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Short communication

Long-term monitoring of a damaged historic structure using a wireless sensor network

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ABSTRACT

Recent advances on sensing and data communication systems have allowed the optimization of the structural health monitoring systems, as well their employment for long-distance remote monitoring of civil structures. Moreover, structural health monitoring techniques can be particularly interesting for heritage constructions assessment, because they allow a real-time analysis of the structural properties, and the collected data can be used as support of safety maintenance. This work describes the strategies employed for structural health monitoring of a damaged historic structure from the XVI century, namely the Foz Côa Church (in Portugal), beside the results of 1-year monitoring of the displacements observed on the structural elements of the church. Additionally, the influence of the temperature and relative humidity were studied. Removing the environmental influences from the observed displacements in the structural elements allowed to conclude that these are not motived by the damage progression, instead they are related with influence of environmental parameters.

1. Introduction

Recent advances on the field of sensorial systems and wireless communications, as well their implementation on cost reduction, have contributed significantly to dissemination and employment of Structural Health Monitoring (SHM) in support of the structural characterization and safety assessment [1,2]. In fact, sensing systems with embedded microprocessors and wireless communication represent a deep change on a way that structures are assessed, monitored and controlled [3], taking into account that these techniques allow the remote access in real time to the parameters monitored. In the last two decades, a considerable high number of cases of SHM employment on different civil structures typologies (i.e. bridges, towers and buildings) is described in the literature [4,5], overcoming several technical issues, while a few cases of SHM of Heritage Constructions (HC) have been reported [6].

In fact, historical structures constitute an interesting challenge for development of SHM due to variability and complexity of their structural components, which demand for advances in the monitoring strategies, as well in the data processing approaches. Additionally, for an assertive and reliable assessment of the HC, the data offered by SHM, that generally is focused in specifics components of the constructions, need to be discussed with information on the current state and global behavior of the structure under service operation. Moreover, it is important to highlight that all strategies employed for characterization and assessment should be conducted with respect to historic value of the construction and without inducing new damage emergence, as stated by [7]. Recent developments on the SHM field, related with HC, reported in the literature will be summarized and discussed following.

In [8], the Torre Aquila, a medieval tower with valuable artworks, was instrumented with accelerometers, relative displacements, via temperature and relative humidity sensors. The sensors were connected to the data acquisition system that sends the collected Basically, the SHM was focused on providing information on the vibration and displacements of the tower, as well of the environmental effects on the measurements. The work also demonstrates how the collected information can be used to predict anomalous situations of the behavior of the tower under service.

According to [9], the walls' inclination of a historic wooden church undergoing rehabilitation was monitored through a simplified wireless sensor network, and even with the low sensitivity of the sensorial modes, they were able to identify long-term trends in the tilt of the church walls. In [10], a sensorial system composed by 19 fiber optical displacement sensors and 5 temperature sensors was employed for monitoring of the damages on Santa Casa de Misericordia de Aveiro, and the collected data was used for updating a finite element model for to assess the damage state of the church.

Following, the long-term dynamic monitoring of the Basilica S.

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Maria di Collemaggio was reported by [11], where the authors describe the strategies of sensor network design and data processing, focused on seismic assessment. The SHM was focused on the management of the structural safety for situations where the structure can be subjected to natural disasters, such as earthquakes. The dynamic characterization of the church was carried-out, and the data was used in computational simulations. Furthermore, the data acquisition systems were composed by accelerometers connected wirelessly to a signal processing station. The results allowed the clear detection of the interaction between the masonry structures with an existing protective installation, and the modal information identified from different excitation sources (i.e. release tests, seismic events, etc.) was used for updating a finite element model on the church. Further reading on this case study can be found in [12] and [13].

Even that dynamic monitoring of HC constitutes a relevant topic for safety assessment [14,15], studies establishing a link between the environmental effect with structural behavior are also particularly interesting because they can provide useful information to understand cyclic displacements behavior in stony masonry elements and its damage mechanisms. According to [16], in heterogeneous materials, as stone masonries with low tensile strength capacity, the actuation of small tensions can easily make emerge cracks, mostly first appearing on the connection zones. Even thermal effects can produce sufficient tension to produce a crack, due to the different thermic behavior of the stone and the mortar. Moreover, in historic structures, several thermal cycles over the time can develop plastic deformation on the structural components, cracks and its progression.

