Static and dynamic tests of Salgueiro Maia cable-stayed bridge

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ABSTRACT: This paper presents the static and dynamic tests of the Salgueiro Maia cable-stayed bridge, which crosses the Tagus River near Santarém. Some innovative procedures were used during these tests, like an upgraded hydrostatic leveling system to measure vertical displacements or the measurement of the cable forces by the vibrating method and by force cells. The dynamic tests allowed the identification of 32 modes of the natural vibration of the structure, using the technique of output-only modal identification. The experimental results are compared with the analytical values computed with a finite element model of the bridge.

1 INTRODUCTION

The Salgueiro Maia cable-stayed bridge is a road bridge that crosses the Tagus River near the city of Santarém. This bridge was instrumented during the construction and its behavior is being experimentally followed since then. Before it was opened to the traffic, the new bridge was subjected to static and dynamic load tests. This paper, after a brief description of the structure, presents the procedures used in the static and dynamic tests. Both static and dynamic experimental results are also compared with the analytical values evaluated with a finite element model of the bridge.

2 BRIEF DESCRIPTON OF THE BRIDGE

The Salgueiro Maia Bridge is a cable-stayed bridge with a main span of 246 m and a total length of 570 m (Figure 1).

The stay cables suspend the bridge deck from two masts that are monolithic with the deck. These masts have a height of 50 m above the deck and are in reinforced concrete up to the level of the first cables, and from there on have a steel-concrete composite structure. In total the bridge has 72 cables (18 in each side of each mast). There are three types of cables, with 55, 61 and 73 tendons, and their lengths vary from 31 m up to 131 m.

The bridge deck has a cross-section formed by a 10.0 m by 2.5 m hollow rectangular shape caisson with an upper lateral slab and pre-cast concrete bracing's. Since the cables are anchored at the deck axis, the designer (Martins, 1995) adopted a box-girder cross-section in order to

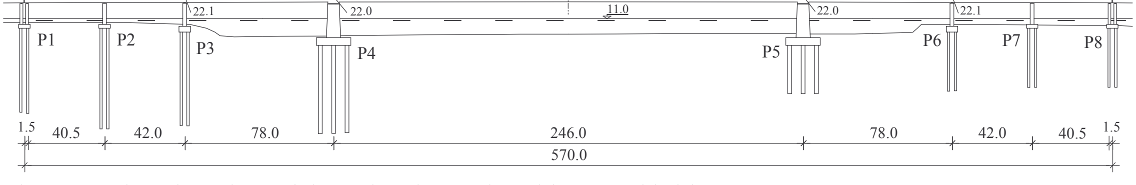


Figure 1. Elevation view of the Salgueiro Maia cable-stayed bridge

provide an adequate torsional stiffness and strength to the bridge deck.

Due to the axial suspension, the stresses at the box-girder webs had to be transferred to the axis. This was done with diagonal steel elements that were placed connecting the bottom corners of the caisson to the middle axis of the upper slab. Those diagonal elements can be seen in the view of the cross section of the bridge deck presented in Figure 2.

