

Upgrading of São João Bridge Structural Health Monitoring System

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Summary

São João Bridge is a railway bridge, 1028 m long, with a main span of 250 metres. This bridge was instrumented during its construction and its structural behaviour has been experimentally followed since then. After fifteen years in service, the system used for this purpose was updated in order to get automatic data acquisition as well as dynamic monitoring, with remote access and real time data processing. This paper presents how the original sensors were integrated in the new structural health monitoring system and the new devices used. Finally, some experimental results are presented and compared with the analytical values predicted by a finite element model.

Keywords: prestressed concrete bridge, structural health monitoring, automatic data acquisition, hydrostatic levelling system, time dependent behaviour, real time data processing.

1. Introduction

São João Bridge is a railway bridge crossing the River Douro, in Oporto, Portugal. Designed by Edgar Cardoso, it has been open to traffic since 1991.

This bridge was instrumented during the construction and its structural behaviour has been experimentally followed since then. The original observation plan includes the measurement of strains and temperatures in concrete, horizontal displacements at expansion joints in abutments, vertical displacements in the deck and rotations at the bottom and top of the piers. However, the observation of the bridge was based only on periodical measurements.

Recently, the structural health monitoring system was updated in order to get automatic data acquisition as well as dynamic monitoring, with remote access and real time data processing. All the original sensors that could be used by the automatic acquisition system were kept and several news sensors were introduced to measure vertical displacements, horizontal displacements at expansion joints, and to measure rotations. The data acquisition is guaranteed by nine data loggers connected through a local fibre optic cabling network. All the measured values are processed by an industrial computer kept in the bridge.

After the description of the bridge, this paper presents the experimental procedures used in upgrading the structural health monitoring system, as well as some experimental results measured since bridge construction, which are compared with the analytical values predicted by a finite element model.

2. Brief description of the bridge

São João Bridge is a prestressed concrete bridge, with a total length of 1028 m, including a main span of 250 metres, two 125 m side spans and approaching viaducts from both sides of the river banks (Fig. 1).

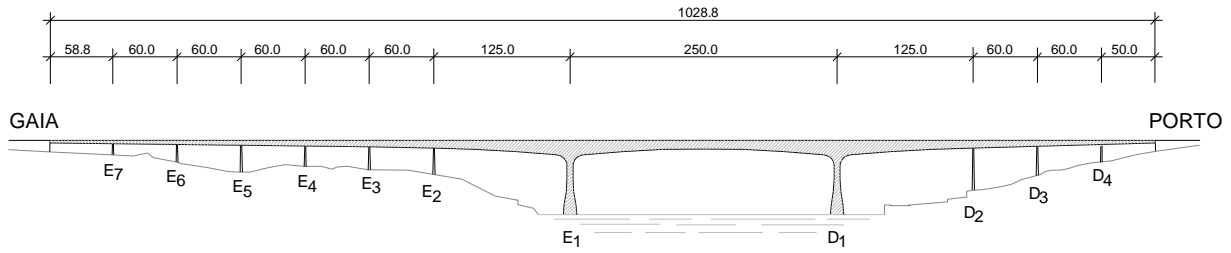


Fig. 1: São João Bridge general layout

The twin-cell box main girder, built by the cantilever method, has a trapezoidal cross-section with a variable height of 12 m near the main piers decreasing to 7 m at midspan. The bottom slab thickness decreases from 2.45 m near the main piers to 0.30 m at midspan.

The main piers, 50 m high, have a circular cross section becoming rectangular at the top of the piers.

To prevent the long-term deflection due to creep effects in concrete and losses in prestressing steel, the bridge has external prestressing in the three major spans. For this purpose fourteen cables of 5000 kN were used, and it is possible to increase the number of cables to twenty [1].



Fig. 2: General view of São João Bridge

3. Original observation plan

The original observation plan includes the measurement of strains in 14 sections (Fig. 3), the measurement of temperatures in 6 sections (S1, S6; S7, S9, S11 and S12), vertical displacements, rotations and horizontal displacements at expansion joints in both abutments.

