Assessment of a Damaged Bridge Based on Modal Identification from Ambient Vibration Tests

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Abstract. The dynamic characteristics of a structure reflect its global structural behaviour. It is common practice to perform structural damage detection based on changes in the modal parameters between a reference state and the current (possibly damaged) state, using ambient vibration tests. However, the environmental and operational conditions also affect the structural dynamic characteristics, therefore the exclusion of these effects is necessary in order to correctly identify the damage.

This paper presents a case study of a 40-years-old bridge located on the reservoir of Aguieira Dam. This bridge was severe damaged due to internal swelling reactions in concrete which affected particularly the piers and foundations and was disabled in 2015.

Between 2011 and 2021, eight ambient vibration tests and 20 geodetic survey campaigns were carried out. A statistical analysis procedure was used to remove environmental and operational effects on the identified structural dynamic characteristics to assess the progression of the bridge damage. Finally, a joint analysis of the results obtained by both methods is established.

The study demonstrates that, using statistical analysis tools, it is possible to detect the changes in the dynamic characteristics, caused by the structural damage. The results obtained from the ambient vibration tests were also confirmed by geodetic survey.

Keywords: Damage evaluation · Dynamic characterization · Environmental conditions · Internal swelling reactions in concrete · Multiple Linear Regression

1 Introduction

In Portugal the internal swelling reactions in concrete is coming to an emerging cause of bridge degradation. These reactions cause expansion of the affected concrete that generally leads to cracking and decrease of its mechanical properties, which may cause large structural damage due to unexpected deformations and additional stresses in reinforced concrete [1]. Although this expansive process is already well known through numerous laboratory tests, it remains some lack of knowledge about its progression in existing structures. This situation requires the development of efficient techniques for monitoring the structural effects of those reactions.

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Modal characteristics depend on the global and the local stiffness of the structure as well as its boundary conditions, motivating its experimental determination, as a way to evaluate those global and the local structural characteristics. Therefore, monitoring the evolution of modal characteristics over time may allow detecting structural damage, through the detection of changes in those modal parameters, particularly, the natural frequencies.

However, the environmental conditions and operational actions also affect the structural dynamic characteristics, making necessary the separation of these effects from the dynamic characteristic's changes.

The paper refers to a case study of a 40 years-old bridge with severe damage, caused by swelling reactions in concrete. Since 2011, a set of ambient vibration tests and geodetic surveying campaigns were carried out to structural integrity monitoring and assessment.

After a brief description of the studied bridge and its damage, this paper presents the ambient vibration tests carried out, the bridge modal parameters identified, the Multiple Linear Regression technique used to remove environmental and operational effects on the identified bridge dynamic characteristics, as well as the assessment of the degradation progress.

2 Description of the Bridge

The old bridge over the river Dão is a pre-stressed reinforced concrete structure, opened to traffic in 1976. It has a total length of 340 m, including seven intermediate spans of 40 m and two extreme spans of 30 m (Fig. 1).

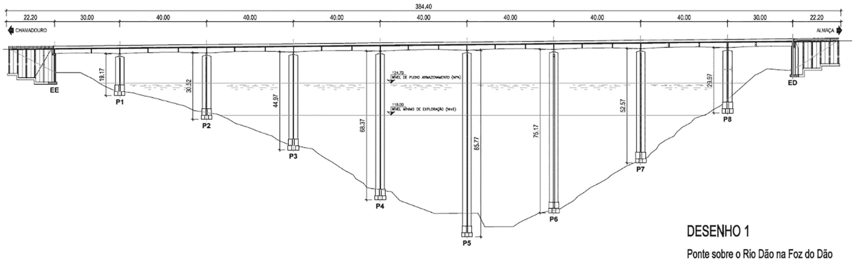


Fig. 1. Elevation view of the bridge.

The deck cross section has a 0.16 m to 0.25 m thick slab supported by a set of four longitudinal beams, spaced by 4.00 m. The deck is 15.20 m wide, and the beams have a variable height, from 2.00 m at the mid span to 2.50 m on the piers.

