Structural Health Monitoring of Cabala Bridge in Angola

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Summary

This paper presents the Structural Health Monitoring of Cabala Bridge, over Kwanza River, in Angola. Besides the interest in the information given by such system operating in this region of Africa, some innovative procedures were used, like scour monitoring and water level measurement by radar system. Static and dynamic tests carried out by the end of construction are also presented, and the experimental results are compared with the values computed by the numerical model developed.

Keywords: concrete bridges, structural health monitoring, time-dependent behaviour, bridge load testing, ambient vibration tests, bridge scour monitoring

1. Introduction

Structural Health Monitoring of a bridge is the most accurate and efficient method to assess its performance in service, to determine the condition of the bridge and to detected any deterioration or damage. The installation of a SHM system in a bridge in Angola was an excellent chance to gain knowledge about the structural and material behaviour of a bridge built and functioning in the specific conditions of this region of Africa

The SHM system of Cabala Bridge includes the measurement of vertical displacement, rotations, strains and temperatures inside the concrete, besides an in situ characterization of concrete's creep and shrinkage is being performed. In addition to the structural component, the instrumentation aims the continuous monitoring of bridge scour, water level and weather conditions.

Finally this paper presents the procedures used in the static and dynamic tests carried out preceding the bridge entry into service. Both static and dynamic experimental results are also compared with the values evaluated with a finite element model of the bridge.

2. Bridge description

The Bridge over Kwanza river near Cabala in Angola is a roadway prestressed concrete bridge, 14,6 m wide, with a total length of 1534 m, including a main bridge and approaching viaducts from both sides of the river banks.

The bridge was designed by Armando Rito Engenharia and built by Teixeira Duarte, SA. [1]. The construction began in September 2008 and was completed on August 2010.A general view of the bridge is presented in Fig. 1.

The bridge and approaching viaducts constitute two continuous structures, separated by an expansion joint: the northern part, with a length of 760 m, includes the North Viaduct, the main bridge and a length of 300 m of the South Viaduct; the southern part includes the remaining length of the South Viaduct (774 m).

The main bridge has a span of 250 m and two 125 m side spans. The deck is a continuous prestressed concrete box-girder, with a depth varying between 3,0 m and 7,0 m, cast in place by the balanced cantilever method (Fig. 2).

Fig. 1 – General view of Cabala Bridge over Kwanza river

The main piers are made in reinforced concrete. Each pier shaft transfers the loads to the foundation by pile caps, with nine piles. The piles have 1,5 m diameter and depths reached 75 m.

Fig. 2 – Balanced cantilever erection

Both approaching viaducts have a current span of 30 m and a double-webbed cross section, with no diaphragms and a constant depth of 3,0 m (Fig. 3).

The viaducts were cast in place by the span-by-span method using an upper-slung movable formwork.

The pile/pier concept, where the piers are the natural extension of the piles, was used. For both viaducts, these components have a diameter of 1,5 m.

The deck is supported on pot-bearings at the piers and abutments.

Fig. 3 – South approaching viaduct

3. Bridge monitoring system

3.1 General

The focus of the bridge monitoring system is the structural behaviour; however, it also includes the study of the creep and shrinkage of concrete, a hydraulic component and a weather station. Besides the presentation of these four components, some attention is given to the automatic data acquisition system and to the electrical supply.

3.2 Bridge structural behaviour

Bridge structural monitoring includes the measurement of vertical displacements, rotations and concrete strains, as presented in Fig. 4.

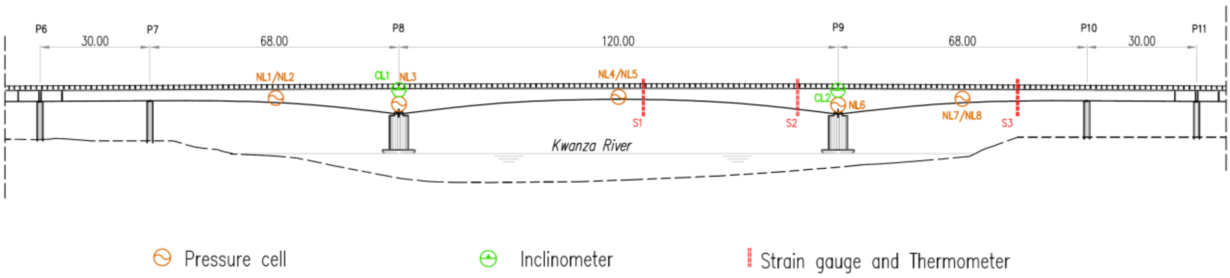

Fig. 4 – Structural monitoring plan

The measurement of vertical displacements is carried out through an upgraded hydrostatic levelling system associated to pressure cells. These cells are placed in the three mid-span sections of the bridge, in order to measure the vertical displacement, and also at top of the piers P8 and P9, to serve as reference. This solution was previously used in the long-term monitoring [1] and in several load tests [3][4].

