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# ANALYSIS OF THE TEMPERATURE EFFECTS ON A LONG-SPAN REINFORCED CONCRETE ARCH BRIDGE MEASURED BY A MONITORING SYSTEM

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**Abstract**. This paper describes the research work involving the temperature analysis on a long-span reinforced concrete arch bridge located at Porto, taking advantage on the experimental data acquired by a customized monitoring system, which is composed of accelerometers, temperature sensors and displacement sensors on expansion joints. The measurement campaigns were organized in two phases. In a first stage, only 4 temperature sensors were installed at the bridge deck, which were updated to more 4 units installed in the arch on a second stage of instrumentation. In this paper, the instrumentation plan is detailed and the customized sensors are described. The temperature signals on the deck, as well as the displacements at one expansion joint are characterized. It was concluded that the temperature data may be used to produce approximate estimates of the displacements at the expansion by means of linear correlations between these variables.

**Key words**: Structural Health Monitoring (SHM), temperature effects on structures, arch bridges, customized sensors.

## 1 INTRODUCTION

Temperature is an external action that may affect significantly the structural behaviour of structures, particularly large structures, as it is the case of long-span bridges [1]. The displacements imposed by this action may originate high amplitude internal forces, leading to a significant increase in internal stresses and excessive cracking of reinforced concrete elements. It also may damage elements subject to cyclic movement such as expansion joints. Therefore, the experimental monitoring of these large structures is a very useful tool that can be used to identify structural damage and enable its subsequent repair or reinforcement [5].


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However, structural monitoring generally demands sophisticated and expensive monitoring systems which prevents its widespread use [2].

In this context, this paper describes the research work where temperature effects in a long-span bridge is observed recurring to customized sensors, aiming at using an instrumentation solution at an attractive cost, while being reliable and robust.

The structure under analysis is Arrábida bridge located at Porto (see Figure 1). This outstanding concrete arch bridge was built in 1963, and in the year of its construction it had the world record for the span of a structure of this type. However, because this bridge is located close to the sea, it is exposed to a relatively aggressive environment, causing the structure to often present construction pathologies, mainly the detachment of concrete and subsequent exposure of the reinforcements. In 2003, the bridge underwent inspection and repair works that included structural rehabilitation in reinforced concrete elements that were degraded, repairs on the deck and replacement of expansion joints [3]. Nevertheless, at the present time, in 2023, this structure is again presenting a considerable degradation in some sections, with its rehabilitation planned in the short term. This fact led the R&D unit CONSTRUCT to establish a protocol with the Infrastructures of Portugal (IP- owner of the bridge) aiming the structural monitoring of the bridge by using a new generation of data acquisition systems.

**Figure 1**: Arrábida bridge located at Porto.

## 2 INSTRUMENTTION PLAN

### 2.1 Location and implementation of the sensors

Aiming at the continuous characterization the dynamic properties of Arrábida bridge, 4 accelerometer modules were installed at the north side at the deck level, as indicated in Figure 2. These devices are named as 2M, 4M, 6M and 16J. The accelerometers with code ending in "M" were placed on the upstream side, while the ones ending in "J" were installed on downstream side. This configuration was chosen in order to capture the dynamics of the first vibration modes of the structure. Sensors 4M and 16J were positioned at the same point in the elevation view, but on opposite sides of the deck, enabling a better identification of the torsion vibration modes [7].

On the other hand, the installation of temperature sensors was divided in the two phases, being 4 of them initially positioned in transversal structural beams bellow the deck of the bridge. In this case, two of them were located at the north joint (T1M, T2J) and the other two near to the mid span of the bridge (T3M, T4J). In a second phase, 4 additional temperature sensors were installed in the upper side of the arch as it follows: three of them in the upstream side (T5M, T7M and T8M) and one of them in downstream side (T6J), as shown in Figure 3.

Finally, the displacement sensors were both initially installed in the north expansion joint of the bridge, one in upstream side and the other downstream side aiming at identifying possible lateral movement of the deck. However, because this movement was not observed, in a second stage one of the displacement sensors was moved to north expansion joint, as indicated in Figure 4.