The piers have a diamond-shaped hollow cross-section, with direct foundation, whose height varying from 20 m to 85 m. As a downstream dam controls the water level of the river, only the upper part of the piers, about 15 m length, are permanently above the maximum reservoir level. Seasonally, the reservoir level varies about 15 m.

The left abutment and the piers P1 and P2 are connected to the deck by sliding bearings. The support of the deck on the remaining piers and the South abutment is carried out through fixed bearings.

The visual inspections of the bridge, including underwater inspections, were carried out. Some structural damage was identified, such as excessive deformation of the deck, construction defects and cracks in the longitudinal beams, especially vertical ones associated with bending resulting from the reduced prestressing (Fig. 2). In the piers, particularly in their lower part, was visualized cracking due to swelling reactions in concrete (Fig. 3).

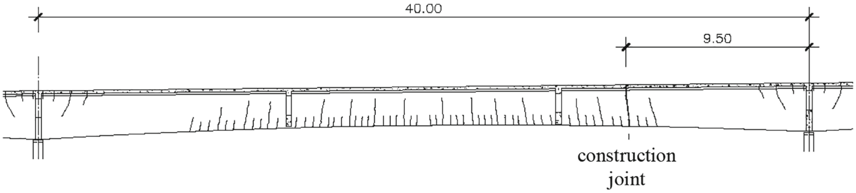


Fig. 2. Cracks in longitudinal beams.

Fig. 3. Structural damage in the bridge.

Because of these severe damages, traffic restrictions on the bridge were imposed in May 2012. Finally, in August 2015, the bridge was closed to traffic after a new one was built, just 5 m from the downstream side.

3 Output-Only Modal Identification

3.1 Ambient Vibrations Tests

Between 2011 and 2021 eight ambient vibrations tests were performed in situ to determine the structural dynamic characteristics, which were used to assess the service conditions of the bridge, in the first phase, and to detect a significant stiffness loss that could cause a possible collapse.

The first ambient vibration test took place in April 2011 [2]. By this way, the bridges dynamic characteristics were found out and were taken as a reference state for further structural integrity assessment. In addition, the results were used to calibrate a numeric model of the bridge, which would be applied for structural damage detection.

During 2012 and 2013, four vibration tests were carried out semiannually. Lately, in November 2017, 2018 and 2021, new tests were conducted on the disabled bridge.

In all tests, the bridge vibration was acquired using Kinemetrics ES-U force balance accelerometers at a sampling rate of 500 Hz.

3.2 Environmental and Operational Conditions

The ambient vibration tests were carried out in spring and autumn seasons, in April/May and November/December. It was intended to realize the tests under similar environmental and operating conditions, particularly the ambient temperature and the reservoir level.

As shown in Fig. 4, the reservoir level was lower in the fall-winter season, achieving the lowest level in November 2017, due to the severe drought suffered in Portugal. Naturally, the air temperature during the fall-winter season is lower than in the spring season, with a difference of about 15 ºC.

The road traffic and wind action on the structure could cause dynamic responses with variable amplitude, which reflected on the vibration levels recorded during the tests. Thus, the effective or quadratic mean values (RMS) of the accelerations reveal the action intensity (Fig. 5). In fact, the first test had the highest accelerations' RMS because it was carried out without any traffic restrictions. Thereafter, between May 2012 and August 2015, speed limits on the bridge were imposed, as well as the heavy traffic banned. Finally, in August 2015 the bridge was disabled.

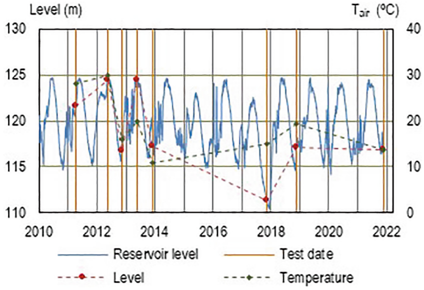


Fig. 4. Reservoir level and air temperature.

