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Structural Integrity Procedia 00 (2017) 000–000

Structural Integrity
Procedia

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2nd International Conference on Structural Integrity, ICSI 2017, 4-7 September 2017, Funchal, Madeira, Portugal

Dynamic Assessment of the São João Bridge Structural Integrity

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Abstract

São João Bridge, crossing the River Douro, in Oporto, is open to traffic since 1991. It is a prestressed concrete bridge, with a main span of 250 m and a total length of 1028 m. Its structural behaviour has been monitored since construction. In 2014, a vibration-based continuous monitoring system was installed on the bridge. An integrated procedure was developed to automatically carry out the data processing and to extract the modal parameters in real time, using the Stochastic Subspace Identification technique (SSI) and cluster analysis. This paper presents the evolution of its structural health monitoring system, as well the procedure developed for the dynamic assessment of the São João Bridge. Some experimental results are presented and compared with the values predicted by a finite element model. The influence of both environmental conditions and operational factors is discussed.

Keywords: Structural Health Monitoring; Structural Integrity

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1. Introduction

São João Bridge is a prestressed concrete railway bridge, ballast-free tracks laid (Fig. 1). Designed by Edgar Cardoso, this bridge crossing the River Douro, in Oporto, Portugal, is open to traffic since 1991.

This bridge was instrumented during the construction and its structural behaviour has been experimentally followed since then. However, the observation of the bridge was based only on periodical measurements. Ten years ago, this system was updated in order to introduce automatic data acquisition with remote access.

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Fig. 1. São João Bridge

In 2014, a vibration-based continuous monitoring system, including 6 uniaxial accelerometers, was installed on the bridge. In order to achieve the identification of modal parameters of the structure on real-time, an integrated procedure was developed to automatically carry out the data processing and to extract the modal parameters, using the Stochastic Subspace Identification technique (SSI) and cluster analysis.

This paper presents the evolution of its structural health monitoring system, as well the procedure developed for the dynamic assessment of the São João Bridge. Some experimental results are presented and compared with the values predicted by a finite element model. The influence of both environmental conditions and operational factors is discussed.

2. 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 meters, two 125 m side spans and approaching viaducts from both sides of the river banks (Fig. 2). For the railway platform is used ballast-free tracks laid.

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 (Fig. 2). The main piers, 50 m high, are rigidly connected to the deck. In all other piers, the bearings are fixed (Fig. 3), except for the pier E7 where there is a link bearing.

At the abutments, special devices are used (Fig. 4) for allow the free deformation under slow requests, such as temperature and time-dependent material properties of concrete (creep and shrinkage), but ensure the transmission of horizontal forces resulting by a sudden, rapid action such as braking or earthquake.

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 till twenty (Bastos, 1993).

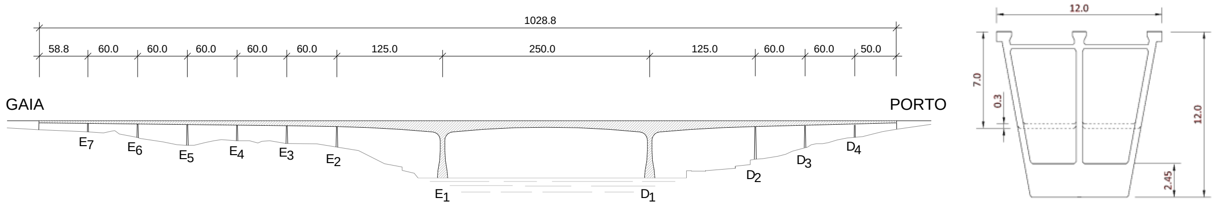


Fig. 2. General layout

Fig. 3. South Viaduct

Fig. 4. Anti-seismic device at abutments

3. The structural health monitoring system

The original observation plan includes the measurement of strains, temperatures, vertical displacements, rotations and horizontal displacements at expansion joints in both abutments (Castanheta, 1993). Besides measurements in the structure, an in situ study of the creep and shrinkage of concrete was carried out using specimens made with the same concrete of the bridge. These specimens were kept inside an experimental segment, built in the river bank.

The importance of São João Bridge, the large investment in its initial instrumentation and the posterior advances 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 (Santos, 2009). Another target was the monitoring of the bridge's dynamic characteristics.

