Modal identification from ambient vibration tests on a cable-stayed bridge

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ABSTRACT: A cable-stayed bridge recently built in Coimbra, Portugal, was subjected to static and dynamic load tests, before it was opened to the traffic. Those tests included the ambient vibration tests presented in this paper. Dynamic tests with loaded trucks crossing the bridge with different speeds were also performed and are briefly referred. The paper describes the testing procedure and the modal identification techniques that were used to process the measured accelerations. The dynamic characteristics obtained with output-only modal identification techniques are presented and compared with the ones evaluated with a finite element model of the bridge.

1 INTRODUCTION

The evaluation of the actual dynamic characteristics, or modal identification, of civil engineering structures is particularly important for the calibration of analytical and numerical models that are to be used in studying the behavior of those structures to various types of loads like traffic, wind or seismic loads.

Another area where modal identification of civil engineering structures, is having an increasing interest, is in structural health monitoring. This is due to the fact that the dynamic properties are directly related to the stiffness, mass and energy dissipation mechanisms and to their spatial distribution in a structure. Therefore, the dynamic characteristics, like frequencies, damping and mode shapes, also reflect the actual global condition of a structural system (structural health). Situations of structural damage can, eventually, be detected from changes in the identified dynamic properties.

Different experimental techniques can be used to perform in-field dynamic tests in civil engineering structures. From forced vibration tests, where different types of excitation equipments can be used, to ambient vibration tests, which rely on the natural sources of excitation like wind or traffic, Paultre et al. (1995), Felber and Cantieni (1996).

For structural health monitoring it is important to be able to evaluate the dynamic characteristics without the need to interrupt the normal use of a structure (for instance in a bridge, without interruption of the usual traffic). With natural input testing or ambient vibration testing it is possible to satisfy this requirement, since it consists in the measurement of the dynamic responses induced by the loads to which the structures are usually subjected, like wind or traffic. Therefore, from the various types of dynamic tests that can be applied in civil engineering structures, ambient vibration testing is the more reasonable approach if there is the purpose to apply it periodically (or even continuously with permanent equipment) during the lifetime of a structure.

In recent years there has been also a considerable development at the level of the equipments for measurement of the dynamic response of structures. Sensors are having a higher sensitivity and data acquisition systems a better resolution, both allowing to measure adequately structural responses with very small amplitudes.

Important developments have been made also in what concerns the modal identification methods for output only situations, Andersen et al. (1999), Peeters (2000), Ventura and Brincker (2000). Some of those methods require a considerable computational effort, but which is easily handled with the computing speed and storage capacity of today's computers.

Considering the several reasons referred in the previous paragraphs, it is natural that at the Structures Department of LNEC, there has been an increasing activity in the application of ambient vibration tests and output-only modal identification, for evaluation of the dynamic characteristics of bridges, Rodrigues and Campos Costa (1999, 2000), Rodrigues (2001).

In recently built bridges, for which LNEC is usually required to perform reception load tests, there has been a major concern in doing an evaluation of the dynamic properties as complete as possible and that can be considered as corresponding to a reference situation of the structure, to be taken into account for monitoring its condition during its lifetime.

The work presented in this paper was developed within the reception load tests performed in a cable-stayed bridge recently built in the city of Coimbra in Portugal. Those tests were performed before the bridge was opened to the traffic and included static load tests, Santos and Xu (2005), and dynamic tests, Rodrigues (2005), involving the ambient vibration tests herein presented and also dynamic tests with loaded trucks crossing the bridge with different speeds.

In this paper, after this introduction, the Coimbra cable-stayed bridge is briefly described. Next, the equipment used in the tests and the testing procedure are presented. The following items address the modal identification methods that were used to process the recorded accelerations and present the main results that were obtained. Finally the characteristics estimated from the tests are compared with the ones evaluated with a finite element model and some conclusions are made about the work that was developed.

2 DESCRIPTION OF THE BRIDGE

The Coimbra cable-stayed bridge is a roadway bridge that crosses the Mondego river in the eastern part of the city of Coimbra. It has a total length of 330 m and a main span with 185 m. An elevation and a plan view of the bridge are presented in Fig. 1.