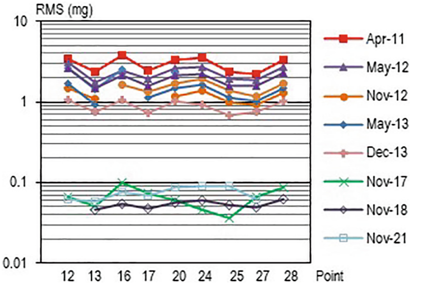


Fig. 5. Vertical Acceleration's RMS.

3.3 Modal Identification

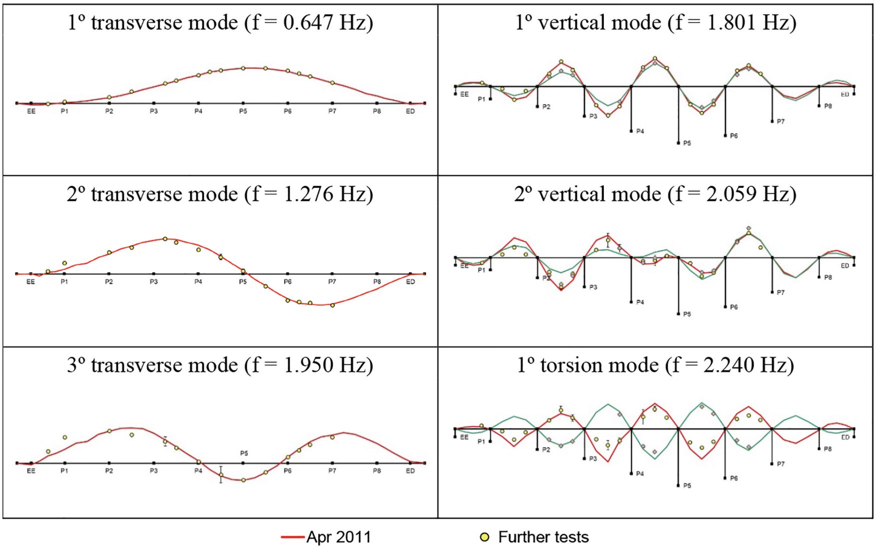
The acceleration time series were initially pre-processed and decimated to a sampling frequency of 25 Hz. Therefore, the structural modal parameter identification was developed up to the frequency of 10 Hz, applying the technique of Enhanced Frequency Domain Decomposition (EFDD) [3].

In all tests, it was possible to identify the simile vibration modes, except in the last one, some higher order vertical and torsion modes were not the same. It should be noted, in 2021, when the last test was carried out, the concrete jersey barriers on the bridge were removed, corresponding to a decrease of about 2.6% in the structure's mass.

The frequency of the first 6 vibration modes obtained from 8 tests is presented in Table 1 and their mode shapes are illustrated in Fig. 6.

Table 1. Evolution of the bridge dynamic characteristics.

Mode	2011.04	2012.05	2012.11	2013.05	2013.12	2017.11	2018.11	2021.11
T1 (1° transv.)	0.647	0.648	0.669	0.646	0.671	0.680	0.675	0.687
T2 (2° transv.)	1.276	1.277	1.332	1.264	1.341	1.365	1.349	1.380
V1 (1° vert.)	1.801	1.738	1.890	1.790	1.908	1.954	1.963	2.079
T3 (3° transv.)	1.950	1.929	2.036	1.909	2.046	2.116	2.035	2.071
V2 (2° vert.)	2.059	1.994	2.151	2.077	2.181	2.204	2.220	2.378
TOR1 (1° tors.)	2.240	2.168	2.312	2.209	2.384	2.408	2.417	2.573


1° transverse mode (f = 0.647 Hz)

1° vertical mode (f = 1.801 Hz)

2° transverse mode (f = 1.276 Hz)

2° vertical mode (f = 2.059 Hz)

3° transverse mode (f = 1.950 Hz)

1° torsion mode (f = 2.240 Hz)

Fig. 6. Structural vibration modes.

