Static and Dynamic Tests of Arade Bridge in the A2 Highway

J. RODRIGUES, L. O. SANTOS and X. MIN

ABSTRACT

This paper presents the static and dynamic tests of the Arade bridge, located at the A2 highway, in Algarve, Portugal, which were performed at the end its construction, before it was opened to the traffic. In the static load tests, several quantities, like displacements, rotations and strains, were measured in the structure, under the effects of loaded trucks placed in different positions along the bridge deck. The dynamic tests consisted in ambient vibration measurements and in tests with trucks crossing the bridge at predefined velocities in order to evaluate the dynamic effects of that action. In this paper, both static and dynamic experimental results are presented, discussed and compared with the values computed with a finite element model of the bridge.

1. INTRODUCTION

The Arade bridge and its approach viaduct are prestressed concrete structures that extend up to a total length of 777 m. The bridge has a five span box girder deck with a main span of 110 m and a total length of 397 m. The approach viaduct is a continuous girder with 10 spans with 38 m each. Figure 1 shows elevation and plan views of Arade bridge and its approach viaduct.

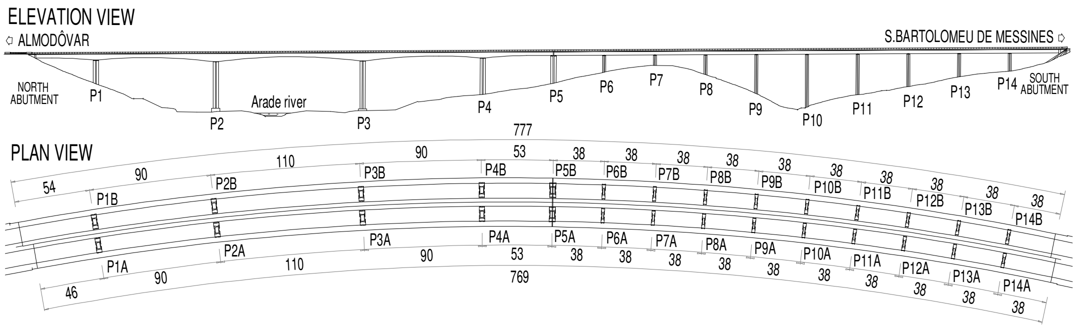

Figure 1. Elevation and plan views of Arade bridge and its approach viaduct.

LNEC – National Laboratory for Civil Engineering, Structures Department, Av. do Brasil, 101, 1700-066 Lisboa, Portugal, Jorge.Rodrigues@lnec.pt

The Arade bridge goes from the North abutment up to pier P5 and the approach viaduct goes from pier P5 to the South abutment (see figure 1). Both in the bridge and in the viaduct, there are in fact two independent and similar structures, A and B, the first one for the North-South lanes and the other one for the opposite direction lanes.

The Arade bridge is slightly curved in plan and the maximum height of its piers is 50 m. Its box girder deck has a width with 18 m and a maximum height of 6.4 m.

The Arade bridge and its approach viaduct were designed by Armando Rito [1]. A general view of the bridge and the viaduct is presented in figure 2.

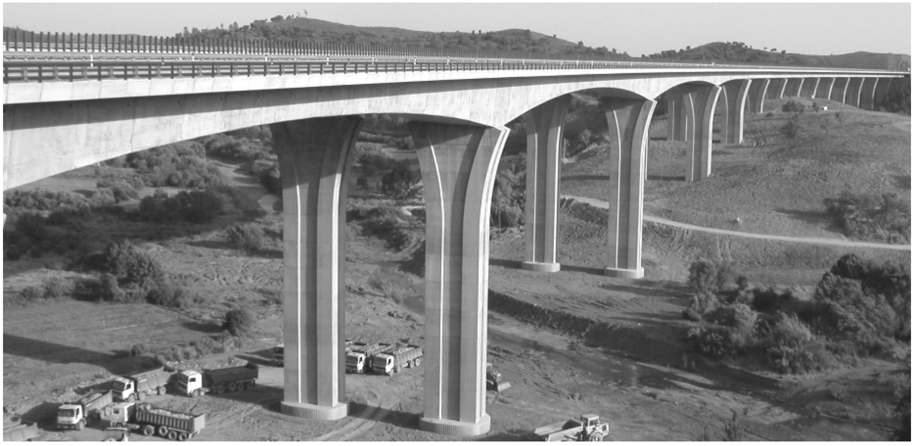

Figure 2. General view of Arade bridge and its approach viaduct.