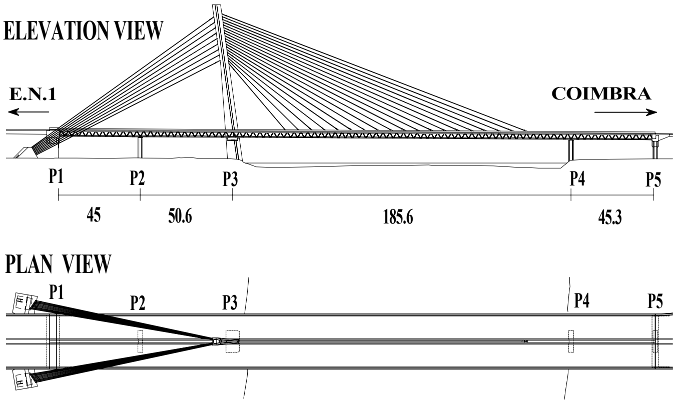

Figure 1. Elevation and plan views of the bridge

The bridge has a composite deck comprising two prestressed concrete slabs, held apart, at the upper and lower levels by four inclined truss panels. Each truss panel is composed of steel diagonals, connected directly to the concrete slabs since there are no steel truss members. The roadway lanes run on the upper level slab, while in the lower lever slab there is a pedestrian walkway. A cross-section of the bridge deck is presented in Fig. 2.

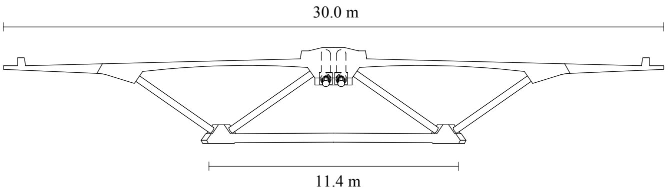

Figure 2. Cross-section of the bridge deck

The deck of the main span of the Coimbra cable-stayed bridge is suspended from 19 pairs of cable stays, connected to a single inclined mast with a height of 68 m above the roadway deck. There are also 9 pairs of retention cable stays that connect the mast to two concrete anchorage blocks.

A general view of the Coimbra cable-stayed bridge is presented in Fig. 3.

Figure 3. General view of the Coimbra cable-stayed bridge

3 DYNAMIC TESTS

3.1 *Equipment used in the tests*

The ambient vibration tests of the Coimbra cable-stayed bridge were carried out using the following equipment:

- one laptop computer;
- 15 Kinemetrics Uniaxial Episensor (ES-U) accelerometers;
- five power supply and signal conditioning units with respective cables for power and signal transmission;
- data acquisition equipment from National Instruments, including:
  - DAQ Card AI-16XE-50 data acquisition board with A/D conversion at 16 bits;
  - SCXI-1000DC chassis;
  - SCXI-1140 boards with sampling and hold circuits, to perform the simultaneous acquisition of several signals from different sensors.

The ES-U accelerometers are force balance acceleration sensors from Kinemetrics. They have a high dynamic range (greater than 145 dB) and low noise performance. Their bandwidth goes from DC to 200 Hz, which is an important feature for testing long span bridges like the Coimbra cable-stayed bridge.

The ES-U accelerometers also have a user selectable full-scale range, which allows using them in several different situations.

In order to use the ES-U accelerometers, a system for power supply and signal conditioning was developed at the Centre for Scientific Instrumentation (CIC) of LNEC. This system comprises 5 power supply and signal conditioning units. Each of these units can be connected to three accelerometers and contains two 12V batteries, analog filters and amplifiers so that the user can select gain factors of 1, 2, 5, 50, 100, 200, 250, 400 and 1000. The units are connected to the sensors with relatively short cables (20 m) and to the data acquisition system with long cables that, at the present, go from 50 m up to 200 m. Between these long cables and the data acquisition system there is a small box to convert the long cables to BNC terminals.

A scheme of all the equipment used in the ambient vibration tests of the Coimbra cable-stayed bridge is presented in Fig. 4.

