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MONITORING OF A RAILWAY BRIDGE RECURRING TO COSTUMIZED SENSORS

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Abstract

The continuous monitoring of transport and energy infrastructures is an area that has lately assumed great importance in the management of these systems. In the past, only commercial monitoring systems were used for static and dynamic monitoring. More recently, due to the latest technological advances, the use of customized sensors begins to play a very significant role in this field. Compared to commercial systems, customized solutions are more accessible in terms of cost, while solving some monitoring system problems mainly associated to the lack of robustness of some classic solutions and the consequent high effort to maintain equipment. In this context, this work describes the implementation of a customized system used to observe an old steel railway bridge. Various types of sensors were used, including strain gauges, temperature sensors, accelerometers, and displacement sensors in the bridge's expansion joints. The layout of this instrumentation is explained and justified. In addition, the results of a preliminary ambient vibration test are presented, which allows understanding the dynamics of the structure.

Keywords: Railway bridges, Customized sensors, Structural monitoring, Modal analysis.

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1 INTRODUCTION

Interest in the rail network, especially in Europe, as a sustainable and cost-effective means of transportation has increased over the past few years. The maintenance and safety of existing old bridges has been a growing concern for railway administrations. In general, their economic and cultural impact implies that "retrofit" is preferable to building new bridges [1].

Currently, concerns about the aging and structural degradation of a large number of civil infrastructures, along with the need to validate the behavior of new structures with a high level of complexity and the construction of flexible structures prone to excessive vibrations, have contributed to significantly increase the interest in vibration-based health monitoring programs [2].

Displacements profiles in railway bridges under service loads are important parameters in assessing the bridge condition [3]. Dynamic effects due to train movement on bridges can be high, leading to deterioration of the bridge and, eventually, increase in maintenance costs and reduction in its lifetime [4]. However, measuring bridge responses in the field is usually expensive and challenging due to high costs of sensing equipment [3].

In addition, there is always a set, greater or lesser, of uncertainties related to the structural characteristics. In particular, in structures with high lifetime, in which it is even more difficult to be evaluated [5]. According to statistics from 17 European railway administrations, there are more than 73,000 railway bridges that are more than 110 years old, which represents 35% of railway bridges in Europe. More than 31% of all bridges are between 60 and 110 years old [6].

Therefore, monitoring the structural health of railway bridges is becoming an increasingly relevant requirement in transportation infrastructure management [6] and techniques to identify modal parameters, such as natural frequencies and vibration modes based on field tests emerge as an essential tool to support their analysis. It is important to always focus on procedures that allow synthesizing the performance and development of tests and tools for processing the collected information [5].

Moreover, continuous monitoring of transportation and energy infrastructures is an area that has strongly contributed to the management of new systems, along with Operational Modal Analysis that aims at identifying the modal parameters of a structure under serviceability conditions. The implementation of solutions for continuous identification of these parameters based on structural responses to environmental excitation is an important strategy in structural health monitoring of bridges, given the need for the development of new processing tools to extract and interpret easily, effectively and usefully the collected data.

With this regard, the main objective of the present research was to develop a structural monitoring system using a new generation of sensors applied to a railway bridge located in Portugal, in order to calibrate the numerical model of the bridge structure and prove the effectiveness of these sensors. Given the current obstacles in monitoring, particularly related to their costs, it is of great value to provide a monitoring system that overcomes the disadvantages of classical solutions. The development of numerical models supported by relatively inexpensive instrumentation becomes an effective tool for reliable dynamic analysis, as well as for the knowledge of important parameters related to the structure's characteristics, such as actual traffic loads.

2 TREZÓI RAILWAY BRIDGE

2.1 Historical aspects

Trezói bridge is located in the center region of Portugal along the Beira Alta line, which is an international railway route that connects Portugal to Spain. This bridge (Figure 1) was built as part of the project to replace the existing bridges on the Beira Alta route, which took place during the 1950's, and opened to traffic on August 20th 1956. This replacement was funded by the Marshall Plan, with the German Fried House. Krupp designed, manufactured and assembled the 6 major bridges of this line, which led to the demolition of the previous ones designed by Gustave Eiffel House [1].