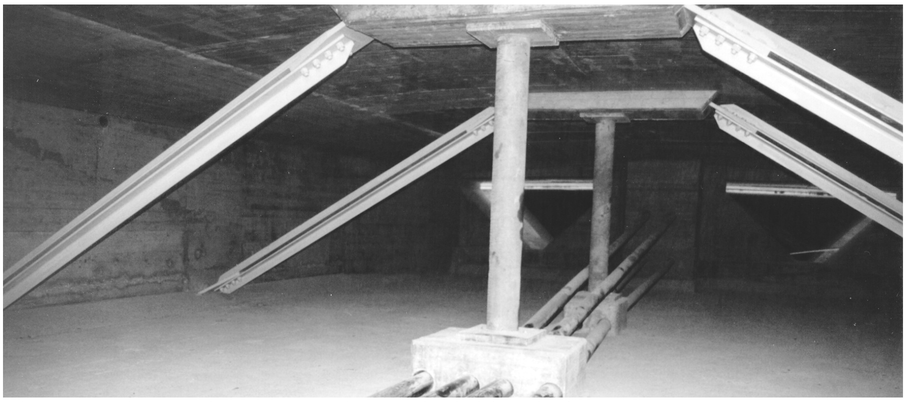


Figure 2. View of the cross-section of the bridge deck

The stresses at the masts are transmitted to the piers through a thick element that stiffens the connection of the masts to the deck. In each of the piers P4 and P5, the deck and masts are supported by 20 high damping rubber bearings (HDRB) that provide a high level of seismic isolation to the bridge superstructure. In this respect, according to Marioti & Duarte (1999), the Salgueiro Maia Bridge was the largest application of HDRB bearings in the World and was the first one in a cable-stayed bridge.

Besides the main cable-stayed bridge, the new crossing of the Tagus River also comprises approach viaducts that are formed by 9 continuous structures with a length of 378 m and a smaller one with a length of 336 m. On the right side of the main bridge the approach viaduct has a total length of 1470 m and on the left side it has a total length of 2268 m. The approach viaducts have a cross-section similar to the one of the main bridge, which adds to the aesthetically pleasant overall aspect of this new crossing of the Tagus River.

3 OBSERVATION DURING AND AFTER CONSTRUCTION

During and after construction of the bridge, several sections were instrumented (Figure 3) to measure displacements, rotations, strains and temperatures. The distribution of the equipment in the deck cross section is exemplified in Figure 4.

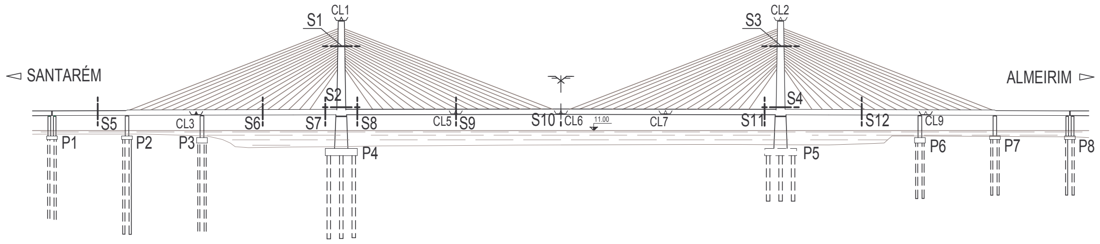


Figure 3. General observation plan of the Salgueiro Maia cable-stayed bridge

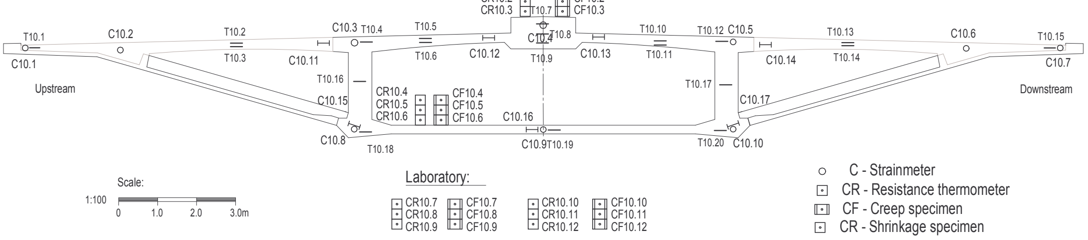


Figure 4. Cross section of the Salgueiro Maia cable-stayed bridge (S10)

Noteworthy in the general observation plan was the measurement of vertical displacements by an upgraded hydrostatic leveling system associated to pressure cells and the use of force cells to measure cable tensions.

The monitoring of this bridge includes also vibrating-wire strain meters to measure concrete strains, resistance thermometers placed across the thickness of the elements to obtain the thermal gradients and the use of air bubble clinometers to evaluate rotations. Besides measurements in the structure, a study of the creep and shrinkage of concrete was made using specimens placed over the deck and inside the box girder, in several sections.

4 FINITE ELEMENT MODEL

A three dimensional, linear, elastic numerical model of the bridge was developed to evaluate its response to static tests and its dynamic characteristics.

Shell elements were used for modeling the deck and beam elements for the piers and masts. The HDRB bearings between the deck and the piers were modelled with link elements.

Before the load tests the preliminary FE model was used to estimate the deformation of the structure subjected to 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.

