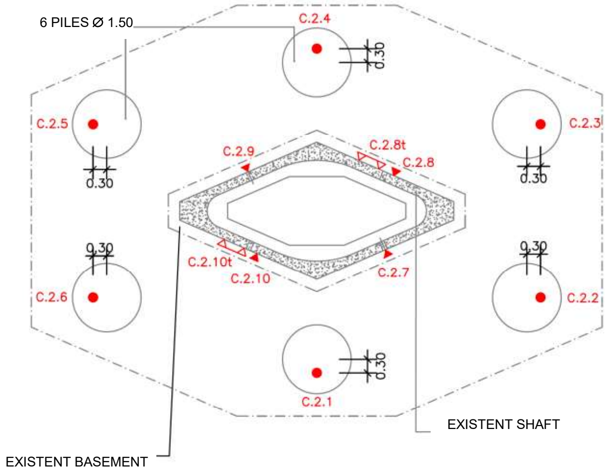

Figure 3.7: Layout of an instrumented section

Finally, as a significant part of the piers of the São João das Areias Bridge was not jacketed, in a section close to the top of the pier P2 (section S0), two surface vibrating-wire strain gauges were installed (Figure 3.9), as well as two LVDT (Figure 3.10), in order to monitor the evolution of its deformation.

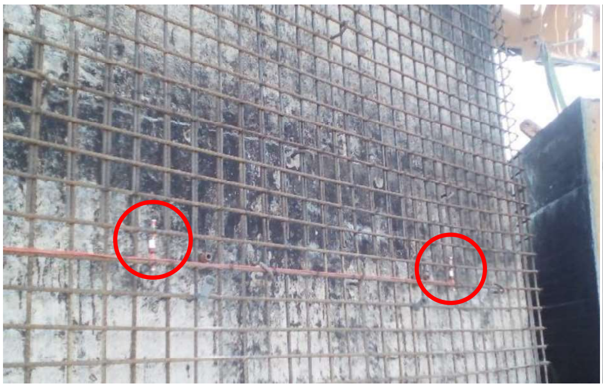

Figure 3.8: Strain gauges inside jacketing concrete

Figure 3.9: Strain gauge on the concrete surface

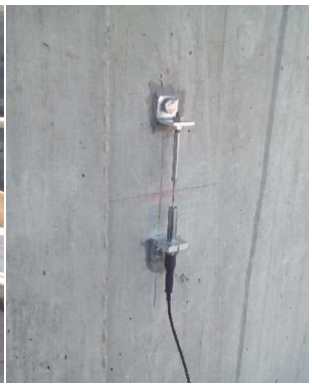

Figure 3.10: LVDT on the concrete surface

In addition, in section S1 of São João das Areias Bridge resistivity sensors were installed along the thickness of two walls of the jacketing, with different exposure conditions, in order to monitor the humidity inside the concrete. In the same section, three cores were extracted from the original concrete and instrumented in the laboratory with three pairs of graphite electrodes placed at different depths from the surface: 3 cm, 5 cm and 10 cm. Then, the cores were placed again in its original hole and properly buffered, to avoid the water entry except by the outside surface. Since the temperature affects the resistivity, a PT100 sensor was installed together each core, in order to be clear the significance of the measured values of resistivity provide by the graphite electrodes.

In both bridges, a data acquisition system (DAQ) composed by a DT80G logger and two Datataker CEM20 channel expansion modules, from Datataker, were installed. Also, a router Teltonika RUT500 was installed in order to allow the remote communication, essential for the automatic feed of the database, and thus, for the data processing and storage.

4. PRELIMINARY RESULTS

The slowness of swelling processes does not allow expecting drawing conclusions before a few years of monitoring. However, the initial results are fundamental for the characterization of the current situation and, consequently, for the detection of any changes resulting from the degradation of the concrete.

The rehabilitation works on both bridges ended in late 2017. In the first months of 2018, there was a recurrent power failure, so there are only consistent and continuous measurement records starting in August of that year. For this reason, the examples of measured values presented include only data obtained from this date.

The strains measured in the piles of pier P3 of the Criz II Bridge are shown in Figure 4.1. The seasonal effects are clear in this figure, as a result of the significant temperature variations measured in the piles by the thermistors installed inside the strain gauges (Figure 4.2). The daily average air temperature is also shown in Figure 4.2.