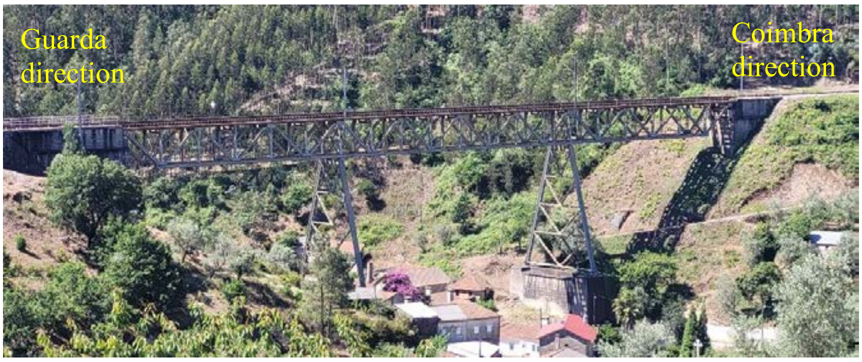


Figure 1: Trezói Bridge

2.2 Description of the bridge

Trezói bridge is a steel railway bridge with a length of 126m, divided in three spans, two external spans of 39m and an internal span of 48m. The deck is made of two trusses of the Warren type, with parallel continuous flanges of 5.68 m high and a constant width of 4.4 m. The distance between the vertical uprights of the deck is 6.50 m at the extreme spans and 6.00 m at the central span. In addition, the structure comprises 19 main sections (Figure 2).

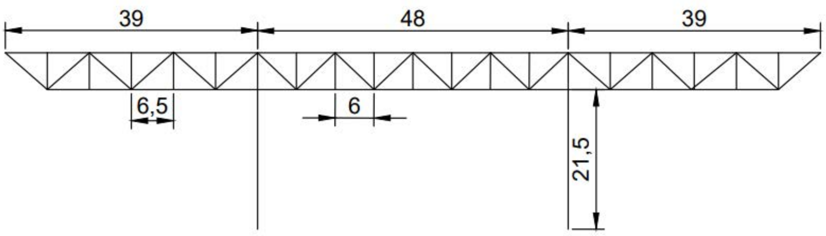


Figure 2: Bridge dimensions

2.3 Previous research work

In the past, this bridge was equipped with a classical monitoring system aiming at determining the modal parameters of the structure and measuring traffic loads. The construction of that system was time consuming and very challenging, as the structure is under the village of Trezói, which required complex cabling, installation time, maintenance, and dependence on an external power supply. This lead not only to higher equipment costs, but also labor costs, since the equipment is not easy to integrate into the structure and takes up a lot of space. The heavy operating system and software installed in a computer end up generating frequent failures in data acquisition.

According to [7] for a typical modal analysis, installation time, whether on a building or bridge, consumes more than 75% of the total test time and the installation cost for large structures approaches 25% of the total cost. In bridges, the problem is further complicated by the skeletal nature of these structures. In addition, repeated temperature and humidity changes and exposure to direct corrosive sunlight, significantly accelerate the degradation of sensors and cables.

For these reasons, the development of a new monitoring system for this structure based on customized sensors has the objective of overcoming the difficulties associated to the mentioned problems. Starting by being smaller in size, and thus easily integrated into the structure (Figure 3a), it was possible to use several sensors at the same time (Figure 3b). In addition, they have no cables, which facilitated the installation and maintenance. It is intended, through their use, to systematize and simplify each step of the process of measurement, collection and storage of data, as they are robust, accurate and have low energy consumption.

a) b)

Figure 3: Example of new sensors

3 DEVELOPED COSTUMIZED SENSORS

3.1 Introduction

Many existing monitoring algorithms and strategies assume a sophisticated hardware infrastructure that has high initial cost, low cost to benefit, expensive system installation, and costly operation and life cycle maintenance. In particular, current state-of-the-art hardware systems for monitoring structures use cables to transmit sensor signal data to a central unit, and in most cases involve many cable lengths to cover the large spatial distances. Long cables also result in degradation of the sensor signal [7].

In this regard, in recent years the range of sensing technologies has expanded rapidly, while sensor devices have become cheaper. This has led to a fast expansion in condition monitoring of systems, structures, vehicles, and machines using sensors [8].

In this work, several types of customized sensors are used, including strain gauges, temperature sensors, accelerometers, and displacement sensors in the bridge's expansion joints, which are detailed in next sections.

3.2 Strain gauges

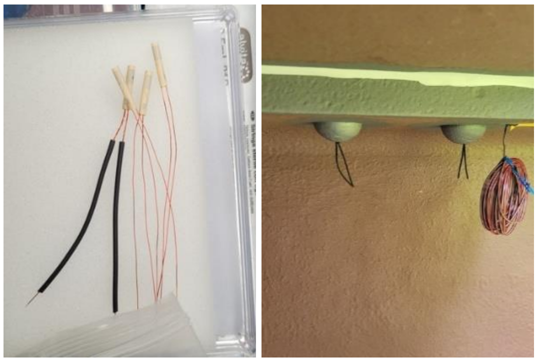
Strain gauges are sensors that allow deformation to be measured. When they are compressed, its electrical resistance decreases, and when they are stretched it increases. The resistance variation, which is directly proportional to the strain variation, is usually measured using an amplification circuit known as Wheatstone bridge.

