Structural Health Monitoring of concrete bridges

Case Study: The São João das Areias bridge

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Abstract

The present paper presents the structural health monitoring carried out on the São João das Areias bridge. This bridge was monitored during the foundations and pillars rehabilitation works, that has shown some structural problems related to alkali-silica expansive reactions.

The monitoring system installed on the bridge predicts an ongoing monitorization of several entities that most characterize the structure behaviour. The main results achieved during a period of a year of the ongoing monitoring were used for the numerical model calibration. This model, when well calibrated, was the essential tool for simulation possible structural anomalies that might occur on the bridge and evaluate all the effects in the structure.

The monitoring system installed included the development of a statistic model that can predict the structure behaviour through the correction of environmental effects. In this way, it was possible not only to control deviations from the predictable behaviour but also to estimate alert states associated with damage limits. Finally, the numerical model allowed the study of the alert meaning in the integrity of the different instrumented sections.

Keywords: *structural monitoring; different type of sensors; alert states; deterioration effects, numerical models*

1. Introduction

Monitoring structures has proven to be a valid strategy for the follow up for the effective structural condition. The real-time measure of some entities allows an immediate diagnosis, very useful to weather possible damages before they became serious problems.

This paper is referred to the structural monitoring system installed on the São João das Areias bridge and is owed to an expansive process of the concrete material due to alkalis-silica reactions. The main anomalies lie at the foundation level and pillars bases that had shown some intense cracking with potential implications on the structure safety.

The structural monitoring that took place on the bridge is presented with the main results and their use in the numerical model calibration. Studies on damage scenarios and alert levels will also be presented with some conclusions.

2. Structural Health Monitoring (SHM) System

Structural health monitoring can be defined as a non-destructive in-situ structural evaluation method that uses any of several types of sensors which are attached to, or embedded in, a structure. These sensors obtain various types of data which are then collected, analysed and stored for future analysis and reference. The data can be used to assess the safety, integrity, strength, or performance of the structure, and to identify any damage in it. SHM normally refers to activities focussed on assessing the condition of the structure.

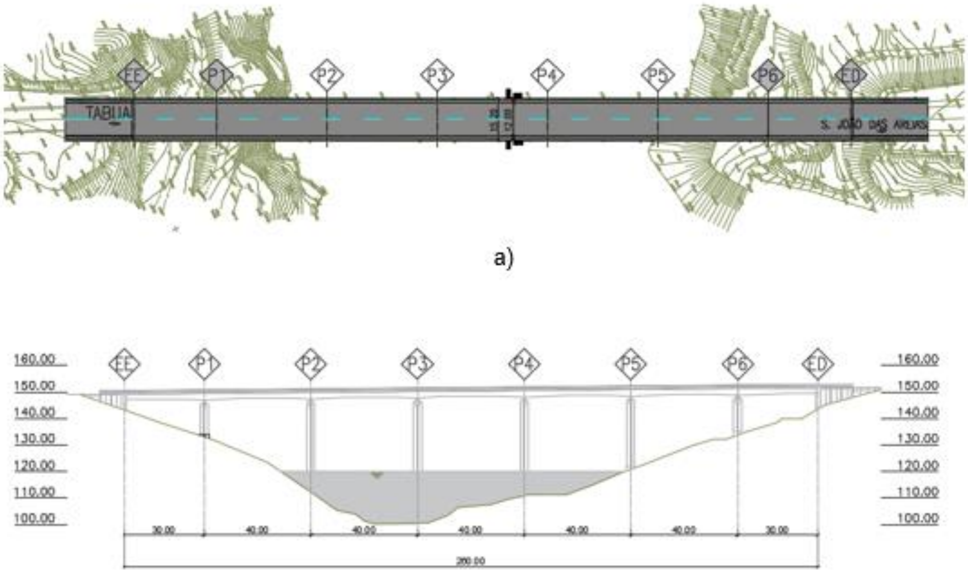
2.1. SHM System Components

As stated before, structural health monitoring refers to the continuous or periodic monitoring of a structure using sensors that are either embedded in it or attached to it. The data achieved by the sensorial system are, at a first place, saved in the Data Acquisition System that can either process it or send it directly through the communication system. In the second case, the data is then saved and stored for later transformation in valuable information to the structural behaviour analysis. SHM systems are applicable to all types of civil engineering structures, including concrete bridges. A modern SHM system will typically consist of five common components, namely:

- A sensorial system;
- Data Acquisition System (DAS);
- Communication system;
- Storage and diagnostics of processed data and;
- Structural behaviour analysis.

