8th European Workshop On Structural Health Monitoring (EWSHM 2016), 5-8 July 2016, Spain, Bilbao
www.ndt.net/app.EWSHM2016



# Illustrating the relevance of SHM in a case study: the Foz Tua centenary railway bridge

Filipe MAGALHÃES[1], João PACHECO[1], Álvaro CUNHA[1]

[1] CONSTRUCT-ViBest, Faculty of Engineering (FEUP), University of Porto
PORTUGAL filipema@fe.up.pt; acunha@fe.up.pt

**Key words:** Railway Bridge, Dynamic Monitoring, Operational Modal Analysis.

**Abstract**

*The present work describes the dynamic monitoring activity developed in a railway bridge that crosses the Tua River, in Portugal, a centenary steel riveted deck with a length of 180 m, supported by five masonry piers. Owing to the present construction of a new hydroelectric powerplant in its vicinity, the bridge was equipped with a monitoring system, in order to observe if the construction activities would interfere with its structural integrity. This paper characterizes the monitoring project, starting with the description of the system hardware and software that is then complemented with the analysis of the results from the last four years of continuous tracking of the bridge modal parameters.*

## 1 INTRODUCTION

This contribution is focused on a railway bridge over the Tua River, a tributary of the Douro River, in a region at the Northeast of Portugal classified as UNESCO World Heritage.

This steel riveted railway bridge constructed in 1882 is composed by a steel truss deck with a height of 3 meters and a total length of 169 meters, divided into 6 spans supported by 5 masonry piers, three of them being founded in the river bed.

In 2011, it was started the construction of a new hydroelectric powerplant at Tua River, with a dam about 1km upstream the railway bridge (see Figures 1 and 2). Since the dam is also going to be used to store water pumped from the Douro River, the Tua river bed is being deepen in order to create an adequate channel from the Douro River to the water outlet.

Before the beginning of the construction of the power plant, in June 2011, the Laboratory of Vibrations and Structural Monitoring (ViBest, www.fe.up.pt/vibest) was contracted to equip the bridge with a Structural Health Monitoring system, in order to continuously observe the impact of the construction activities, that include blasting operations and the retrofitting of the bridge piers associated with the deepening of the river bed.

The monitoring system comprises temperature sensors, accelerometers at the deck and at the top of the piers, clinometers at the top of the piers and geophones at the piers bottom and at the abutments. The continuous recording of all these sensors signals is complemented by periodic topographic measurements.

This paper describes this monitoring project, starting with a characterization of the bridge and of all monitoring hardware and software components. Then, an integrated analysis of the results provided by all the installed sensors is presented and the relevance of SHM is demonstrated with observations associated with some relevant construction operations with clear impact on the bridge behavior.

Figure 1: View from downstream at an early stage of the dam construction: Railway Bridge, Roadway Bridge and Dam site [1].

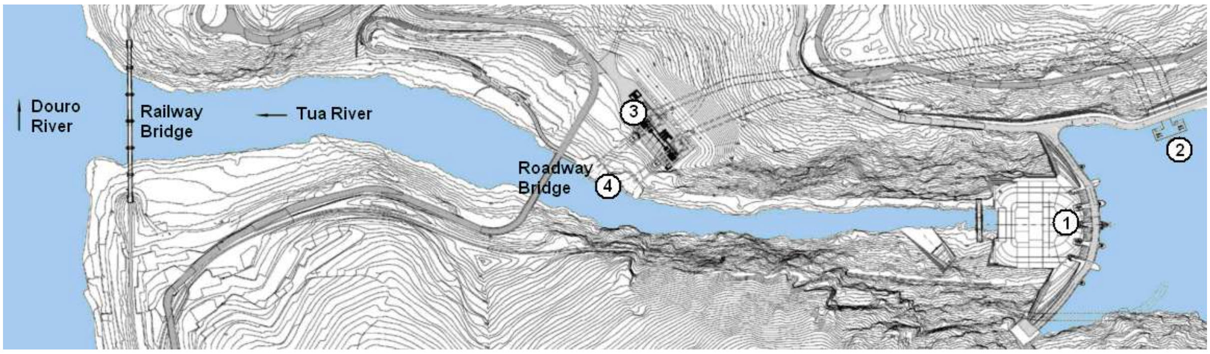

Figure 2: Location of the bridges (Roadway and Railway) and of the hydroelectric power plant components: 1-Dam; 2-Water Intake; 3-Powerhouse and Substation; 4-Outlet [1].