In the case of Trezói bridge, two types of strain gauges are used. In the case of type 125SL, which is a linear pattern strain gauge (see Figure 4a), they are used to measure strains in beams and rails. They have a resistance of 350 Ω, measuring strains in one direction only. The grid length of the sensor is 3.2mm, and was installed in a quarter-bridge 3-wire scheme.

On the other hand, LB11 type strain gauges (Figure 4b) are cylindrical, and they are used for measuring strain in some rivets. They have a resistance of 120 Ω and also work in a quarter-bridge 3-wire connection.

The data acquisition is a customized system which is currently under implementation. It is composed of NAU7802 modules which amplifies, filter and digitalize the signals with a resolution of 24 Bits. The module integrates a microcontroller, a microSD card to save data locally, and a precision Real-Time-Clock used to organize a folder structure with data files. The system is powered by lithium batteries. In order to guarantee high autonomy, the system is activated only when trains are crossing the bridge, being activated by the signal acquired by an accelerometer installed in the rails.

a)



b)

Figure 4: a) Strain Gauge - 125SL; b) Strain Gauge - LB11

3.3 Accelerometers

These devices are composed of a tri-axis MEMS accelerometer which is commanded by means of an ATmega microcontroller (see Figure 5). The data is continuously acquired and saved locally in a microSD card. Files have a duration of 10 minutes each and are organized in a folder structure identified according to the time and date of the measurements.

The MEMS accelerometer is of digital type integrating a 20 – bit ADC, and includes internal antialiasing filters, programmable frequency rate and dynamic range. In this application, the frequency rate was fixed at 62.5 Hz, being the low-pass cut-off frequency set to 15.625 Hz and the high-pass cut-off frequency set to 0.24 Hz.

This system is powered by 5 batteries of 3400 milliamps capacity each, enabling an autonomy of 3.3 months in continuous operation.

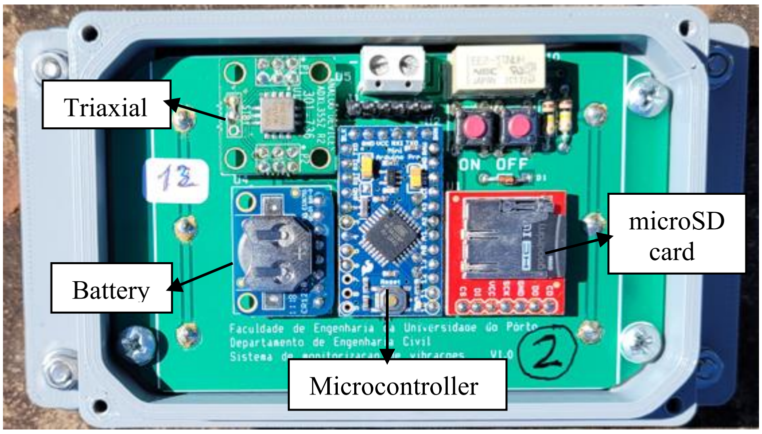


Figure 5: Accelerometers

3.4 Temperature sensors

The temperature sensors used in the developed instrumentation are of DS18B20 type from MAXIM company (see Figure 6). These digital sensors measure temperatures from -55°C to +125°C, having an accuracy of ±0.5°C from -10°C to +85°C, which is adequate for this application. The major advantage of this sensor is its simplicity, because no extra hardware is required and because it has a 3-wire communication with the microcontroller. In addition, due to the unique 64-Bit address, a high number of sensors can be used simultaneously through a single digital port on the microcontroller.

The temperature sensors are connected to the same units of the strain gauges which store temperature readings each 10 minutes.

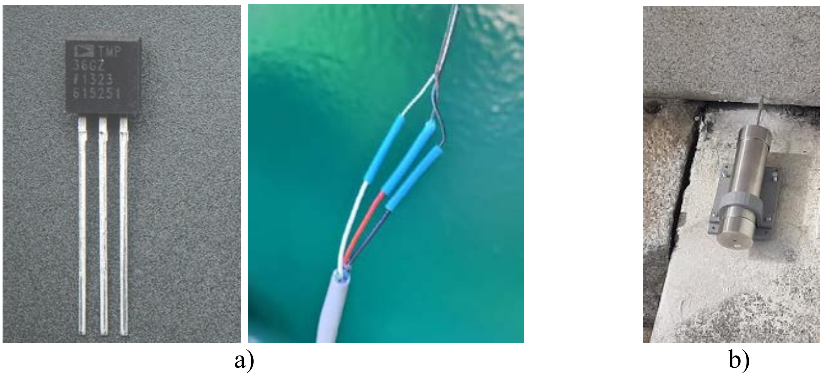


Figure 6: a) Temperature sensors; b) Displacement sensor

3.5 Displacement sensors at expansion joints

For displacement measurement at expansion joints, a capacitive sensor is used (see Figure 6b). It allows measurements with 0.01mm precision in a range from 0 to 2 meters maximum. In practice, to prevent the sensor from being too long, the measuring range is adjusted according to the expected displacements, often measuring in the range 0-150mm. It is programmed to take acquisitions every 10 minutes. A set of four lithium batteries guarantee an autonomy of at least 1 year.