3. The São João das Areias bridge

The São João das Areias bridge is located in the Coimbra district. The bridge (Figure 1), designed by Prof. Edgar Cardoso and built in the late 70s, presents a prestressed and reinforced concrete deck with 260m length, distributed through seven different spans, five of which with 40m of length and the other two with 30m.



a)

b)

Figure 1: The São João das Areias bridge

The cross-section is formed by a beamed slab deck with four longitudinal beams with variable height (2,0m to 2,50m) and wide (0,50m to 0,30m). The slab thickness is also variable with and a minimum of 0,16 and a maximum of 0,25 m in the connection to the beams.

The bridge is supported on six pillars, numbered between P1 and P6 and ranging from Tábua to São João das Areias (Figure 1). All the pillars have the same section (Figure 2) which is a hollow lozenge with 0,20 m in width and with axles length of 3 m and 6 m.

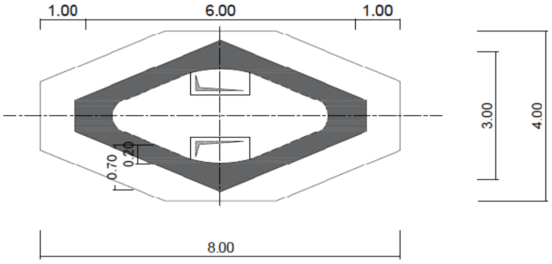


Figure 2: Pillars and basements section

The bridge has direct foundations and the connection to the pillars is made through a basement with the same section of the pillars but with 0.70m in width and axles length of 4m and 8m. In what concerns to the connection between the deck and the infrastructure, the pillar P2 to pillar P5 requires a fixed support in the two directions. In the case of pillars P1 and P6 as well as the both abutments the connection is based on a support that is longitudinal free and transversal fixed.

3.1. Monitoring System

The monitoring system consists of several electrical sensors for measuring entities such as longitudinal and transversal rotations on the top of all the pillars, joint displacements on both bridge abutments and air and material temperature. The Data acquisition system is consisting of a DT80 and a CEM20, two equipment from Data Taker. The data communication is made through a ethernet protocol and stored in a website to be easily looked up.

3.1.1 Rotations on the top of the pillars

Both longitudinal and transversal rotations are measured through electrical inclinometers using the type LSOC-1-C present on Figure 3. All the six pillars were monitored with two of those equipment, one that is responsible for measure longitudinal rotations and the other for transversal rotations.

Figure 3: inclinometers of th type LSOC-1-C

3.1.2 Joint displacements

Figure 4 shows the type of displacement sensor used on this case study. The joint displacements were measured using the LVDT type DCRH2000C/371 and it’s relevant to mention that positive results mean a joint opening and consequently a deck shortening.

Figure 4: LVDT type DCRH2000C/371

3.1.3 Air and concrete temperature

Temperature effects have a huge influence on the structure behaviour, it is not only responsible for structural changes but also affects the sensor equipment installed. The temperature sensors used was those of the type PT100 presented on Figure 5.

Figure 5: PT100 sensor temperature type

3.2. Main results achieved

Figure 6 and Figure 7 show the results measured from the temperature sensors installed on the deck, span T4 and on the pillar P3, while Figure 8 show the results for the transversal and longitudinal rotations on pillar P2 and Figure 9 show the joint displacements on the both right and left bridge abutments.