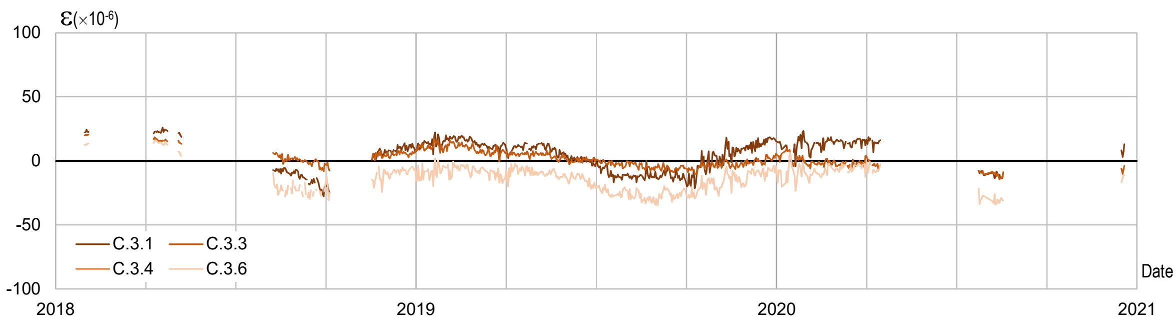

Figure 4.1: Criz II Bridge: strains measured in the piles of the pier P3

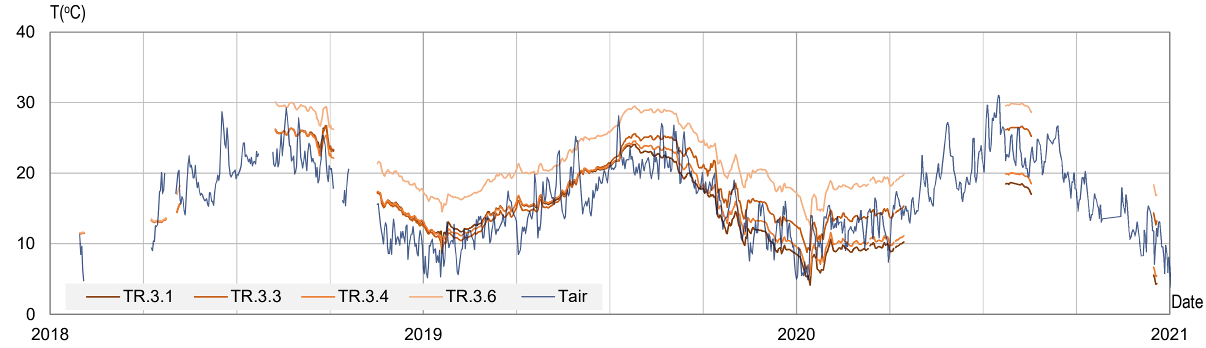

Figure 4.2: Criz II Bridge: temperatures measured in the piles of the pier P3

Among the experimental values obtained at the São João das Areias Bridge, Figure 4.3 shows the strains measured in the pier P3 piles, as well as in the respective original shafts. Also in these values, the effect of seasonality is clear. In fact, the variation of temperature measured by the thermistors integrated in the strain gauges is significant (Figure 4.4).

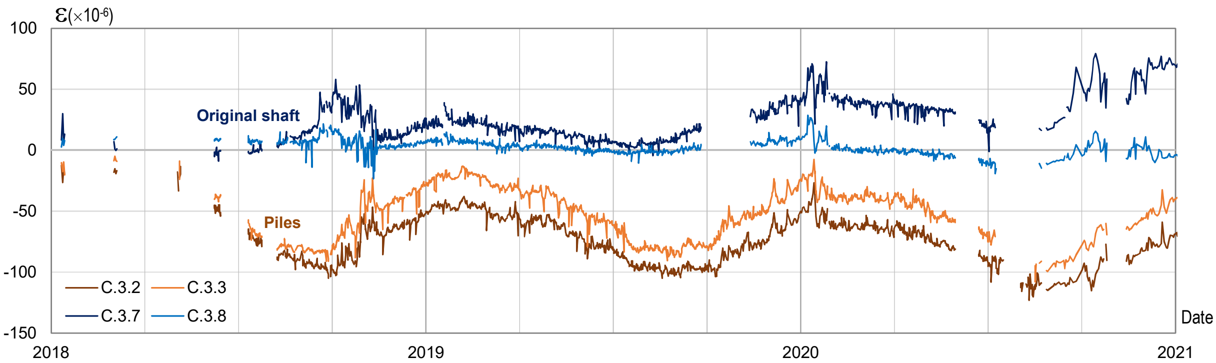

Figure 4.3: São João das Areias Bridge: strains in the piles and in the original shaft of the pier P3