5 STATIC TESTS

5.1 *Testing procedure*

The static tests were carried out in two phases: in the first one a concentrated load of 1 860 kN, made by a line of six loaded trucks, was used (Figure 5); the second phase of the test was performed with twenty loaded trucks with a total weight of 3 527 kN (Figure 6).

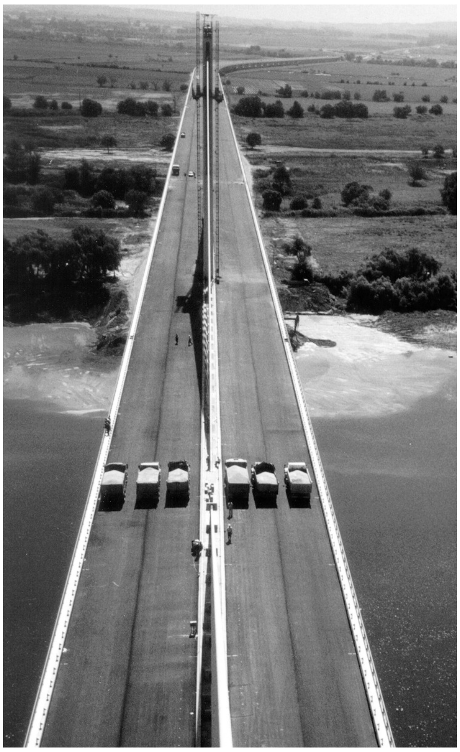


Figure 5 Concentrated load

Figure 6 Highest load used during static tests

For both static and dynamic tests additional equipment was installed. For the static tests, geodetic methods were used to measure vertical displacements and accelerations were measured in some cables in order to evaluate the cable tension from their vibration frequencies.

5.2 *Main results*

Figure 7 presents some of the influence lines, obtained with the use of the concentrated load: vertical displacements at the mid-span of the main span, rotations at the top of one tower, a cable tension and strains at the deck (section S6).

The first chart shows the influence line of the vertical displacements at the mid-span of the main span and includes experimental results obtained with geodetic methods and hydrostatic leveling. The cable tension chart presents the results obtained using both experimental methods, force cell and vibration, which show a good agreement with the computed values.