Transversal and longitudinal rotations were measured by two-axis gravity referenced inclinometers Schaevitz T233/T235, located at the top of piers P8 and P9.

Strains inside the concrete are measured by 24 vibrating-wire strain gauges, placed in three sections of the deck, marked in Fig. 4 (S1 to S3). In these sections were also installed several resistance thermometers PT100 placed across the thickness of the elements to obtain the thermal gradients.

The distribution of the equipment in a deck cross-section is exemplified in Fig. 5.

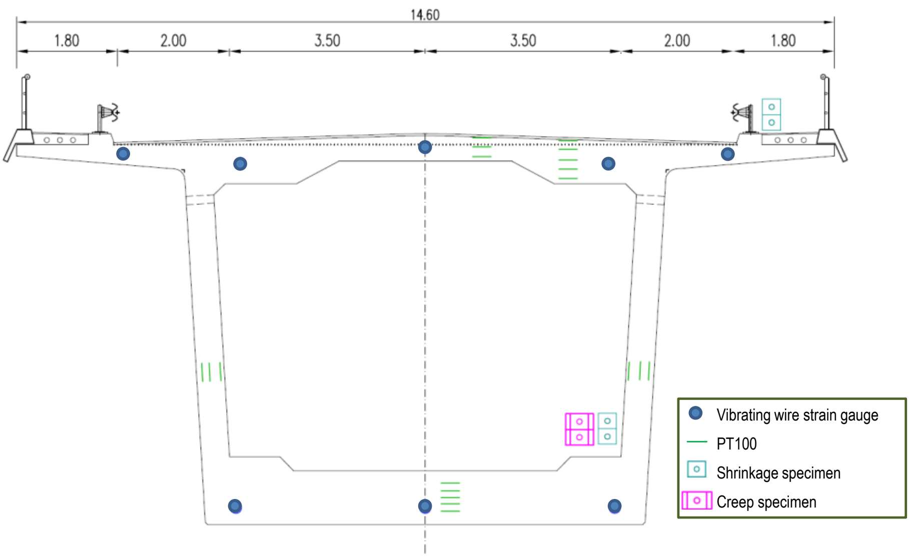

Fig. 5 – Bridge deck cross section S2

3.3 Concrete time dependent behaviour

Besides measurements in the structure, a study of the creep and shrinkage of concrete was made using specimens placed in sections S1 to S3.

Fig. 6 – Creep and shrinkage specimens

The specimens were made with the same concrete of the bridge and maintained in the same environmental conditions of the structure. In order to prevent evaporation two opposite faces are sealed. Inside of each prism a vibrating wire gauge is placed to measure concrete strain. The 17 shrinkage specimens are not loaded, subject only to environmental conditions. The 6 creep specimens are subject to a constant axial load imposed by hydraulic jacks, which maintain the pressure level.

All creep specimens are placed inside the box girder, but there are shrinkage specimens also over the deck. *Fig. 6* presents creep and shrinkage specimens placed at section S2.

This study, which requires a longer period to be conclusive, may provide important data about the time-dependent behaviour of concrete, mainly due to the specific environmental conditions.

3.4 Monitoring of bridge scour and water level

An acoustic scour meter UDM200 is used to monitor the scour depth surrounding the pier P8. This sensor is an underwater acoustic distance meter, based upon the reflection of sound waves, which can measure distance from the transducer's face to an object with an accuracy of less than 1 cm.

Fig. 7 – The acoustic scour meter mounted in pier P8

The sensor is mounted in the upstream side of the pile caps as presented in both pictures of Fig. 7.

The need for monitoring only the upstream side derives from the fact that the flood flow regime is sub-critical and, for that type of flows, scour holes develop more significantly upstream.

The information obtained will be of most interest to the knowledge of the actual behaviour of the river bottom during the occurrence of floods.

Fig. 8 – The radar level sensor

The monitoring of the water level is done by an impulse-radar sensor for non-contact level measurements (OTT RLS).