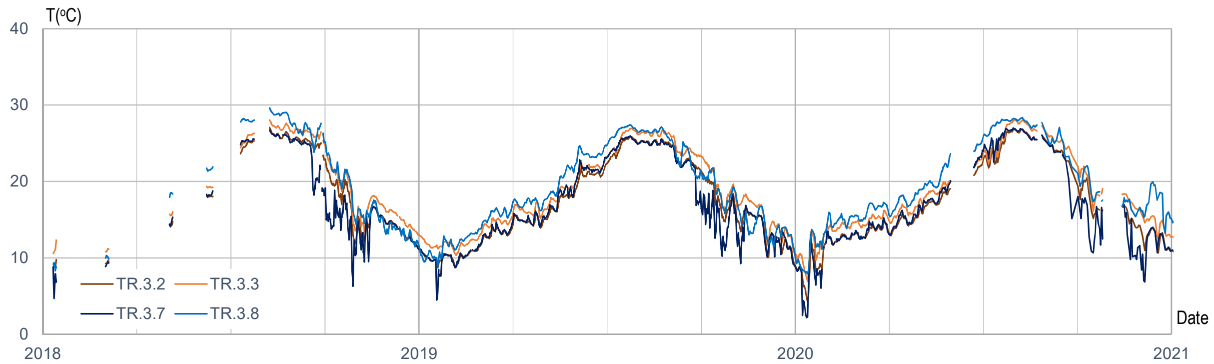

Figure 4.4: São João das Areias Bridge: temperature in the piles and in the original shaft of the pier P3

To give a general idea about the bridge global structural behaviour, the movements of the expansion joints at both abutments are presented in Figure 4.5, as well as the rotations at the top of piers P2 and P5 in Figure 4.6.

The behaviour of the joints is, of course, strongly associated with temperature variation, no other behaviour change was identified.

