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Article

Development and Implementation of a Fully Customised System for Monitoring a Long-Span Cable-Stayed Bridge Undergoing Rehabilitation Works

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Abstract

This work explores the key capabilities of emerging sensing technologies in the context of Structural Health Monitoring (SHM) of civil infrastructures, aiming at contributing to the research on integrated and intelligent systems for more accessible and efficient monitoring solutions. As a case study, this study focuses on analysing the static and dynamic behaviour of the Edgar Cardoso stay-cable Bridge during its rehabilitation, recurring to a fully customized transducers and equipment. The developed system integrates sensors capable of measuring accelerations, displacements and temperature, which are connected to an autonomous data acquisition and transmission network. A digital interface was also developed to store, process and visualize the collected data, allowing remote access for later interpretation and analysis. The results confirmed the effectiveness of the developed system, which enabled the identification of the dynamic properties of the structure in terms of natural frequencies and vibration modes. The effects of traffic loads, as well as the correlations between temperature and structural displacements were also identified. Furthermore, the estimation of the axial forces in the stay cables permitted to study the influence of wind actions and traffic loads in these elements. The results demonstrate the potentialities of customized sensing solutions as effective tools for the management, maintenance, and long-term preservation of strategic infrastructures.

Keywords: structural health monitoring (SHM); stay-cable bridges; customized monitoring systems; edge computing; digital databases and interfaces; traffic loads and temperature effects on structures

1. Introduction

Structural monitoring in Civil Engineering plays a key role in the safety, durability and efficient management of infrastructures, enabling the early detection of anomalies and the implementation of preventive maintenance strategies. Traditionally, bridge inspection has relied on manual methods, which, while effective, are often time-consuming, labour-intensive, and subjective to human error [1,2]. As a result, there has been a growing interest in the development and implementation of Bridge Health Monitoring (BHM) systems, which utilize advanced technologies to continuously assess the condition of bridge structures in real-time in ensuring the safety and longevity of bridge infrastructures worldwide [3–5].

The emergence of new generation detection technologies (NGs) represents the cutting edge of sensor innovation, developed to transcend the limitations inherent in conventional detection systems [6,7]. Furthermore, the advancement of the sensor technologies must be accompanied by the evolution of the monitoring systems themselves, promoting the development of more integrated and intelligent solutions that align with the rapid progress of computational and information technologies [8,9].

New generations of wireless sensors are revolutionizing structural monitoring by offering improved energy efficiency, enhanced connectivity, and reduced costs. The implementation of sensors without damaging the structure is achieved through non-intrusive techniques, such as adhesive-mounted wireless sensors and remote data transmission, ensuring seamless integration with existing infrastructure. These sensors leverage low-power communication protocols, to enable long-range data transmission with minimal energy consumption [10–12]. Advanced materials and miniaturization techniques have increased sensor durability and sensitivity, making them more effective in harsh environments [13]. Additionally, edge computing capabilities in modern wireless sensors allow for on-device data processing, reducing latency and optimizing real-time analytics [14].

The customised sensors developed incorporate a set of design principles that aim to ensure efficiency, robustness and adaptability in SHM systems. These devices operate wirelessly and independently of external power sources, relying on batteries or compact solar panels, which simplifies installation and significantly reduces costs and electromagnetic noise in the signals. Data transmission is optimised through intermittent communication, favouring predefined transfer intervals and low-power sleep modes over continuous data streaming, thus extending the system's autonomy [10,11]. Simplicity and robustness are key aspects, as low-complexity solutions increase reliability and reduce system downtime. Local data processing (edge computing) further improves performance by transmitting only processed parameters rather than complete raw signals, minimizing the data load [14]. The flexibility and customisation of the system allow the integration of multiple detection capabilities into a single module, while maintaining compact dimensions. In addition, the sensors are designed for easy maintenance, with long operational autonomy and simple module replacement in case of failure. Overall, these features result in a cost-effective, energy-efficient and resilient SHM system, suited for long-term monitoring of complex infrastructure. Similar customised sensing approaches have already demonstrated successful applications in bridge monitoring systems, highlighting their potential for efficient and scalable SHM implementations [15].

The developed monitoring system integrated new sensing techniques as Internet of Things, Digital Twin Framework and Multisensory Data-fusion. The designed system not only optimises sensor solutions to meet the specific requirements of the practical case but also incorporates a strong digitalisation component. This digital dimension is achieved through the development of an integrated real-time monitoring platform supported by a database hosted on a web server, ensuring secure and centralised data management [16–18]. The system allows continuous acquisition, storage, and processing of information collected by the sensors, promoting efficient data organisation and long-term accessibility. In addition, a dedicated graphical interface has been developed to facilitate data visualisation and interpretation, allowing for clear and intuitive remote consultation of structural parameters. This integration between hardware and digital infrastructure represents an important step towards the implementation of intelligent monitoring systems capable of supporting decision-making processes in maintenance, safety assessment and structural management.

In this context, the main objective of this paper is to describe the development and implementation of a fully customised monitoring system based on the principles just outlined, highlighting their potential to provide efficient and reliable performance while reducing the complexity and cost of conventional monitoring solutions. In addition, several results extracted from the signals collected in the monitoring campaign are presented, including the identification of the main natural frequencies of the suspension cables and the deck through spectral analysis, the detection of traffic-related patterns from acceleration data, and the estimation of cable stresses using the theory of stretched strings [19] over a period of one month. The influence of environmental factors – particularly wind – on the dynamic response, as well as the correlation between temperature variations and expansion joint displacements, are also discussed. Similar dynamic monitoring approaches have been successfully applied in large bridge structures, such as the Dom Luís I Bridge in Porto [20], further validating the effectiveness of customised sensors and the developed platform as valuable tools for the management and maintenance of complex infrastructure.

2. Description of the Bridge

The case study adopted in this research is the Edgar Cardoso Bridge, a landmark structure in Portuguese engineering, representing the country's first major cable-stayed bridge, inaugurated in 1982 (Figures 1 and 2). Situated in the city of Figueira da Foz, Coimbra District, the bridge crosses the Mondego River, linking the northern parish of Buarcos e São Julião to the southern parish of São Pedro. Commonly known as Ponte da Figueira da Foz, it was designed by the distinguished Portuguese Engineer Edgar Cardoso.



Figure 1. General view of the Edgar Cardoso Bridge in Figueira da Foz.

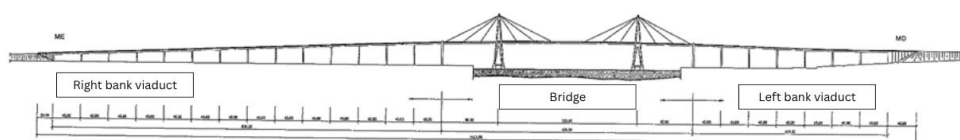


Figure 2. Side view of the Figueira da Foz Bridge, designed by Professor Edgar Cardoso and completed in 1982 [21].

The Edgar Cardoso Bridge is currently undergoing rehabilitation, marking its second major intervention since inauguration (Figure 3). The first significant maintenance work took place in 2005, when structural reinforcements were carried out. Nearly 20 years later, the bridge requires a new intervention to ensure safety and longevity, primarily due to the progressive degradation of the cable suspension system, evidenced by increasing wire breakage. In addition, the deck's metal elements, particularly at the connections with the concrete slab, show significant deterioration. Consequently, rehabilitation of this area has also been included in the repair plan.



Figure 3. Photograph of the Edgar Cardoso Bridge: (a) before rehabilitation; (b) under rehabilitation.

The Edgar Cardoso Bridge has a length of 405 meters, 225 m in the central section and 90 m in the lateral span (Figure 4). The deck, made of steel and concrete, is supported by two self-supporting towers, two transition pillars and six pairs of cables. The free height above the water level is around

40 m with a maximum column height of approximately 80 meters. The retaining ties are anchored to the deck, which in turn is anchored to the transition columns. The deck also has an isostatic central section 30 meters long supported on the south side by fixed supports and on the other side by movable supports.

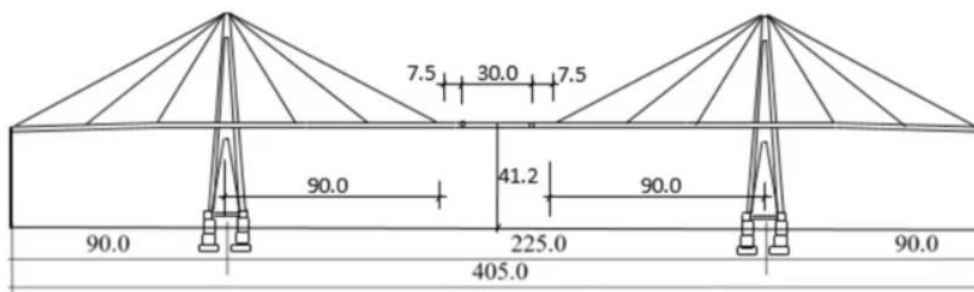


Figure 4. View of the cable-stayed bridge.

The bridge deck is made up of a combination of steel and concrete. As far as longitudinal development is concerned, the deck has two joints in its middle area, which delimit a simply supported central span 30 meters long.

The transverse direction is 20 meters wide (Figure 5) divided into four traffic lanes, a central divider and two sidewalks, one on each side. The platform is made up of a mixed steel-concrete structure in which the metal elements form an orthotropic system with modules 10 meters long and 17 meters wide. The wired concrete slab rests on the stiffening beams and stringers and consists of two cantilevers at the ends, two small spans of 0.50 meters between the twin elements of the stiffening beams and five spans of 3.20 meters between the stringers. Its thickness varies according to the parabolic law that defines the progress of the lower face. The thickness of the slab is 0.20 meters on the supports and 0.13 meters in the spans.

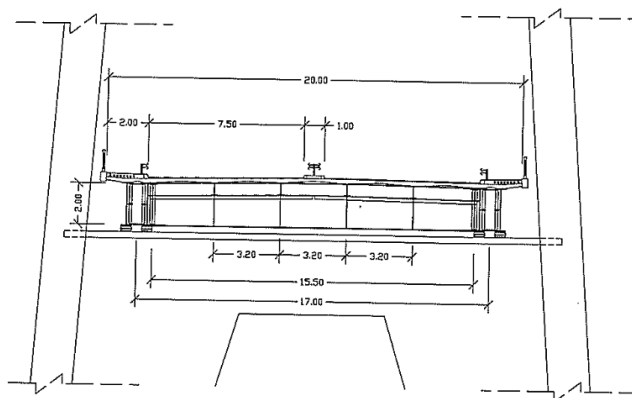


Figure 5. Cross section of the deck.