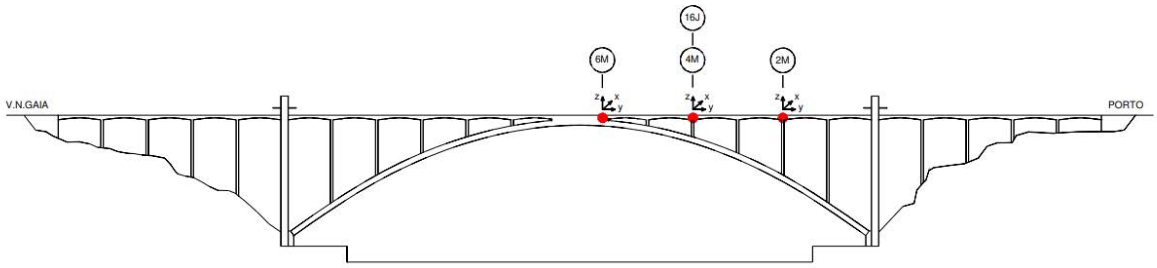


**Figure 2**: Location of the accelerometers.

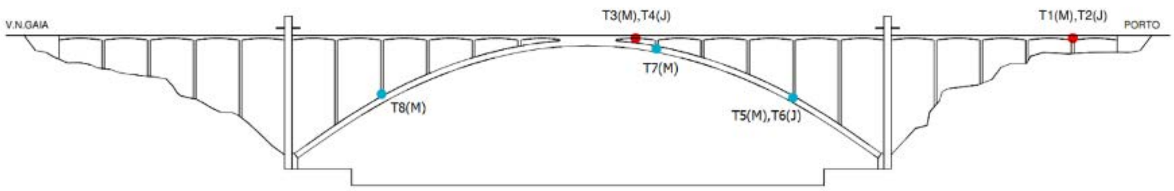


**Figure 3**: Location of the temperature sensors.

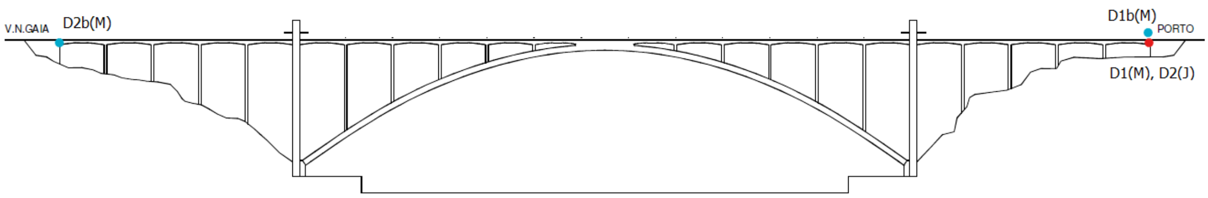


**Figure 4**: Final location displacement sensors at expansion joints.

## 2.2 Description of the customized sensors

The accelerometers modules are composed of an Arduino-based microcontroller that commands the entire process of data acquisition. The adopted accelerometer is the ADXL355 from Analog Devices Company. This digital tri-axis accelerometer presents some interesting features like the low-noise and the 20-bit Analog-to-Digital resolution. It has programmable sampling rate and programmable band-pass digital filters. In this application, the sampling rate was set to 62.5 Hz, and the low and high cutoff frequencies of the band-pass filter were fixed at 0.0024 Hz and 15.625 Hz, respectively, allowing the characterization of a significant number of the first natural frequencies of the bridge.

The data collected by the accelerometer's modules are saved locally on a microSD card. The 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. No wireless data transmission is available, allowing saving batteries and guaranteeing high autonomy of the device. The model used in this bridge accommodates 5 lithium batteries of 18650 type, allowing for an autonomy of 3.3 months. The synchronization of the acquired signals between the different accelerometer modules is guaranteed through the use of GPS. Figure 5a and 5b shows some photos of the accelerometer module installed in the bridge.

The temperature sensors are of DS18B20 type. These digital sensors measure temperatures from -55°C to +125°C, having a resolution of 0.125°C and an accuracy of ±0.5°C from -10°C to +85°C, which is adequate for general applications in structural monitoring. In this application, these sensors were inserted 15 cm inside the concrete sections and then wired to the data acquisition system installed inside a polycarbonate box. The temperature readings are taken with a periodicity of 10 minutes, being the data saved locally in a microSD card. No wireless data transmission is available. Because the system is practically all the time in sleep mode, only 3 batteries of 18650 type guarantee an autonomy of at least 1 year of measurements. Figure 6a and 6b shows a photo of the temperature sensor inside a stainless-steel capsule, as well as a photo of one instrumented section.