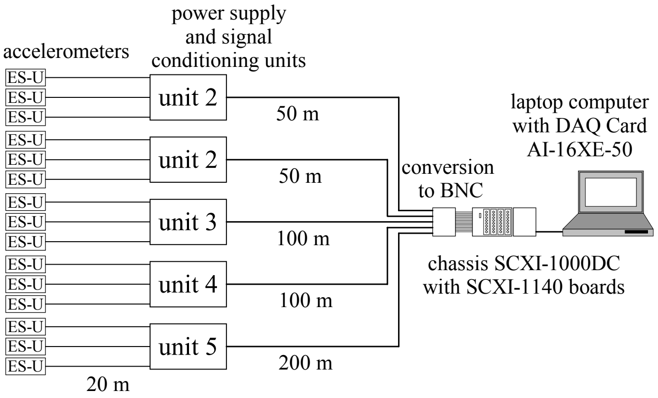

Figure 4. Equipment used in the ambient vibration tests

In the ambient vibration tests of the Coimbra cable-stayed bridge, the ES-U accelerometers were configured with a sensitivity of 40 Volt/g and the gain factor at the power supply and signal conditioning units was configured to 50. With this configuration, the minimum acceleration amplitude that could be measured was 0.15 μg.

The instrumentation for the dynamic tests with traffic of loaded trucks included also electrical strain gauges. In those tests, the system for the ES-U accelerometers was used with a configuration 10 times less sensitive than for the ambient vibration tests. This was achieved by changing the gain factor, at the power supply and signal conditioning units, from 50 to 5.

In both types of tests, the data acquisition was performed with software developed in LabView, National Instruments (2004).

3.2 *Testing procedure*

In the ambient vibration tests of the Coimbra cable-stayed bridge, accelerations were measured in 68 points of the deck and also in the top of the mast. The points on the deck were located in the lower level slab (pedestrian walkway), see Fig. 5.

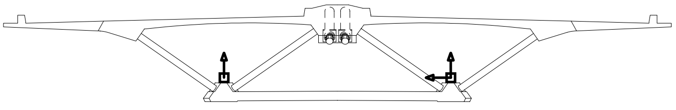

Figure 5. Placement of the accelerometers in the lower deck

The tests were performed in a total of 11 set-ups. From the 15 available sensors, 6 were considered as reference sensors and remained at the same points during all the set-ups, while the remaining 9 roving sensors were placed in the other points, changing their position from set-up to set-up.

For the preparation of the tests, namely for the selection of the reference points, it was important to do some pre-test analysis with a finite element model of the bridge.

In each set-up of the ambient vibration tests, accelerations were measured during a total time of 55 minutes. The records were acquired with a sampling frequency of 1000 Hz and were latter pre-processed with low-pass filtering at 8 Hz using a 8 poles Butterworth filter and decimation to a sampling frequency of 20 Hz.

The ambient vibration tests were performed before the bridge was opened to the traffic. At the time the tests were done, there were still some construction works going on in the bridge and in its approach viaducts, therefore there were a few cars crossing the bridge from time to time. However, in the majority of the set-ups, the measured vibrations were mostly induced by wind.

Besides the ambient vibration tests, the dynamic tests included also a series of tests where 4 of the loaded trucks used in the static tests, Santos and Xu (2005), crossed the bridge independently and successively with velocities of 15, 30, 45, 60 and 75 km/h.

4 MODAL IDENTIFICATION

The modal identification analysis of the Coimbra cable-stayed bridge, from the ambient vibration tests data, was performed using a frequency domain output-only modal identification method, the enhanced frequency domain decomposition method (EFDD), Brincker et al. (2001), implemented in the software Artemis Extractor, SVS (2002). The EFDD method is an improvement of the frequency domain decomposition method (FDD), Brincker et al. (2000).

Basically, there are three frequency domain output-only modal identification methods: the basic frequency domain method (BFD) or peak picking method (PP); the frequency domain decomposition method (FDD); and the enhanced frequency domain decomposition method (EFDD). The common data for these methods are the estimates of the spectral density functions of the response of a structural system. Usually, those estimates are obtained using a procedure that consists in: division of the response records in several, eventually overlapped, segments, whose size determines the frequency resolution of the spectral estimates; application of a signal processing window in order to reduce the effects of leakage; computation of the DFT of the windowed data segments trough the use of the FFT algorithm; computation of averaged auto and cross spectra considering the DFT's of the data segments.

Once the estimates of the spectral density functions are evaluated, the procedures to analyze them, in order to extract the modal properties of a system, are slightly different in each of the methods BFD, FDD and EFDD.