4 INSTRUMENTATION PLAN

4.1 General aspects

The Trezói railway bridge was instrumented with the sensors described before, aiming the following objectives: i) Measurement of traffic loads on the main structural elements; ii) Measurement of the traffic characteristics in terms of several parameters, such as train velocity, direction, daily frequency, number of carriages, train type, loads per axle, etc.; iii) measurement of the temperature effects at the expansion joints; iv) and continuous measurement of the bridge dynamics aiming at the Operational Modal Analysis of the structure.

In addition, it is intended to measure the strains in some rivets in order to evaluate fatigue damage in these important structural elements. Moreover, the use of strain gauges in the diagonals close to the extreme supports, as well as in the central columns at theirs bases, will be useful to determine the full weight of the train when it is on the structure, and consequently, confirm the loads applied by the train.

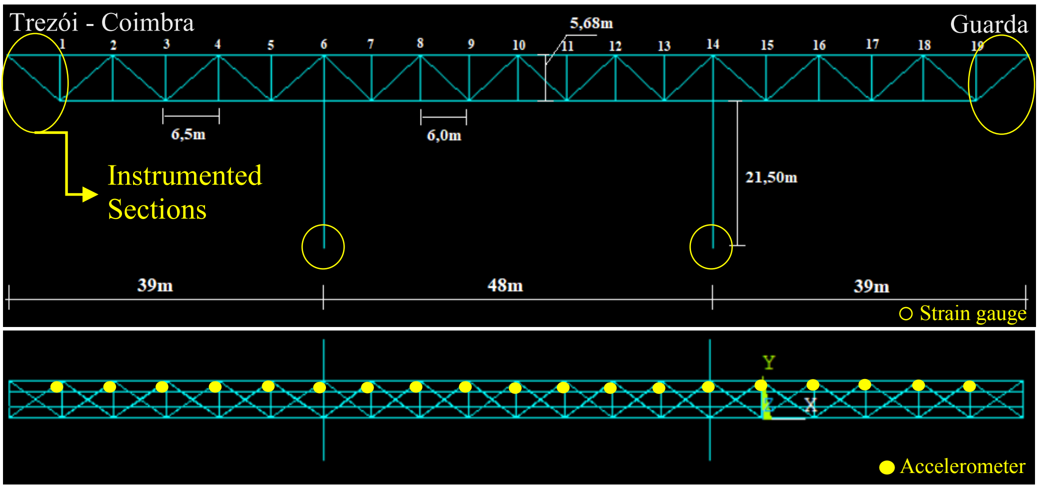


Figure 7: Instrumented sections

4.2 Location and implementation of the sensors

The location of the strain gauges in the structure is represented in Figure 7. In beam 0 (first transversal beam from Trezói side), strain gauges 1 and 2 are near the support, at the top and bottom flange respectively, and strain gauges 3 and 4 are in the middle of the beam, in the same order (Figure 8 and 9). In this same beam, strain gauges 5 and 6 were installed at 2 rivets, and two temperature sensors T1 and T2 were installed close to strain gauge 1 and 4. In beam 20 (first transversal beam from Guarda side) other temperature sensors were at the same distance as beam 0. The first and last truss diagonals were also instrumented near the external supports (Figure 10) using strain gauges on each side of the U-shaped profiles (strain gauges 7 and 8 in Trezói side and strain gauges 12 and 13 in Guarda side). Figure 8 presents the schematic of the distances on the beam 0 and 20 (Figure 8a), and on the diagonals (Figure 8b), while Figure 9 and 10 presents the corresponding photos.