The monitoring of dynamic properties is based on the measurement of accelerations in the main span: transverse accelerations are measured at mid-span and at the top of both main piers; vertical accelerations are measured in mid-span and quarter span. Dynamic acquisition is being carried out by Gantner e.series (Fig. 5). The data is acquired continuously, with a sampling frequency of 250 Hz. The binary record file size is around 24MB per hour.

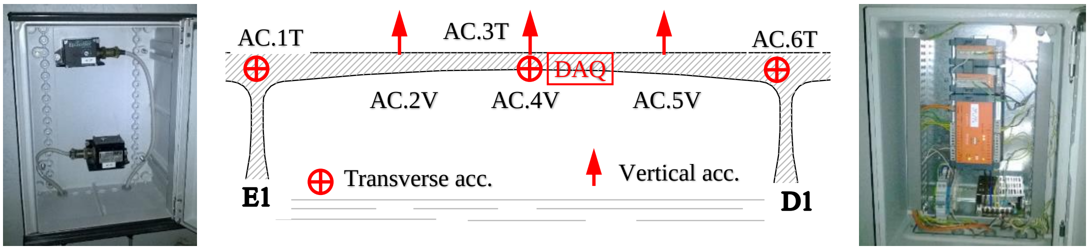


Fig. 5. Structural dynamic monitoring

4. Operation modal analysis

In order to perform automatic identification of structural modal parameters based on structural responses (outputs) when the structure is under its operating conditions, an Operational Modal Analysis (OMA) procedure is applied with the purpose of achieve an accurate estimation of natural frequencies, mode shapes and modal damping ratios.

In the proposed OMA (Xu *et al*, 2016), the models parameters of dynamic systems are evaluated using the COVariance driven Stochastic Subspace Identification (SSI-COV) method, based on the assumption that the input is a realization of a stochastic process (white noise). A stochastic state-space model is fitted to the correlation functions of the structural response. The modal identification of the systems is then performed through evaluation of dynamic characteristics of adjusted models. Finally, the modal parameters automatic selection is carried out by a cluster analysis procedure based on the Euclidian distance criteria.

Before the modal identification process, the acceleration time series were pre-processed with the following operations: trend removal; low-pass filtering with an 8 poles Butterworth filter; and decimation of the records. However, for railway bridges, the white noise assumption could be violated, once the vibration under the operation condition consists three types:

- Forced vibration during the rail traffic;
- Free vibration immediately after the train leaves out the bridge;
- Ambient vibration caused by the ambient action (wind) in the intervals between the circulations.

Although the forced vibrations are short in duration, the spikes may reach much higher than ambient vibration amplitudes. In case of the São João Bridge, for example, the vertical acceleration in the middle span may be greater than 400 mg during the train crossing, while the acceleration due only to ambient vibration does not exceed 1 mg, as shows Fig. 6. Furthermore, the rail traffic, particularly freight trains due to the value of axle load, adds a significant mass on the structure, which may cause the dynamic parameters perturbation.

To remove the forced vibrations the root mean square (RMS) criterion is used. The maximum RMS value for the vibration to be considered ambient vibration is attuned for the monitoring structure. For the São João Bridge, consider whether the ambient vibration if the acceleration RMS is less than 0.2 mg. After the forced vibration removed, the power spectral density clearly shows peaks of resonance frequencies (Fig. 6).

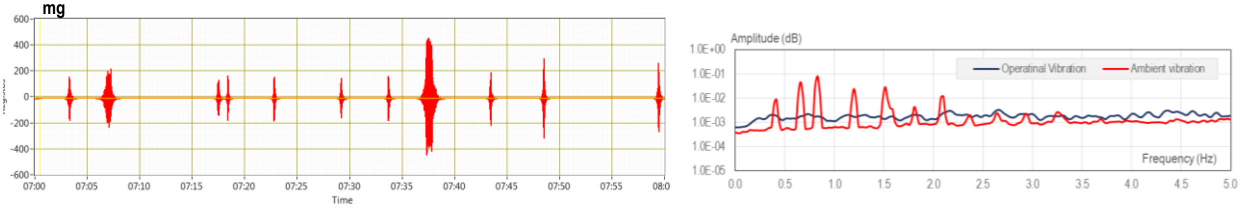


Fig. 6. A hourly record and the power spectral densities of the operational and ambient vibration

5. Modal identification of the Sao Joao Bridge

5.1. Finite element model

A three dimensional, linear, elastic numerical model of the bridge was developed in SAP2000 (CSI, 2010) to evaluate its response to the dynamic characteristics.