The static and dynamics tests of the Arade bridge presented in this paper, were performed in June 2002, at the end of its construction and before it was opened to the traffic [2]. They refer to structure A, that corresponds to the lanes carrying the traffic that goes from North to South. The main purpose of the tests was to do an experimental evaluation of the behavior of the bridge under static and dynamic traffic loads and of its dynamic characteristics (natural frequencies, mode shapes and damping ratios).

In the static tests, 12 loaded trucks were used, corresponding to a maximum load of 4470 kN. During these tests, several quantities, like displacements, rotations and strains, were measured in the structure, under the effects of the loaded trucks placed in different positions along the bridge deck.

In the dynamic tests, measurements of accelerations in the structure under ambient excitation (mostly wind) were performed, as well as under the effect of trucks crossing the bridge at predefined velocities.

Besides the experimental work, a finite element model of the bridge was also developed, in order to compare the results from the tests with the ones computed with the model.

2. FINITE ELEMENT MODEL OF THE BRIDGE

A finite element model of the Arade bridge was developed using the software SAP2000 [3]. It is a three dimensional, linear, elastic model of the structure. The deck of the bridge was modeled with shell elements and the piers were modeled with beam elements with a box cross section. The connection between the deck and the piers was modeled as a rigid one in piers P2 and P3 and with some deformability, using link elements, in the other piers. The boundary conditions at the base of the piers, were considered as rigid for the vertical displacement and rotation around the vertical axis and modeled with spring elements for the other degrees of freedom.

A general view of the finite element model developed for Arade bridge is presented in figure 3.

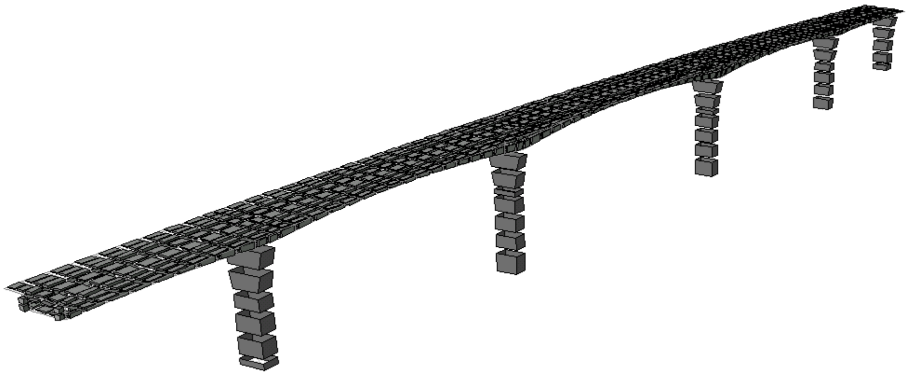

Figure 3. General view of the finite element model developed for Arade bridge.

3. STATIC TESTS

3.1 Testing procedure

The static tests were performed with 12 loaded trucks with a total weight of 4470 kN. These trucks were placed in 7 different load positions along the deck, in accordance to a load plan that maximizes several important effects in the structure, however without inducing unwanted situations of early cracking.

Some views of the static load tests are presented in figure 4.

Figure 4. Some views of the static load tests.

During the static tests, vertical displacements, rotations and strains were measured at several sections of the bridge, using different kinds of equipments.

The vertical displacements in 6 cross sections of the bridge, were measured with a hydrostatic leveling system associated with pressure cells. In 3 cross sections, the vertical displacements were also measured using a more traditional mechanical equipment (deflectographs).

Longitudinal rotations were measured in the top of piers P2 and P3 and in the mid-span section between those piers. Transverse rotations were also measured in this last section. Mechanical air-bubble clinometers were used for these rotation measurements.

Strains were measured with inductive strain meters placed at the mid-span section between piers P2 and P3.