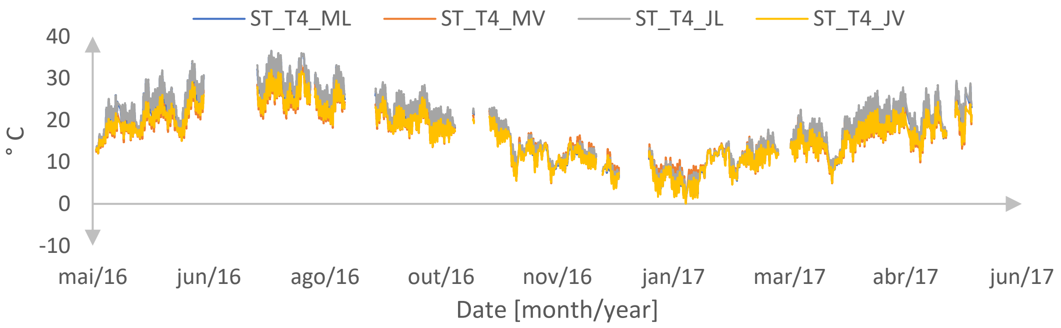


Figure 6: Concrete temperature in the span T4

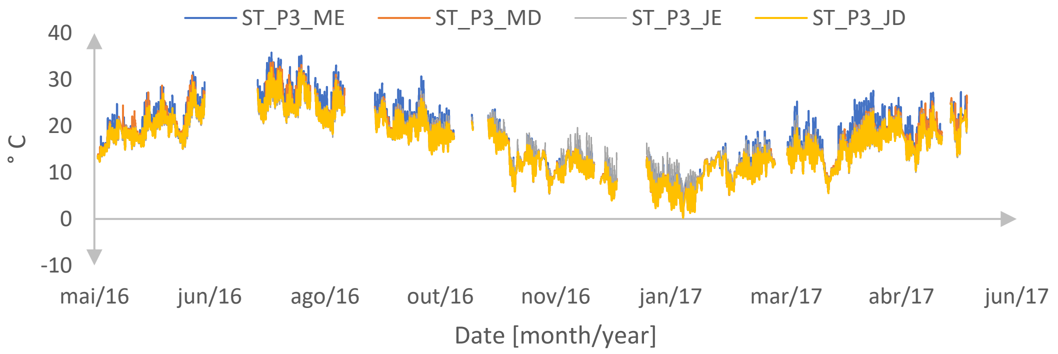


Figure 7: Concrete temperature in the pillar P3

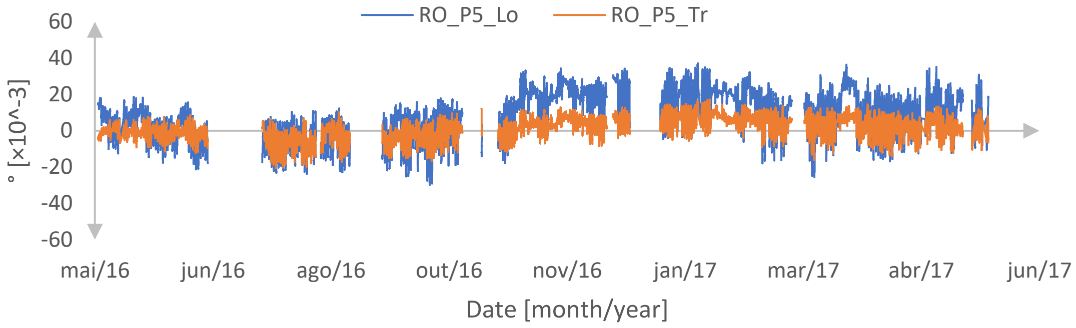


Figure 8: Longitudinal and transversal rotations on the top of the pillar P5

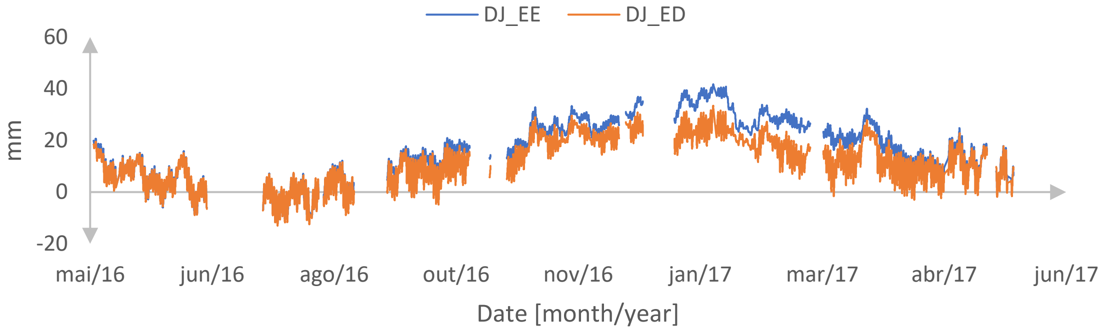


Figure 9: joint displacements on right and left abutments

The results achieved show a tendential structure behaviour strongly connected to the environmental effects, particularly related to the season and diary temperature evolution. The slow changes in the joint displacements and pillar rotations are related with the clear season changes felt in the local, during the year. Figure 6 and Figure 7 show the seasonal effect and allows a distinguish of what is considered as the hot months (May to September) and the cold ones (October to March). In the case of structures like bridges these variations are related to the uniform temperature component and to the combination of its effects on pillars and deck (Reis, 2001).

Through those figures is also perceptible that there were diary changes associated to sunstroke and related to differential temperature component which introduced on the bridge some reversible displacements and rotations.

4. The São João das Areias bridge behviour

4.1. Numerical model of São João das Areias bridge

Based on the bridge configuration, in the three-dimension model of São João das Areias bridge were used several elements to model the different structural elements. The beams were individually modelled using a frame element with a T section and considering their development in the longitudinal direction of the bridge. A shell element with the thickness of 0,205m was used to represent the span slab. To represent the pillars, as they have the same section in all their development, a frame element was used. Their foundations were represented as an inlay while the abutments were considered as longitudinal free and transversal fixed supports. The all model can be seen at Figure 10.