On the other hand, the displacement sensors used to measure the static and dynamic movements of the expansion joints are of capacitive type and work inside a stainless-steel cylinder enclosure fixed at one side of the joint. It has a shaft that must be connected to the other side of the joint to measure the relative displacement between the two points. Inside the cylinder it is installed all the electronics of the data acquisition system, as well as 4 batteries type 18650 for powering the system which may work in two different selectable modes, namely static mode and dynamic mode. The static mode is directed to measure static or slow movements of the joints, taking one measurement every 10 minutes. This way it is possible to keep the system working for long periods without battery replacement (typically more than 1 year). On the other hand, dynamic mode uses a sampling frequency of 5 Hz, which allows measuring dynamic components of the joint movements. However, in this case the autonomy is limited to 3 months of operation with the use of 4 batteries. So far, only the dynamic mode has been used in Arrábida bridge. One of the significant features of this sensor relies in its ability to take measurements with 0.01 mm precision in a range from 0 to 2 meters. 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, which was adopted in this case. Figure 7a and 7b shows two photos of the displacement sensor installed in this structure. As can be seen, after installing the sensor, mechanical and visual protection is used to prevent or minimize acts of vandalism, as the sensors are accessible from the deck.

a) 

b) 

**Figure 5**: Accelerometer modules: a) view inside the module; b) view on the bridge

a) 

b) 

**Figure 6**: Temperature sensors: a) view inside the module; b) view on the bridge.

a) 

b) 

**Figure 7**: Displacement sensor at expansion joint: a) view of the cylinder enclosure; b) external protection.

## 3 ANALYSIS OF TEMPERATURE EFFECTS

### 3.1 Characterization of temperature measurements

In this paper, only the data from the first phase of measurements is analysed. In this case, the temperature records were taken in the deck sections by sensors T1 to T4. Figure 8 depicts the annual temperature variation recorded by these sensors from August 2021 to August 2022. It can be observed higher temperatures in summer season, followed by a decrease of temperatures in winter season. In the considered period, the temperature varied approximately between 7ºC and 31ºC.

The temperature signals can be separated in three different components: daily variations, trend variations and annual variations. The daily and annual variations are easy to visualize in Figure 8. However, the temperature signals are also marked by a trend component that depends on some daily fluctuation of more or less warm or cold days. It was concluded that, to model numerically the temperature variations it is necessary to separate the trend component and the daily component, being the annual variation coupled to the trend component. This may be done by applying adequate lowpass or highpass filters to the temperature signals. Figure 9 represents the effect of applying a lowpass filter to temperature measured by sensor T1, by filtering frequencies higher or equal to the daily frequency. This way, the trend component of the temperature may be clearly seen. By applying a highpass filter to the same signal, with the cut-off frequency below the daily frequency, the trend component is filtered, and the signal remains with only the daily component, as seen in Figure 10. In this case, the daily component represents the residual of the temperature signal when extracting the trend component.