The acquisition of the data from the pressure cells of the hydrostatic leveling system was performed with one automated system DataTaker DT515. The deflectographs and the mechanical air bubble clinometers are manual reading equipments. The inductive strain meters were connected to the data acquisition system that was also used for the dynamic tests and that will be specified bellow.

3.2 Main results

During the static tests a large amount of experimental information was obtained concerning the structural behavior of the bridge under static loads. Only some illustrative results are presented in this paper.

Figure 5, for instance, shows the computed and measured vertical displacements for 3 load positions. It is clear in that figure that there is a good agreement between the vertical displacements measured with the hydrostatic leveling system and the ones measured with the deflectographs. There is also a good agreement between the measured values and the ones computed with the finite element model.

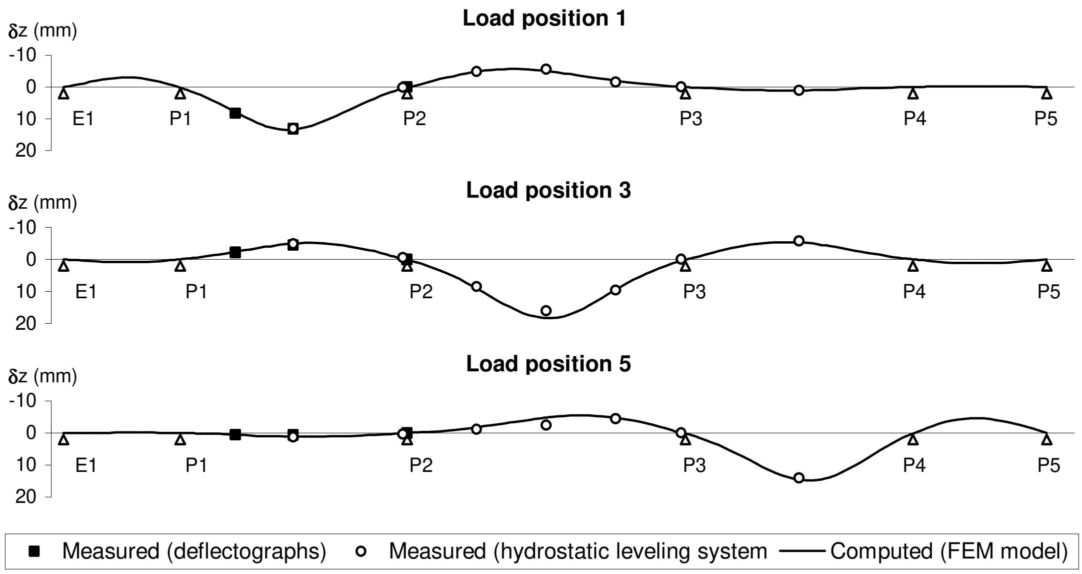

Figure 5. Comparison between measured and computed vertical displacements.

Table I shows the strains measured with 2 inductive strain meters and the strains computed with the results from the finite element model. A reasonably good agreement was also achieved between the measured and computed strains.

TABLE I. COMPARISON BETWEEN MEASURED AND COMPUTED STRAINS (με)

		Load position						
		1	**2**	**3**	**4**	**5**	**6**	**7**
strain meter 1	**measured**	-5	41	47	48	-4	38	43
	computed	-7	47	55	55	-7	35	48
strain meter 2	**measured**	-9	39	44	46	-9	40	35
	computed	-7	46	54	54	-7	50	36

4. DYNAMIC TESTS

4.1 Testing procedure

The dynamic tests were performed with two main purposes. The first one was to identify the dynamic characteristics of the bridge (vibration frequencies, mode shapes and damping ratios). The second one was to evaluate dynamic amplification factors (DAF) [4, 5] associated with the traffic of loaded trucks. An ambient vibration or natural excitation test was performed in order to accomplish the first objective, while for the second purpose, a series of tests with loaded trucks crossing the bridge with different velocities was carried out.

The equipment used in the dynamic tests included 15 Kinematrics uniaxial EpiSensor (ES-U) accelerometers, power supply and signal conditioning equipment developed at the Scientific Instrumentation Centre of LNEC and data acquisition equipment from National Instruments (DAQ board AI-16XE-50 and a SCXI-1000DC chassis with SCXI-1140 sampling and hold boards). In the tests with traffic of loaded trucks, the signals from the inductive strain meters were also recorded.