Shell and frame elements were used for modelling the deck (Fig. 7). The piers were simulated by frame elements. For simulate the connection between the deck and the main piers (E1 e D1) were used body constraints. The bearings at the top of the other piers and abutments were modelled by link elements.

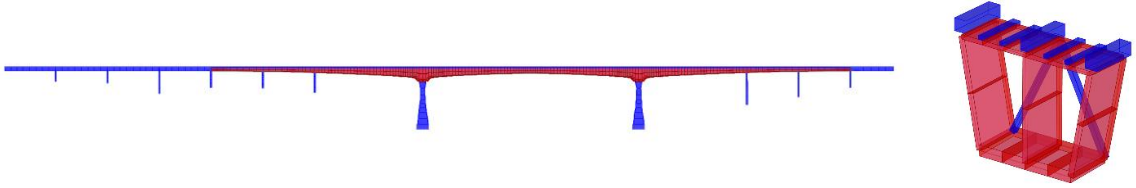


Fig. 7. Structural finite element model

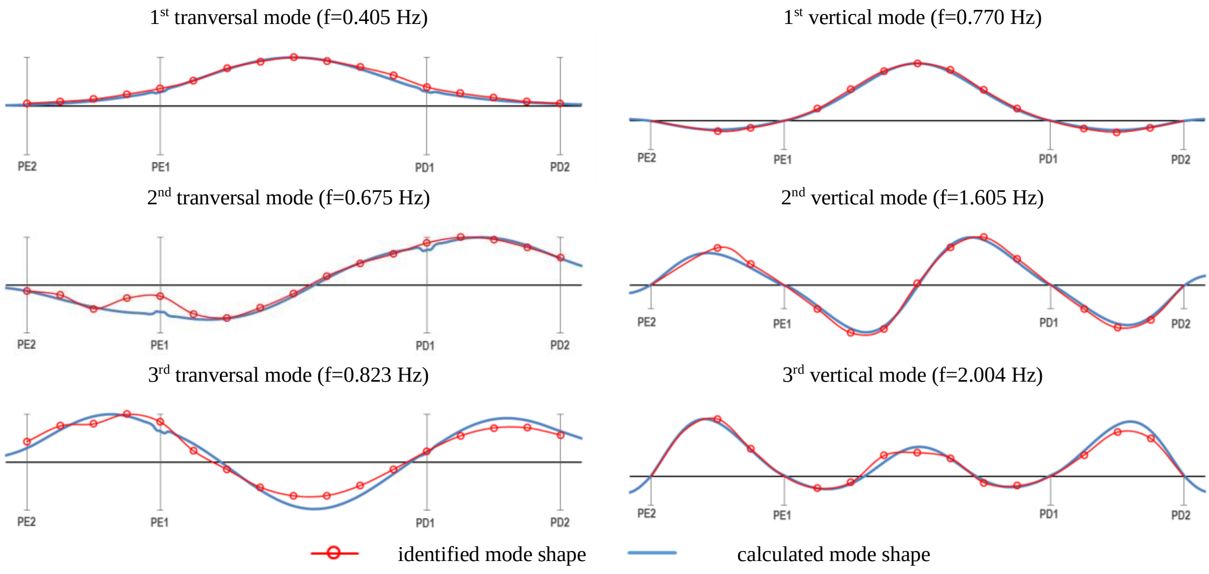
Due to the high density of reinforcement steel, for the concrete weight density was taken 25.4 kN/m^3. The remaining dead load of 16.6 kN/m was also considered. Thus, the total weight of the structure is about 282 000 kN.

5.2. Dynamic tests

Dynamic tests were performed to obtain experimentally the dynamic characteristics of the structure, namely, the vibration frequencies, mode shapes and damping ratios. In June 2016, the dynamic tests of the São João Bridge were carried out in nine set-ups. During these tests the 7 uniaxial accelerometers placed in the deck and the main pier D1. The records at each set-up had a time length of about 60 minutes, using a sampling rate of 500 Hz.