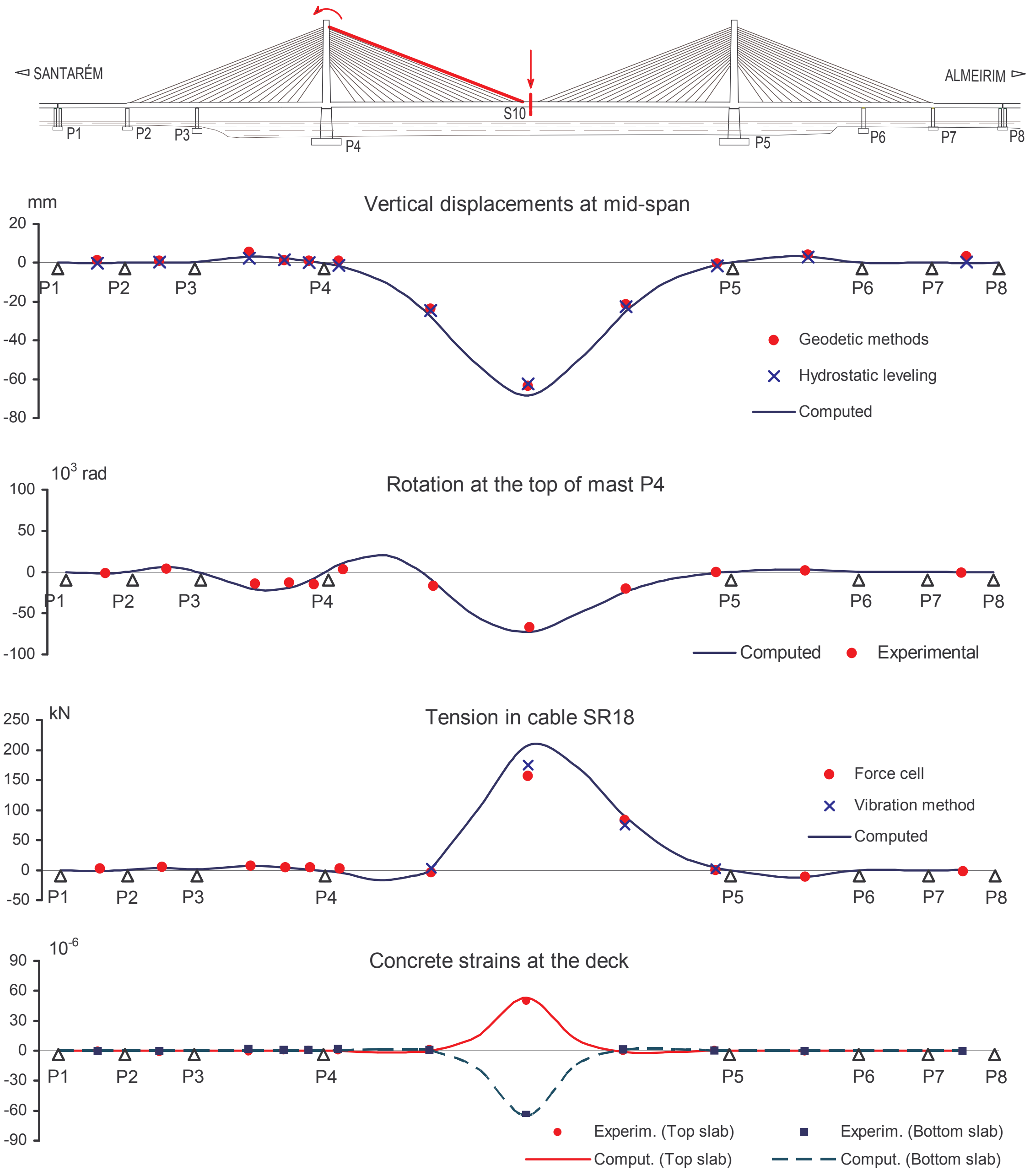


Figure 7 Influence lines

Figure 8 shows the deck deformations occurred with the load trucks placed at mid-span. The good agreement between, on one hand, values measured with geodetic methods and values measured with hydrostatic leveling and, on the other hand, between experimental and analytical results are obvious.

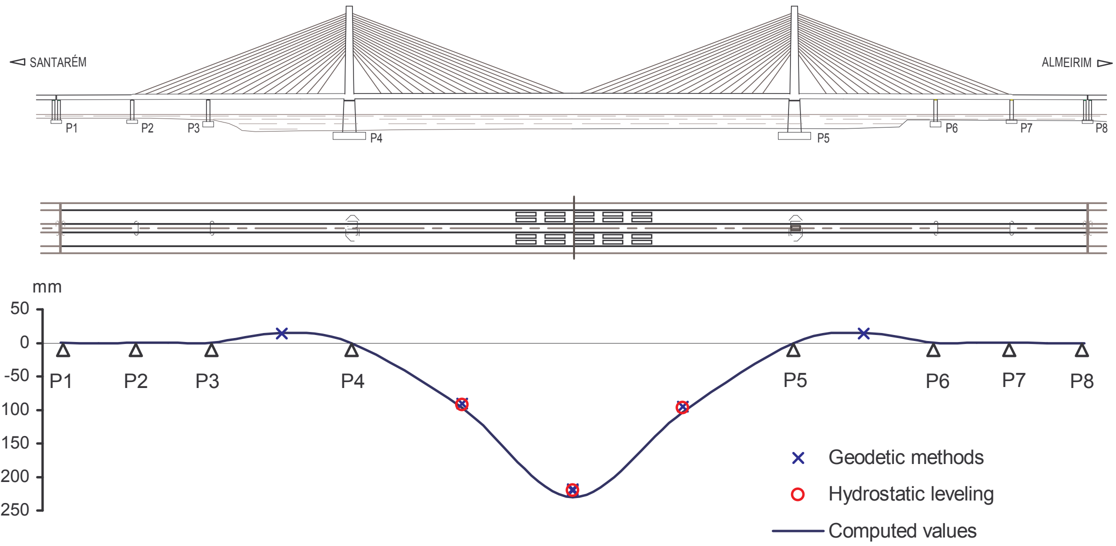


Figure 8 Deck deformations for trucks at mid-span

6 DYNAMIC TESTS

6.1 *Testing procedure*

Dynamic tests were performed to identify the dynamic characteristics of the structure (vibration frequencies, mode shapes and damping ratios). These tests included ambient vibration tests, tests with trucks passing over wood planks in order to apply an impulsive load to the structure and, finally, some tests with trucks crossing the bridge at well-defined and controlled velocities.