Figure 10: São João das Areias bridge numerical model

As mentioned before, the model calibration was done recovering to the results achieved during a year of observation. The Table 1 refers to the numerical values obtained in the model after attention calibration and to the comparison to the real ones.

Table 1: Numerical and real values for the different entities

Entities	Real values	Numerical values	Error
DJ_EE	5 mm	5,1 mm	2%
DJ_ED	11 mm	10,1 mm	8%
RO_P2_Lo	$30,0\times10^{-3}$ °	$28,36\times10^{-3}$ °	5%
RO_P2_Tr	$12,0\times10^{-3}$ °	$14,32\times10^{-3}$ °	**16%**

The model results present in the table above were corrected by a transformation factor (1,25 in the longitudinal direction and 1,30 in the transversal direction) to considered the pillars modelling with a frame element instead of considering shells element to model the six different pillars walls. The table 1 also shows that the error between the real values felt by the bridge and the numerical ones are not significant. All the entities have errors with rates around the 10%.

4.2. Damage scenarios analisys

The case study presents a bridge which pillars bases and foundations had shown some damage due to concrete deterioration. While the ongoing rehabilitation works are not concluded, the risk of possible structural changes in this particularly area is not guaranteed. As the consequences for the entire structure are completely unpredictable it is imperative to try to anticipate those effects.

For this propose, the most convenient way to do that is recovering to the calibrated model and simulate a damage in the pillar bases through, for instance, a rotation imposition. The selected pillars were the P1 and P2, as they have different kind of connection to the bridge deck and the effects on the structure are unsurprising different. In this case, the rotations were imposed with the value of $1,0\times10^{-3}$ ° and the bridge deformed shape for the two cases are present on Figure 11 and Figure 12, individually for pillar P1 and pillar P2.