## 2 FOZ TUA RAILWAY BRIDGE

This steel riveted railway bridge constructed in 1882 belongs to the Douro Line, a railway line running next to the Douro river, that in the past connected the city of Porto with the Spain border (nowadays the last part of the line is decommissioned). The bridge crosses the Tua River at its mouth with the Douro River through a steel truss deck with a height of 3m and a total length of 169m, divided into 6 spans, two end spans with 24.5m and 4 intermediate spans with 30m. The deck is supported by 5 masonry piers, three of them being founded in the river bed (see Figure 3). In the longitudinal direction, the deck is only fixed to the central pier, the connections with the other piers and with the two abutments allow relative movements. In the transversal direction the deck is fixed to all piers and also to the abutments.

Due to the deepening of the river bed, the three central piers undertake important structural changes, the free height being increased about 3m, as illustrated in Figure 4. Piles have already been constructed around the central piers, beams have been casted to connect the masonry piers with the top of the piles and, finally, the rock massif around the new piles will be removed.

Figure 3: Railway Bridge, view from upstream.

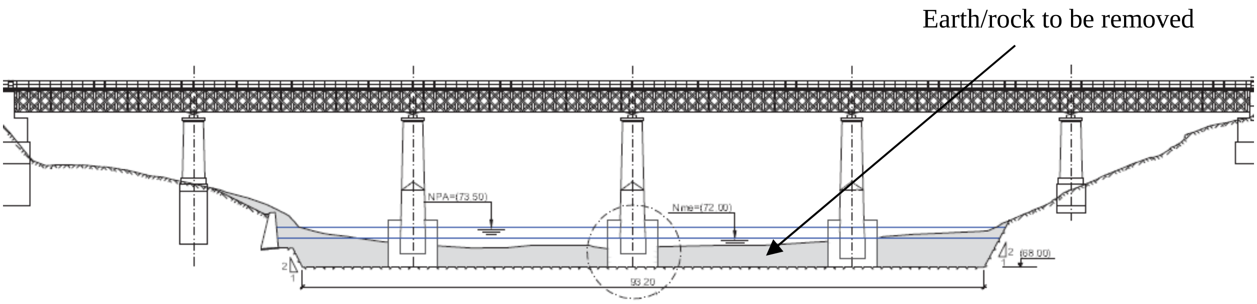


Figure 4: Retrofit of the bridge piers foundation [2].

## 3 BRIDGE TESTING AND MODELLING

An ambient vibration test was performed before the installation of the monitoring system. This covered 23 sections of the deck, 4 of them being instrumented at both edges, as well as the top section of the 3 piers founded on the river bed.

Figures 5 and 6 present the estimates of the bridge most relevant natural frequencies and mode shapes. Good quality mode shapes for both the vertical and the lateral directions were obtained.

A detailed numerical model of the bridge (Figure 7) has also been built in order to try to explain the changes that will be reported in the presentation of the monitoring results. A very good fitting could be immediately obtained for the vertical bending modes, whereas for the lateral modes, the boundary conditions are still being tuned in order to achieve an adequate fitting with realistic parameters for the foundation massif and piers material.

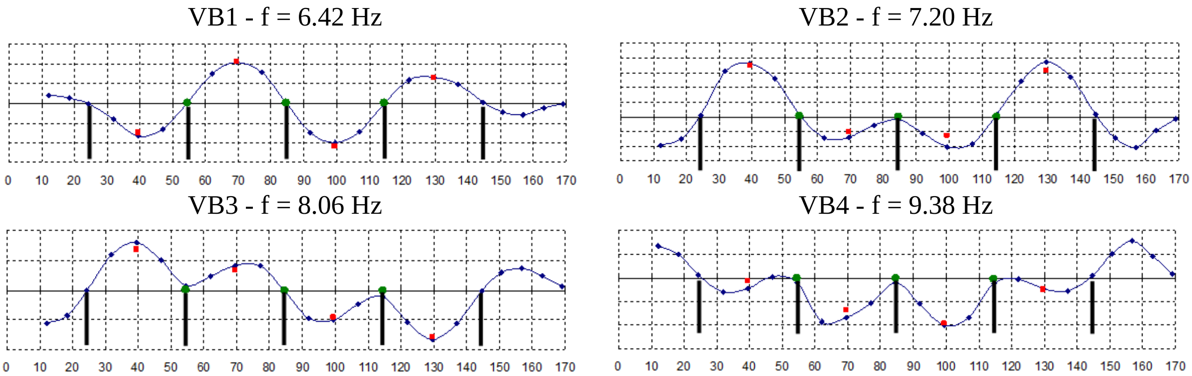


Figure 5: First four vertical bending (VB) modes
(blue – deck downstream; red - deck upstream; green – piers top).