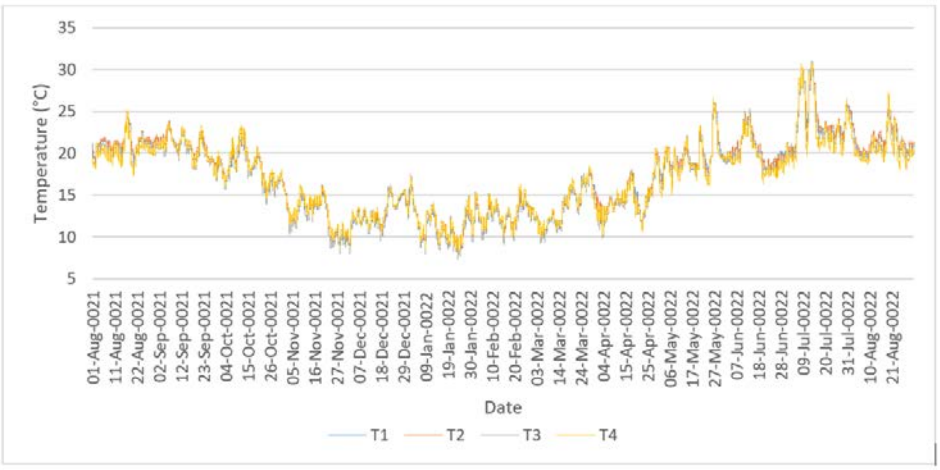


**Figure 8**: Temperature records from August 2021 to August 2022 measured by sensors T1, T2, T3 and T4.

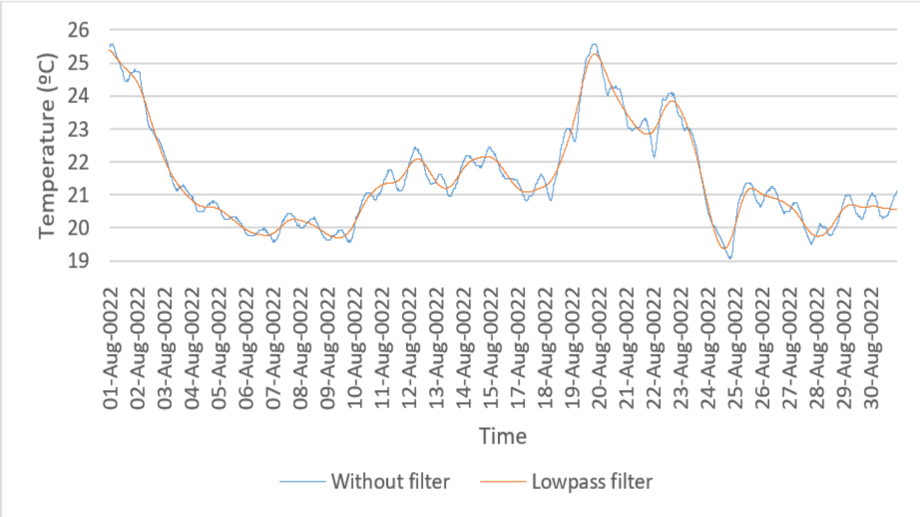


**Figure 9**: Temperature variation of sensor T1 during August/2022: obtaining the trend component by applying a lowpass filter.

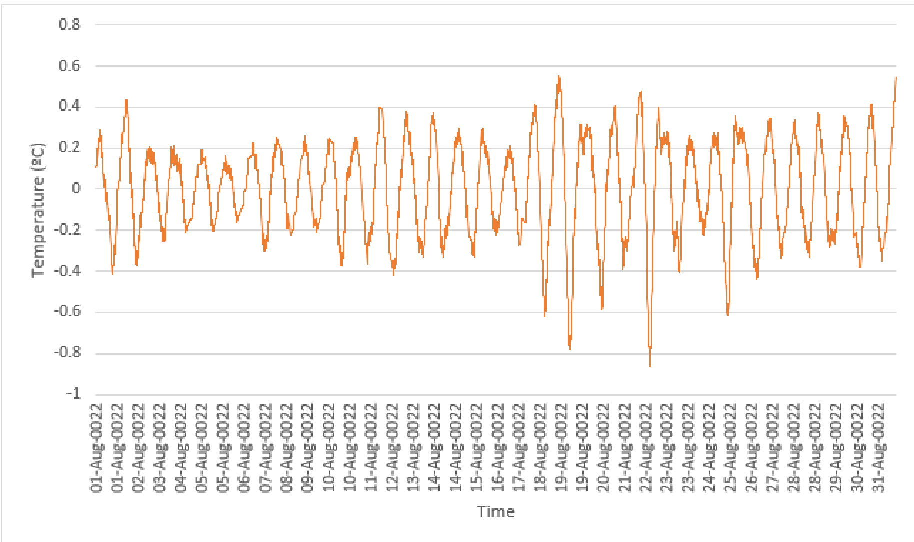


**Figure 10**: Temperature variation of sensor T1 during August/2022: obtaining the daily component by applying a highpass filter.