4 Evolution of the Dynamic Characteristics

The structural stiffness changes cause variations in the natural frequencies of the structure. However, there are many sources other than damage that also induce variations in the modal parameters.

According to some studies [4–6], the temperature variation can induce changes in the deformability of the roadway construction materials, such as bituminous, as well as in the structural concrete. If the temperature reduces from 25 °C to 15 °C, the bituminous deformability modulus may increase by 50% and the modulus of elasticity of concrete at 28 days increases by about 3%.

Secondly, the water mass inside the piers varies with the reservoir level, affecting the dynamic characteristics of the bridge.

Finally, the vibration level caused by the traffic and wind actions may have an impact on the cracked structural elements, modifying their stiffness and dynamic responses. The decrease in vibration level, due to the traffic interdiction, may have led to a slight increase in the stiffness of the cracked elements, as explained by [7].

In the present case study, the experimental results show clary the influence of the environmental and operational factors, particularly, the ambient temperature and reservoir level. Therefore, the detection of any structural changes is only possible after removing the environmental and operational effects on the modal parameters' variation.

For this purpose, the Multiple Linear Regression (MLR) technique was used. In the present case study, the ambient factor was considered using the average values of the air temperature measured during the test. The reservoir level and the RMS of the vertical acceleration were taken into account as operational factors. At last, the degradation progression was assumed as linear function of the time (days).

Presuming that the experimentally identified frequencies are affected by the environmental and operational actions, as well as the degradation progress, the relationship between the dependent variable y (identified frequency) and the explanatory variables (actions) can be expressed by:

$$y = A_0 + A_T T + A_L L + A_R R + A_D D + \varepsilon \tag{1}$$

where T – Air temperature; L - Reservoir level; R – RMS of the pre-processed vertical acceleration at point 20; D -Time (day) past since the 1st test; ε – remained value.

If the MLR model is acceptable, the difference between the measured and predicted values, ε, should be random samples with normal distribution. However, the small sample of the tests hinders the regression analysis. To check the statistical significance of the proposed MLR model, the statistical test F was applied to the results obtained between 2011 and 2017. A variable with a higher P-value was removed to keep the Significance F of the regression below 0.05.

As expected, the reservoir level has significant impact on the identified frequencies, with negative correlation, the temperature has some effect in the first vertical modes with no clear effects in the transverse modes and the deck vibration level influences the transverse modes. Finally, the effect of the elapsed time could be noted in the transverse modes, whose frequency would decrease with time.

Using the MLR models, it is possible to remove frequency variations affected by environmental and operational changes and to estimate the equivalent natural frequencies f_{eq}, for the reference conditions, in April 2011, Eq. (2):

$$f_{eq} = f - A_T \times dT - A_L \times dL - A_R \times dR \tag{2}$$

As results, the equivalent natural frequencies between 2011 and 2017 and the variations are shown in Fig. 7. The forecast errors of the MRL models and the respective 99% confidence interval are represented in Fig. 8.

Based on the MRL models, it was also achievable to estimate the expected frequencies for 2018 and 2021, as presented in Fig. 7. The prediction errors for these cases were positive and out of the 99% confidence intervals, as shown in Fig. 8. It means the structural state may not deteriorate in recent years as much as predicted by the MRL model or the structural behavior had some changes. It should be remembered that, in

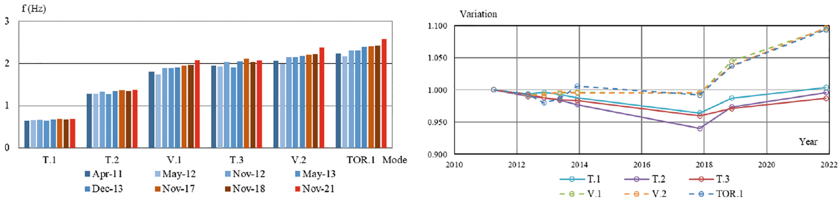


Fig. 7. Equivalent natural frequencies evolution.