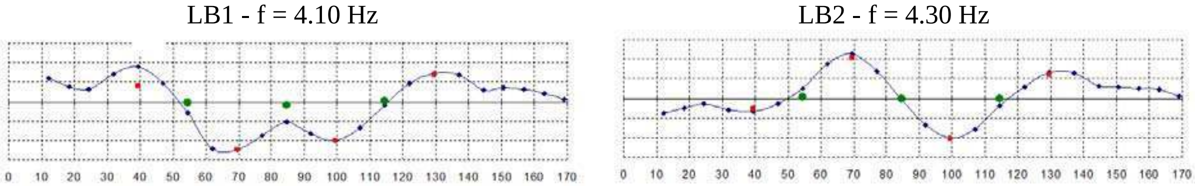


Figure 6: First two lateral bending (LB) modes
(blue – deck downstream; red - deck upstream; green – piers top).

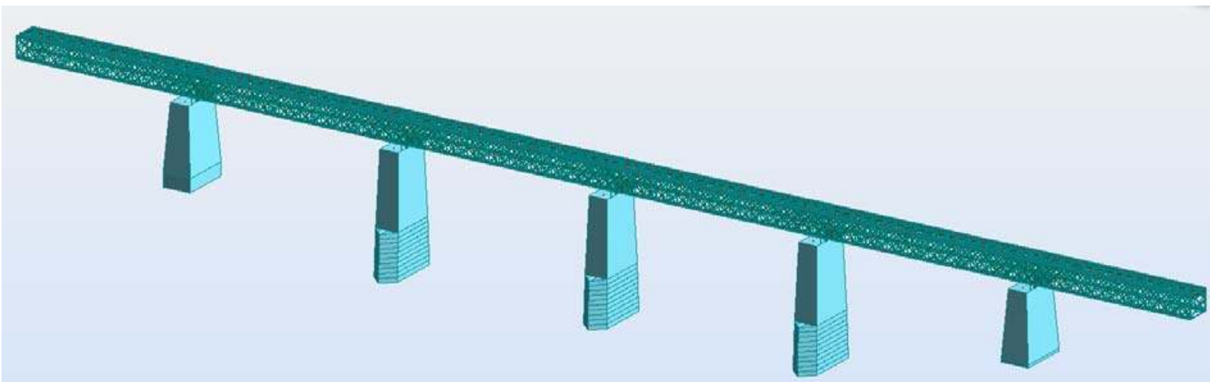

Figure 7: Bridge Model

# 4 MONITORING SYSTEM

## 4.1 Hardware

The bridge is equipped with a monitoring system composed by three subsystems: one based on accelerometers whose main purpose is to monitor the structural condition of the bridge, another based on geophones installed at the abutments and piers bottom sections to monitor the amplitude of the vibrations induced by rock blasting operations and another one composed by bi-axial clinometers at the three central piers tops to detect any movements due to the construction activities at their foundation.

The first system was designed to continuously collect acceleration time series in carefully selected points, whose subsequent processing should allow the accurate identification of the main dynamic properties of the instrumented structure. After the characterization of the temporal evolution of the bridge dynamic properties, an accurate detection of structural anomalies is only possible if the temperature effects are minimized. Thus, the monitoring system also include temperature sensors.

The acceleration time series are collected by force-balance accelerometers connected to two 24-bit digitizers distributed along the bridge deck, which also collected the data observed by four temperature sensors distributed in one representative cross section of the deck.

The distribution of the sensors aimed the maximization of the quality of the collected information and the minimization of the number of sensors to reduce the system cost and took into account the results of the ambient vibration test and the importance of the piers behavior. Figure 8 represents the degrees of freedom instrumented with accelerometers.

All sensors of each system are connected to the corresponding observation boxes located in one of the bridge abutments or at the top of one of the piers. This contains a digitizer and/or a field processor, a modem with a 3G internet connection and power supply backed up by a battery. The acceleration, temperatures and rotations are continuously collected at rates of 50Hz, 1Hz and 1 reading each 10 minutes, respectively. The data is organized in text files that are downloaded and processed by a server located at ViBest/FEUP.