## 3.2 Displacement sensors at expansion joints

In Figure 11, the annual results of relative displacement at upstream and downstream sides of the north expansion joint are shown (D1-M and D2-J). During the periods from November 6th 2021 to November 9th 2021 and December 27th 2021 to January 11th 2022, there was a lack of data in both sensors due to a delay in the battery replacement, leading to a battery failure of the system in that periods. It can be seen that displacements vary approximately from -13mm to 31mm. It's worth mention that the zero displacement is stipulated as an initial reference value from which relative displacements were measured.

The analysis of this records permits to verify the trend behaviour of expansion of the bridge for positive displacements during the summer season, characterized by higher temperatures. During winter season the trend is in negative direction, corresponding to a retraction of the deck. As in temperature sensors, the displacement in the expansion joints can also be divided in different components. However, in this case, beyond the daily, trend and annual components, it can be also observed a dynamic component that is only observed in an amplified scale [4], which will be not analysed in this paper.

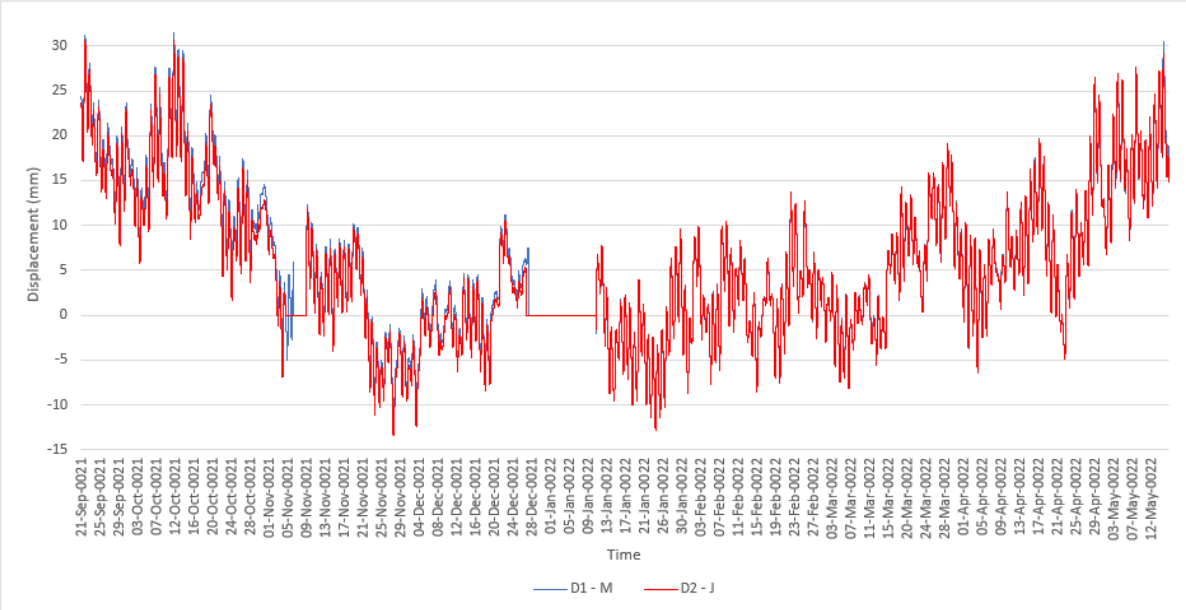


**Figure 11**: Displacement variations in the north joint during Sep/2021 to May/2022 (sensors D1-M and D2-J).

### 3.3 Correlation between temperature and displacement at expansion joints

Taking into account the temperature and the displacements in the expansion joints described before, a mathematical correlation between these variables was sought. For this purpose, daily components and trend components were correlated separately. Regarding daily components, firstly the temperature signals were aligned in time with the displacement signals by removing a delay of 2.5 hours between them. Then, the temperature versus displacement chart was plotted and a linear correlation line was obtained, as shown in Figure 12.

Regarding the trend component of temperature and displacement, the corresponding time signal alignment is not necessary as they have the same phase shift. Therefore, in Figure 13 the temperature versus displacement chart is plotted and the linear correlation was found.

Even both correlation factors R are not very close to unity (although correlation factor in the case of the trend components is higher than in the case of the daily components), it should be possible to take advantage of these correlations in order to estimate joint displacements from temperature measurements and vice-versa [6].