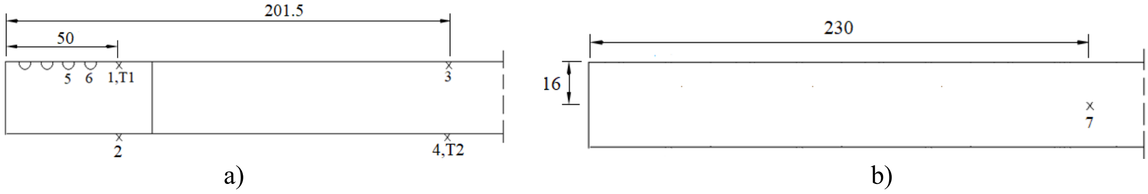


Figure 8: Strain gauges distances (cm): a) on beams; b) on diagonals

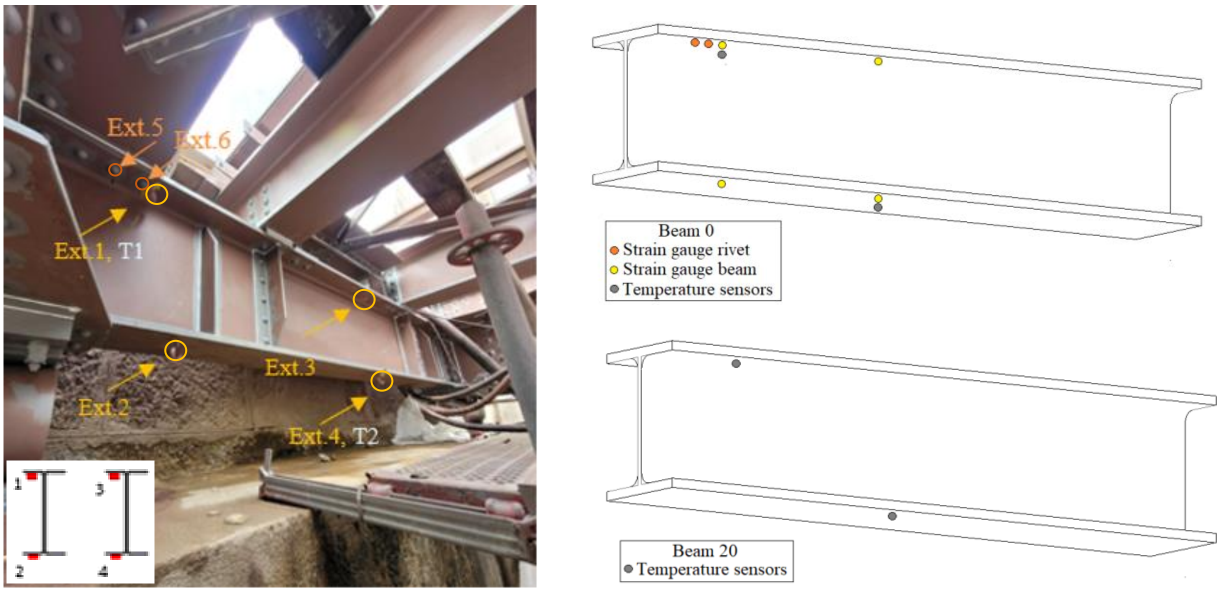


Figure 9: Location of strain gauges in beams

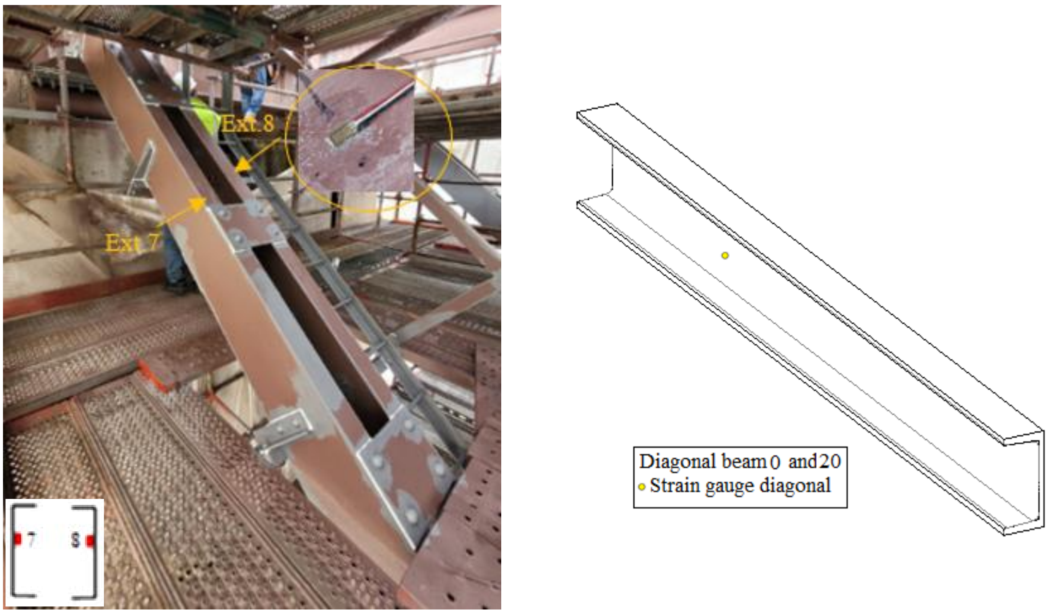


Figure 10: Location of strain gauges in diagonals

To determine the train's direction (Trezói - Guarda or Guarda - Trezói), train's speed, number of axles and distance between them, as well as applied loads, strain gauges were installed in the rail (strain gauge 9, 10 and 11) at three different distances from the Trezói side abutment (3.30m, 1.79m and 1.82m) as shown in the Figures 11 and 12.