In the BFD method, Felber (1993), the auto-spectra are normalized and averaged in order to obtain an averaged normalized power spectral density function (ANPSD) that, in principle, shows all the resonance peaks corresponding to the vibration modes of a system. Identification of the frequencies of those peaks gives a first idea about the frequencies of the vibration modes of a system. Further analysis is needed of the coherence function and also of the amplitude and phase relations between the records obtained along the different experimental degrees of freedom. Both the coherence function and the amplitude and phase relations are evaluated with the elements of the spectral density functions matrix. At the frequencies of the natural vibration modes of a system, the coherence function should present values close to 1. The amplitude and phase relations between the different degrees of freedom are evaluated with the H_1 estimate of the transmissibility frequency response function and can be considered as an estimate of the modal components, from which the mode shapes of a system can be constructed.

In the FDD method the spectral density functions matrix is, at each discrete frequency, decomposed in singular values and vectors using the SVD algorithm. By doing so, the spectral densities are decomposed in the contributions of the different modes of a system that, at each frequency, contribute to its response. In each frequency, the dominant mode shows up at the 1^{st} singular value spectrum and the other modes at the other singular values spectra. From the analysis of the singular values spectra it is therefore possible to identify the auto power spectral density functions corresponding to each mode of a system, which may include parts of several singular values spectra, depending on which mode is dominant at each frequency. In the FDD method, the mode shapes are estimated as the singular vectors at the peak of each auto power spectral density function corresponding to each mode.

The EFDD method is closely related with the FDD technique, with only some additional procedures to evaluate the damping and to get enhanced estimates of the frequencies and mode shapes of a system. In the EFDD method, the analysis of the singular values spectra, takes a further step forward. The selection of the auto-spectra corresponding to each mode of a system is performed based on the values of the MAC coefficient between the singular vectors at the resonance peaks and at their neighboring frequency lines. Those SDOF auto-spectral density functions are then transformed back into the time domain by inverse FFT, resulting in auto-correlation functions for each mode of a system. Enhanced estimates of the frequencies of the modes of a system are obtained from the zero crossing times of those auto-correlation functions. The damping coefficients are estimated from the logarithmic decrement of those auto-correlation functions. Finally, the estimate of the mode shapes is also enhanced, considering all the singular vectors within each SDOF auto-spectral density function, weighted with the corresponding singular values.

In order to apply the EFDD method to the data obtained in the ambient vibration tests of the Coimbra cable-stayed bridge, the spectral density functions of the acceleration responses were estimated with the FFT algorithm applied to windowed and overlapped samples with 1024 values each. Since the sampling frequency of the records is 20 Hz (after pre-processing) the frequency resolution of the estimated spectra is 0.02 Hz.

Fig. 6 shows the averaged spectra of the first two singular values of the spectral density functions matrices of the vertical accelerations measured in the Coimbra cable-stayed bridge.

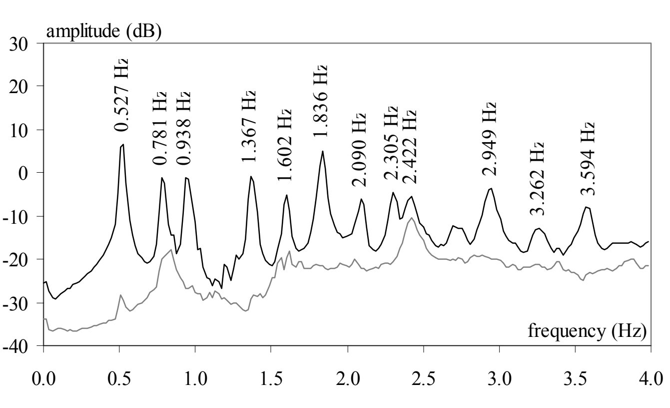

Figure 6. Singular values spectra of the vertical records

The frequencies corresponding to the most evident resonance peaks in the 1st singular value spectrum are also shown in Fig. 6. Notice, considering the above description of the EFDD method, that those frequencies don't correspond exactly to the frequencies that are identified with that output-only modal identification method.

Fig. 7 shows the normalized auto-correlation functions corresponding to the 1st vertical and the 1st torsion vibration modes of the Coimbra cable-stayed bridge.