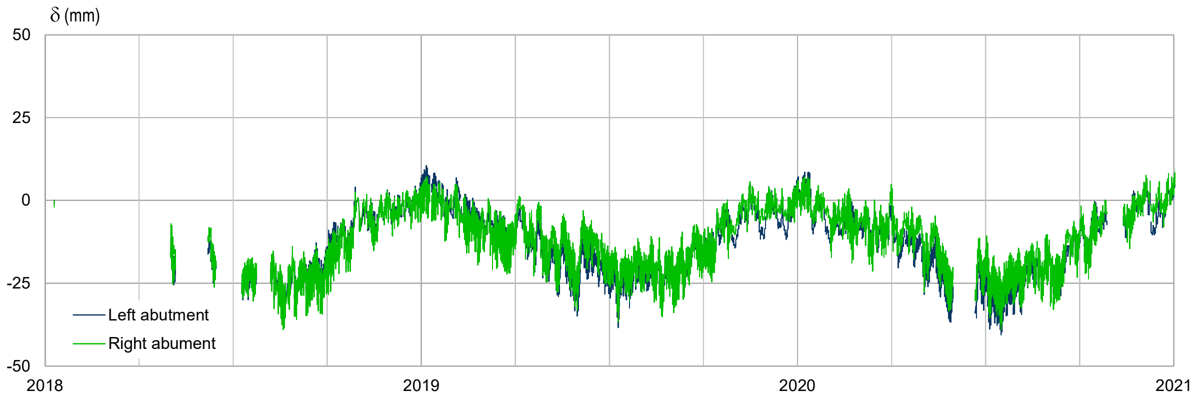

Figure 4.5: São João das Areias Bridge: movements of expansion joints

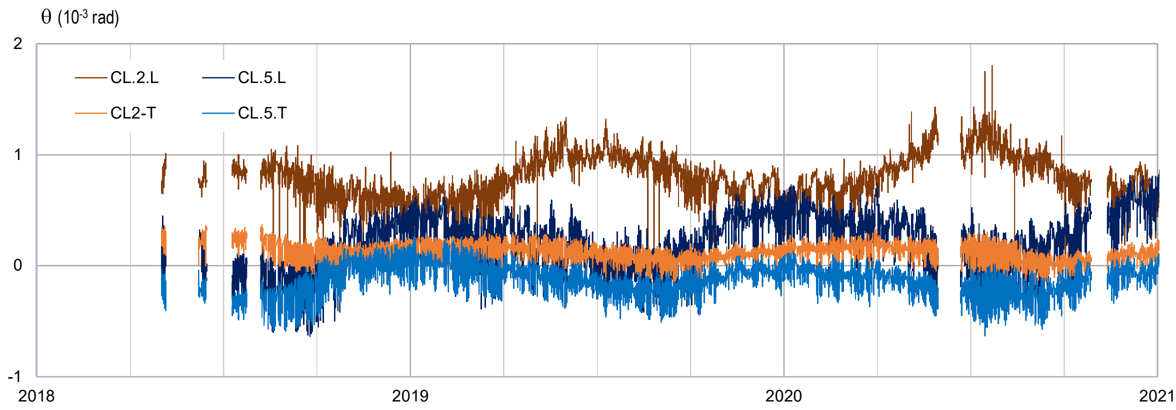

Figure 4.6: São João das Areias Bridge: rotations at the top of piers P2 and P3

Regarding the rotations at the top of the piers, two situations are distinguished: the transverse rotations remain stable over time, while the longitudinal rotations present greater variations but, fundamentally, associated with the seasonal cycle. An interesting point is the symmetry of the longitudinal rotations at these two piers, arranged symmetrically in relation to the centre of the bridge.

5. ANALYSIS OF PRESENTED DATA

The values measured by the SHM system over time include the thermal effect on structural behaviour. The identification of structural changes requires the removal of those effects.

For this purpose, the Multiple Linear Regression (MLR), a statistical process control tool, was applied to time histories of the different measured parameters. The aim is to reproduce the part of the variance in measured parameters associated with changes in environmental and operational conditions [7].

Assuming that the variation of the measured values in the structure results from temperature changes, the relationship between the dependent variable y (observed values) and the explanatory variables x can be expressed by:

$$y = A_0 + \sum_{1}^{n} A_i x_i + \varepsilon \quad (1)$$

The ambient temperature and the temperature inside the structure (inside the piles or the piers) in the instrumented sections were considered as explanatory variables.

If the MLR model is adequate, the difference between the measured and predicted values, ε, should be random samples with normal distribution. Any deviation could be an indication of an extraordinary event occurrence or changes over time.

As the structural effects of the temperature variations are present in the different measured parameters, only a part of the acquired information was selected for presentation.

In Figure 5.1, the strains variations measured in the pile 3.1 of Criz II Bridge are represented, as well as the corresponding values estimated by the MLR model. Using this model to remove the temperature effects, the residual values of MLR, meaning the difference between the measured values and the values estimated by the model, are shown in Figure 5.2.

Similarly, the strains variations measured in the pile 3.3 of São João das Areias Bridge and the corresponding values estimated by the MLR model are represented in Figure 5.3. The resultant residual values are shown in Figure 5.4.

Finally, the same procedure was applied to the values of the variation of the gap at the right abutment of São João das Areias Bridge. Thus, the measured values and the values estimated by MLR model are represented in Figure 5.5. The corresponding residual values are shown in Figure 5.6.