The present work contributes for the SHM implementation through the strategy description, and monitoring of the Foz Côa Church (Portugal). Moreover, this work reports the monitoring period between March 13th 2015 to March 29th 2016 and discuss the relative displacements and tilt records in some structural elements of the church, as well analyses the environmental influence on the displacements collected by the wireless sensor network.

2. The Vila Nova de Foz Côa Church

The Foz Côa Church (Fig. 1) is a stone masonry building from XVI century, located at Vila Nova de Foz Côa, 390 km North from Lisbon, Portugal. The Church presents a *Manuelino* architectural style, with regular geometry, composed by three naves which are separated by columns and arches. It's dimensions are 37.00 m of length and 16.00 m of width, with a maximum height at the main façade of 13.30 m.

Fig. 2. Photograph of column 2, evidencing its inclination.

The main façade is characterized by an exposed granitic stone masonry (Fig. 1a) where the arch on the main door is decorated with *Manuelino* marks and there are three bells on the top. At the interior side of the church, two plans of columns and arch represent the division between the main nave with the left and right naves. Fig. 1c shows the interior view of the Church.

The church presents some damages, essentially cracks and deformation along the structural elements. The walls and columns on the right side are significantly deformed, especially the columns, as can be observed in the details in Fig. 2, whereas some vertical cracks on the main façade can be observed, as demonstrated in Fig. 3. Fundamentally, the main deformations and cracks are related with two seismic occurrences, namely the earthquakes of 1755 and 1969, being the first one related with the deformation of the structural elements inside of the church, specifically on columns and arches, while the last seismic occurrence has been pointed as the responsible by the emergence of cracks in the main façade (Fig. 3).

Over the years, several inspections and interventions were carried out in order to minimize the damage progression, such as the one

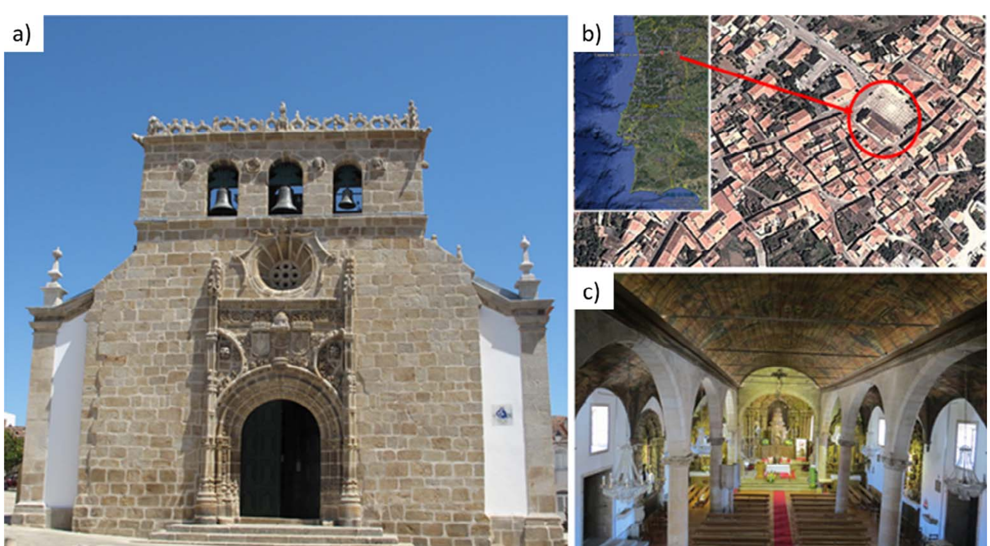

Fig. 1. Foz Côa Church: (a) main façade, (b) geographic location, and (c) interior view of the Foz Côa Church.