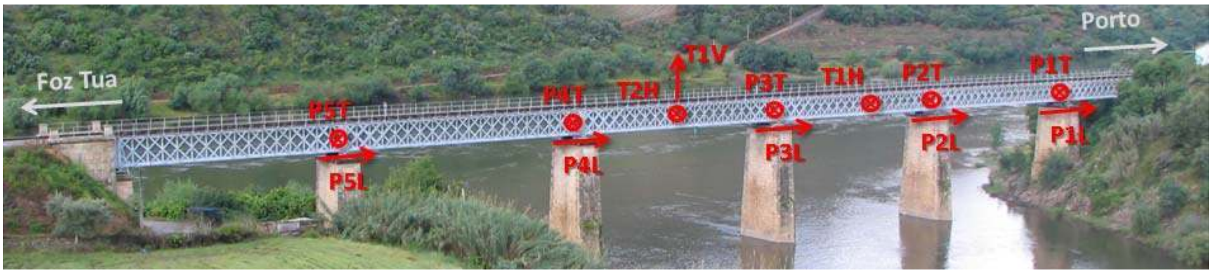


Figure 8: Degrees of freedom instrumented with accelerometers.

The systems that evaluate the vibration levels at the abutments and pier bottoms (a total of 7 points) is based on tri-axial geofones that record short velocities time series (some minutes) when a predefined trigger is reached. These are very important to check if the vibrations produced by rock blasting operations do not overcome the limits imposed by the Portuguese Standards. After all important blasting operations, the results provided all the components of the monitoring system (vibration velocities, rotations of the piers and natural frequencies) are checked in order to ensure that no damage was introduced in the bridge.

The monitoring system of the railway bridge started its operation at May 2012 with a reduced number of sensors (not covering all the piers) and was then upgraded in June 2014 to the present configuration, before the beginning of the construction works on the piers foundations.

### 4.2 Sofware

The processing of the data collected by the clinometers and geofones is quite straightforward. In the case of the clinometers, the reading are directly considered in plots that represent the variation of the rotations over time. For the geofones, the vibration resultant (considering the three measured orthogonal directions) at each time instant is calculated and its maximum identified.

The processing of the acceleration time series is more demanding and is accomplished with a monitoring software developed at ViBest/FEUP - DynaMo [3].

The monitoring system organizes the continuously collected acceleration time series in files with 30 minutes. This are handled by DynaMo software that was configured to perform the following tasks every 30 minutes:

- establish a FTP connection with the field processor and download the most recent file;
- backup the original data file in a database;
- pre-process of the temperature readings to obtain an average temperature for each half hour;
- pre-process of the acceleration time series, which includes trend elimination, filtering and down-sampling;
- characterize the acceleration amplitude by maxima and root mean squares values (RMS);
- construct colour maps in the frequency domain;
- identify the bridge modal parameters (natural frequencies, mode shapes and modal damping ratios), based on its response under normal operation, using state of the art output only modal identification algorithms;
- apply statistical tools to minimize the temperature effects on the identified modal parameters;
- store all the obtained results in a database;
- publish the most important results on a webpage.

The most important and challenging task is the continuous automated identification of the modal parameters. In the present application, after testing alternative output only algorithms [4], it was concluded that good results could be obtained combining the poly Least Squares Complex Frequency Domain method (p-LSCF) with a routine based on clusters analysis to automate its application. A description of this approach and of its theoretical background can be found in reference [5].

## 5 MONITORING RESULTS

This section is just focused on the results provided by the monitoring system component for the condition assessment, since the results provided by the other components are less relevant from the scientific point of view, still very informative from the practical point of view.

The accelerations time series collected at the piers tops are used to create frequency domain color maps like the ones represented in Figure 9 for piers P2 and P4 using channels P2L and P4L (see Figure 8). This color maps represent the time evolution of average spectra, representing the areas with more energy, associated with resonant frequencies, with hotter colors. The horizontal alignment with more energy represent the natural frequency of the first piers bending mode. It can be seen that during the presented period it is observed in both piers a sudden increase of the first bending natural frequency from about 4.5Hz to about 5Hz (P2 at 14/04/2015 and P4 at 13/08/2015). This is motivated by the cast of the concrete beam that connects the old masonry piers with the new piles, which increases their stiffness at the base.