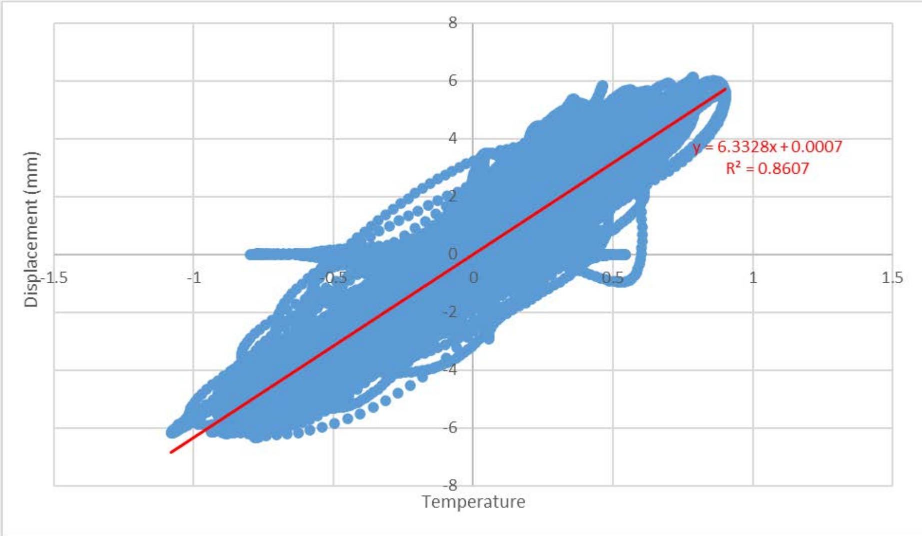


**Figure 12**: Temperature versus displacement chart – daily components (Sep/2021 to May/2022).

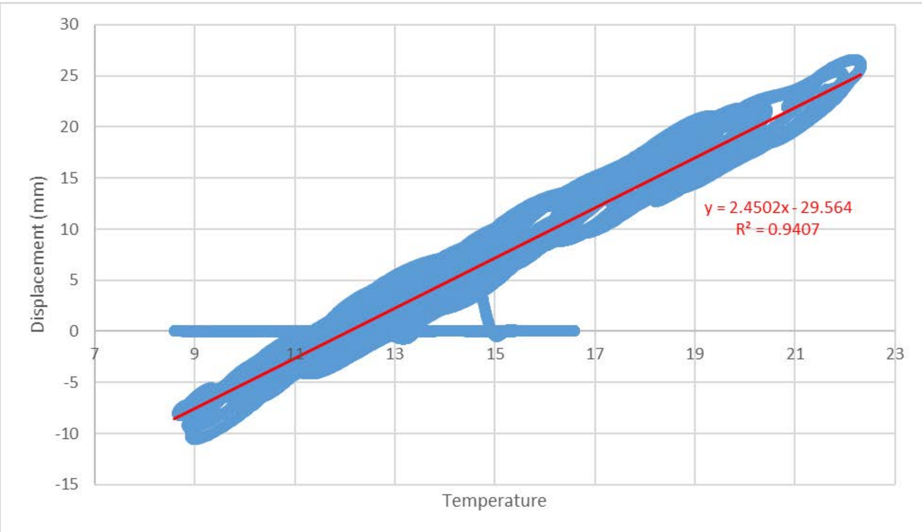


**Figure 13**: Temperature versus displacement chart – trend components (Sep/2021 to May/2022).

Knowing that the total values of both variables may be obtained by summing the respective trend and daily components, the estimate of the total displacement in the expansion joints, according to the obtained numerical correlations, may be estimated as:

$$D = 6.3328 \cdot T_{DC} + 0.0007 + 2.4502 \cdot T_{TC} - 29.564$$

$$D = 6.3328 \cdot T_{DC} + 2.4502 \cdot T_{TC} - 29.563$$

Where:

$D$ is the estimated total displacement
$T_{DC}$ is the daily component of the measured temperature
$T_{TC}$ is the trend component of the measured temperature

As a result, Figure 14 shows a comparison between the measured displacement at the north expansion joint (D_measured) and the estimated displacement (D_estimated) using the temperature measurements. Despite the previous comments related to correlation factors, the approximation between the two curves is very good. This means that by measuring the temperature in appropriate sections of the bridge it will be possible to estimate with good precision the displacements in critical sections of the structure.