The bridge has two concrete pylons with 84.4 m to support the vertical reactions (Figures 6). Each pylon has four concrete legs with hollow squared section, inclined longitudinally and transversely, connected at the top by a transversal beam and under the deck by a concrete laminate plate. At the base level, the towers are supported by four circular hollow piles, with an exterior diameter of 5 meters and wall thickness of 0.4 meters. The pile blocks are interconnected by prestressed I-sections concrete beams.

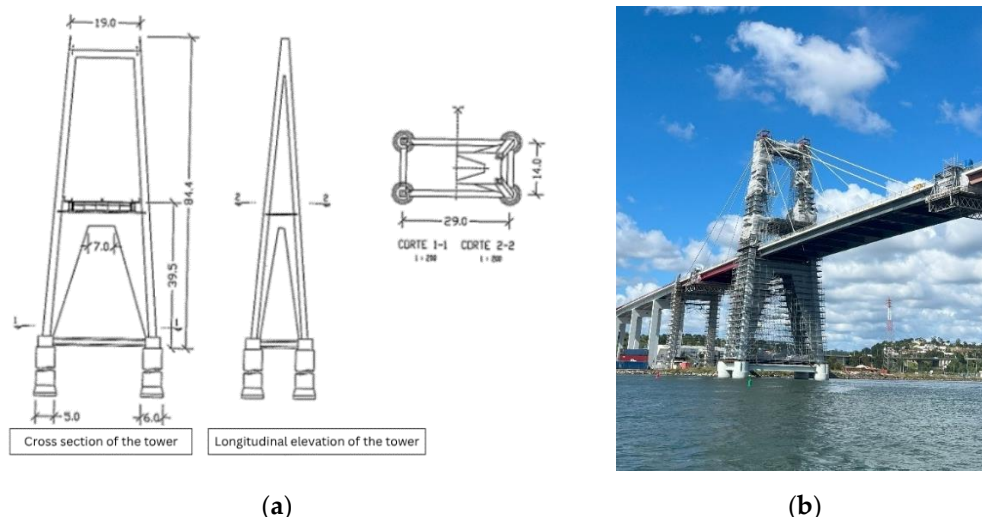


Figure 6. (a) Geometry and dimensions of the Figueira da Foz Bridge towers; (b) Photograph of the north bridge tower under rehabilitation.

The viaducts are made up of beamed slab decks, each containing 4 longitudinal beams separated by 5.2 meters, with continuous spans of 45 m supported on hollow pillars, whose heights vary between 13 and 34 meters (Figure 7).

The beams, which vary in height from 2.3 meters to 2.8 meters, are prestressed longitudinally. In contrast, the slab, which varies in thickness from 0.22 meters to 0.18 meters, is prestressed transversely. The beams are braced transversally every 15 meters.

The viaduct pillars consist of two hollow rectangular columns, joined at the top by a hollow beam. The beams are supported on the pillar crosspieces by means of bolts and lead braces. At the transition pillars, the viaducts are supported by movable roller-type metal devices with guides. At the abutments, the viaducts are supported by strapped neoprene braces equipped with a Teflon sliding plate, installed during the rehabilitation work. In addition, to control the effects of seismic action, viscous dissipaters were installed between the decks and the abutments. Although all the drawings represent the viaduct on the right bank, the same structural configuration and considerations apply to the viaduct on the left bank.

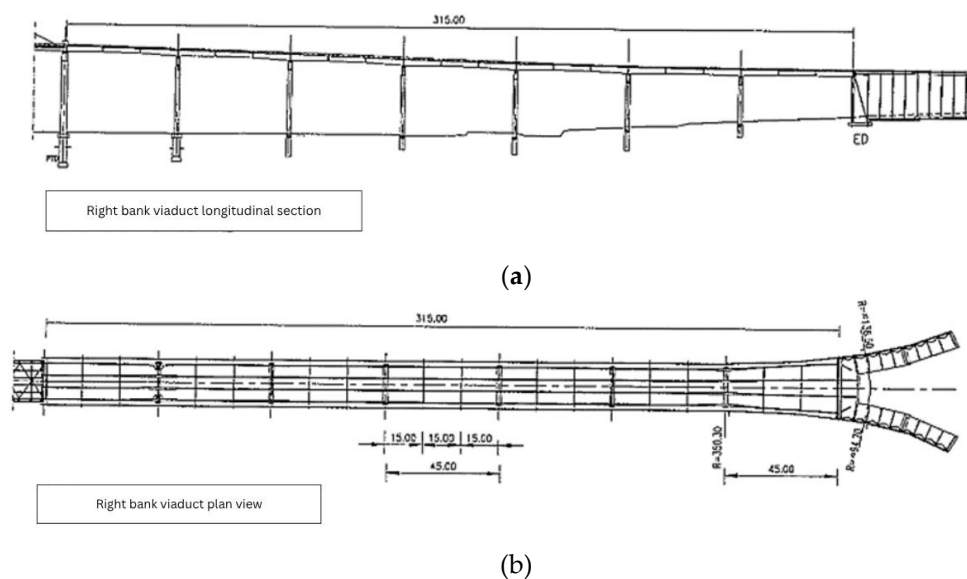


Figure 7. General representation of the right viaduct of the Edgar Cardoso Bridge: (a) Right bank viaduct longitudinal section; (b) Right bank viaduct plan view.

The suspension cables are arranged in a fan shape, symmetrically on each side of the towers and are tied to the deck's stiffening beams, 30 m apart (Figure 8). The cables are continuous between the central span and the lateral span, and the towers are equipped with saddles at the top.

The stay cables are made up of parallel steel wires: 109 strands are used on cables 1/6, 61 strands in intermediate cables 2/5, and 37 strands on cables 3/4. Each cable is protected by a galvanized and painted steel wire winding.

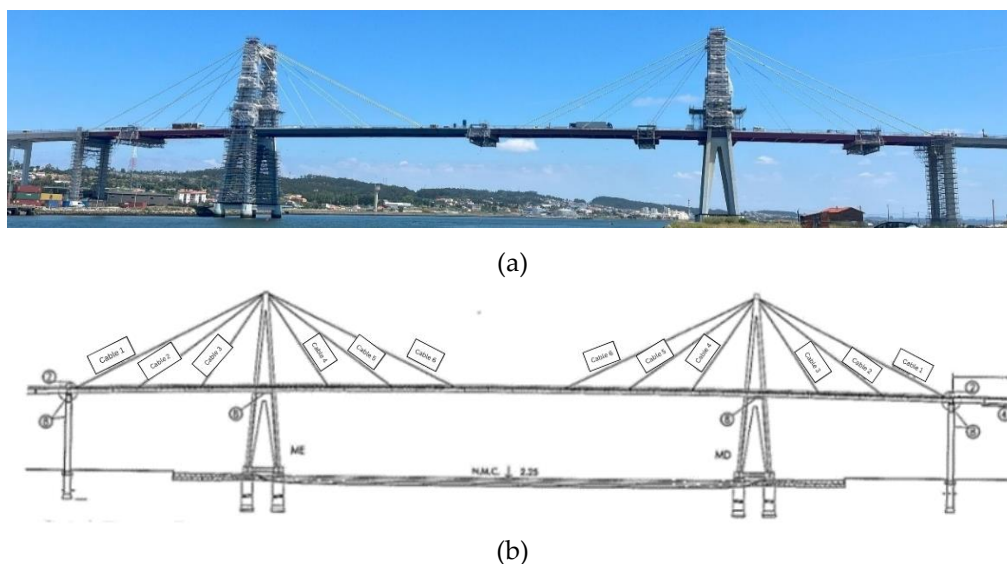


Figure 8. (a) Photograph of Edgar Cardoso Bridge; (b) General representation of the Edgar Cardoso Bridge.

3. Development of Customized Sensors

In this monitoring program, data was collected from seven transducers (Figure 9). As part of the installation, the structure was equipped with three accelerometers, two temperature sensors, two displacement sensors and one reception station ensuring comprehensive data acquisition for analysis.

For consistency and clarity throughout this document, the accelerometers will be referred to as **ACC**, the temperature sensors as **T**, the displacement sensors as **DSP**, and the receptor sensor as **R**, as presented in Table 1.

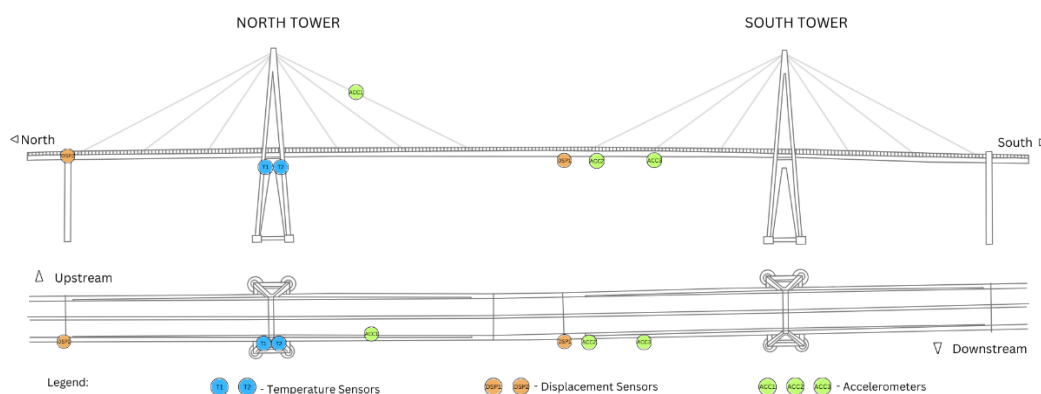


Figure 9. Instrumentation plan location.

Table 1. Nomenclature of devices.

Nomenclature	Device
ACC	Accelerometer

DSP	Displacement Sensor
T	Temperature Sensor
R	Reception Station

One of the objectives of this project was to monitor the structure using autonomous wireless sensors capable of transmitting data without cabling, thereby efficient communication without physical constraints. In short, the installed sensors transmitted information remotely to the reception station located at the company facilities near the construction site, where the data were recorded locally and simultaneously sent to the database. The full features of the system will be described in detail in the following sections.

The sensors developed for this monitoring system are autonomous, requiring no wiring and enabling flexible installation. Compact in size, they were designed and built in the university's laboratories, ensuring high precision and reliability. Each sensor was fully customized to the specific characteristics of the object under study, providing optimized integration and an appropriate response to the monitoring requirements.