During each measurement this sensor sends radar pulses down to the water surface, the pulse are then reflected from the surface of the water and detected by the receiving antenna of the sensor.

The RLS is mounted on the underside of the bridge deck, as presented in Fig. 7, which is very convenient to the sensor integrity.

3.5 Weather conditions

Fig. 9 – Vaisala Weather Transmitter WXT520

Knowledge of weather conditions is interesting because it allows a better understanding of the time dependent behaviour of concrete, as well as establishing a relationship between rainfall and water river level.

For this purpose a Vaisala Weather Transmitter WXT520 was installed near the bridge, to measures barometric pressure, humidity, precipitation, temperature, and wind speed and direction (Fig. 9).

3.6 Data acquisition system

The data acquisition of all the sensors installed on the bridge is done by datalogger Datataker DT80G units associated to some expansion modules CEM 20. All the loggers are connected to a local network.

The management of all measured data is assured by an industrial computer 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.

Fig. 10 – Data acquisition system

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.

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 database server. Here, the measured data is analysed and compared with predicted values.

Fig. 10 presents the enclosure placed inside the box girder to house a datalogger (top left), the router (top center), the industrial computer (top right), two CEM 20 units (center) and a UPS (bottom).

3.7 Electrical supply

A proper electrical supply is essential for the monitoring system presented. For this purpose two situations were distinguished: construction and service.

Suring the construction, two UPS were installed to protect data and equipment from power problems by supplying clean and reliable power.

After construction, eight photovoltaic panels were installed. These panels, combined with large batteries placed inside the box girder, ensure the electrical supply of the whole monitoring system with great stability.

Fig. 11 shows a view of the photovoltaic panels and also shows the batteries inside the box-girder.

Fig. 11 – Photovoltaic panels and the batteries

4. Bridge testing

4.1 General

By the end of construction static and dynamic tests were carried out. For these tests some additional equipment was used, namely for dynamic tests. Besides the main bridge, also three spans of the south approaching viaduct were tested.

A three dimensional finite element model of the bridge was developed in SAP2000 to evaluate its response to the static tests and its dynamic characteristics. Shell and frame elements were used for modelling the deck, as presented in *Fig. 12*. The piers were simulated by frame elements. Finally, the bearings at the top of the piers and abutments were modelled by link elements.

Before the load tests the preliminary FE model was used to estimate the deformation of the structure caused by static loads and the frequencies and shapes of the natural vibration modes. After the tests, the FE model was calibrated with the results from the static load tests, and then adjusted to the dynamic characteristics identified with the dynamic tests.

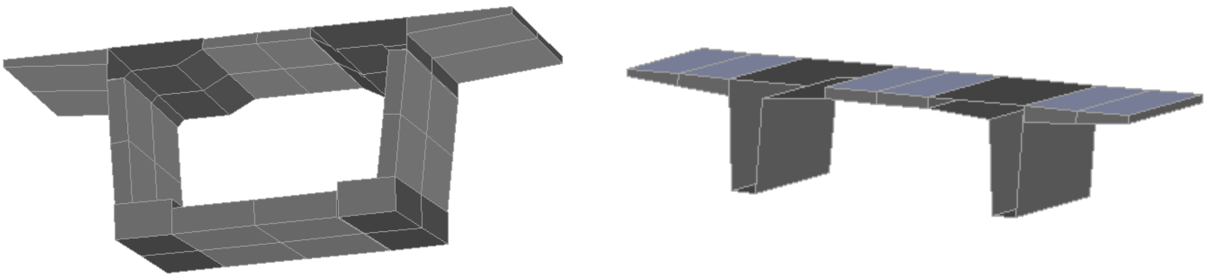

Fig. 12 – Segment model of the bridge deck and viaduct

4.2 Static load tests

The static tests were carried out in three phases: in the first one a concentrated load of 855 kN, made by a line of three loaded lorries, was placed in 13 positions between piers P7 and P13; in the second phase this concentrated load run very slowly across the bridge (moving load); finally, the third part of the test was performed with nine loaded lorries with a total weight of 2 637 kN. These lorries were placed in nine different positions.

During the static tests all the sensors of the structural health monitoring system were used as well some additional equipment installed to measure vertical displacements at mid-span sections between piers P10 e P13.