The ambient vibration test was carried out in 7 set-ups. During these set-ups, vertical, transverse and longitudinal accelerations were measured at 26 sections of the bridge, with 6 reference transducers fixed in 2 of the sections, while the others were being moved from set-up to set-up. A scheme showing the points of the structure that were instrumented with accelerometers is presented in figure 6. The reference transducers were placed in points 32, 34, 37, 38, 39 and 41.

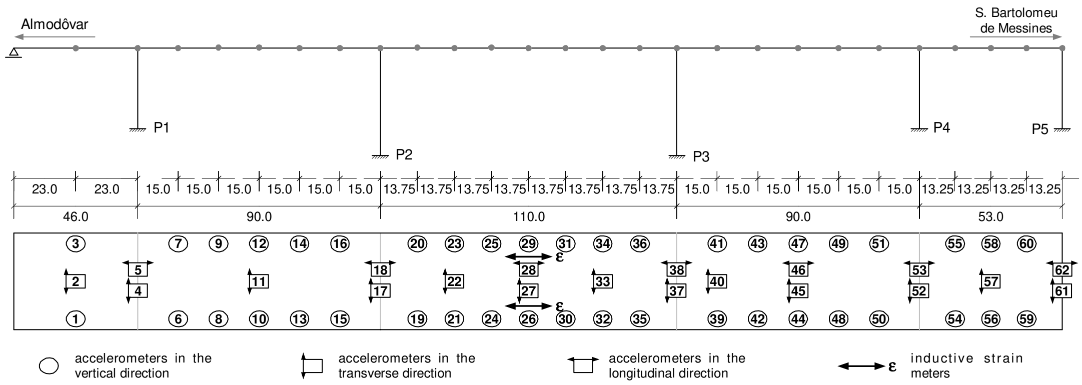

Figure 6. Scheme of the points instrumented with accelerometers in the dynamic tests.

In each set-up of the ambient vibration test, the acceleration responses were recorded during about 22 minutes, using a sampling frequency of 200 Hz. The records obtained in this way, were latter pre-processed with low-pass filtering at 20 Hz using a 8 poles Butterworth filter and decimation to a sampling frequency of 50 Hz.

Besides the ambient vibration tests, the dynamic tests included also a series of tests where 3 of the loaded trucks used in the static tests, crossed the bridge independently and successively with velocities of 15, 30, 45, 60 and 75 km/h.

4.2 Modal identification

The analysis of the ambient vibration tests data was performed using an output-only modal identification method – the enhanced frequency domain decomposition method (EFDD) [6, 7] – implemented in the software ARTeMIS [8].

In order to apply the EFDD method, the spectral density functions of the acceleration responses were estimated with the FFT algorithm applied to windowed and overlapped samples with 2048 values each. Since the sampling frequency of the records is 50 Hz (after pre-processing) the frequency resolution of the estimated spectra is 0.024 Hz.

In the EFDD method, the spectral density functions matrix is decomposed in singular values and vectors (SVD). From the analysis of the singular values spectra thus obtained, it is possible to select more clearly the SDOF spectra corresponding to the response in each mode of a system. By applying the inverse Fourier transform to those SDOF spectra, the corresponding auto-correlation functions are obtained, from which the frequency and the damping are estimated. In the EFDD method, the mode shapes are obtained from the singular vectors, corresponding to the selected SDOF spectra, weighted with the respective singular values.

Figure 7 shows the spectra of the first 3 singular values of the spectral density functions matrix. The frequencies that were identified with the EFDD method as corresponding to natural vibration modes of the bridge are also indicated in figure 7.

In total, the characteristics of 22 natural vibration modes of Arade bridge were identified using the EFDD method. Those characteristics are resumed in table II.

The mode shapes identified for the first 4 vertical modes are presented in figure 8. The corresponding mode shapes computed with the FE model are also presented in that figure. In general, a good agreement was obtained between the identified modal characteristics and the ones computed with the FE model.