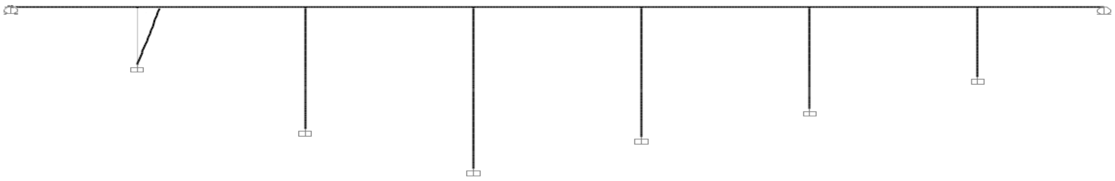


Figure 11: Bridge deformed shape when the rotation imposition on the pillar P1

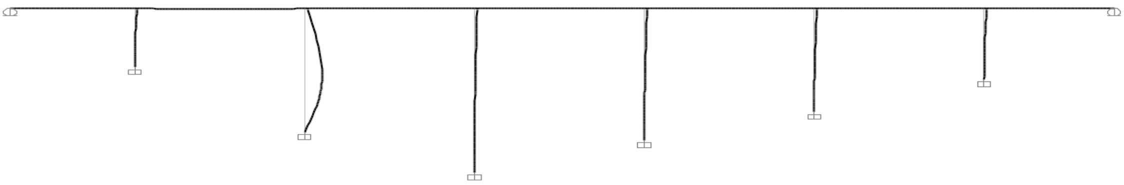


Figure 12: Bridge deformed shape when the rotation imposition on the pillar P2

The single effect of this action has meaningful effects not only on the pillar itself with top rotations of $1,0\times10^{-3}$ ° for pillar P1 and $0,6\times10^{-3}$ ° in the case of pillar P2, but also in what concerns to the deck. In this, the model shows joint displacements with values of 1,5mm when the study is carried on, of course, the pillar P2, the one that is fixed to the span.

4.2.1. Alert limits and surveillance system

To complete the structural behaviour analysis and to detect possible structural changes, the structural health system included the development of a statistic model able of estimate the structural behaviour evolution through the isolation of environmental effects, in this case the measured temperatures. This model generated a series of estimated values for the entities that most characterize the structure behaviour. The difference between these values and the real ones was considered an indicator named *resíduo* and was carefully evaluated over time, because, fundamentally, it draws attention to any behaviour change and allows for an immediate action. For other hand, it was the essential bases for the implementation of damage limits. Figure 13 shows the *resíduo* indicator for the pillar P2.

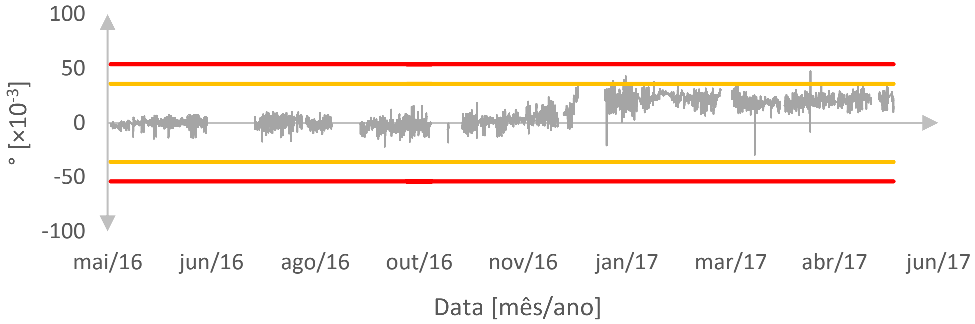


Figure 13: *Resíduo* indicator of pillar P2 longitudinal rotation

The red and yellow lines present on the figure are related to the red and yellow limits. Those limits were created and defined by the design team and means an alarm level which means an abnormal rotation value. When the indicator values reach these levels the monitoring system sends a notification to all involved employers.