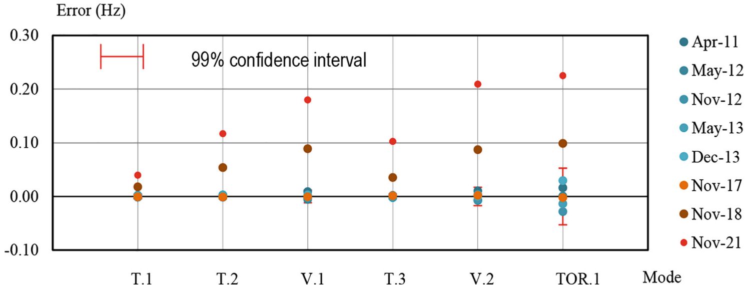


Fig. 8. Forecast errors and deviations.

2021, when the last tests were carried out, the concrete jersey barriers were removed, consequently the natural frequencies should be increased.

5 Structural Modelling and Damage Evaluation

In the present case study, the model simulation was used to simulate the behavior of the damaged structure, without involving the detailed degradation process.

For this purpose, a three-dimensional finite element model was developed. Shell and frame elements were used for modelling the deck and the piers (Fig. 9).

The soil deformability at the foundation was simulated applying uniformly distributed elastic supports. The water inside the piers was considered, presuming that the corresponding mass vibrates together with the piers.

For the structural concrete elements, the deck and the piers, the Young's modulus was considered as 34 GPa. However, for the damaged deck elements (light blue) was applied the reduced value of 22 GPa.

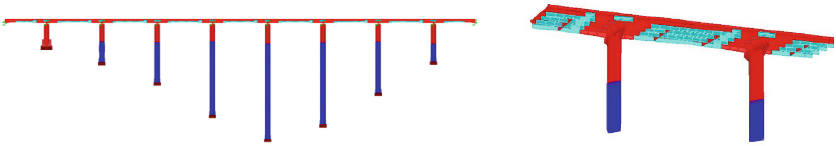


Fig. 9. Finite element model.

The numerical model was calibrated using the experimental results from the first test in April 2011. Then, the influence of the different parameters on the natural frequencies was studied.

The reservoir level varies between 110 m and 124 m. The sensibility analysis shows the level variation makes changes in the transvers modes and the 1st vertical mode (Fig. 10). On the other hand, the deck damage affects essentially the vertical and torsion modes, while the piers' damage has a larger impact on the transverse modes (Fig. 11).

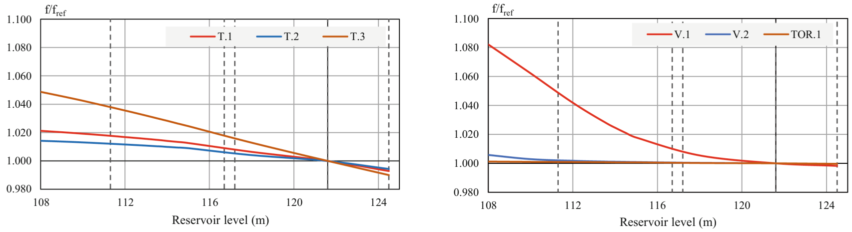


Fig. 10. Water level vs frequencies.

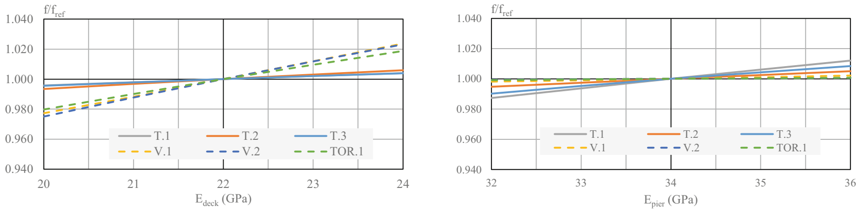


Fig. 11. Damaged concrete stiffness vs frequencies.