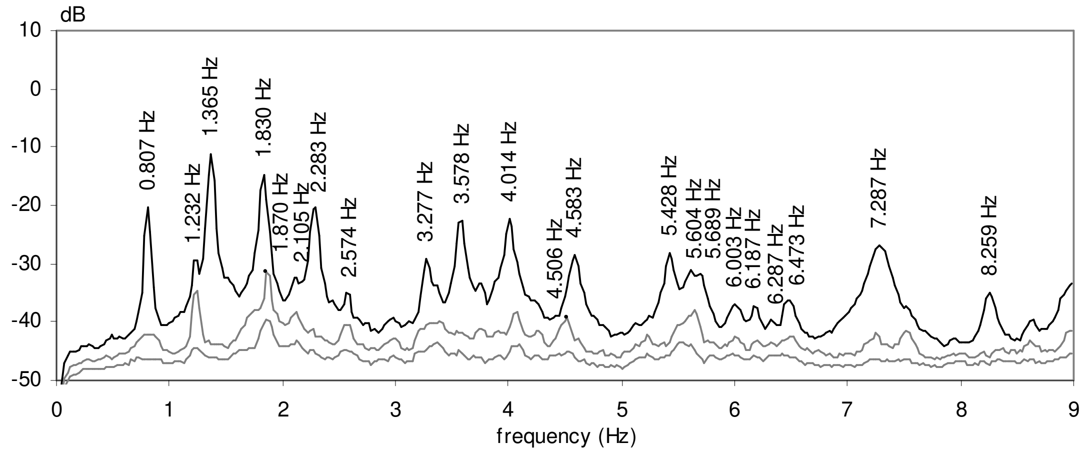

Figure 7. Spectra of singular values of the spectral densities matrix and identified frequencies.

TABLE II. DYNAMIC CHARACTERISTICS IDENTIFIED FOR ARADE BRIDGE

mode	f (Hz)	ξ (%)	type of mode	mode	f (Hz)	ξ (%)	type of mode
1	0.807	1.9	transverse	12	4.506	0.8	transverse
2	1.232	1.5	transverse	13	4.583	0.9	vertical
3	1.365	1.2	vertical	14	5.428	0.7	vertical
4	1.830	1.0	vertical	15	5.604	0.7	torsion
5	1.870	1.2	transverse	16	5.689	0.8	vertical
6	2.105	1.5	longitudinal	17	6.003	0.7	vertical
7	2.283	1.0	vertical	18	6.187	0.5	torsion
8	2.574	1.2	transverse	19	6.287	0.4	torsion
9	3.277	1.3	transverse	20	6.473	0.6	torsion
10	3.578	0.8	vertical	21	7.287	1.0	vertical
11	4.014	0.7	vertical	22	8.259	0.5	torsion