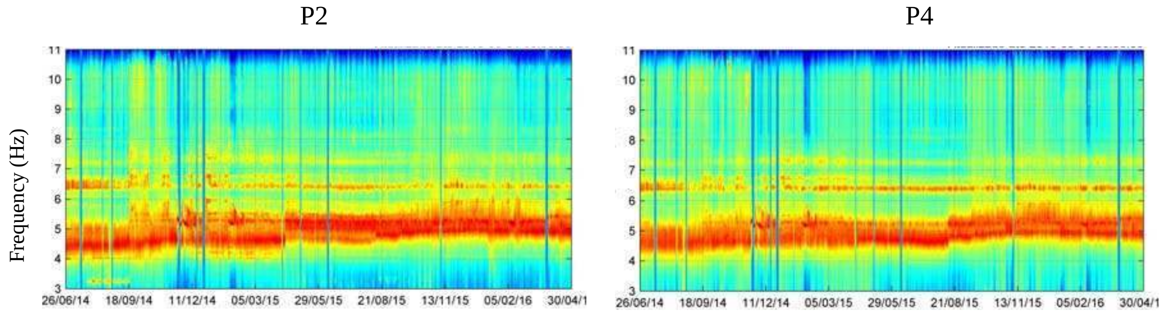


Figure 9: Colour maps with the time evolution of the frequency content of the acceleration time series measured at the top of piers P2 and P4 along the longitudinal direction of the deck (from 26/06/2014 to 30/04/2016).

Figure 10 describes the time evolution of the bridge first three global natural frequencies, associated with the modes shapes LB1, LB2 and VB1 (see Figures 5 and 6) continuously and automatically estimated with the p-LSCF method. The gap without results correspond to a period during which the system was expanded (as referred in the last paragraph of section 4.1). It is observed the influence of the temperature in the three natural frequencies, which present lower values during the warmer periods (from June to September). The application of regression models, using as predictors the measured temperatures and adopting for training period the first two years of monitoring, permitted to minimize the effects of the temperature [6], as illustrated in Figure 11. In the plots with the corrected natural frequencies for the lateral bending modes it is observed a slight decrease during November 2015, this might be motivated by the partial removal of the rock massive around some of the new piles of the central piers.

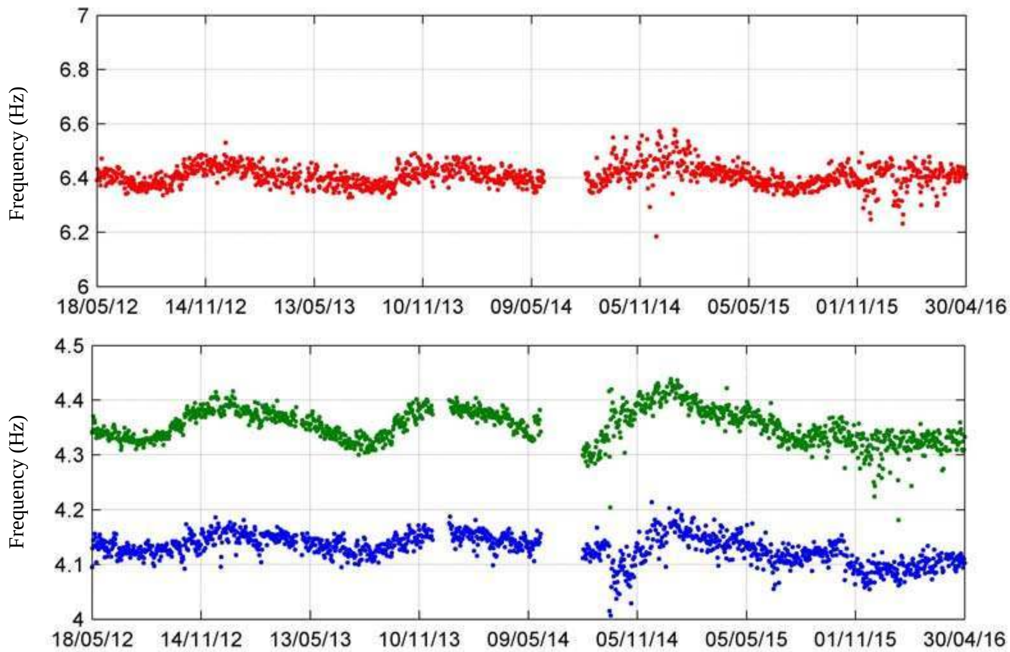


Figure 10: Time evolution of the daily average of three natural frequencies (in Hz) of the bridge from 18/05/2012 to 30/04/2016 (first vertical bending mode at top and first two lateral bending modes at bottom).