Fig. 13 – Lorries during the static load test

The use of a line of lorries as concentrated load allowed the experimental evaluation of influence lines, even though it was not a single axle load [6]. Some examples are presented: a vertical displacement (Fig. 14), a longitudinal rotation (Fig. 15) and concrete strains at section S1 (Fig. 16).

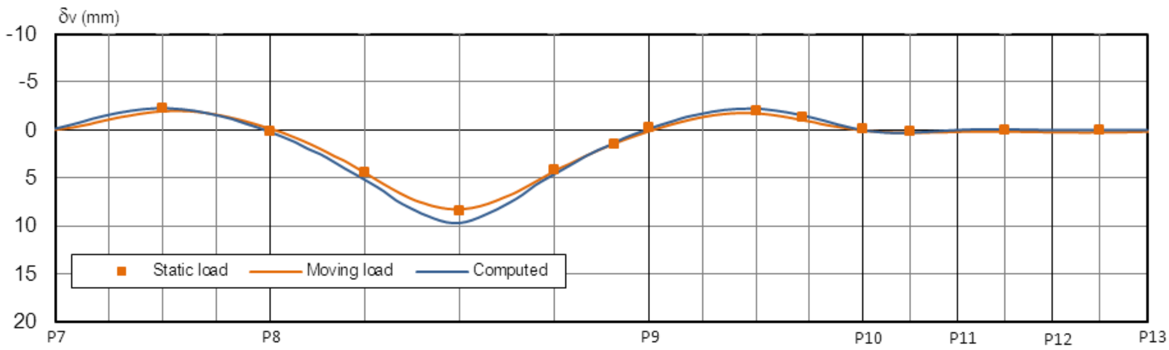

Fig. 14 – Influence line of vertical displacement at central mid-span

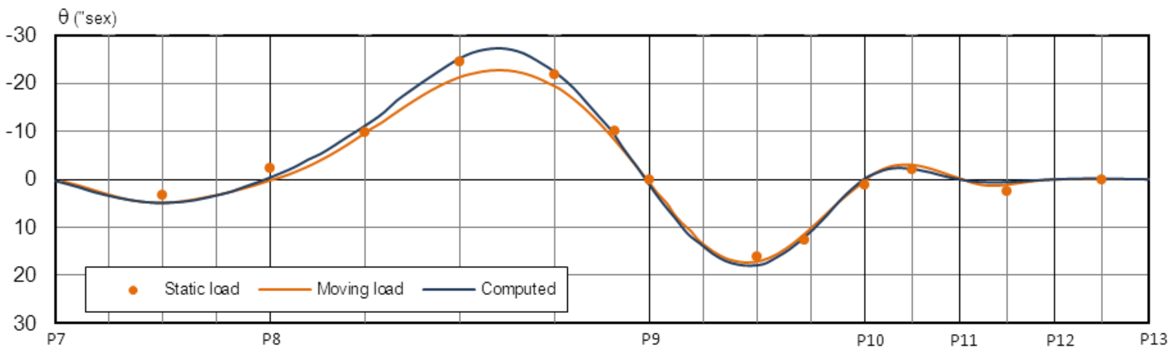

Fig. 15 – Influence line of longitudinal rotations at top of pier P9

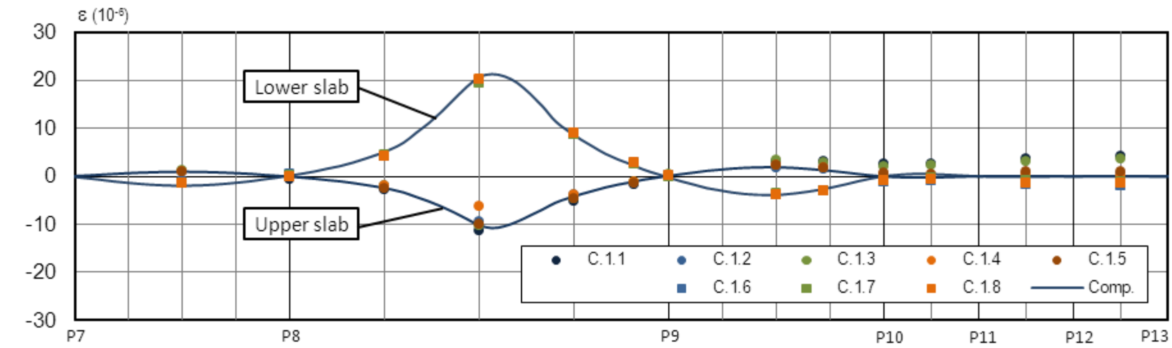

Fig. 16 – Influence line of concrete strains at section S1

The maximum vertical displacements of the deck occurred when nine load trucks were placed at the central mid-span. Deck deformations in that situation are presented in Fig. 17.