3.1. Accelerometers

The accelerometers are composed of an Arduino-based microprocessor that controls the entire process of data acquisition (Figure 10). The accelerometer used is a micro-electro-mechanical system (MEMS) type, namely the ADXL355 from Analog Devices Company. It has programmable sampling rates and programmable bandpass digital filters. The model used for the Edgar Cardoso Bridge incorporates an XBee radio to transmit data to the receiver, with the collected data also being stored locally on a microSD card to ensure robustness against potential data loss. This device accommodates five lithium batteries of 18650 type. The nominal voltage of each battery is 3.8V, and the capacity is 3400 mAmps, ensuring an autonomy of approximately 2 months in continuous operation. The synchronization of the acquired signals between the different accelerometers is guaranteed by GPS.

The developed accelerometers are housed in a BUD PN-1323 external box made of polycarbonate, light grey in color, ensuring durability and protection. The enclosure has external dimensions of 90mm (width) x 115 mm (depth) x 55 mm (height), providing a compact and secure structure for the components. The total weight of the unit is 0.6 kg, making it lightweight and easy to install.

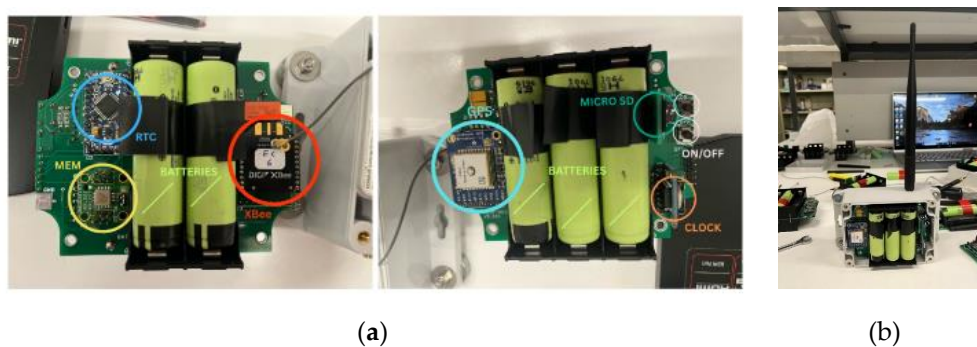


Figure 10. Accelerometer module: (a) internal components and (b) casing module.

The accelerometer ACC1 was installed on the cable with the aim of evaluating the installed axial force to which it is subjected and the vibrations levels of the cable. The device was placed on the cable-stay system attached on the top of the protective plastic sleeve, to not damage the cable, using metal chains. In this particular sensor, the microprocessor was changed to a Teensy 3.2 with higher power consumption than Arduino, leading to reduction of the expected autonomy to about 1 month.

On the other hand, accelerometers ACC2 and ACC3 were placed on the deck with the objective of identifying the dynamic parameters of the bridge deck. The accelerometer ACC2 was placed on the deck near the anchorage of cable 6 and the ACC3 device was placed near the anchorage of cable

5. The modules were fixed by magnetic attachment to the metal beam, without causing any damage to the structure.

Installing devices on the cable and on the deck made it possible to separate the natural frequencies of the bridge deck and the cable.

3.2. Temperature Sensors

The temperature sensors are the DS18B20 model from Maximum Integrated Company (Figure 11). The digital sensors measure temperatures from -55°C to $+125^{\circ}\text{C}$, with a resolution of 0.125°C and an accuracy of 0.5°C from -10°C to $+85^{\circ}\text{C}$, which is adequate for general applications in structural monitoring. No extra hardware is required, making this sensor simple and effective. The sensor has three-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 microcontroller. In this application, the sensor was constructed using PTFE and stainless steel, materials that provide excellent durability and resistance to harsh environments. The sensor is equipped with two cables, ensuring stable connectivity and efficient data transmission. The temperature readings are acquired at 10-minute intervals, with the data being stored locally on a microSD card and transmitted wirelessly to the receiver, after which the system enters sleep mode.

These modules are housed in a BUD PN-1323 enclosure with the same characteristics as the one used for the accelerometers, as described in Section 3.1. They are powered by three 18650 batteries, providing an autonomy of more than one year, which exceeds that of the accelerometers since the device operates in sleep mode for most of the time. The total weight of the unit is also 0.6 kg, ensuring it is compacted and simple to set up.

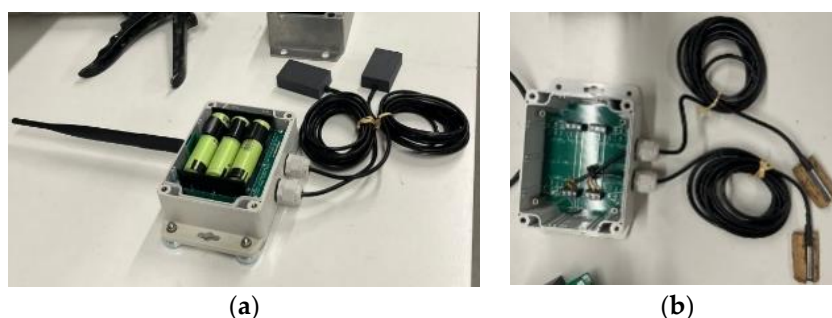


Figure 11. Temperature sensor: (a) view inside the module; (b) view of the BUD PN-1323.

During the installation of the transducers, thermal paste was applied to ensure direct contact between the sensors and the measured element. This paste enhances thermal conduction from the steel to the sensors. The remaining area was insulated with cork to isolate the sensors from the ambient temperature.

The two sensors, and their housing, were fixed to the underside of the bridge deck without any exposure to sunlight. The first sensor, T1, was placed on the surface of the concrete structure and the T2 sensor was installed on the surface of the longitudinal steel beam. No drilling was required, just the use of glue. The installation of these devices was made possible using scaffolding in the north tower.

3.3. Displacement Sensors

The displacement sensor used is of the capacitive type and works inside an aluminum quadrangular cross-section with dimensions of 8×8 cm and length of 26 cm (Figure 12). The objective of using these devices is to evaluate the temperature effects on the structure, as well as to measure dynamic displacements originated by traffic loads.

The sensor is powered by four 18650 type batteries. Data access is provided through local storage on a memory card, with the Xbee radios transmitting the condensed information to a receiver each

10 minutes. In terms of autonomy, this device when operating in static mode (one reading each 10 minutes) batteries may last more than 1 year. In dynamic mode (which was selected in this application) batteries ensure an autonomy of about 2 months. The dynamic mode was programmed to work with a sampling frequency 5 Hz. One of the significant features of this sensor is related to its ability to take measurements with 0.01 mm and precision in a range from 0 to 2 meters. In practice, to prevent the sensor from being too long, the measuring range was adjusted to measure in the range of 0-150 mm.



Figure 12. Displacement sensor: (a) interior board with batteries; (b) sensor casing.

Two displacement sensors were implemented on the structure. DSP1 was installed on the fixed support on the central section of the bridge, while the other sensor, DSP2 was placed on the north expansion joint. Both sensors were implemented on the downstream side.

3.4. Reception Station

The receptor, a battery-powered data reception station installed inside a BUD PN-1328 box, is dedicated to collect data sent by all sensors (Figure 13). This device has a Xbee radio to communicate with the sensors and has an ESP8266 module that provides an internet connection to send data to a database. The wireless network is provided by a local hotspot. The receiver was installed on the company facilities, receiving data from the various sensors with a time stamp of 10 minutes. This information is then saved locally and sent to an SQL database.



Figure 13. Receptor case at the company facilities.

4. Monitoring System Architecture

As just described, the system is composed of multiple sensors, each one collects specific types of data and sends them to the reception station (Figure 14). This unit identifies and organizes incoming data from the different sensors, converts the sensor readings into a standardized format and sends the processed data to the database. The database acts as the core repository of the system. It stores all incoming data and enables further processing through two parallel pathways for analytical processing and for display on the website. The data is analyzed using algorithms and statistic tools. The database feeds information to the website interface, allowing engineers to monitor the structure in real-time. The website provides visual dashboards and historical data.

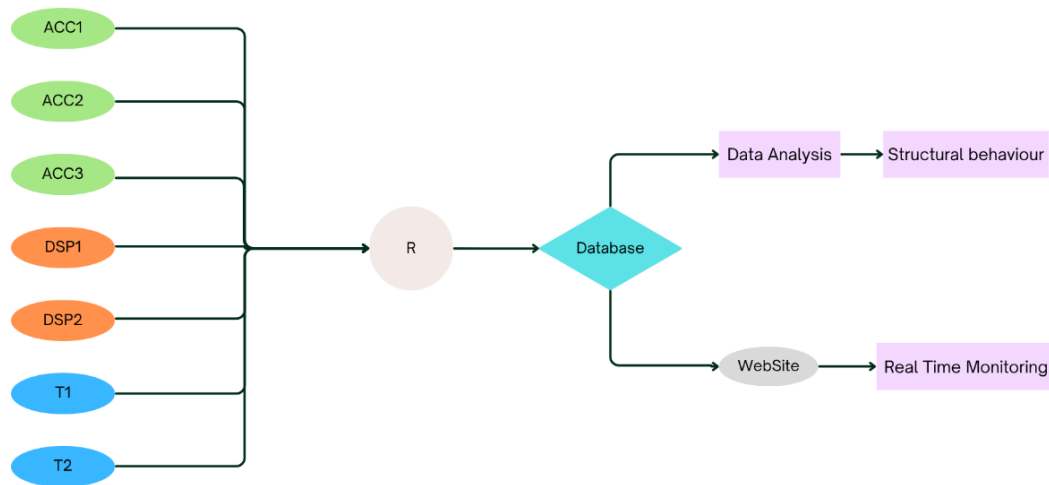


Figure 14. Schematic representation of the Structural Health Monitoring System.

4.1. Transmission of the Data

In order to reduce the amount of transmitted data, which can reach high volumes especially in the case of dynamic measurements, each local sensor was programmed using edge computing tools. Edge computing refers to a computational paradigm in which data processing is carried out locally at the sensor level, rather than relying entirely on remote servers or cloud infrastructures. This approach significantly reduces communication latency, minimizes bandwidth requirements, and increases the overall autonomy of the system.

As data are received from the seven sensors, a file structure is created in the receiver module to store the 46 distinct parameters collected from these sensors. Since data transmission between the sensors and the receiver is performed via XBee modules, it must be taken into account that this technology does not support the simultaneous reception of data from multiple sensors. Therefore, it is necessary to schedule the transmission time for each sensor, which is achieved by introducing a time delay for each transmission.

The complete process begins with the creation of a file at each 10-minute interval in the receiver module. DSP1 then initiates its transmission 15 seconds after file creation, sending information such as battery voltage, along with the average, RMS, maximum, and minimum values of the measured signals. Similarly, DSP2 starts its transmission 30 seconds after the beginning of the 10-minute interval, reporting parameters analogous to those transmitted by DSP1. This procedure is repeated for each sensor by introducing successive communication delays, ensuring that the various parameters collected by the sensors are transmitted sequentially. The complete sequence of time delays and transmitted parameters is presented in Appendix A.