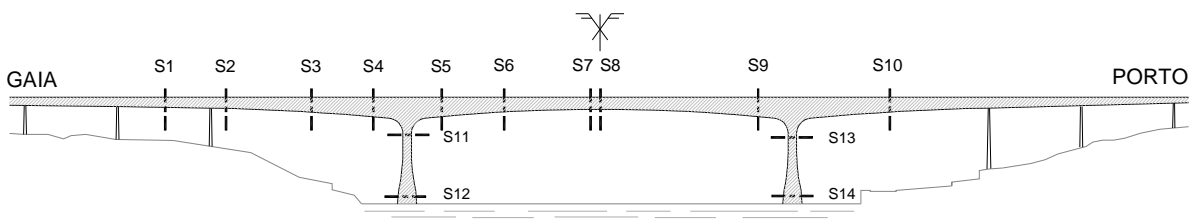


Fig. 3: General observation plan of the bridge

The measurement of concrete strains was made using 124 vibrating-wire strain gauges. In the highest sections, near the main piers, besides the strain gauges placed in the top slab, some devices were positioned in the webs and in two different levels in the bottom slab, due to the huge thickness of this slab. Fig. 4 shows the distribution of strain gauges in the section S5.

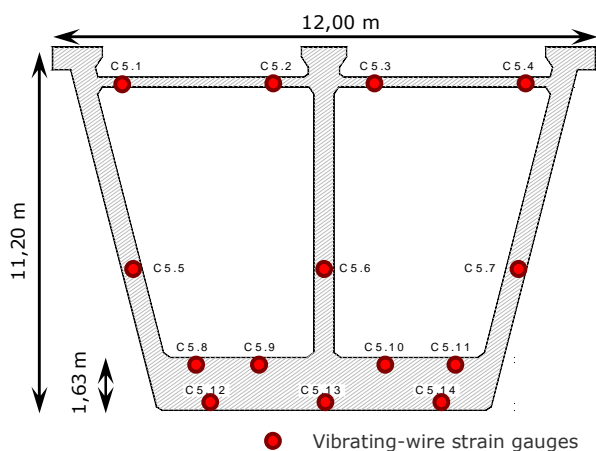


Fig. 4: Instrumented cross section (S5)



Fig. 5: Creep specimens

In order to measure thermal gradients in concrete, 97 thermocouples were placed across the thickness of the elements of the six different sections.

The original observation plan of this bridge also includes the use of air bubble clinometers to evaluate rotations in the top and bottom of the main piers and mechanical strain gauges to measure the horizontal displacements in both abutments. The measurement of deck vertical displacements was made by means of geometric levelling.

Besides measurements in the structure, a study of the creep and shrinkage of concrete was done using specimens made with the same concrete of the bridge.

These specimens were kept inside an experimental segment (Fig. 5), built in the river bank. The shrinkage specimens were not loaded, subjected only to environmental conditions. The creep specimens were subject to a constant axial load imposed by hydraulic jacks, which maintained the pressure level.

A detailed description of the experimental procedure followed in this study and the methodology developed for the processing of the data measured in these specimens is presented in [2]. This methodology includes the identification of the specimen's deformation due to temperature variations, the statistical evaluation of the experimental data and the use of a non-linear regression to fit the MC90 models to the experimental data.

Even with the extensive instrumentation presented, the observation of São João Bridge was only based on periodical measurements.

4. Upgraded SHM system

The importance of São João Bridge, the large investment in its instrumentation and the facilities available nowadays in the field of structural health monitoring were the main reasons for the decision of upgrading the observation system. The main purpose of this upgrade was to install an automatic data acquisition with remote access, allowing real time data processing. Another target was the monitoring of the bridge's dynamic characteristics.

In the definition of the new SHM system, the first step was the integration of all the original sensors allowing automatic acquisition. That was the case of the vibrating-wire strain gauges and the thermocouples.

The measurement of deck vertical displacements, horizontal displacements at the abutments and rotations required new sensors.