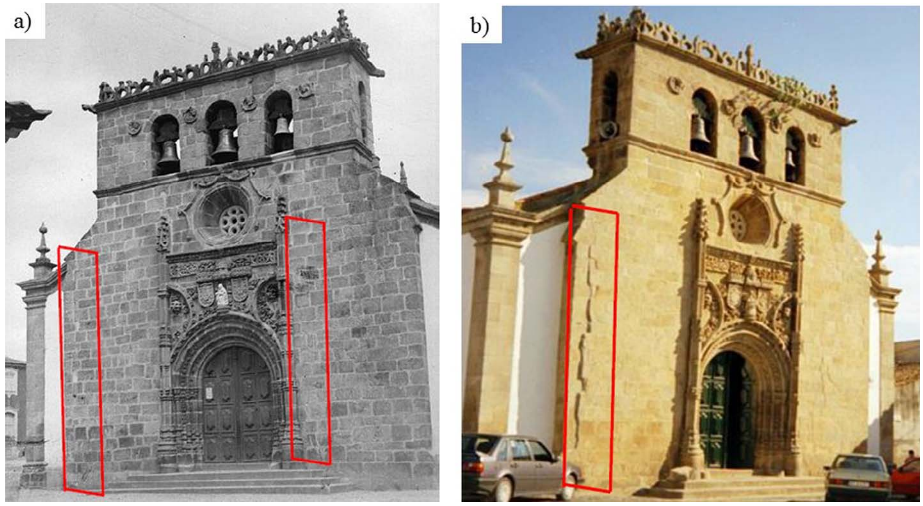

Fig. 3. Main façade of the Foz Côa Church in 1960, undamaged [17](a), and in 1996 with damages (b).

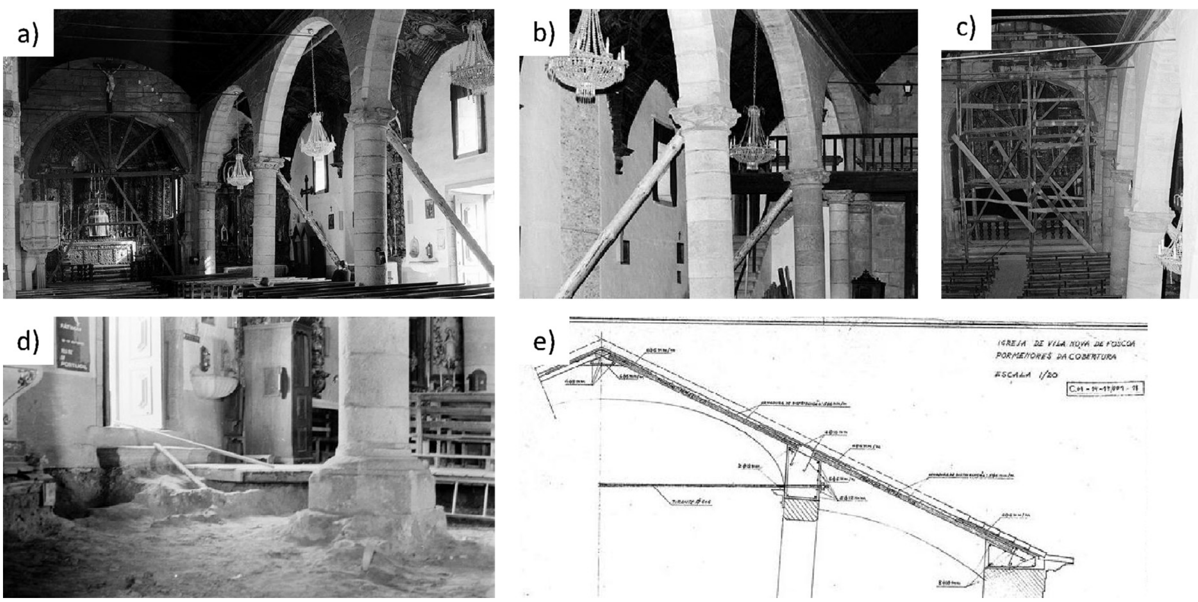

Fig. 4. Main interventions carried out on Foz Côa Church in the 1970s: (a) bracing of the Main Arch and columns, (b) details of the columns bracing and (c) details of the main arch bracing; (d) inspection performed on foundations elements and (e) detail of project of the reinforced concrete roof slab built during the retrofitting measure [17].

performed in the 1970s, characterized essentially through bracing of the columns on the right and left naves (Fig. 4a and b) and main arch (Fig. 4c). Additionally, an inspection on the foundations elements was carried out (Fig. 4d) in order of to investigate the soil properties and its influence on damages progression. The experimental investigation concluded that the soil presented good characteristics without settlement risk. The retrofitting process included the arches and columns stabilization through the construction of a pre-stressed concrete slab, shown in Fig. 4e. After that, the relative displacements and column deformation were reduced, and the cracks emergence minimized, a fundamental measure for keeping the structural safety of the Church. However, new cracks have been observed in the arches and in the columns and the absence of periodic registers on relative displacements of the columns makes difficult to assess if the damages emergence are related with temperature effect or with structural problems.