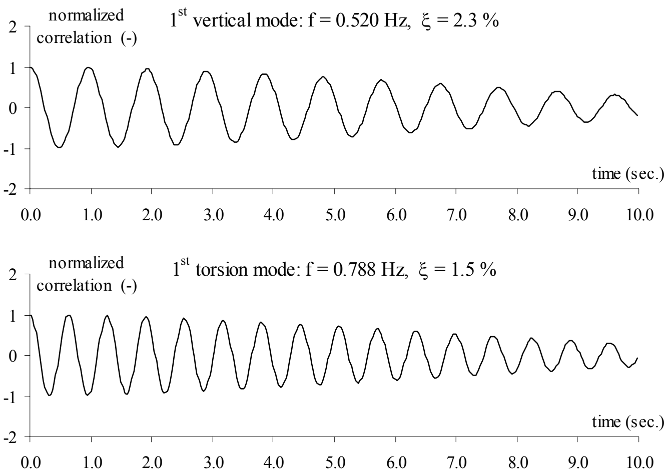

Figure 7. Normalized auto-correlation functions

Figs. 8 to 13 show the frequencies, damping ratios and configurations of some of the vibration modes identified with the EFDD method for the Coimbra cable-stayed bridge.

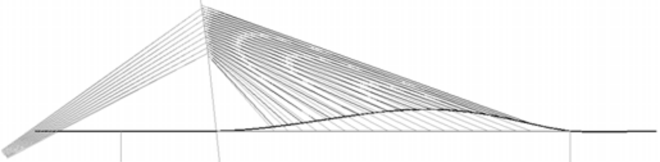

Figure 8. 1st vertical mode: f = 0.520 Hz, ξ = 2.3 %

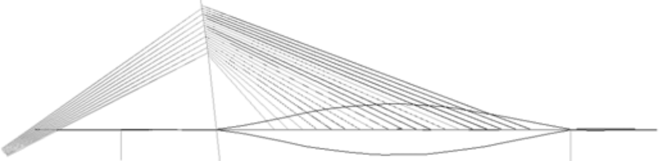

Figure 9. 1st torsion mode: f = 0.788 Hz, ξ = 1.5 %

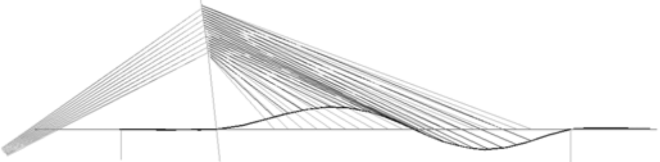

Figure 10. 2nd vertical mode: f = 0.945 Hz, ξ = 1.4 %

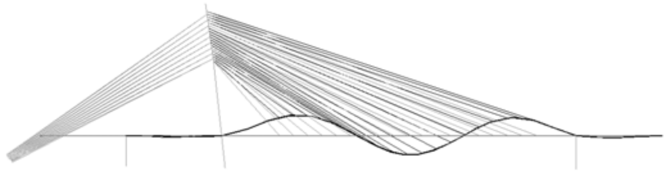

Figure 11. 3rd vertical mode: f = 1.370 Hz, ξ = 0.9 %

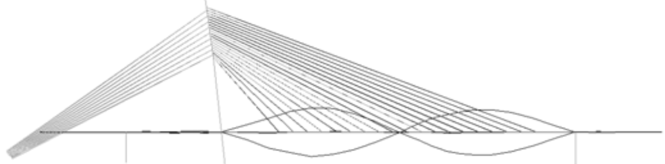

Figure 12. 2nd torsion mode: f = 1.600 Hz, ξ = 0.9 %

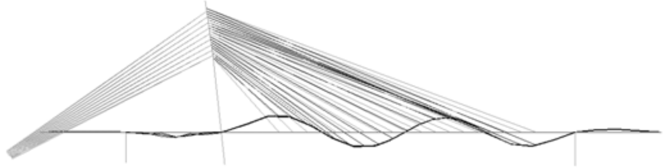

Figure 13. 4th vertical mode: f = 1.830 Hz, ξ = 0.7 %

5 COMPARISON WITH A FE MODEL

A finite element model of the Coimbra cable-stayed bridge was developed using the software SAP2000, CSI (2002). It is a three dimensional, linear, elastic model of the structure. The deck of the bridge was modeled with shell and beam elements and the piers and mast were modeled with beam elements.

A general view of the developed finite element model is presented in Fig. 14.