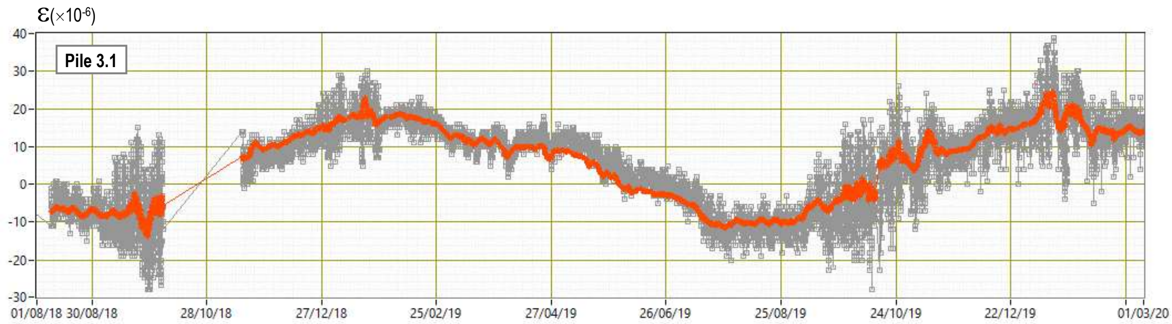

Figure 5.1: Strains in pile P3.1 of Criz II Bridge: measured values and values estimated by MLR model

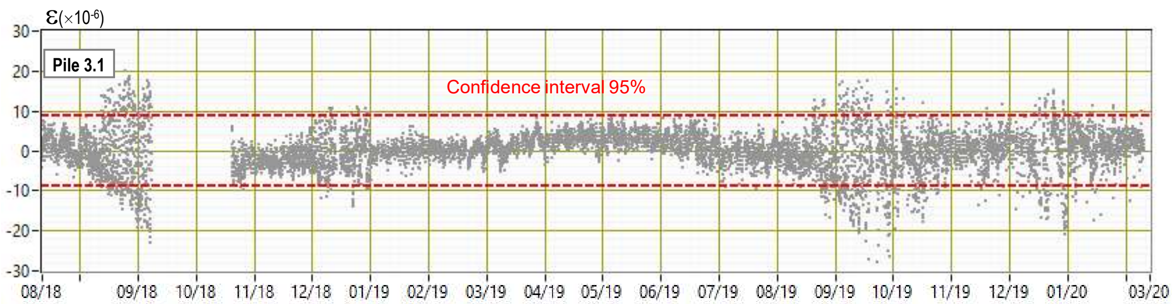

Figure 5.2: Strains in pile P3.1 of Criz II Bridge: residual values of MLR

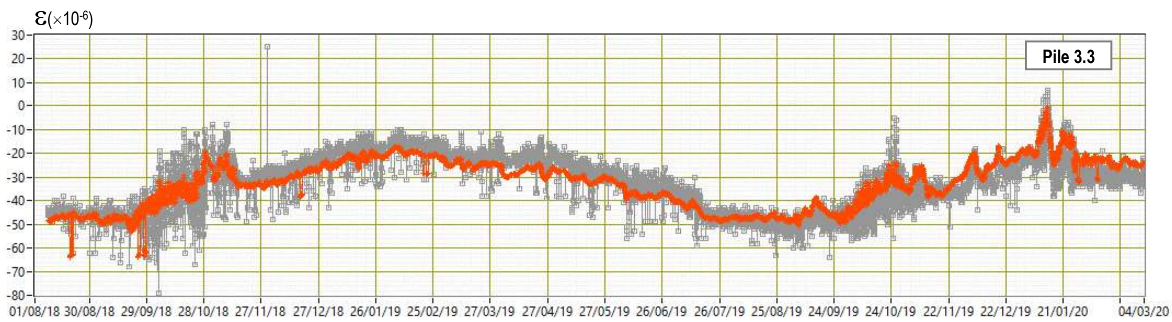

Figure 5.3: Strains in pile P3.3 of S.J.A. Bridge: measured values and values estimated by MLR model

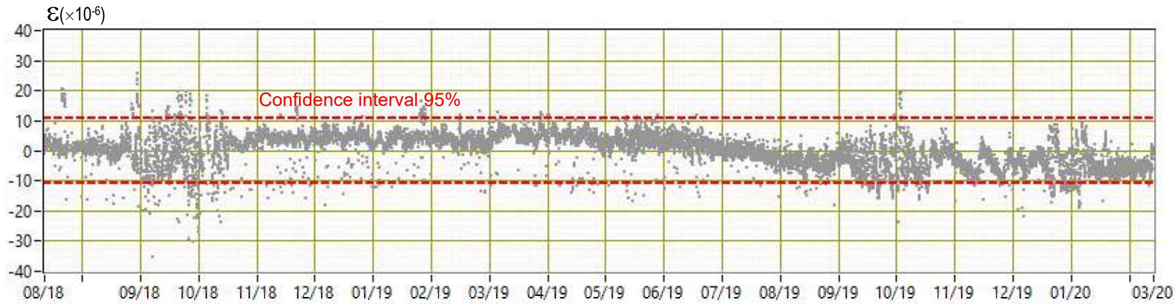

Figure 5.4: Strains in pile P3.3 of São João das Areias Bridge: residual values of MLR

The analysis of these figures allows concluding that after the period of little more than a year of monitoring, it is not yet possible to identify variations in behaviour that can be clearly associated with stiffness losses resulting from the swelling reactions of the concrete.