4.2. Data Management

With regard to data management following acquisition by the receiver unit located at the construction site, the system architecture was designed to encompass the entire processing chain, from data storage to final user visualization.

The process begins with the deployment of a MySQL database hosted on a server. The database was specifically designed to accommodate the wide range of parameters collected during the monitoring campaign. The resulting schema consists of 46 columns, each corresponding to a specific measurement parameter. The database structure was implemented directly in MySQL and managed using DBeaver, which provides a graphical interface for organizing, visualizing, and handling tables and attributes.

Data collected by the receiver unit are transmitted to the server-hosted database, with PHP used as the backend language to manage the communication between the receiver and the database

system. In addition, a Python environment was configured to establish the database connection and automate the insertion of incoming data streams, ensuring reliable and continuous data storage.

Once stored, the data can be accessed and processed using MATLAB for analysis and modelling, and Python for data handling and visualization tasks. An HTML-based website serves as the user interface, connecting directly to the database to retrieve and visually present the monitoring data to the end user.

After configuring the database infrastructure, the final step consisted of setting up the ESP-N platform and implementing the complete data transmission workflow, from the sensors to the receiver and subsequently to the database system.

The complete data management flow is illustrated in Figure 15.

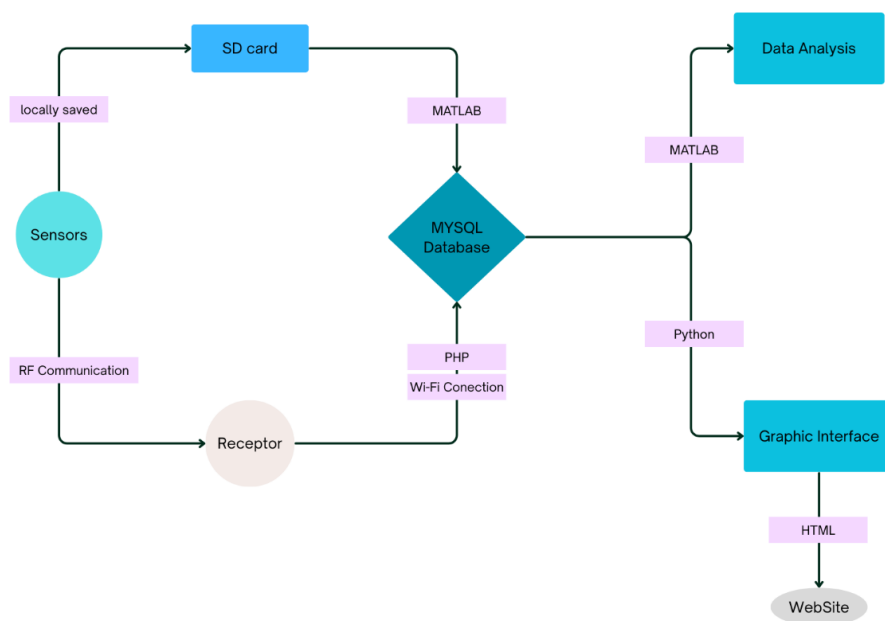


Figure 15. Flowchart of the monitoring system with sensors, showing the data flow from collection to the graphical interface and website.

4.3. Graphical Interface

The main objective in the development of the graphical user interface was to design a platform that is both visually appealing and modern, while maintaining a high level of accessibility and usability (see Figure 16). The intention was not only to provide an attractive and intuitive environment for the user, but also to ensure that the consultation of data and results could be performed in a straightforward and efficient manner, without the need for advanced technical knowledge. Particular attention was given to the balance between aesthetics and functionality, so that the interface could support a clear visualization of complex information while minimizing potential barriers to navigation.

In detail, the developed platform incorporates a dedicated section for structural instrumentation where the spatial distribution of the installed sensors is represented through a clear and interactive schematic of the bridge [22]. The main objective of this module is to provide users with an intuitive visualization of the monitoring system, allowing for a rapid understanding of both the type of sensors deployed and their precise locations.

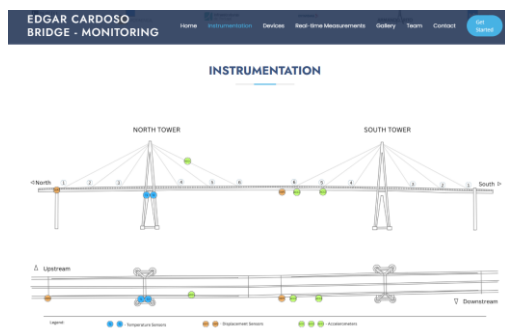
Other module provides a comprehensive overview of the monitoring devices installed on the Edgar Cardoso Bridge, presenting each sensor individually with details regarding its location and the physical quantity measured. By structuring the information in this manner, the platform enhances clarity and ensures that users can quickly identify the function and role of each device within the overall monitoring system.

The Real-Time Measurements section of the platform is designed to provide continuous visualization of the data acquired from the installed sensors. In this module, measurements from devices such as battery voltage, temperature sensors, displacement sensors, and accelerometers are displayed in the form of interactive graphs that update dynamically, allowing the user to monitor structural responses as they occur. In addition to graphical representations, the system can also present the acquired data in tabular format, ensuring both a detailed numerical view and a more intuitive visual interpretation. This dual approach reinforces the analytical capabilities of the platform, enabling users to cross-reference real-time fluctuations with historical patterns and to extract meaningful insights for structural health monitoring.

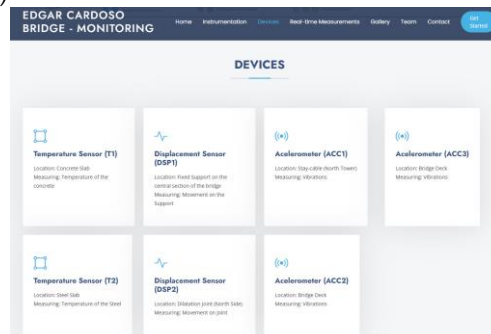
The platform also includes complementary sections that enhance both contextual understanding and communication. The Gallery section provides a visual record of the instrumented areas and the overall structure under monitoring, offering users a direct perspective on the physical installation of the sensors. The Team section presents the members involved in the development and implementation of the project. Finally, the Contact section facilitates communication between users and the project team, ensuring accessibility for inquiries, collaborations, and future developments and information.



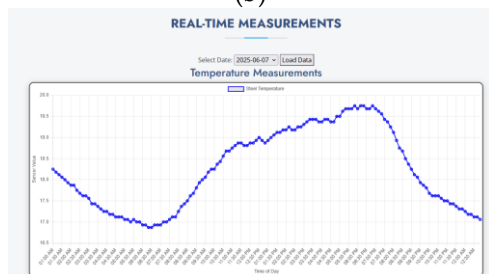
(a)



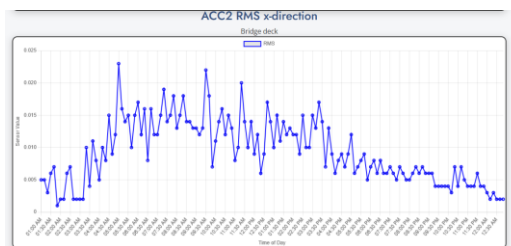
(b)



(c)



(d)



(e)

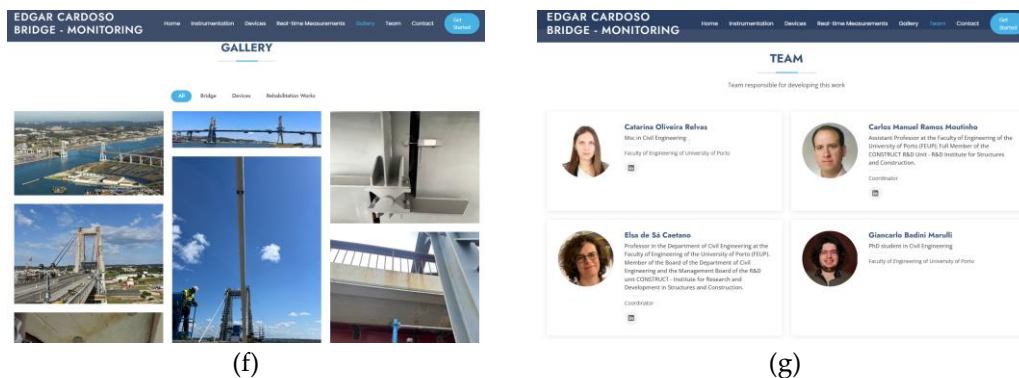


Figure 16. Web interface of the Edgar Cardoso Bridge Monitoring System: (a) Homepage; (b) Instrumentation layout; (c) List of services; (d) and (e) Real-time measurements; (f) Gallery of images from the monitoring system; (g) Team involved in the process.

5. Data Analysis and Discussion of Results

In terms of data processing, MATLAB was used to analyze the collected measurements, with dedicated processing routines developed and adapted to the characteristics of each sensor. The use of MATLAB provided significant advantages, such as its extensive library of built-in functions for signal processing and data visualization, as well as its flexibility in handling large datasets with efficiency.

5.1. Sensors Batteries Performance

The first analysis focused on evaluating the battery autonomy of each sensor to ensure one month of continuous structural monitoring. It is worth mentioning that, throughout the entire monitoring period, no battery replacements were required for any of the sensors, with the sole exception of the receiver module, due to a later extension of the monitoring period.

It should also be noted that the ACC3 sensor did not provide reliable data during the campaign, as it was removed during maintenance and intervention works carried out on the bridge. This resulted in a complete interruption of its monitoring record. For this reason, the results associated with ACC3 are excluded from the subsequent analysis.

In this context, Table 2 summarizes the battery performance of each sensor during the monitoring period, which allow to conclude that the battery life of the sensors was satisfactorily achieved for this project. Depending on the type of sensor, the power consumption of each module can be quite different, which leads to cases where the batteries did not run out by the end of the monitoring period, and so the corresponding effective lifetime is unknown.

Table 2. Comparison between expected and effective lifetimes of the sensors.