During the ambient vibration tests, accelerations induced by the traffic of loaded trucks and wind, were measured using five Geosys GSR-16 strong motion recorders, fifteen Kinemetrics Uniaxial Episensor (ES-U) accelerometers, signal conditioning equipment developed at the Scientific Instrumentation Centre of LNEC and data acquisition equipment from National Instruments (DAQ board SCXI-1200 and a SCXI-1000DC chassis with SCXI-1140 sampling and hold boards), besides two laptop computers.

In the ambient vibration tests the ES-U accelerometers were used in eight set-ups and the GSR-16 recorders were used in four set-ups. In total, accelerations were measured at 33 sections of the bridge deck and at the top of the two masts (see Figure 9 and Figure 10). In the different set-ups, some transducers were fixed in one of the sections while the others were being moved from set-up to set-up. In each set-up the ambient vibration data was acquired during a time length of about 20 minutes using a sampling rate of 50 Hz.

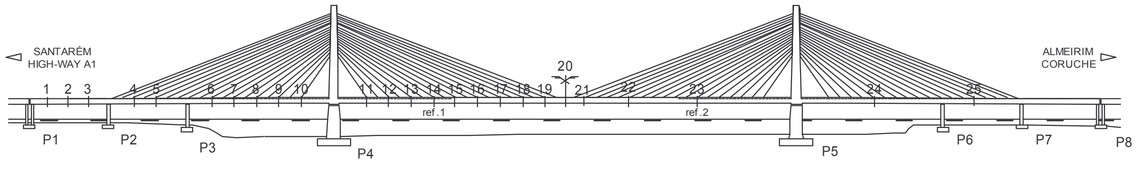


Figure 9 Dynamic tests: sections instrumented with the ES-U accelerometers

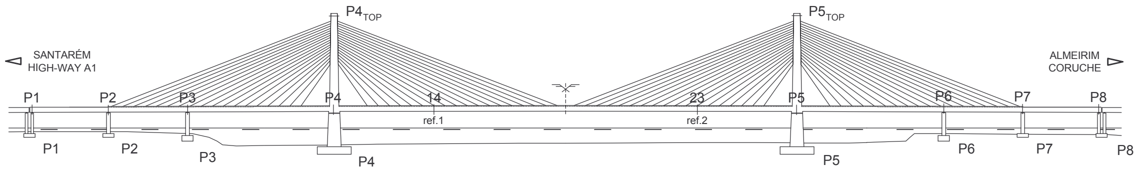


Figure 10 Dynamic tests: sections instrumented with the GSR-16’s

6.2 *Modal identification*

The technique used for the analysis of the recorded acceleration response of the Salgueiro Maia cable-stayed bridge was the basic frequency domain method (Ventura & Brincker, 2000) or peak picking method (Andersen *et al*, 1999). This is a widely used method that basically involves the computation of auto-spectra, coherence functions between different measurement points and estimates of the frequency response functions, also between different measurement points. The method was implemented in a computer program using Labview. A more detailed description of the applied modal identification procedures was presented by Rodrigues (2001).

A total of 32 vibration mode shapes of the bridge were identified from the analysis of the dynamic tests data; some of them are presented in Figure 11 (vertical modes), Figure 12 (torsional modes) and Figure 13 (transverse modes). In those Figures the identified mode shapes are compared with the ones computed with the finite element model and the error bars in the identified mode shapes represent the 95 % confidence intervals on the estimate of the modal components.