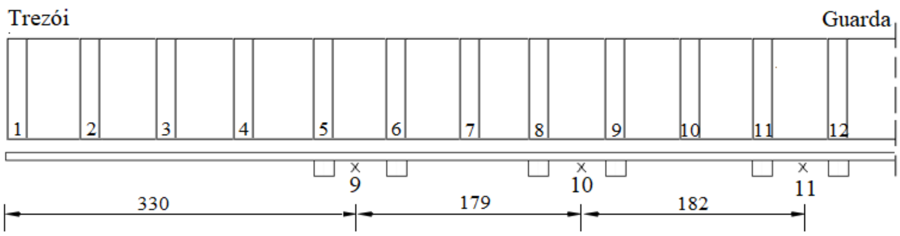


Figure 11: Strain gauges location on the rail

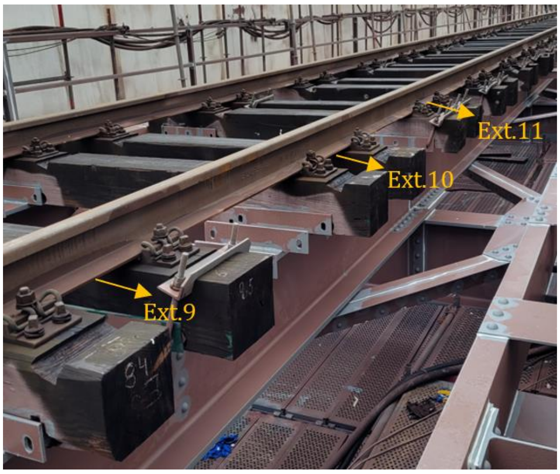


Figure 12: Location of the rail strain gauges in situ

5 PRELIMINARY AMBIENT VIBRATION TESTS

5.1 Sensor's layout

The developed accelerometer modules were tested in a preliminary dynamic characterization of the bridge by means of an ambient vibration test, where the dynamic response was obtained through the measurement of accelerations when the structure was submitted to ambient loads such as wind and small ground vibrations induced by car traffic close to bridge. Environmental conditions such as temperature, humidity, wind, solar radiation that vary with time can affect the identification of modal characteristics [9].

The test consists of instrumenting the bridge, processing the signals, analyzing and interpreting the results [9]. In this case, one sensor was placed in sections 1 to 19 (Figure 13), using S1 as a reference for time synchronization of the others.

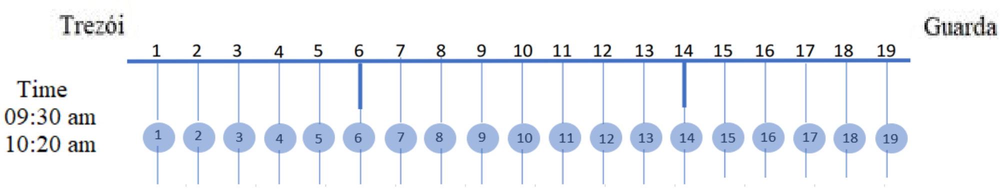
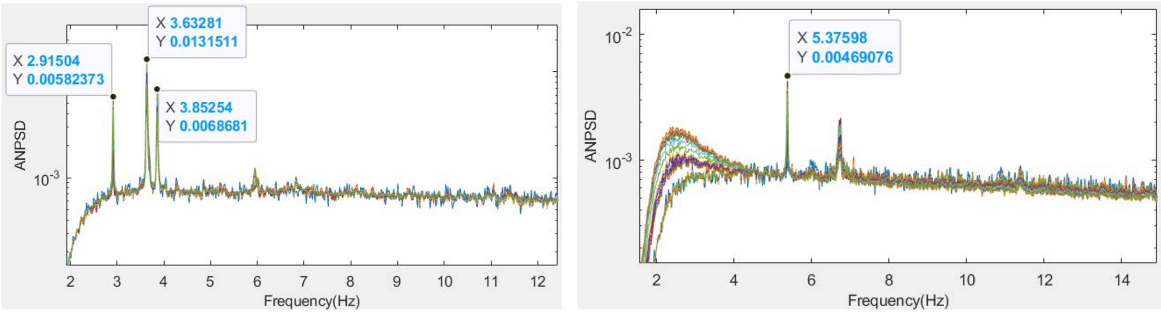