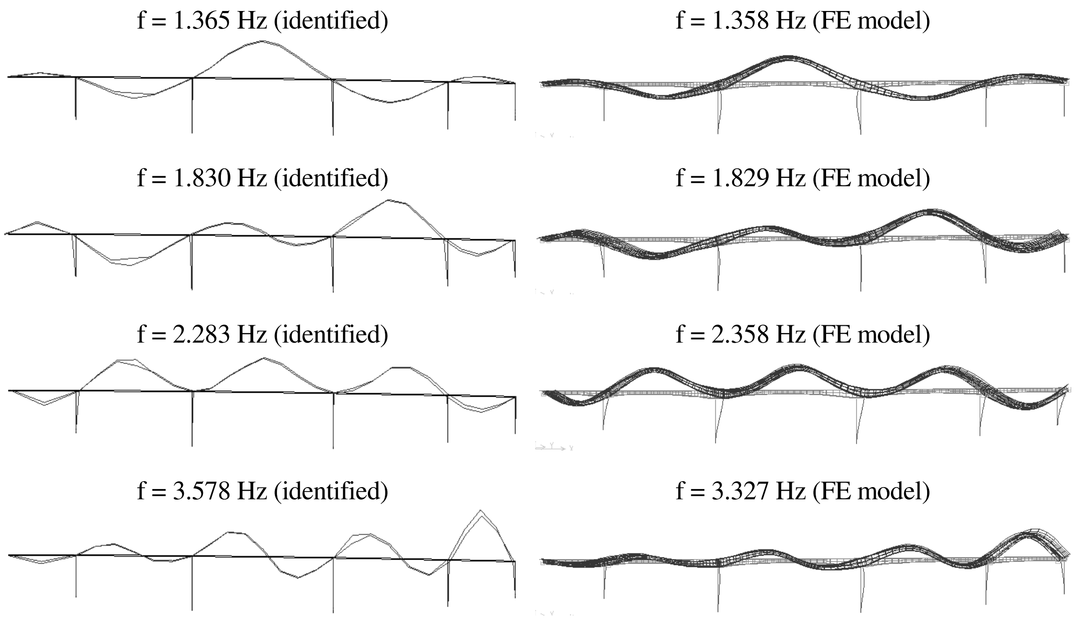

Figure 8. Identified and computed mode shapes for the first 4 vertical modes.

4.3 Dynamic amplification factors

The data collected in the dynamic tests with loaded trucks crossing the bridge with velocities of 15, 30, 45, 60 and 75 km/h, was analyzed in order to evaluate the maximum values of strains and accelerations.

The measured strains were also considered for the evaluation of the dynamic amplification factors (DAF) associated with the traffic of loaded trucks. The DAF's were evaluated as the relation between the maximum strain recorded at one given velocity and the maximum strain recorded at the velocity of 15 km/h (considered as the "static" value corresponding to one given truck).

Table III resumes the results that were obtained, showing the average values computed with the records from 2 strain meters and from the crossings of 3 loaded trucks. The values presented in table III show that there is an increase of the DAF with the increase of the velocity, although for 60 km/h and 75 km/h the DAF value is about the same and equal to around 1.15.

TABLE III. DYNAMIC AMPLIFICATION FACTORS

velocity	15 km/h	30 km/h	45 km/h	60 km/h	75 km/h
DAF	1	1.09	1.12	1.15	1.14

5. CONCLUSIONS

The static and dynamic tests of the Arade bridge, presented in this paper, were conducted by LNEC at the end of its construction, in order to evaluate its structural behavior under static and dynamic traffic loads and its dynamic characteristics.

The hydrostatic leveling system associated with pressure cells showed to be an accurate equipment to measure vertical displacements in box girder bridges.

The use of natural excitation dynamic tests with an appropriate output-only modal identification method, was also successful, since it allowed to identify 22 natural vibration modes of the bridge.

The experimental results from the static and dynamic tests showed a good agreement with the values computed with a finite element model of the structure.

The data obtained about the structural behavior of Arade bridge is an important contribution to characterize its actual condition at the end of the construction and before its opening 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

The authors would like to acknowledge the cooperation of Mr. Armando Rito designer of the Arade bridge, BRISA the Portuguese Highways Company and all the LNEC technicians that participated in the static and dynamic tests herein presented.

REFERENCES

1. Rito, A. September 2000. “The Arade River Bridge and its Approach Viaduct”, Design Documents, Lisbon (in Portuguese).
2. Santos, L. O., J. Rodrigues, Xu Min and J. A. Fernandes. July 2003. “Static and Dynamic Tests of the Arade River Bridge in the Almodôvar / S. Bartolomeu de Messines Branch of the A2 Highway”, LNEC Report 204/2003 NOE, Lisbon (in Portuguese).
3. CSI. 2000. “SAP2000 – Integrated Finite Element Analysis and Design of Structures”.
4. Paultre, P., O. Chaallal and J. Proulx. 1992. “Bridge Dynamics and Dynamic Amplification Factors - A Review of Analytical and Experimental Findings”, *Canadian J. of Civil Eng.*, 19:260-278.
5. Paultre, P., J. Proulx and M. Talbot. 1995. “Dynamic Testing Procedures for Highway Bridges Using Traffic Loads”, *J. of Structural Eng.*, 121(2):362-376.
6. Brincker, R., L. Zhang and P. Andersen. 2000. “Modal Identification from Ambient Responses Using Frequency Domain Decomposition”, presented at the XVIII International Modal Analysis Conference, February 7-10, 2000.
7. Brincker, R., C. Ventura and P. Andersen. 2001. “Damping Estimation by Frequency Domain Decomposition”, presented at the XIX International Modal Analysis Conference, February 5-8, 2001.
8. SVS – Structural Vibration Solutions. 2002. “ARTeMIS Extractor Handy”, Release 3.1, Denmark.