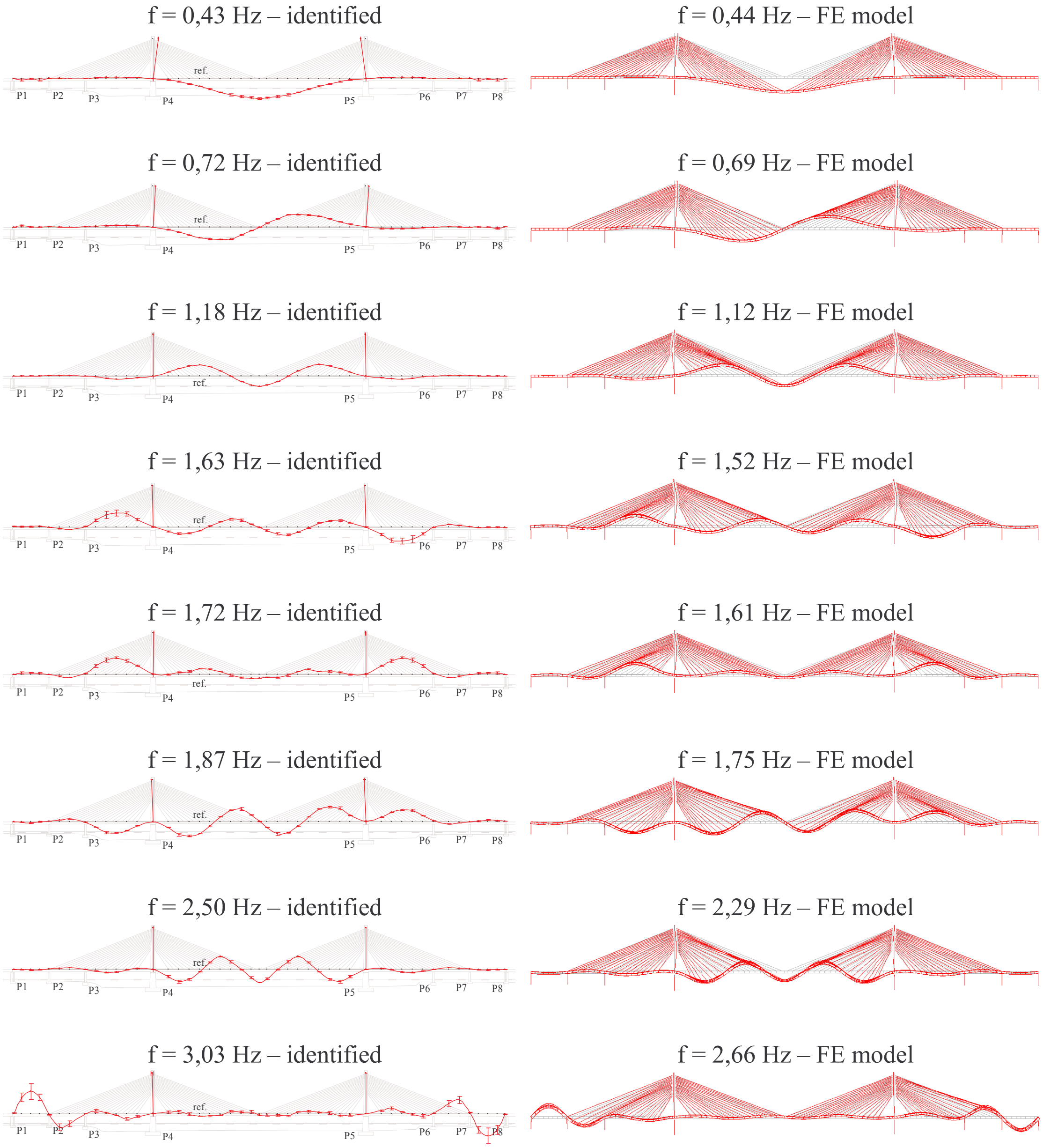