Figure 13: Accelerometers Location

5.2 Identification of modal parameters

The natural frequencies and corresponding mode shapes were identified using the SSI-COV method [2]. The Average Normalized Power Spectral Density (ANPSD) involving all sensors are indicated in Figures 14a) and Figures 14b), separated in lateral and vertical direction, respectively, from which some natural frequencies can be observed.



a) b)

Figure 14: ANPSD (a) lateral (b) vertical

The analysis of the peaks on the ANPSD spectra relative to the lateral and vertical directions, allows to verify the existence of global vibration modes in a frequency range from 2 to 6 Hz. Three lateral frequencies, first: 2.91 Hz, second: 3.63 Hz, and third: 3.85 Hz, and a vertical frequency of 5.37 Hz are clearly identified. The use of SSI-COV method allowed to estimate de corresponding modal shapes, which are indicated in Figure 15 and 16.

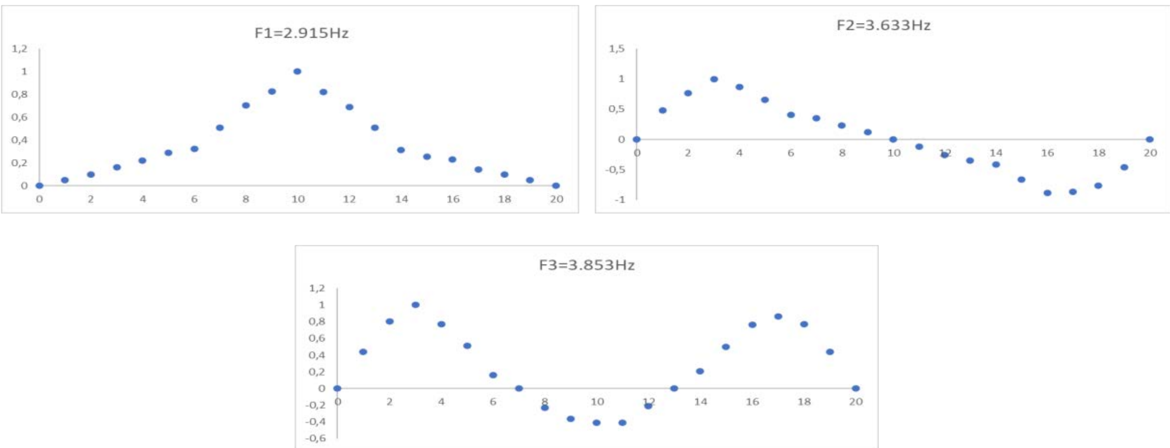


Figure 15: First, Second and Third Lateral Modes

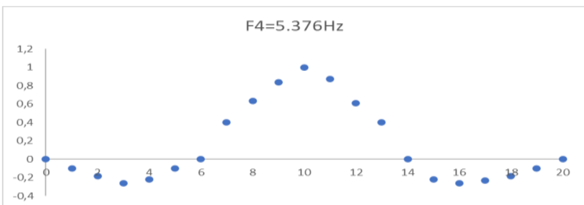


Figure 16: First Vertical Mode

6 NUMERAL MODEL

6.1 General aspects

The numerical model was developed to study the static and dynamic behavior of the structure. It was possible to calibrate the model in terms of frequencies and vibration modes by using the results from the ambient vibration test, making the necessary adjustments in some parameters, such as mechanical characteristics of sections and support conditions.

The model was developed using Robot Strucutral Analysis Professional (2023) and Ansys 2021 R2 software. The modulus of elasticity adopted for all bars was 200 Gpa, comprising a total of 14 different sections. The transverse beams in the deck and the stringers supported on them, where the sensors were installed, are I-section profiles IPE 750137 and IPE 550, respectively (Figure 9), while the diagonals are formed by double sections in U-profile UPN 350 (Figure10).

Regarding the support conditions, the bridge is composed of metal supports that allow free rotations in the plane of the structure. In the Trezói side support, longitudinal displacements are allowed, while in the Guarda side support they are restricted. The connection between the deck and the columns allows displacements along the longitudinal direction of the bridge and rotation in all directions.

6.2 Numerical vs experimental modal parameters

The numerical model of the bridge deck vibrations presents the first 4 modes with frequencies below 6 Hz, corresponding to the field measurements. The model results are presented below, in figures 17 and 18 for the first lateral modes, and figure 19 for first the vertical mode.