The structural modal parameter identification was performed with the software ARTeMIS (SVS, 2005), using the technique of Enhanced Frequency Domain Decomposition (EFDD). A total of 30 vibration modes were identified based on measured response only. Some identified mode shapes are illustrated in Fig. 8.

The developed FE model was used to validate the experimental results of the dynamic tests. The natural frequencies and mode shapes computed by the updated FE model were compared to the modes identified from the tests, as illustrate in Fig. 8 and Table 1. In general, a very good accordance was achieved.



1st tranversal mode (f=0.405 Hz)

1st vertical mode (f=0.770 Hz)

2nd tranversal mode (f=0.675 Hz)

2nd vertical mode (f=1.605 Hz)

3rd tranversal mode (f=0.823 Hz)

3rd vertical mode (f=2.004 Hz)

Fig. 8. Identified and calculated mode shapes of the São João Bridge

Table 1. Dynamic characteristics of the São João Bridge

Modes identified from transverse accelerations						Modes identified from vertical accelerations					
Mode	DMS		Test		FEM	Mode	DMS		Test		FEM
	f (Hz)	ξ (%)	f (Hz)	ξ (%)	f (Hz)		f (Hz)	ξ (%)	f (Hz)	ξ (%)	f (Hz)
T.1	0.406	0.07	0.405	1.96	0.413	V.1	0.772	0.08	0.770	1.08	0.771
T.2	0.656	0.08	0.675	1.26	0.662	L.1	1.217	0.49	1.223	1.86	1.225
T.3	0.825	0.07	0.823	1.05	0.817	V.2	1.608	0.22	1.605	0.85	1.659
T.4	1.195	0.09	1.193	0.73	1.185	V.3	2.009	0.14	2.004	0.90	1.894
T.5	1.529	0.25	1.530	0.95	1.534	V.4	2.389	0.17	2.395	0.61	2.238
T.6	2.085	0.27	2.089	0.66	1.917	V.5	2.570	0.17	2.576	0.61	2.326

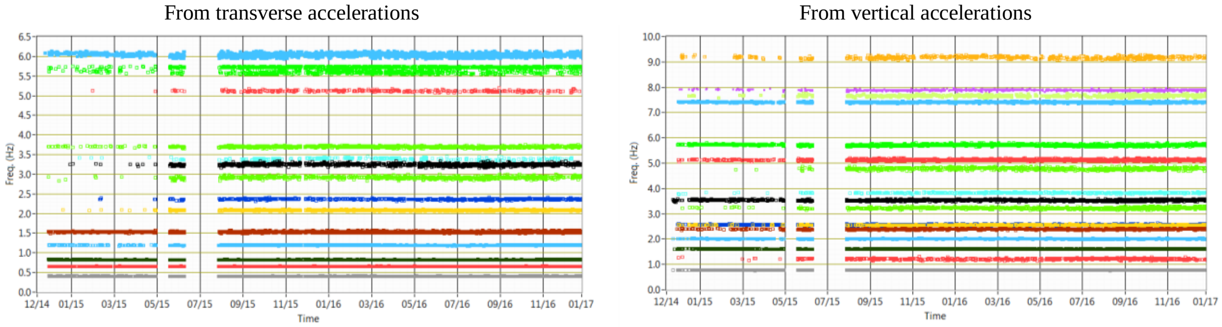
T – Transverse mode; V – Vertical mode; L –Longitudinal mode.

5.3. Continuous dynamic monitoring

The dynamic monitoring system has been operating since October 2014. The proposed OMA methodology was implemented in the continuous monitoring system.

Every time, when an hourly record finished, the modal identification is carried out automatically. The record is pre-processed with a low-pass filtering at 10 Hz and then decimated to 25 Hz. The vibrations associated with the rail traffic are eliminated. Finally, the operational modal analysis is performed separately for vertical and transverse accelerations.

Fig. 9 presents the natural frequencies identified from the hourly measurements in the period between October 2014 and December 2016. As shown, the proposed methodology is able to identify about 30 vibration modes based the vibration acquired from few accelerometers. The median values of the dynamic characteristics for each identified mode are presented together with the test and numeric results in Table 1.