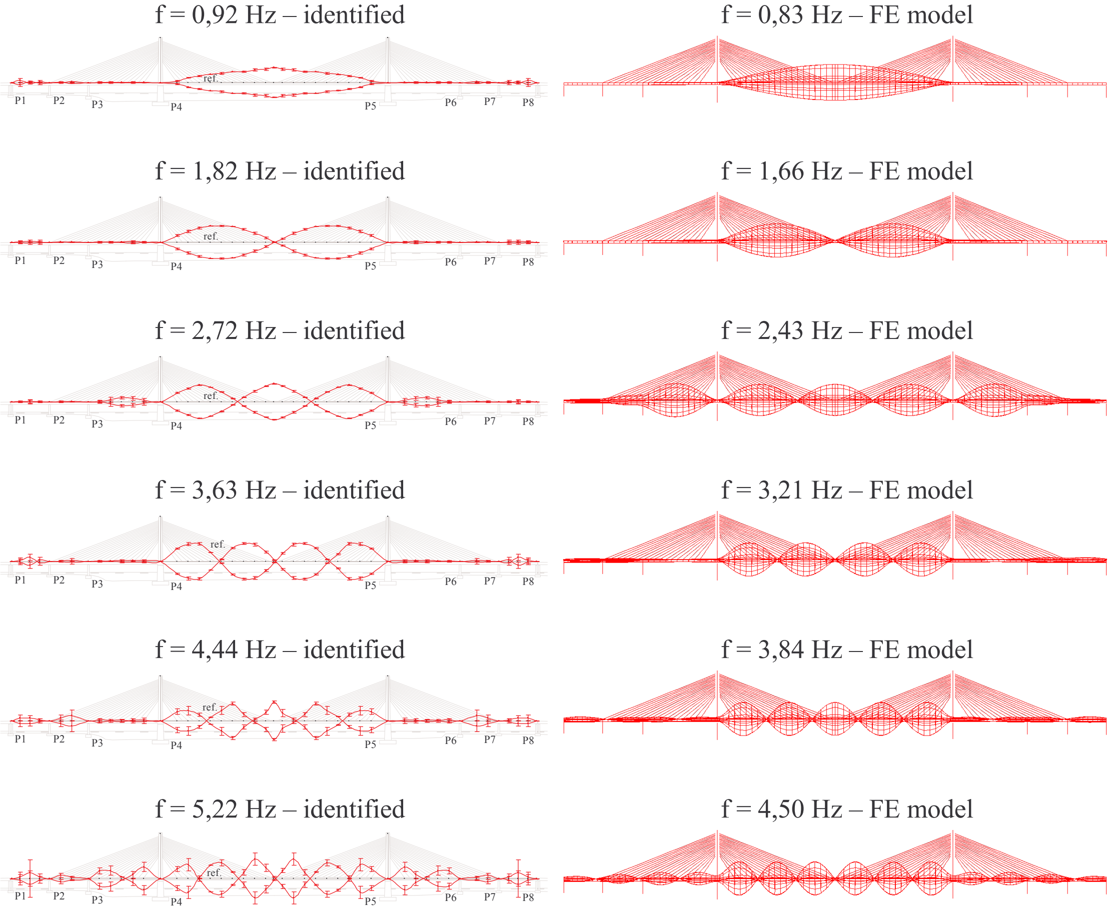