Sensor	Expected Lifetime	Effective Lifetime
DSP1	2 months	2.1 months
DSP2	2 months	Unknown
T1, T2	> 1 year	Unknown
ACC1	1 month	1.1 months
ACC2	> 1 month	2.16 months

5.3. Temperature Measurements

The temperatures were recorded over time for two different materials: steel and concrete, by using respectively T1 and T2. As shown in Figure 17, both sensors follow a similar pattern, reflecting the influence of environmental conditions in both materials. The sensor in the steel generally shows slightly higher temperature fluctuations compared to the sensor in the concrete, which is consistent with the higher thermal conductivity and lower thermal inertia of steel. Additionally, this sensor is

installed on the steel beam that supports the deck, which is directly exposed to solar radiation, causing the expected temperature range to be greater. On the other hand, the temperature sensor installed in the concrete tends to exhibit a more inertial response of lower amplitude, as the material stores and releases heat more gradually. The peaks observed on certain days are likely related to periods of increased solar exposure, while the overall gradual increase in reference temperatures from May to August reflects the expected seasonal warming. Monitoring these temperature variations is essential to understand their potential impact on structural behaviour, as temperature changes can influence material properties, boundary conditions and, consequently, the static and dynamic response of the bridge.

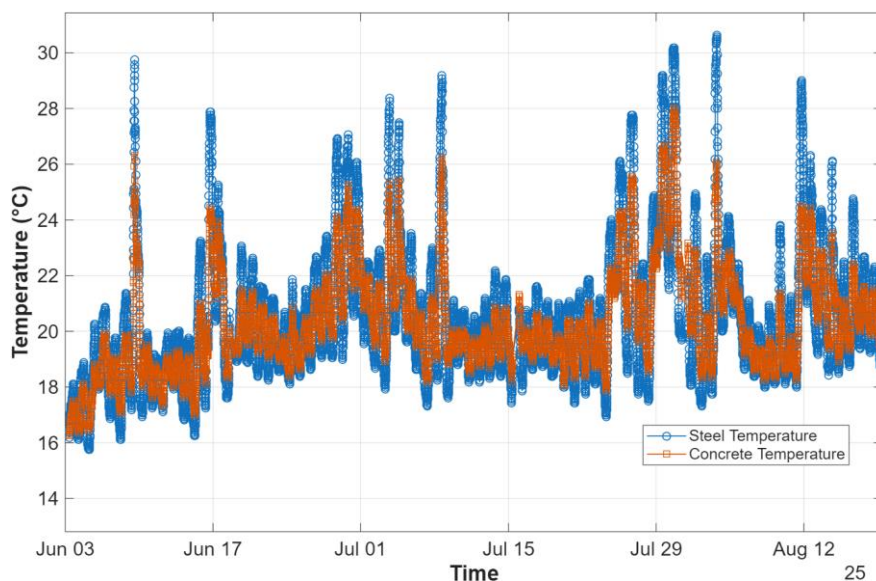


Figure 17. Temperature measurements registered during the monitoring program.

5.4. Acceleration Data

5.4.1. Stay Cable Vibrations

The RMS values of acceleration signals in the transversal/vertical plane measured over time, indicated in the map of Figure 18, reveals clear patterns that can be associated to the bridge's operating conditions. The darker regions corresponding to lower vibration levels, match weekends and holidays, during which traffic intensity is considerably reduced, resulting in lower levels of vibration of the stay cables. In contrast, the lighter areas are concentrated on weekdays, reflecting higher levels of dynamic excitation linked to regular traffic flow. Within these weekdays, peak RMS values are consistently observed during rush hours, namely in the morning and late afternoon, coinciding with commuting periods when the bridge experiences the highest vehicle loads. This behavior highlights the strong correlation between traffic activity and the dynamic response of the structure, also allowing differentiation between regular operational patterns and isolated events of unusually high vibration.

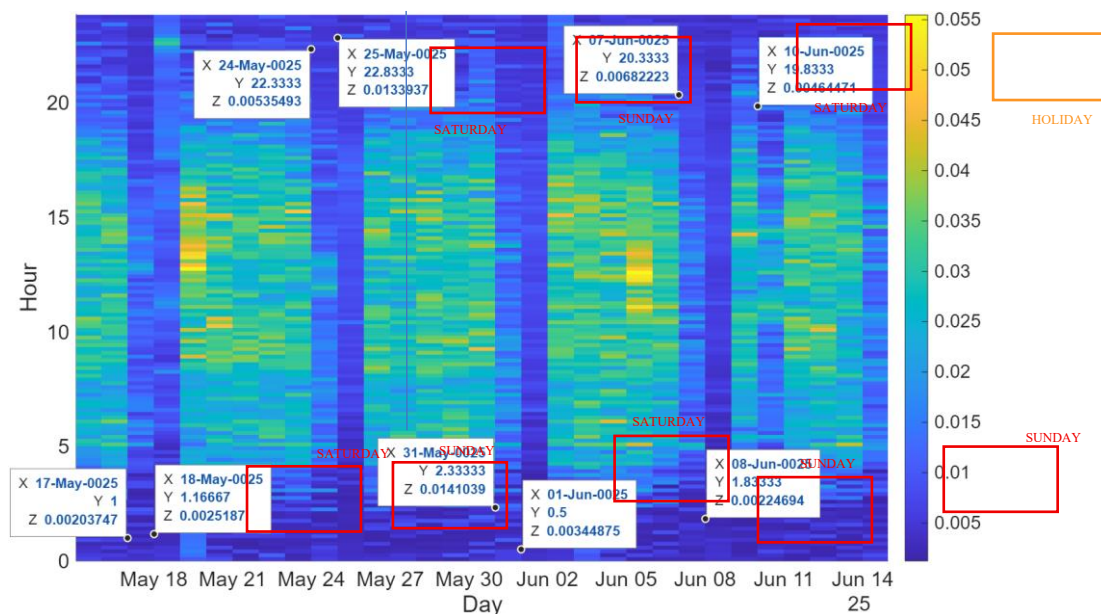


Figure 18. RMS values of acceleration highlighting the weekends and holidays, from 15 May to 15 June (Labels provide a time reference).

With this regard, special attention was given to the identification of strong wind events and their influence on the vibrational response of these structural elements. By analysing abnormal RMS values in the map presented in Figure 19, which refers to vibrations in the lateral direction, several events were identified as originating from wind loads. Specifically, on 22 May, between approximately 12:00 and 18:00, a period of very high and continuous cable vibrations was observed. This behaviour was attributed to wind effects, as traffic loads would not be capable of inducing such high dynamic responses in these elements.

To confirm this hypothesis, a complementary analysis was conducted focusing on that specific period, using meteorological data obtained from Windguru archives, based on measurements from local anemometric stations near the bridge. A detailed view of that time interval, including the RMS acceleration values recorded in the cable and the wind velocity data registered at the “Figueira da Foz” station, is presented in Figure 20. The cross-referenced analysis of these graphs allowed to confirm that there is a clear correlation between strong wind velocities and the vibrations in the bridge cables.

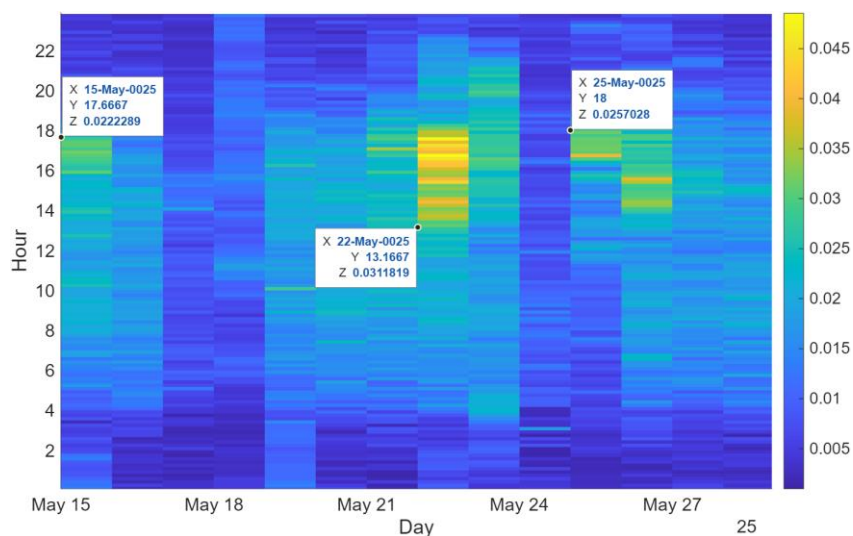


Figure 19. ACC1 RMS records in the lateral direction, from May 15 to May 29.

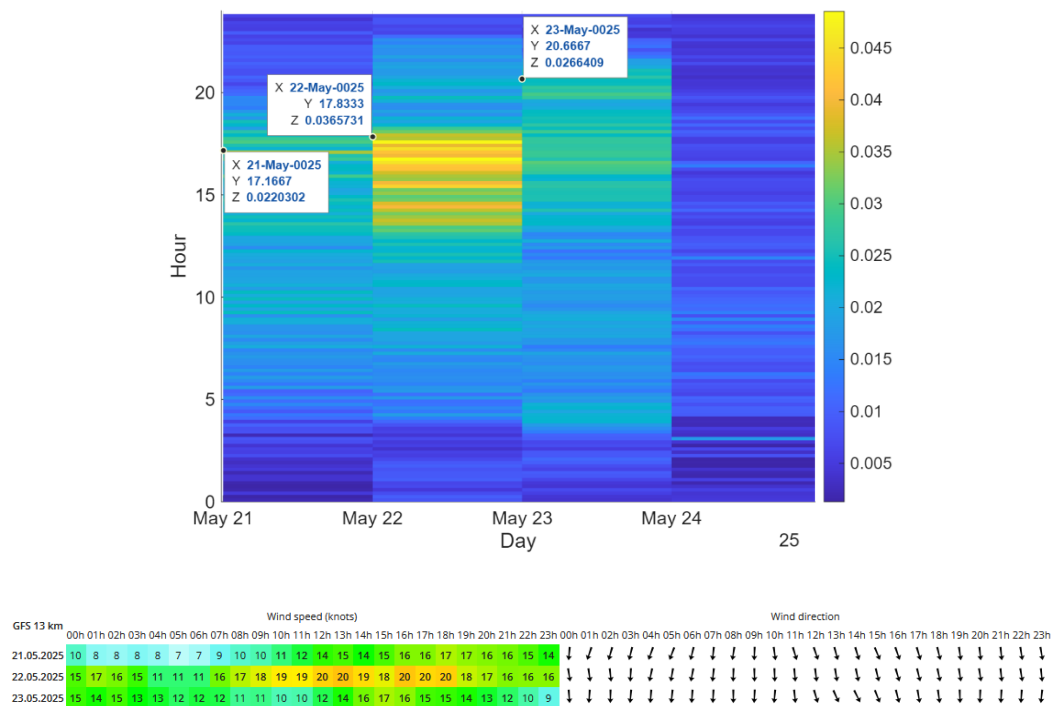
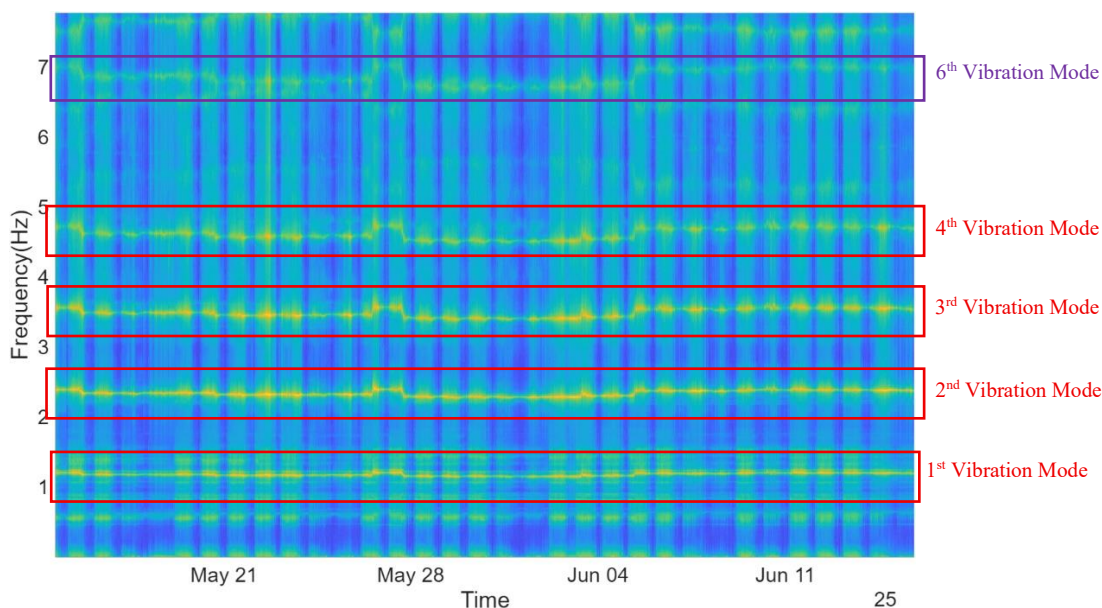