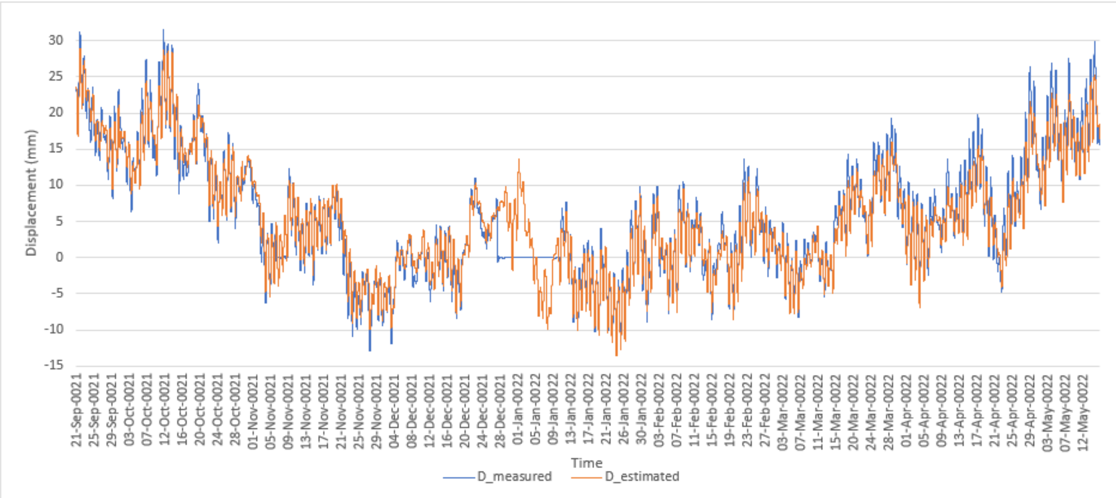


**Figure 14**: Displacement curves (obtained and estimated values during Sep/2021 to May/2022).

## 4 CONCLUSIONS

This paper describes the structural monitoring of a large-span arch bridge recurring to customized sensors, namely, accelerometers, temperature sensors and displacement sensors. It was noted that experimental monitoring of large structures is a very useful tool that can be used to identify structural damage and enable its subsequent repair or reinforcement. However, structural monitoring generally demands sophisticated and expensive monitoring systems which prevents its widespread use.

To overcome this difficulty, new sensors based on accessible technologies may be used for this purpose, as they have several advantages over traditional solutions, particularly related to their direct and installation low costs, greater flexibility, high autonomy, lower maintenance and facilitated equipment replacement or repair.

In the described case study, the temperature signals on the deck, as well as the displacements at one expansion joint of Arrábida bridge were characterized. Taking into account the estimated linear correlations between these variables, it was concluded that by only measuring the temperature of the concrete in some deck sections, it is possible to estimate with good accuracy the movements on the expansion joints.

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## REFERENCES

[1] Félix, C.; Rodrigues, C.; Faria, R.; Figueiras, J.; Afonso, L.; Barata, V. "Design and implementation of the structural monitoring system for the Corgo Viaduct". Encontro Nacional Betão Estrutural, 2012.

[2] Moutinho, C.; Cunha, A. "Contribution to new solutions of instrumentation of Civil structures for continuous dynamic monitoring". IX ECCOMAS Thematic Conference on Smart Structures and Materials (SMART 2019), Paris, France, 2019.

[3] Appleton, J., et al. "Inspecção e Reabilitação da Ponte da Arrábida". JPPE – Jornadas Portuguesas de Engenharia de Estruturas, LNEC, Lisboa, 1998.

[4] Ietka, I. "Evaluation of the structural behavior of arch bridges using a new generation of sensors", Research thesis project, FEUP, 2022.

[5] Cunha, A.; Caetano, E.; Magalhaes, F. & Moutinho, C. "Dynamic identification and continuous dynamic monitoring of bridges: different applications along bridges life-cycle". Structures and Infrastructures Engineering, Vol.14, Issue 4, pp.445-467, 2017.

[6] Jonson, R. A., & Wichern, D. W. "Applied Multivariate Statistical Analysis". 6th ed. 2007.

[7] Magalhães F, Cunha A. "Explaining operational modal analysis with data from an arch bridge". Mechanical Systems and Signal Processing. 25(5):1431–50. 2011.