Fig. 6: Pressure cell in a hydrostatic levelling system



Fig. 7: Magnetostrictive position sensor

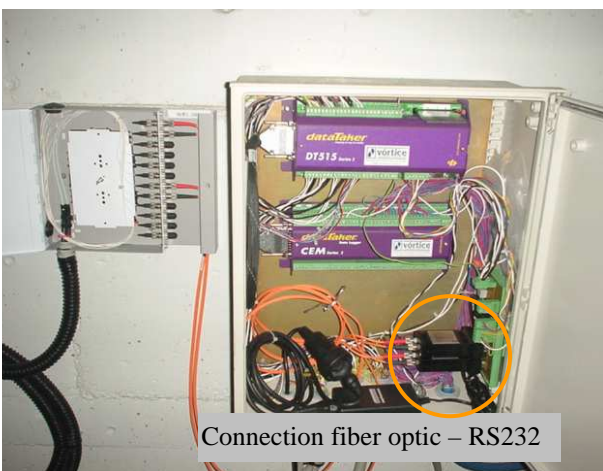


Fig. 8: Logger DataTaker

The use of hydrostatic levelling systems associated with pressure cells was the solution chosen for the measurement of deck vertical displacements (Fig. 6). This solution was previously used in the long-term monitoring, for instance in Salgueiro Maia cable-stayed bridge [3], and in several load tests [4][6]. A system was installed in each box girder cell in order to measure the displacements in both upstream and downstream sides. Pressure cells were installed in the midspan section of the three main spans, in the quarter span of the main span and in the top of the main piers.

For the evaluation of horizontal displacements at expansion joints, four magnetostrictive position sensors were installed (Fig. 7). In each expansion joint, two sensors were installed, one in the upstream side and the other in the downstream side.

Gravity-referenced inclinometers Schaevitz T233/T235 were introduced to measure rotations at the top and bottom of both main piers

The selection of the logger to be employed in the automatic acquisition of all the presented sensors was conditioned by the use of vibrating-wire strain gauges. As a matter of fact, there are a very limited number of loggers able to work this kind of sensors. The solution achieved was the *DataTaker DT515*, and nine of these loggers were installed to read data from hydrostatic levelling systems, magnetostrictive position sensors and gravity-referenced inclinometers, besides vibrating-wire strain gauges and thermocouples.

All the loggers were linked to each other through a local network made with fibre optic cabling and covering all the bridge extension.

The monitoring of dynamic properties is based on the measurement of vertical and transverse accelerations only in the main span. Vertical accelerations is measured in midspan and quarter span; in each section two Kinemetrics uniaxial EpiSensor (ES-U) accelerometers were placed, one in each section side; transverse accelerations is measured at midspan and in the top of both main piers.

The management of all measured data is assured by an industrial computer (Microspace-PC) installed in the bridge for that purpose. This includes data acquisition, data processing and data transfer.

Data acquisition involves the reading of each sensor, according to a previously defined schedule, and the storage of the measured values.

Data processing includes the validation of the measurements, which is very important to obtain reliable data. Erroneous data may appear due to several causes, and may be classified as systematic errors caused by deficiencies in equipment calibration or on the method used, and random errors attributable to various sources such as a breakdown in energy supplies, deficiencies in sensor or logger connections or equipment damage. Reduction of systematic errors involves sensor calibration and the use of different methods for the measurement of the same data.

Random errors cannot be eliminated but can be minimized using statistical techniques [5]. Through these techniques, it is possible to detect and eliminate outliers, values that diverge from the majority of monitored data, which can mask the structure's response and set off an alarm by mistake. There are several methods used to detect outliers and the choice of the appropriate method depends on the sample distribution, if the parameters of the distribution are known, the number and type of outliers to be expected [7]. The method used for outlier detection was the modified z-score test [8]:

$$Z_i^* = \frac{|x_i - \tilde{x}|}{MAD_i \text{ or } S_i \text{ or } Q_i}$$

$$MAD_n = 1.4826 \text{ median}(|x_i - \tilde{x}|)$$

$$S_n = 1.1926 \text{ median}_i(\text{median}_j |x_i - x_j|)$$

$$Q_n = 2.219 \left\{ |x_i - x_j|; i < j \right\}_{(k)}$$

where x_i = sample value; \tilde{x} = sample median; $k = h(h-1)/2$; $h = [n/2] + 1$; and $[]$ = integer.

The changes from the normal z-score method consisted on the substitution of the mean for the median, and as for the standard deviation it was replaced by three alternatives MAD_n , S_n or Q_n . A value is marked as an outlier if Z_i^* is greater than a critical value that depends on the dimension of the sample and of the confidence level. After identifying the outliers they are removed and the median of the remaining records of the sample is calculated. However if a large number of outliers is detected in a sample, that sample should be ignored and the readings must be repeated.