4.2.2. Structural implications of alert limits

Finally, the study carries on with an evaluation of the physical meaning of yellow and red limits. So, for the case of pillar P2, the yellow and red limits are reached when the rotation values are 36×10^{-3} ° and 60×10^{-3} °, respectively. Figure 14 represents the N-M interaction diagram for the pillar section and shows the par of values for the bending moment and the compression level that the pillar was submitted, for both limit cases. The values also can be seen on Table 1.
For this procedure, the structural evaluation includes a second order analysis. So, in a simple way, to consider the material non-linear behaviour the initial stiffness was reduced in 50%. While the numerical model analysis itself takes in account the second order effects through the structure geometry non-linear consideration.

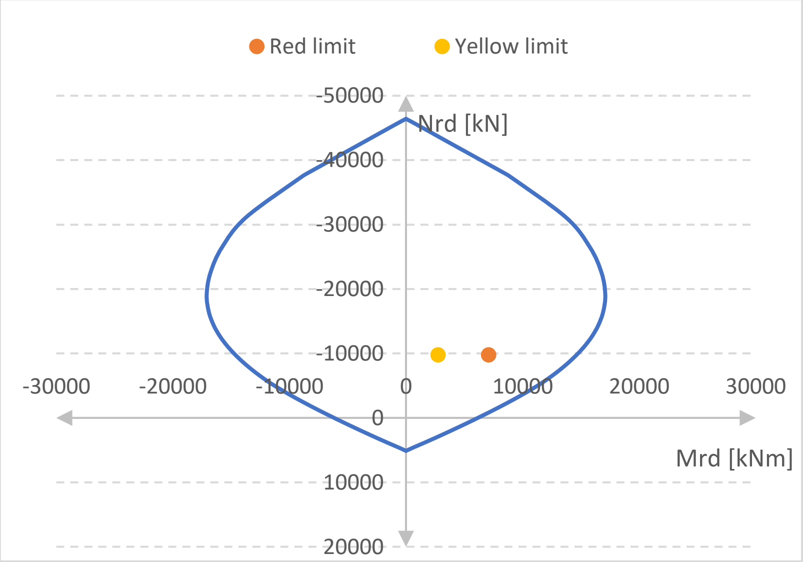


Figure 14: N-M interaction diagram

Table 2: N and M values for limit alerts

	N	M
Yellow limit	-9740 kN	2414,0 kN.m
Red limit	-9740 kN	7093,2 kN.m

The chart present on Figure 14 shows that, for the case of pillar P2, when the rotation values reach the yellow limit, the bending moment expansion values are near 20% of section capacity. On the other hand, as predictable, regarding to red limit values, its implications are worst. In this case the bending moment expansion presents values about 50% of all section capacity.

5. Conclusions

Nowadays, structural health monitoring has become a more and more way of control, manage and evaluate existing structures. Due to many developments in technological areas is now acceptable the use of new sensor and data acquisition systems equipment to get access to essential information about structures behaviour.

In the São João das Areias bridge is clear that the results achieved during the period of a year of the ongoing monitoring reveals that the structure behaviour is very connected to the environmental changes on the local.

A more rigorous evaluation allows the collect of displacements and rotations real values used for the numerical model calibration which propose is making it able to recreate the structure behaviour. The comparison between the real values and the numerical ones reveals errors with values below 10%, which can be considered extremely good.

In what concerns to the statistic model, it estimated the structure behaviour through the isolation of the environmental effects. The different between the real values and the estimated ones generated an indicator that was also carefully controlled. This indicator was the essential bases for the determination of the yellow and red levels considered like ultimate limits for the deflection of the structure behaviour from what was considered as predictable.

Finally, with the well calibrated model it was possible, not only to simulate damages in the pillars bases related to the deterioration conditions and evaluate the effects on the structure, but also to study the influence of the damage limits in the structure integrity. The second point allowed to conclude that, in what concerns to the pillar P2, a rotation on the top with yellow and red limit values leads to bending moment values expansion around 20% and 50%, respectively, of the section capacity.

6. References

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