From transverse accelerations

From vertical accelerations

Fig. 9. Natural frequencies identified by OMA

The analysis of the identified frequencies over time allows detecting the thermal effect. The relationship between the temperature and the frequency is almost linear. This behaviour can be found in all the identified vibration modes, increasing for higher order vibration modes.

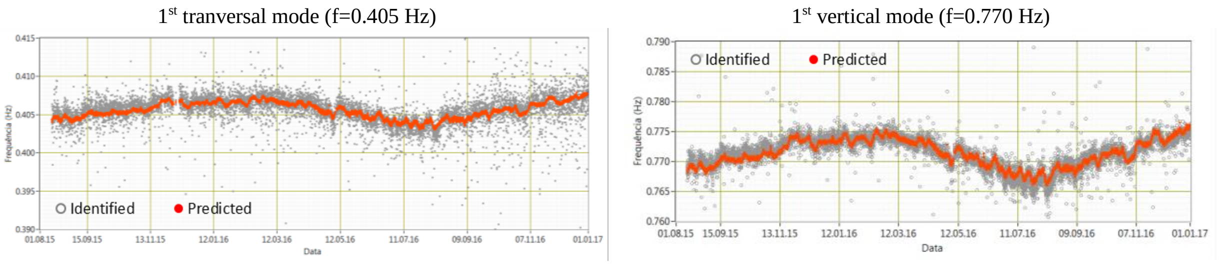
Therefore, the detection of any structural changes, as abnormal occurrences or damages, is only possible if the effects of the environmental and operational factors are removed from the modal parameters variation or minimized. For this purpose, the technique Multiple Linear Regression (MLR) was used. The aim is to reproduce the part of variance in measured parameters that is associated with changes in environmental and operational conditions.

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

$$y = A_0 + \sum_{1}^{n} A_i \, x_i + \varepsilon \tag{1}$$

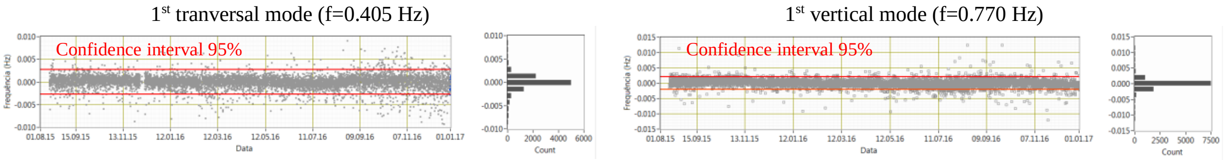
If the MLR model is adequate, the difference between the measured and predicted values, ε, should be random samples with normal distribution. Any deviation could be an indication of an extraordinary event occurrence.

For the case study, as explanatory variables were considered the temperature measured inside concrete, at the top and bottom slabs and the webs. The traffic action is also taken into account. By this way, the time evolution of the identified frequency were explained by the MLR model (Fig. 10) and the random remaining values (Fig. 11), which standard deviation were less 0.002 Hz, have not evidences for unusual changes.


1st tranversal mode (f=0.405 Hz)

1st vertical mode (f=0.770 Hz)

Fig. 10. Time evolution of two natural frequencies and the predicted values by the MLR model


1st tranversal mode (f=0.405 Hz)

1st vertical mode (f=0.770 Hz)

Fig. 11. Remaining values obtained by the MLR model

6. CONCLUSIONS

The São João Railway Bridge was instrumented during the construction and its structural behaviour has been experimentally followed since then. In 2014, a vibration-based continuous monitoring system, including 6 uniaxial accelerometers, was installed on the bridge.

In order to achieve the identification of modal parameters of the structure on real-time, an integrated procedure was developed to automatically carry out the data processing and to extract the modal parameters, using the Stochastic Subspace Identification technique (SSI) and cluster analysis.

The results obtained in the São João railway bridge show the good performance of the developed procedure. It was possible to identify a significant number of vibration modes with only a few accelerometers. However, the mode shapes were roughly defined, what makes hard to match the calculated modes. The vibration test with a larger number of measuring points had become very convenient to find out about 30 modes.

The modal parameters evolution during two years of measurements shows the environmental and operational influence on the modal parameters. The Multiple Linear Regression model was used to remove or minimize effects of the environmental and operational factors in the modal parameters variation. The results permit to characterize the reference state of the structure and can be used to detect an abnormal behaviour.

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