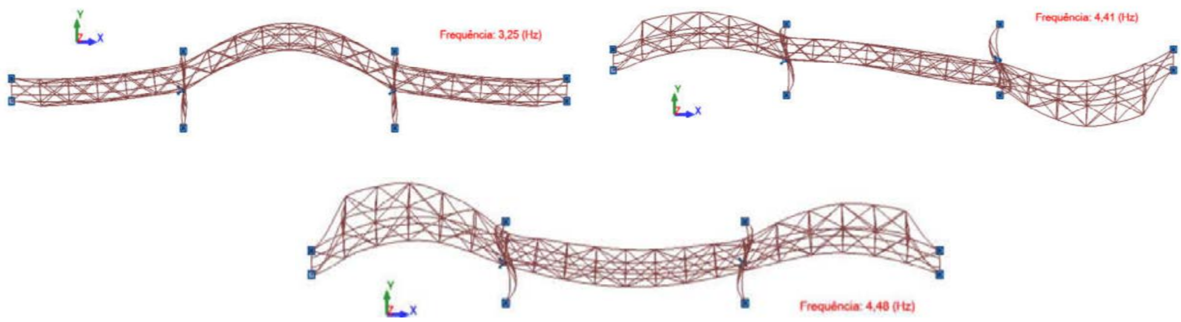


Figure 17: Lateral vibration modes by ROBOT software

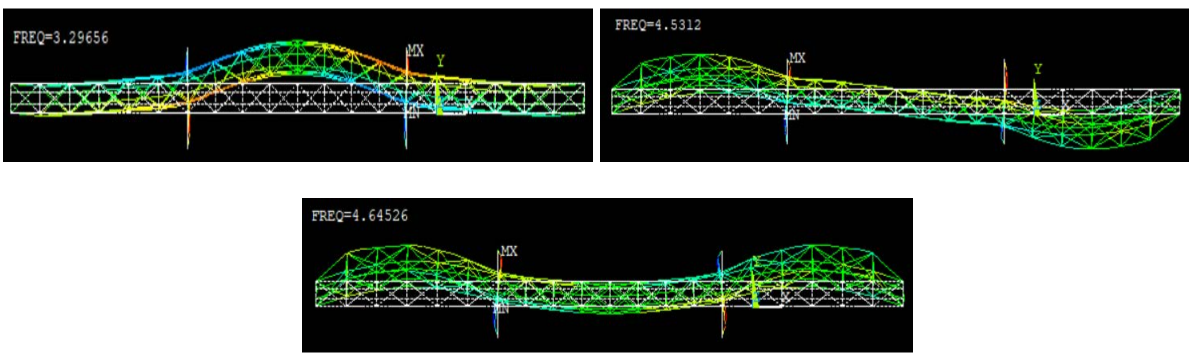


Figure 18: Lateral vibration modes by ANSYS software

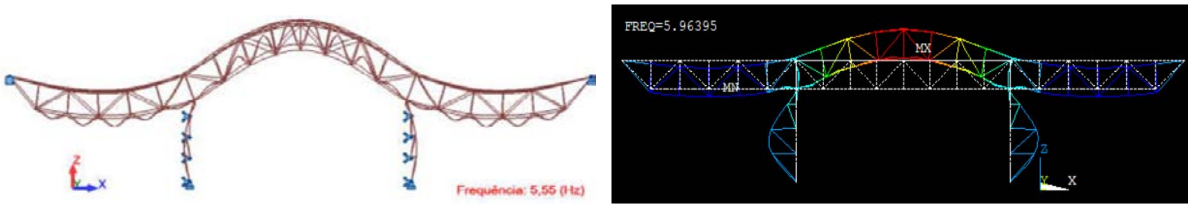


Figure 19: Vertical vibration modes by ROBOT and ANSYS software

The results of the model compared to the natural frequencies obtained experimentally showed small differences. The table below shows the correlation between the values.

Mode	Numerical Model Ansys (Hz)	Numerical Model Robot (Hz)	Ambient Vibration Test (Hz)
1º Lateral	3.296	3.25	2.915
2º Lateral	4.531	4.41	3.633
3º Lateral	4.645	4.48	3.853
1º Vertical	5.964	5.55	5.376

Table 1: Frequency numerical model vs. ambient vibration test

7 CONCLUSIONS

In order to demonstrate the usefulness of monitoring railway bridges, this paper presents a new instrumentation solution that is relatively inexpensive and has credible performance. It was concluded that the customized system can be used to develop research on several topics, such as the actual traffic loads and their effects on the Trezói bridge. Information obtained from the monitoring system is also useful to calibrate numerical models of the structure.

The combination of experimental in-situ testing with the possibility of a relatively large number of sensors has proven to be a reliable and inexpensive methodology for identifying the modal vibration properties of the bridge, increasing its structural reliability and safety for users. The updated numerical model of the bridge will allow prediction of the future condition behavior of the bridge under increased load and/or operating speed.

8 ACKNOWLEDGMENTS

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