Figure 20. ACC1 RMS, 21 to 24 May and corresponding Windguru forecast data, including wind speed and wind direction (Labels provide a time reference).

5.4.2. Stay Cable Natural Frequencies

The spectral maps depicted in Figure 21, which were obtained from the Average Normalized Power Spectral Density (ANPSD) of the accelerometer signals over time considering files of 10 minutes, may be used to identify the natural frequencies of stay cable, visible as horizontal lines of higher intensity. In both measurement directions (lateral and transversal/vertical), several natural frequencies can be identified, with the fundamental frequency located close to 1.2 Hz and higher-order frequencies appearing approximately at 2.4 Hz, 3.6 Hz, 4.8 Hz, and 7 Hz. As can be observed, the natural frequencies remain relatively stable over time, with some variability due temperature variations and to construction-phase issues related to the moving platform on the deck.



(a)

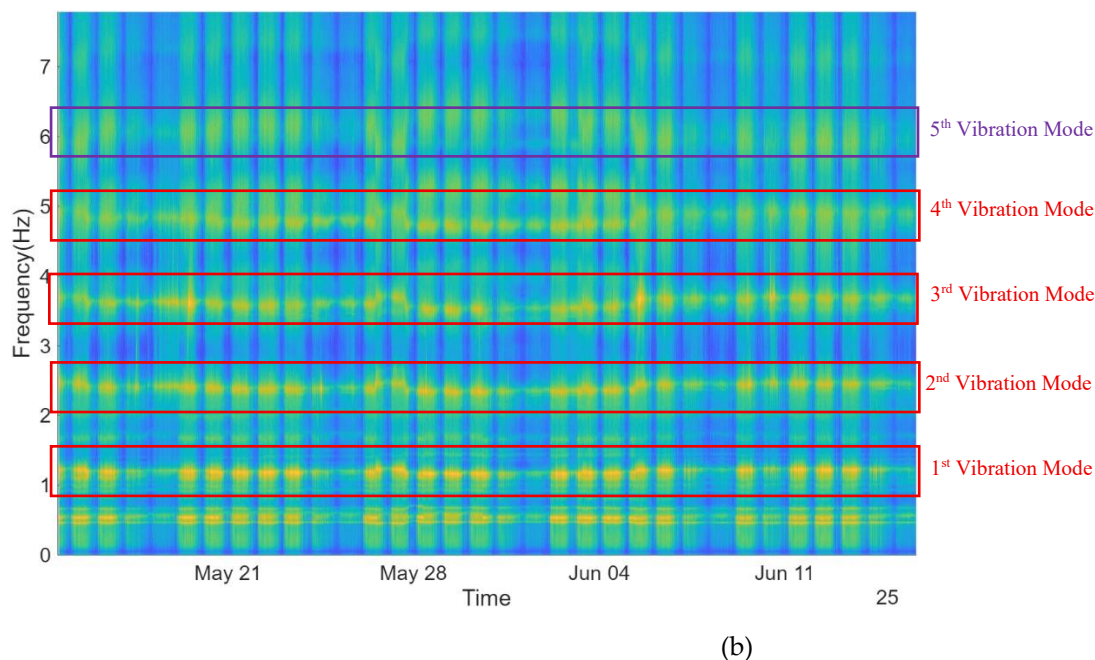


Figure 21. Spectral maps of the accelerometer ACC1: (a) Lateral direction; (b) transversal/vertical .

In fact, by detailing the maximum peak amplitude of the spectrum close to the fundamental frequency, as shown in Figure 22, it can be observed two of variability phenomena. First, the daily variability is clearly associated with temperature effects which play a significant role, since the thermal expansion or contraction of the cable and surrounding structural elements can alter its stiffness and tension, thereby changing the natural frequency. Secondly, the abrupt changes in frequency associated with the movement of work platforms on the bridge, which changes the mass distribution over the deck and, consequently, influence the dynamics of the bridge and corresponding stay cables.

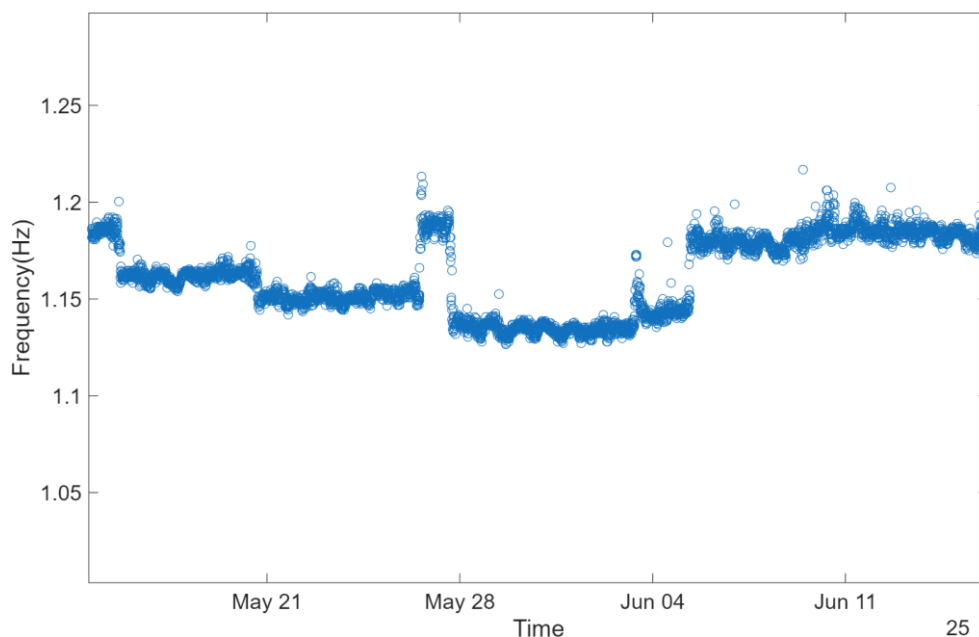


Figure 22. Natural frequency of the stay cable over time.

5.4.3. Accelerations Measured at Bridge Deck

The accelerations recorded on the bridge structure were processed following an analogous procedure applied to the accelerometer installed on the cable. As a result, the RMS values recorded by ACC2 installed in the deck clearly exhibit higher excitation during weekdays, particularly at peak traffic hours, while noticeably lower values are observed during weekends.

The spectral maps indicated in Figure 23, corresponding to both vertical and lateral directions, allows to identify several stable frequency components clearly associated with the natural frequencies of the structure. The first 3 frequencies are 0.45 Hz, 0.55 Hz and 0.7 Hz related to vertical vibrations modes, and the transverse frequency, more difficult to identify, can be estimated at 0.65 Hz approximately.

According to previous studies performed in 2020 (before the ongoing rehabilitation) those frequencies were identified at 0.50 Hz, 0.57 Hz and 0.725 Hz for vertical modes and 0.854 Hz as first transverse vibration mode [23]. At an even earlier date, in 1997, these frequencies were identified at 0.51 Hz, 0.60 Hz and 0.73 Hz, respectively, corresponding to the first 3 vertical vibration modes and 0.87 Hz to the first transverse direction mode [24]. However, taking into account that the actual measured frequencies were evaluated during the rehabilitation works where additional masses are present on the bridge (such as the sliding platform and scaffolding structures) it is expected that natural frequencies are lower in this stage compared to previous tests. For clarity, Table 3 summarizes the first natural frequencies evaluated over time.