f = 0,43 Hz – identified
f = 0,44 Hz – FE model
f = 0,72 Hz – identified
f = 0,69 Hz – FE model
f = 1,18 Hz – identified
f = 1,12 Hz – FE model
f = 1,63 Hz – identified
f = 1,52 Hz – FE model
f = 1,72 Hz – identified
f = 1,61 Hz – FE model
f = 1,87 Hz – identified
f = 1,75 Hz – FE model
f = 2,50 Hz – identified
f = 2,29 Hz – FE model
f = 3,03 Hz – identified
f = 2,66 Hz – FE model

Figure 11 Vertical modes



f = 0,92 Hz – identified

f = 0,83 Hz – FE model

f = 1,82 Hz – identified

f = 1,66 Hz – FE model

f = 2,72 Hz – identified

f = 2,43 Hz – FE model

f = 3,63 Hz – identified

f = 3,21 Hz – FE model

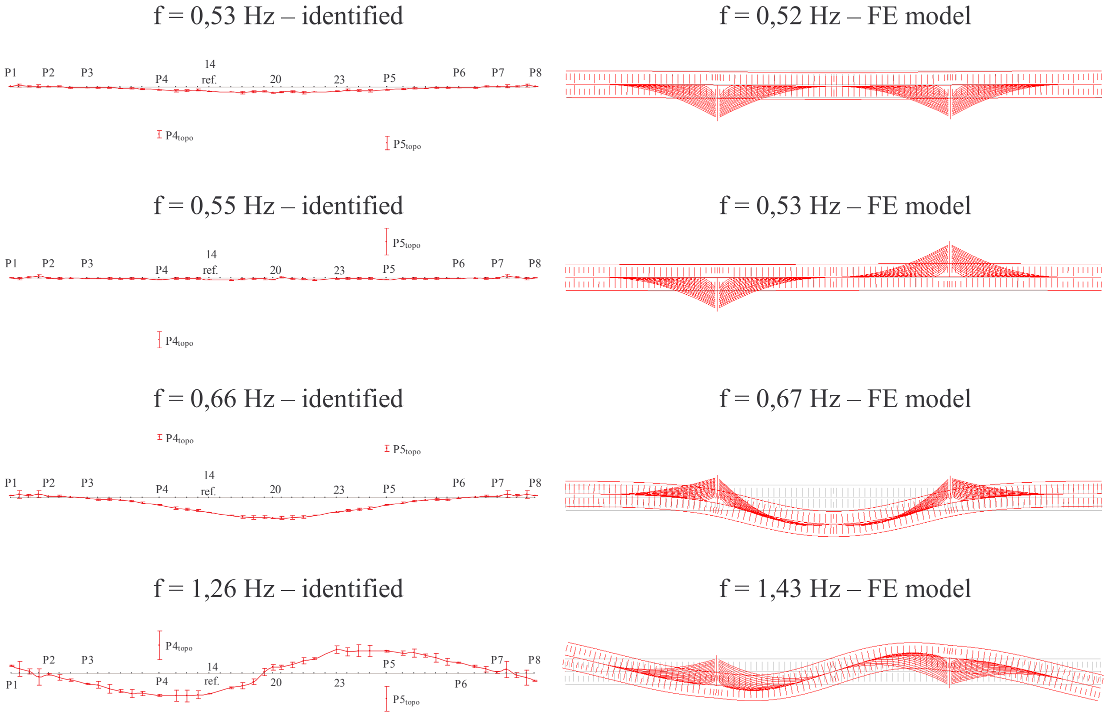
f = 4,44 Hz – identified

f = 3,84 Hz – FE model

f = 5,22 Hz – identified

f = 4,50 Hz – FE model

Figure 12 Torsional modes



f = 0,53 Hz – identified

f = 0,52 Hz – FE model

f = 0,55 Hz – identified

f = 0,53 Hz – FE model

f = 0,66 Hz – identified

f = 0,67 Hz – FE model

f = 1,26 Hz – identified

f = 1,43 Hz – FE model

Figure 13 Transverse modes

7 CONCLUSIONS

The Salgueiro Maia cable-stayed bridge was subjected to static and dynamic load tests performed at the end of its construction and before it was opened to the traffic. These tests were part of several structural health monitoring activities developed by LNEC in this bridge, that were initiated during its construction and include also the long term monitoring of its structural condition.

In the static tests the use of a hydraulic leveling system associated with pressure cells proved to be an accurate way of measuring vertical displacements in box-girder bridges with results analogous to those obtained by geodetic methods. A good correlation was also achieved between the results obtained in the measurement of the cable tension using force cells and with the vibration method.

In the dynamic tests, the use of natural excitation tests (that take advantage of the usual loads to which bridge structures are subjected, like wind and traffic) with an appropriate output-only modal identification method, was quite successful, since 32 natural vibration modes of the bridge were clearly identified.

Both static and dynamic experimental results showed a good correlation with the analytical values evaluated with a finite element model.

The information collected in the tests concerning the structural behavior of the Salgueiro Maia cable-stayed bridge is an important contribution to characterize its actual condition at the end of the construction and before its opening to the traffic. It should be noted that the natural excitation dynamic tests that were performed for modal identification purposes, can also be carried out during the lifetime of the structure without the need to impose traffic restrictions.

ACKNOWLEDGEMENTS

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