Data Transfer assures the transmission of the *in situ* measured data to the office. A router is used for the industrial computer to store the measured values in a database created in an office computer. Here, the measured data is analysed and compared with predicted values. The conclusions about the structure's safety conditions are published in periodical reports.

5. Structural analysis

The prediction of concrete creep and shrinkage is deeply associated with a great uncertainty due to the variability of many parameters, namely those related with environmental conditions. For this reason, in structural analysis of the time dependent behaviour this uncertainty should be taken into account in the modelling of creep and shrinkage.

To take this uncertainty into account, a probabilistic analysis was carried out, considering concrete creep and shrinkage as random variables [9]. The characterization of these variables was based on the experimental values, achieved as previously described. In the analysis performed, creep and shrinkage variability was considered through the Monte Carlo simulation.

The time dependent behaviour of the bridge was analysed using a three-dimensional finite element model developed by the author [9]. This numerical model comprises beam elements, including the concrete and reinforcement contributions, cable elements, prestressing elements and external prestressing elements

The segmental cantilevering process was modelled with phased structural analysis. The numerical simulation was the projection of the construction stages into calculation phases. The model takes into account the time-dependent effects including concrete hardening, creep and shrinkage and prestressing steel relaxation. The creep function was approximated by a finite number of terms in a Dirichlet series [10], which avoid the storage of entire stress history.

6. Experimental results

In order to illustrate the benefits resulting from the updating of the São João Bridge SHM, some experimental results are presented.

Fig. 9 presents concrete strains measured at the upper and bottom slabs of section S5. The difference between the values measured before and after the upgrading is obvious. The mean value and the 90% confidence interval computed by the probabilistic analysis performed are also presented in both charts of Fig. 9: The agreement between calculated and measured values is satisfactory.