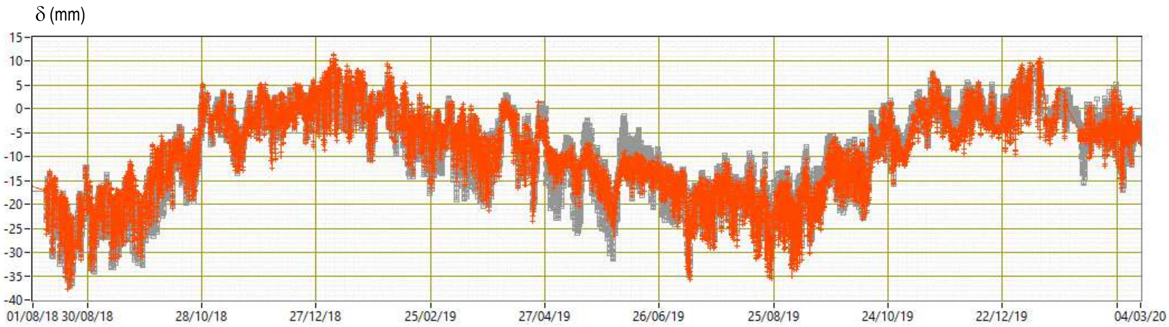

Figure 5.5: São João das Areias Bridge: measured values of the variation of the gap at the right abutment and values estimated by MLR model

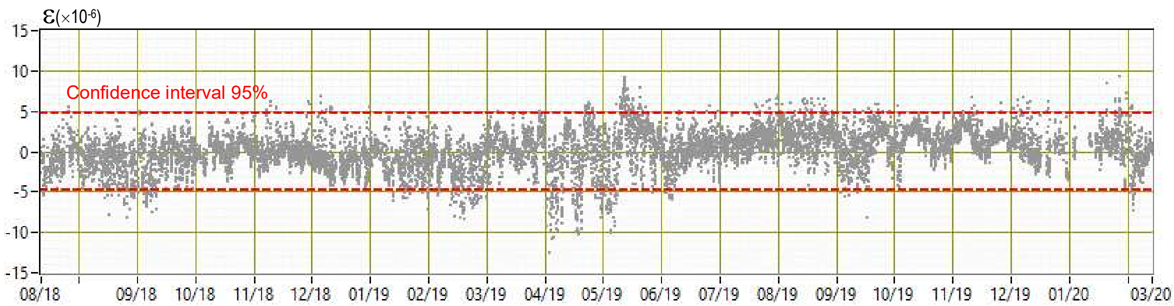

Figure 5.6: Variation of the gap at right abutment of São João das Areias Bridge: residual values of MLR

6. FINAL REMARKS

The structural health monitoring systems installed on the Criz II and São João das Areias Bridges, in addition to the contribution to the efficient management of these bridges, is an excellent opportunity to characterize the structural effects of the swelling reactions of concrete. In effect, the degradation of the concrete resulting from the AAR and ISR swelling reactions will cause a loss of stiffness of the inferior part of the piers, leading to a load transfer to the piles.

These monitoring systems were designed with a great focus on this issue, comprising the measurement of strains within the concrete of the piles of piers P2 and P3 of both bridges and the measurement of strains on the concrete surface in the lower part of the piers, below the pile caps.

The slowness with which expansive phenomena are processed requires a longer monitoring time to allow the drawing of consistent conclusions. However, it is expected that future results are relevant for a better understanding of the performance of these structures and, mainly, for the contribution that the acquired knowledge will give to the reasoning of decisions related to other works affected by swelling reactions.

7. ACKNOWLEDGMENTS

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