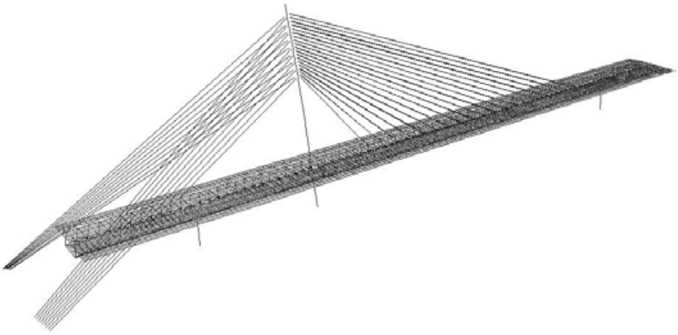

Figure 14. Finite element model of the bridge

Figs. 15 to 20 show the computed frequencies and configurations corresponding to the vibration modes that were shown previously in Figs. 8 to 13. One can see that there is a good agreement between the computed and identified dynamic characteristics, maybe with larger discrepancies in what concerns the frequencies of the torsion modes.

Figure 15. 1st vertical mode: f = 0.517 Hz (FE model)

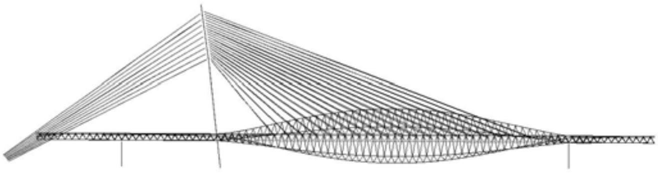

Figure 16. 1st torsion mode: f = 0.895 Hz (FE model)

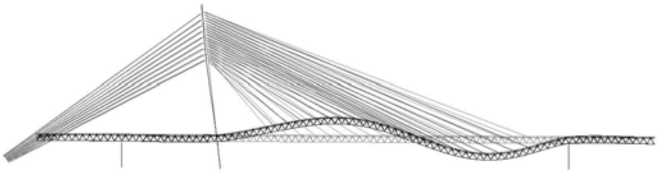

Figure 17. 2nd vertical mode: f = 0.943 Hz (FE model)

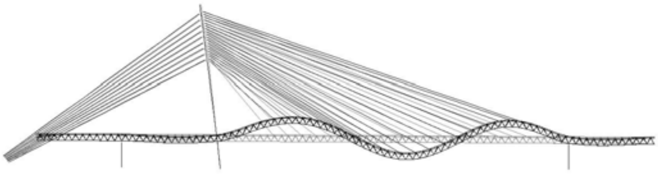

Figure 18. 3rd vertical mode: f = 1.364 Hz (FE model)

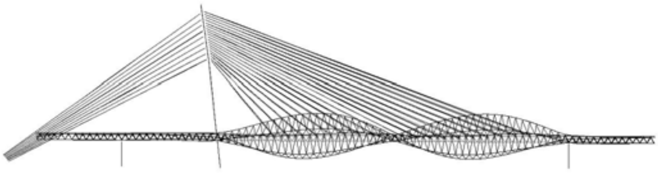

Figure 19. 2nd torsion mode: f = 1.819 Hz (FE model)

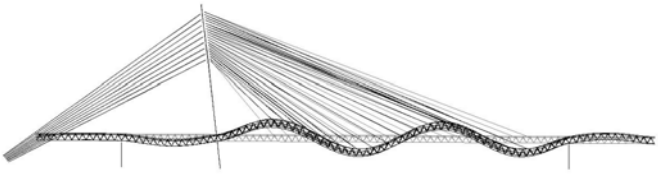

Figure 20. 4th vertical mode: f = 1.821 Hz (FE model)

6 CONCLUSIONS

The ambient vibration tests of the Coimbra cable-stayed bridge, presented in this paper, were conducted by LNEC at the end of its construction, in order to evaluate its dynamic characteristics.

The application of the ambient vibration tests with an appropriate output-only modal identification method was successful, since it allowed to identify several natural vibration modes of the bridge.

The experimental results showed a good agreement with the values computed with a finite element model of the structure.

The identified dynamic characteristics of the Coimbra cable-stayed bridge are an important contribution to characterize its actual condition at the end of the construction and before it was opened to the traffic. It is important to note that the natural excitation dynamic tests that were performed for modal identification purposes can be carried out during the lifetime of the structure without the need to impose traffic restrictions.

ACKNOWLEDGEMENTS

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