For all load cases, a good correlation between numerical and experimental values was achieved.

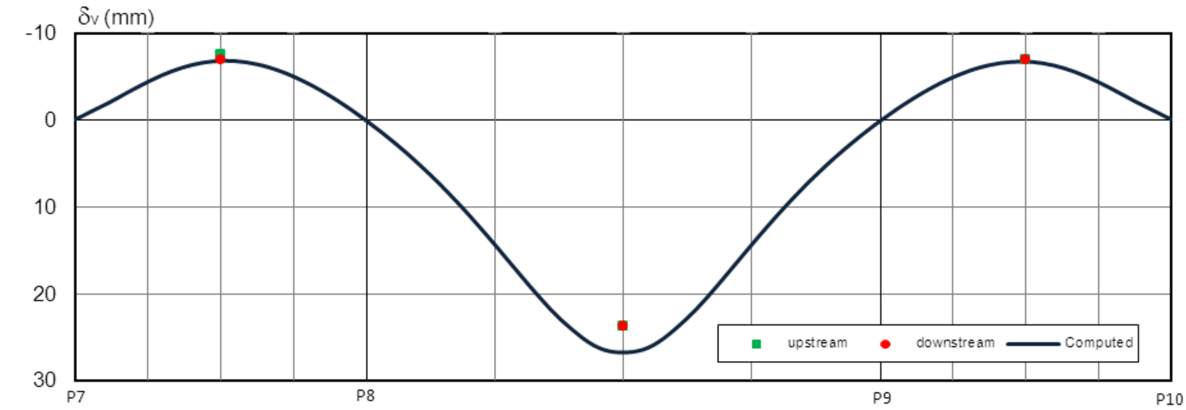

Fig. 17 – Deck deformations for trucks at central mid-span

4.3 Dynamic tests

4.3.1 Testing procedure

The dynamic test was performed to obtain experimentally the dynamic characteristics of the structure (vibration frequencies, mode shapes and damping ratios). During the test, accelerations induced by ambient excitations (mostly wind) were measured using three GeoSIG GSR-18 Strong Motion Recorders. Each GSR-18 measures simultaneously the vertical, longitudinal and transversal acceleration.

The ambient vibration test was carried out in fifteen set-ups. During these set-ups, accelerations were measured at 15 sections of the bridge, with one of the triaxial accelerometers fixed in one of the sections while the others were being moved from set-up to set-up. The localization of the transducers is illustrated in Fig. 18. As indicated in this figure, the fixed equipment is located in point *7j*.

In each set-up the ambient vibration data was acquired during a time length of about 25 minutes using a sampling rate of 100 Hz.

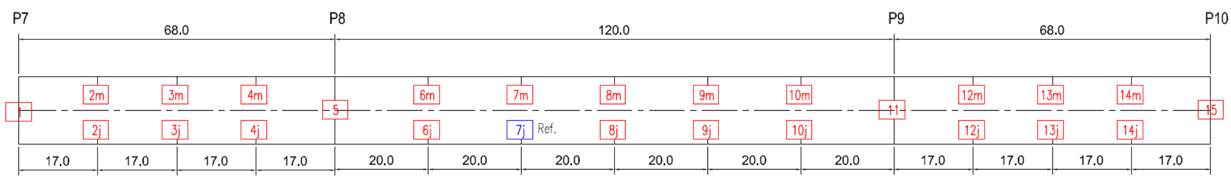

Fig. 18 – Dynamic tests: sections instrumented

4.3.2 Modal identification

The software LNEC-SPA [7] was employed for the modal identification of the bridge. This program allows processing experimental signals and estimating the dynamic characteristics of the structure.

The records obtained in the ambient vibration test, were pre-processed with low-pass filtering at 12 Hz using an 8 poles Butterworth filter and decimation to a sampling frequency of 20 Hz.

Based on the pre-processed data, the Averaged Normalized Power Spectral Density (ANPSD) was estimated. For the sampling frequency of 20 Hz and the data segments with 1024 values, the frequency resolution of the spectra is 0,0195 Hz.