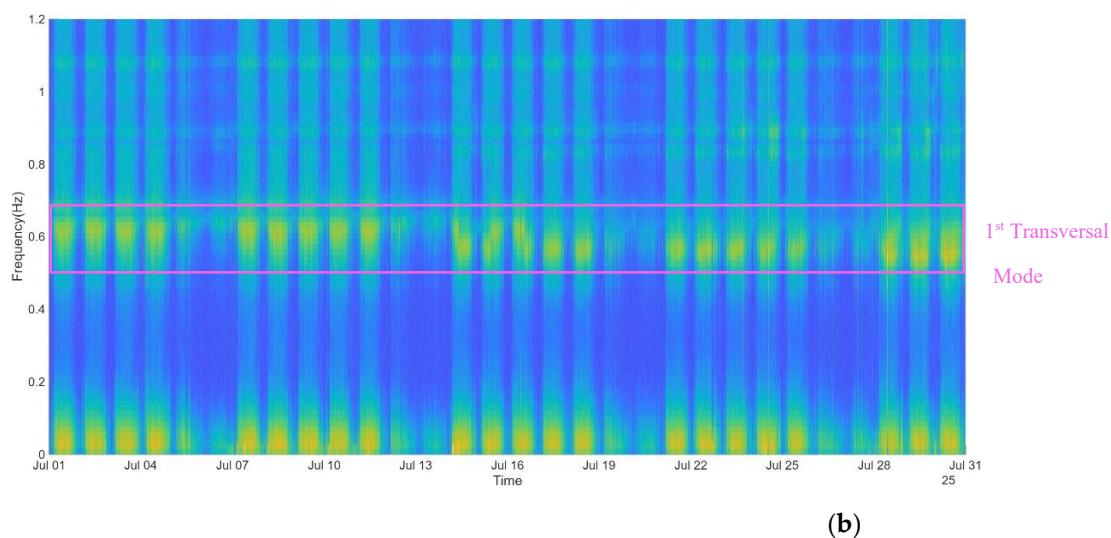
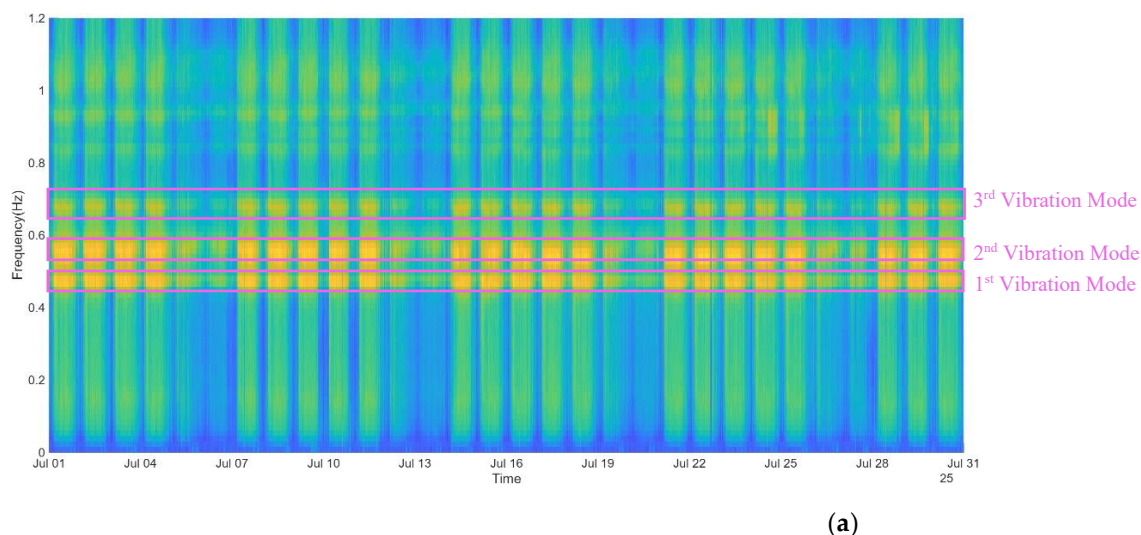


Figure 23. Time–frequency representation (ANPSD) of the bridge deck in two directions: (a) vertical direction and (b) lateral direction.

Table 3. Bridge deck natural frequencies identified over time.

	Vertical vibration modes			Transversal vibration mode
	1st mode	2nd mode	3rd mode	1st mode
2025	0.45 Hz	0.55 Hz	0.70 Hz	0.65 Hz
2020	0.50 Hz	0.57 Hz	0.725 Hz	0.854 Hz
1997	0.51 Hz	0.60 Hz	0.73 Hz	0.87 Hz

5.5. Measurement of Displacements

5.5.1. Rotation of the Hinged Deck Joint

The measurements at the hinged deck joint enabled the analysis of the relative rotation at that section, as the hinge was located directly beneath the sensor, allowing the recorded data to be effectively converted into rotational motion. However, the data collected by these sensors presents significant limitations, which lies in the fact that the sensor was installed in an area subject to frequent maintenance interventions, leading to compromise the reliability and continuity of the measurements. For this reason, the signals from this sensor were not analyzed in this work.

5.5.2. Displacements at the Expansion Joint

For different reasons related to the installation issues, the displacement located at the expansion joint only measured for a dozen of days. However, it was still possible to extract significant information from it. In fact, similarly to what was observed in the accelerometers, RMS amplitudes are substantially higher during weekdays, while they decrease significantly during weekends and public holidays within the monitoring period (see Figure 24). It is worth mentioning that the RMS values refer to the dynamic component of the signal after it has been detrended.

During weekdays, the RMS response often reaches values above 0.3mm, with peaks approaching 0.45mm. These high levels are strongly correlated with increased traffic flow and the presence of heavy vehicles crossing the bridge. During weekdays, the higher number of vehicles, as well the higher displacements of the expansion joint caused by more traffic loads on the bridge results in higher RMS values. In contrast, weekends (highlighted in red) show significantly lower RMS levels, mainly concentrated below 0.1mm. This reduction reflects the considerable decrease in traffic demand during these periods, when light and heavy vehicle traffic is substantially reduced. Consequently, the structural displacements induced in the expansion joint are minimal, leading to low RMS values.

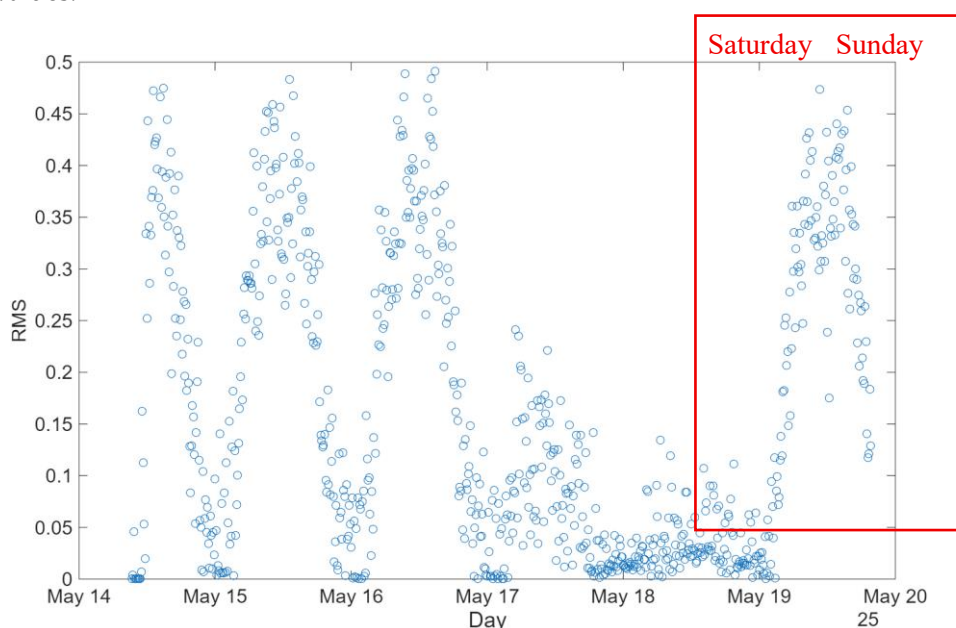


Figure 24. Weekly measurements: differences between weekdays and weekends.

5.6. Correlations of Multi-Sensor Data

5.6.1. Influence of Temperature on Expansion Joint Movement

The displacement observed in the expansion joint of the bridge is directly influenced by temperature variations in the structure. Both steel and concrete structural elements undergo thermal expansion and contraction when subjected to temperature changes. Although their coefficients of thermal expansion are similar (in the order of $10^{-5}/^{\circ}\text{C}$), even small variations in temperature can lead to significant cumulative displacements over the total length of the bridge.

Figure 25 illustrates the cyclical behaviour of temperature and the corresponding joint movement. Progressive contraction is observed during the night, while expansion occurs during the day. Moreover, periods of thermal stability correspond to relatively steady displacement values, while rapid temperature changes are directly reflected in abrupt displacement shifts.

Overall, the data underscores the critical role of temperature-induced movements in joint behaviour. The combination of displacement and temperature measurements provides clear evidence of the joint's expansion and contraction cycles, demonstrating how thermal dynamics govern structural responses.

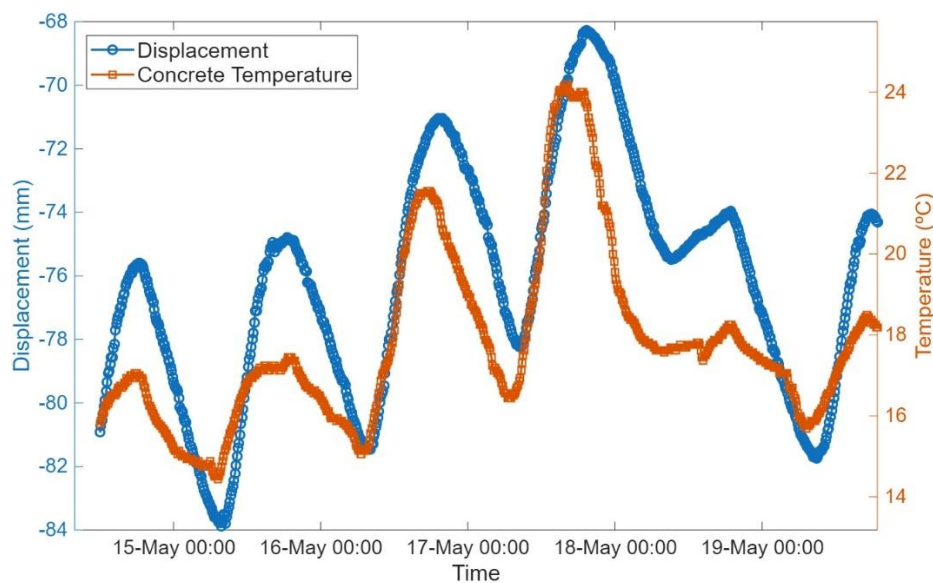


Figure 25. Displacement and concrete temperature values over time.

5.6.3. Influence of Deck Vibrations on Cable Frequency Response

In cable-stayed bridges, it is well established that the natural frequencies identified in the cables reflect not only their local vibration modes but also the global dynamic behavior of the bridge. This phenomenon occurs because the stay cables are directly connected to the deck, and therefore any vertical, lateral, or torsional vibration of the deck is transmitted through the anchorage points to the cables. As a result, the accelerometer signal often contains a superposition of both local cable modes and global structural modes. In practice, the amplitudes of the deck-induced vibrations measured on the cable are generally smaller and can be masked by the dominant cable modes. The observation of deck frequencies in measurements taken on the stay cables should be regarded as a normal and expected outcome of the dynamic coupling between these structural components.

In this case study where one cable was instrumented with an accelerometer (ACC1), several well-defined peaks can be observed, as shown in the spectra of Figure 26. The lower frequency range exhibits peaks associated with the global vibration modes of the bridge deck, while higher-frequency

peaks are primarily linked to the local vibration modes of the stay cable. The intensity of these peaks confirms that the accelerometer location is sensitive to a combination of global and local responses, thereby capturing the coupled dynamics of the system.