However, the existing cracking in the submerged piers would affect the axial stiffness (EA) and the bending stiffness (EI) by different levels. Therefore, the decreasing of bending stiffness of the affected piers sections was studied (Fig. 12). The results show that the decrease in the transverse bending stiffness (EI_{22}) has a larger impact on the transverse modes while the longitudinal bending stiffness changes (EI_{33}) are not perceptible at the frequencies.

It was possible to assess the damage progress through the variation of natural frequencies. As a result, it was concluded that the piers affected by the swelling reactions in concrete had been deteriorating since 2011, but after 2018, the deterioration process has been stabilized.

6 Vertical Displacements Evaluation

The vertical displacements of the bridge were measured in 20 geodetic survey campaigns carried out between 2009 and 2021 [8].

Figure 13a shows the displacements measured at the top of the tallest piers of the bridge. It is clearly the seasonal effect on the displacements, which were much more in

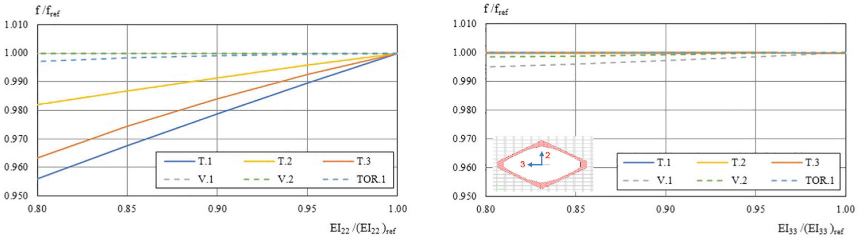


Fig. 12. Bending stiffness of damaged piers vs frequencies.

summer or autumn, between June and October. Using the same procedure described in Sect. 4 the environmental and operational effects can be removed from the measured displacements, as shown in Fig. 13b. The dashed lines indicate the expansion trend of the piers, estimated by the MLR models.

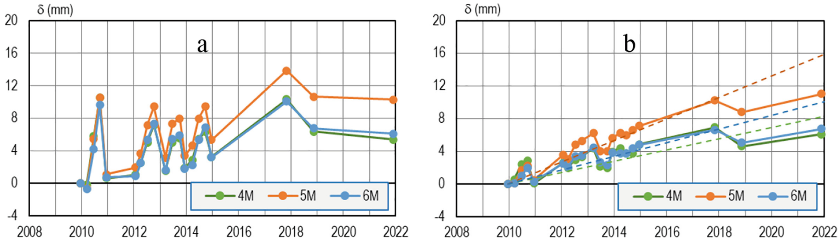


Fig. 13. Geodetic displacements evolution**.**

As shown, the height of the tallest piers (P4, P5 and P6) increased by more than 4 mm between 2009 and 2017. After this period, the expansion process would stabilize. This conclusion was coherent with the results obtained from the ambient vibration test.

7 Conclusions

Between 2011 and 2021 eight ambient vibration tests of the old bridge over river Dão were carried out to assess the bridge behavior and the damage evolution. As results, the structural modal parameters, such as the natural frequencies and the mode shapes were identified and compared.

The Multiple Linear Regression (MLR) technique was used to remove the environmental and operational effects on the natural frequencies. The damage progress was assumed as a linear function of time. The statistical significance analysis shows the time factor was significant in the transverse modes, whose frequency decreased with time, until 2017.

To assess the damaged structure a three-dimensional finite element model of the bridge was developed and calibrated using the experimental results. The sensibility analysis concluded that the reservoir level variation makes changes in the transvers modes and the 1st vertical mode. The deck damage affects essentially the vertical and torsion modes, while the piers' damage has a larger impact on the transverse modes. It was concluded the piers, affected by the swelling reactions in concrete, had been deteriorating since 2011, but after 2018, the deterioration process has been stabilized.

The conclusion was complemented by the results obtained from 20 geodetic surveying campaigns, which prove the ambient vibration tests are efficient techniques for bridge damage detection.

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