Fig. 19 shows the power spectral density estimated for the longitudinal, transverse and vertical accelerations. The peaks of the spectra indicate the existence of structural modes. The identification of those modes involved not only the selection of the peaks in the spectra but also the analysis of the coherence functions between the different measurement points. The values of the frequencies of the vibration modes that were identified for the bridge are included in the corresponding ANPSD's (Fig. 19).

The damping ratio for the identified modes was estimated by Half-Power bandwidth method.

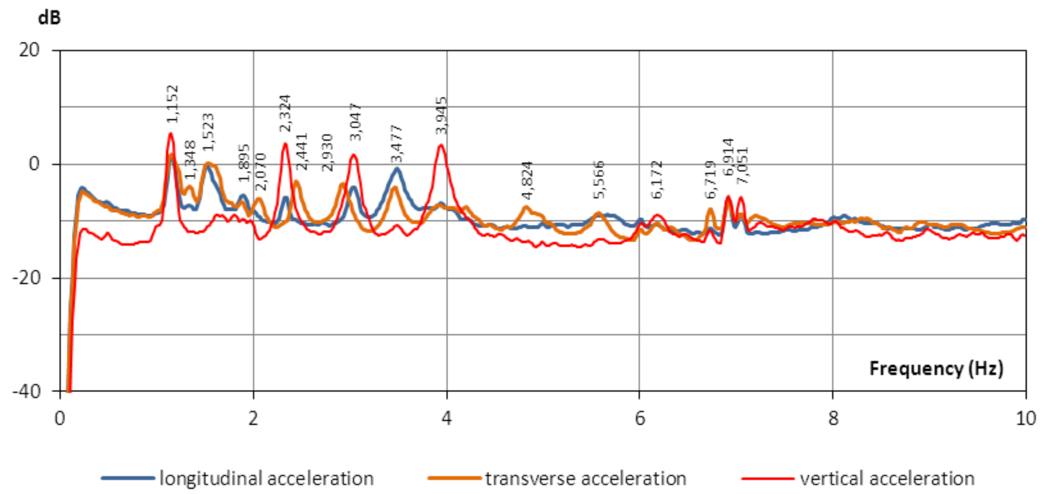

Fig. 19 – Averaged Normalized Power Spectral Density

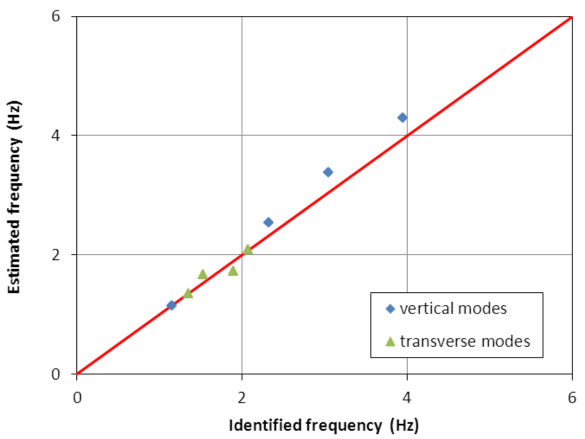

Fig. 20 – Experimental and FE model frequencies

The first vertical vibration mode was identified on 1,152 Hz with damping ratio 1,4%. The first transverse mode was found on 1,348 Hz, which damping ratio is 3,8%.

In Fig. 20 the identified frequencies of the vibration modes of the bridge are compared to the estimated frequencies obtained from the finite element model. The application of the ambient vibration tests with an appropriate output-only modal identification method was successful, allowing the identification of several natural vibration modes of the bridge.

It is important to note that these tests can be carried out during bridge lifetime without traffic restrictions.

5. Conclusions

The structural health monitoring of Cabala Bridge includes the measurement of vertical displacement, rotations, strains and temperatures inside the concrete, besides an in situ characterization of concrete's creep and shrinkage. In addition to the structural component, the instrumentation aims the continuous monitoring of the bridge scour as well as the register of water levels and weather conditions.

The experimental results acquired during the static and dynamic tests carried out at the end of construction were used to validate the numerical model developed and to assess the structural behaviour of the bridge. The calibration of the structural model was a significant outcome of the tests.

The monitoring system of the structural behaviour operating in this bridge will contribute to bridge safety and maintenance, identifying causes of unacceptable responses. In addition, important data will be obtained, increasing significantly the knowledge about the concrete time dependent behaviour and structural behaviour that may be very useful in the construction or rehabilitation of other bridges.

Acknowledgements

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