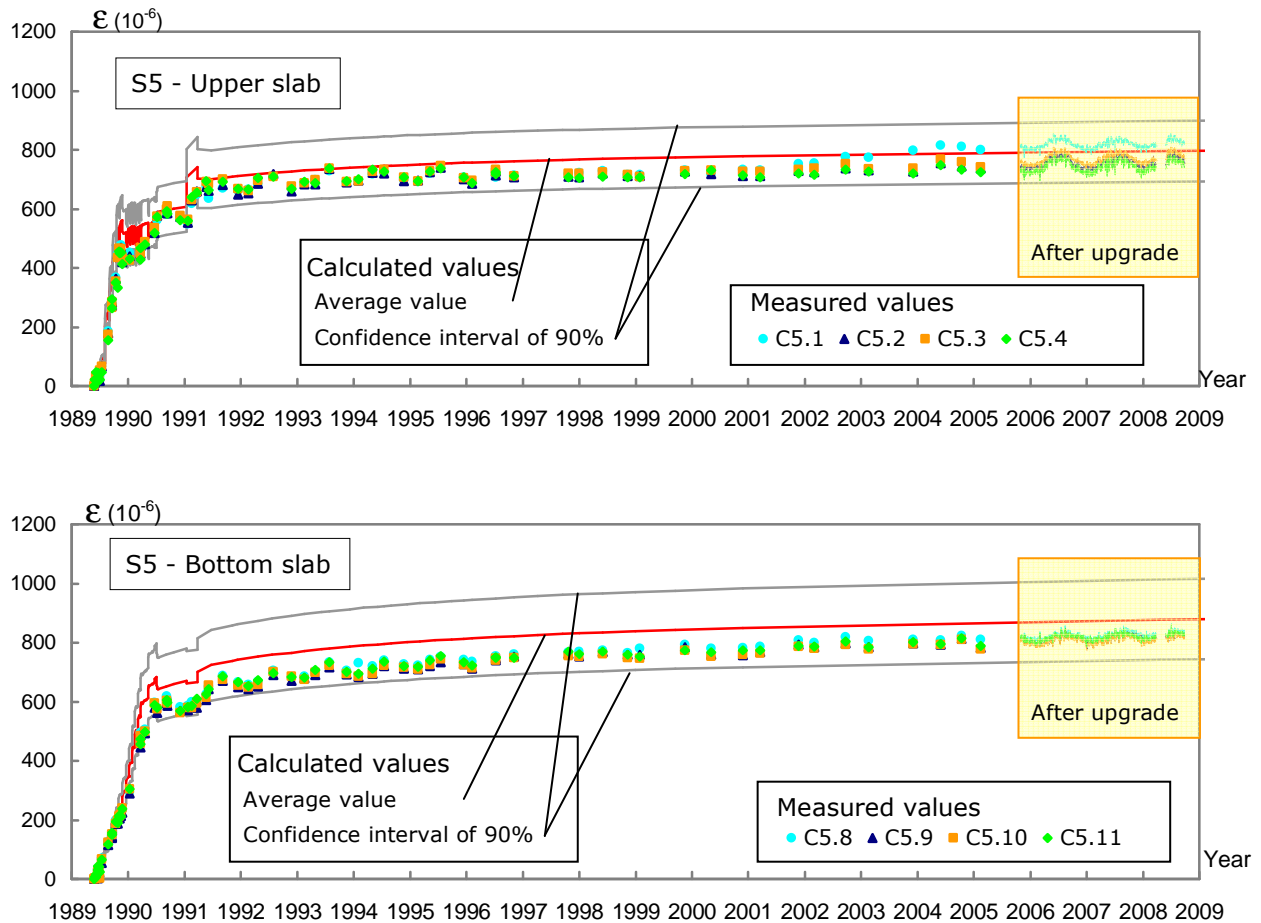


Fig. 9: Concrete strains at section S5

The evolution since 2001 of horizontal displacements at the north expansion joint is presented in Fig. 10. In this case the added value from the upgrade is very clear. In fact, due to the huge influence of the seasonal temperature variation, it is not possible to characterize joint displacements with only a few measurements during the year.

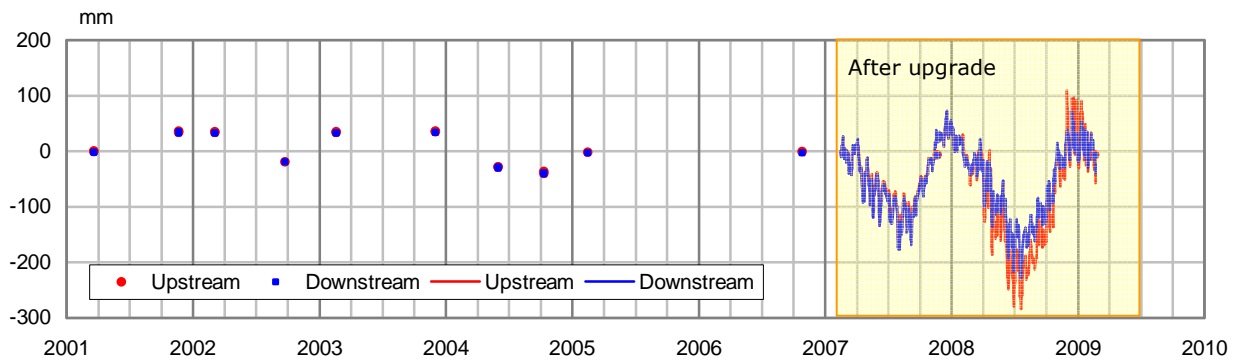


Fig. 10: Horizontal displacements at north expansion joint

7. Final remarks

The upgraded structural health monitoring system introduced in São João Bridge gives more complete and reliable information about the bridge's structural behaviour. As a matter of fact, while the original system only provided measurements twice a year, the upgraded system grants an effective monitoring of the bridge, giving continuous information about its structural behaviour. As well, data processing in real time provides more reliable information, as the result of the detection and elimination of outliers, and, if necessary, the repetition of measurements. A better knowledge of the bridge's structural behaviour is thus possible. It is also possible to anticipate the detection of both equipment and structural problems.

Original mechanical devices can also contribute in bridge monitoring by the validation of measurements made by new devices.

Despite all the benefits, the updating of the structural health monitoring system doesn't avoid periodical inspections, which are very important for the bridge's maintenance.

Acknowledgments

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