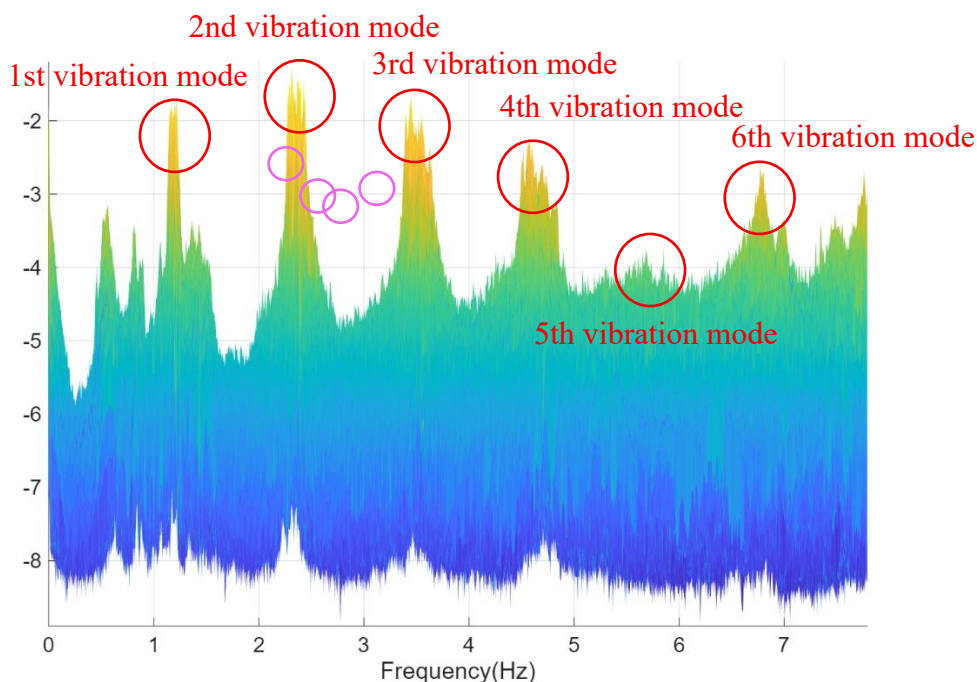


Figure 26. ANPSD obtained from the accelerometer installed in one cable.

5.7. Determination of Cable Tension Forces

Accurate determination of cable tension is critical in the analysis and design of cable-supported structures. Direct measurement of cable forces is often challenging and expensive. Alternatively, the dynamic properties of cables, such as their vibration characteristics, can be used to indirectly estimate axial forces.

The Taut String Theory provides a simplified framework for this purpose. According to this approach, a cable is idealized as a taut string with negligible bending stiffness. The natural frequencies of the cable, which can be obtained from ambient vibrations, forced vibrations, or free vibration tests, are first identified. Based on these frequencies, the axial tension in the cable can be inferred using the relationship enumerated as Eq. (1), where T is the cable tension, f_n is the n -th natural frequency of the cable, m is the cable mass per unit length, l is the cable length, and n is the mode number. This formulation assumes that the cable behaves as a perfectly flexible string, and thus the effects of sag and bending stiffness are neglected.

$$T = 4ml^2 \left(\frac{f_n}{n} \right)^2 \quad (1)$$

Accordingly, utilizing the data obtained from the description of the cables and their characteristics, summarized in Table 4, together with the frequency measurements performed on Stay-cable 6, it was possible to estimate the stresses by applying the proposed method.

Table 4. Characteristics of the cables.

Parameters	Values
Area	163.5 cm ²
m	149.37 kg/m
l	102.42 m

Considering a average natural frequency close to 1.16 Hz, the tensile force was estimated at 8433 kN and tensile stress of about 515.8 MPa, which is in line with the estimates reported in previous studies. In addition, a direct measurement of the cable force was performed after the stay-cable system substitution by Dywidag, which yielded a value of 8.575 kN, further corroborating the experimental estimations. This consistency reinforces the validity of the adopted methodology and provides confidence in the reliability of the experimental data as well as in the assumptions inherent to the taut string model.

Furthermore, considering the time evolution of the estimated natural frequency of the stay cable, as shown in Figure 22, it was possible to derive corresponding estimates of the tensile force in the cable throughout the monitoring period, which are presented in Figure 27. This methodology enables the cable tension to be continuously monitored in situ through a relatively simple procedure, without the need for more sophisticated measurement techniques.

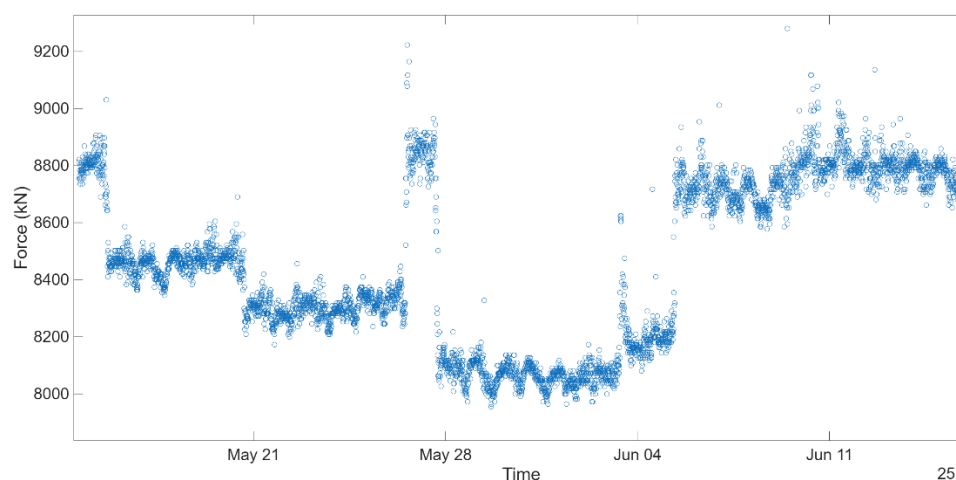


Figure 27. Scatter plot of cable force over time.

6. Conclusions

This paper describes the short-term (one-month) structural monitoring of a cable-stayed bridge undergoing rehabilitation works, using customised sensors, namely accelerometers, temperature sensors and displacement sensors and one reception station.

These sensors were strategically positioned on critical points of the bridge to capture its static and dynamic responses. The system was designed with a strong emphasis on autonomy, low energy consumption, and wireless communication, enabling remote data transmission to a reception station located off-site. In parallel, a digital platform with a database and graphical interface, which ensured the organization, processing and real-time visualization of the information collected was developed, which proved to be fundamental in increasing data accessibility and supporting the future integration of large-scale monitoring systems. The overall evaluation of the system performance is very positive, despite some sensor failures resulting from their installation in locations subject to frequent maintenance interventions, which compromised the reliability and continuity of the measurements.

The analysis of the collected signals was based on digital signal processing techniques, including filtering and spectral analysis, allowing the extraction of some modal parameters of the structure. While the accelerometer installed on a selected cable allowed the identification of the sequence of several natural frequencies of this element, the accelerometers placed on the deck consistently captured the main natural frequencies of the structure. In addition, the displacement and temperature sensors provided complementary information on thermal effects and long-term structural movements.

Based on string theory, the cable forces were estimated from the measured vibration data. The results demonstrated good agreement with the values expected from previous studies, as well as close consistency with the direct force measurements carried out by Dywidag.

Author Contributions: Investigation, C.R.; methodology, C.R. and C.M.; monitoring plan, C.R., C.M. and E.C.; development of sensors, G.M. and C.R.; edging computer, G.M.; experimental work, C.R. and C.M.; modal analysis, C.R. and C.M.; interface platform, C.R.; writing—original draft preparation, C.R.; writing—review and editing, C.R.; supervision: C.M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Receptor File Type description.

Device	Parameter	Time Delay [s]
DSP1	Battery voltage [$V \times 10^2$]	15
	Average Value [$mm \times 10^2$]	
	RMS of the measurements [$mm \times 10^2$]	
	Maximum Relative Value [$mm \times 10^2$]	
	Minimum Relative value [$mm \times 10^2$]	
DSP2	Battery voltage [$V \times 10^2$]	30
	Average Value [$mm \times 10^2$]	
	RMS of the measurements [$mm \times 10^2$]	
	Maximum Relative Value [$mm \times 10^2$]	
	Minimum Relative value [$mm \times 10^2$]	
T1 E T2	Battery voltage [$V \times 10^2$]	45
	Temperature 1 [$^{\circ}C \times 10^2$]	
	Temperature 2 [$^{\circ}C \times 10^2$]	
ACC2	Battery voltage [$V \times 10^2$]	60
	Box Temperature [$^{\circ}C \times 10^2$]	
	Apx [$m/s^2 \times 1000$]	
	Apy [$m/s^2 \times 1000$]	
	Apz [$m/s^2 \times 1000$]	
	Armsx [m/s^2]	
	Armsy [m/s^2]	
	Armsz [m/s^2]	
ACC3	Battery voltage [$V \times 10^2$]	75
	Box Temperature [$^{\circ}C \times 10^2$]	
	Apx [$m/s^2 \times 1000$]	
	Apy [$m/s^2 \times 1000$]	
	Apz [$m/s^2 \times 1000$]	
	Armsx [m/s^2]	
	Armsy [m/s^2]	
	Armsz [m/s^2]	

Device	Parameter	Time Delay [s]
ACC1	Battery voltage [$V \times 10^2$]	90
	Box Temperature [$^{\circ}C \times 10^2$]	
	Apx [$m/s^2 \times 1000$]	
	Apy [$m/s^2 \times 1000$]	
	Apz [$m/s^2 \times 1000$]	
	Armsx [m/s^2]	
	Armsy [m/s^2]	
	Armsz [m/s^2]	
	Frequency band 1 (1.85–2.15 Hz) [$Hz \times 10^3$]	
	Frequency band 2 (2.15–2.45 Hz) [$Hz \times 10^3$]	
	Frequency band 3 (2.45–2.75 Hz) [$Hz \times 10^3$]	
	Frequency band 4 (2.75–3.05 Hz) [$Hz \times 10^3$]	
	Frequency band 5 (3.05–3.35 Hz) [$Hz \times 10^3$]	
	Frequency band 6 (3.35–3.65 Hz) [$Hz \times 10^3$]	
	Frequency band 7 (3.65–3.95 Hz) [$Hz \times 10^3$]	
	Frequency band 8 (3.95–4.25 Hz) [$Hz \times 10^3$]	
	Frequency band 9 (4.25–4.55 Hz) [$Hz \times 10^3$]	

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