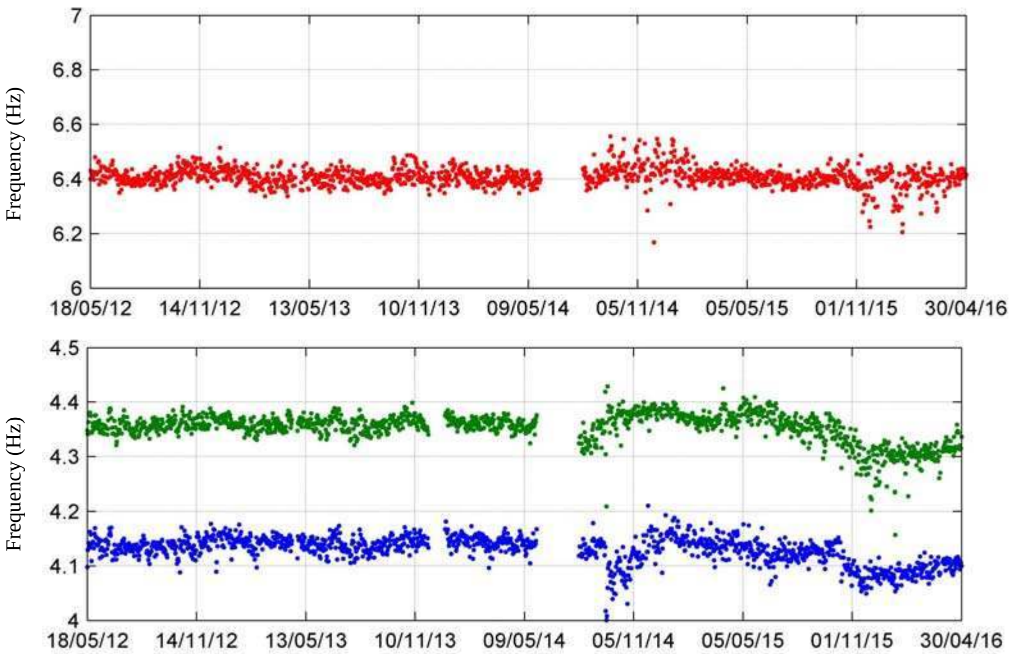


Figure 11: Time evolution of the daily average of three natural frequencies (in Hz) of the bridge from 18/05/2012 to 30/04/2016 after minimization of the temperature effect (first vertical bending mode at top and first two lateral bending modes at bottom).

## 9 CONCLUSIONS

This paper describes an application where the installation of a continuous monitoring system including different components was required in order to permanently check the structural condition of centenary bridge. It summarizes the experimental work performed before the installation, the most relevant components of the installed system and the software adopted to perform the online continuous processing of the collected data. The presented results demonstrate the good performance of the monitoring system and the suitability of the routines implemented in the software developed for continuous online data processing. It is an example where the usefulness of monitoring has been demonstrated in several critical moments of the piers retrofitting. Furthermore, the adoption of advanced tools for vibration based Structural Health Monitoring using operational modal analysis proved to provide valuable information to the owners of the infrastructure.

## ACKNOWLEDGEMENTS

The authors acknowledge the support provided by the dam owner (EDP Produção), by the dam construction consortium (Barragem de Foz Tua ACE), and by the bridge owner (IP – Infra-estruturas de Portugal), as well as all the support provided by the Portuguese Foundation for Science and Technology (FCT) to ViBest / CONSTRUCT / FEUP for the development of research in the area of Long-Term Dynamic Monitoring.

## REFERENCES

[1] EDP, http://www.a-nossa-energia.edp.pt

[2] Retrofit of the foundations of the Foz Tua Railway Bridge, Design Drawings (in Portuguese), CENOR, 2012

[3] Magalhães F., Amador S., Cunha A., Caetano E. "Dynamo - Software for Vibration based Structural Health Monitoring", *6th Int. Conf. on Bridge Maintenance, Safety and Management, IABMAS* , 2012, Stresa, Lake Maggiore, Italy.

[4] Magalhães F., Cunha Á. Explaining Operational Modal Analysis with data from an Arch Bridge, *Mechanical Systems and Signal Processing*, **25**(5), pp. 1431-1450, 2011.

[5] Magalhães F., Cunha A., Caetano E., Online Automatic Identification of the Modal Parameters of a Long Span Arch Bridge, *Mechanical Systems and Signal Processing*, **23**(2), pp. 316-329, 2009.

[6] Magalhães F., Cunha A., Caetano E., Vibration based Structural Health Monitoring of an Arch Bridge: From Automated OMA to Damage Detection, *Mechanical Systems and Signal Processing*, 28, pp. 212-228, 2012.