Nonetheless, even a retrofitted construction need to be periodically assessed to identify the damage progression mechanisms and to avoid dramatic situations. Therefore, for continuous assessment and identify early stage structural movements, a SHM system was installed at the Foz Côa Church, mainly focused on the columns and arches of the lateral right, as well on the main façade. The column 2 (Fig. 2) was assigned as the region with higher deformations, and hence densely instrumented. Column 2 is the main instrumented column presented in Fig. 5.

3. Real-time monitoring system implemented at Foz Côa Church

For the long term-monitoring of the Foz Côa Church, eight sensors were used in total, mainly focused on displacements monitoring of the column 2 and main façade, as shown in Fig. 5. From those, two temperature sensors, one of them designated as T2C, was placed on the top of the main façade while the other one, so-called T1C, was positioned on the top of the column 2, close to a relative humidity sensor. An inclination sensor, C1A, was also installed on the top of the same column, while a linear potentiometer displacement sensor, designated as P1, was placed on the bottom of the same column. Other two linear potentiometer displacement sensors (crack-opening sensor), namely F7 and F8, were placed along the internal wall, on the main façade, while another one, assigned as F4, was installed near the T2C temperature sensor, at the top of the façade.

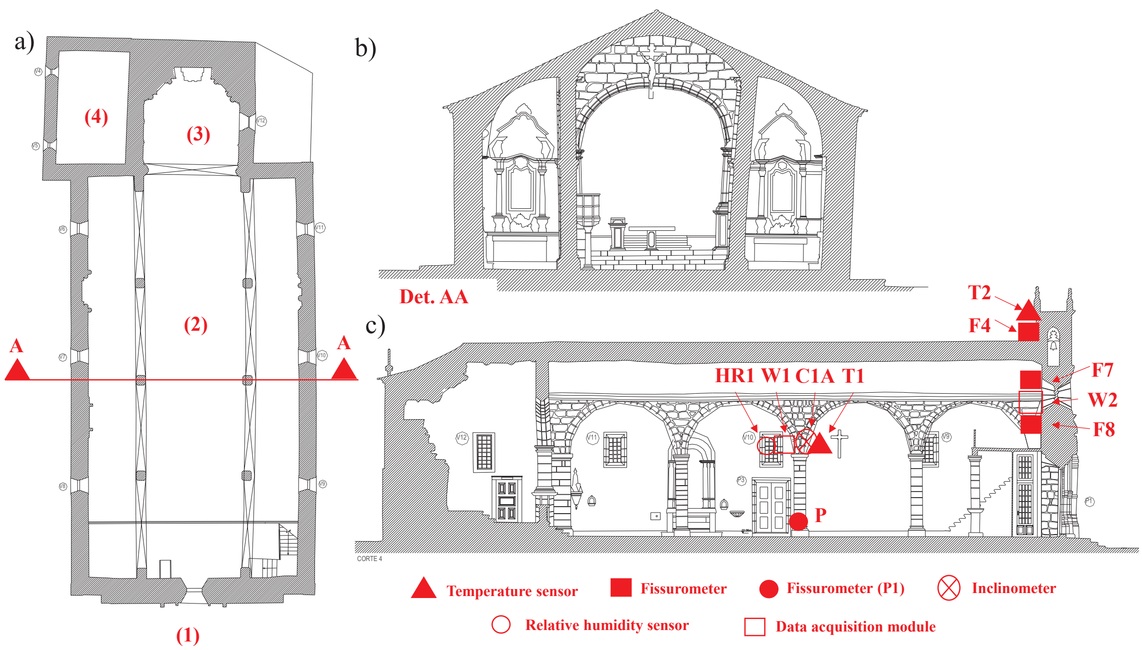

Fig. 5. Geometric view of the Foz Côa Church (a) where 1 - is the main façade, 2 - is the Central Nave, 3 - is the Altar-Mor and 4 - is an office; the transversal view of the detail AA is presented in (b) and the sensors positioning are shown by (c).

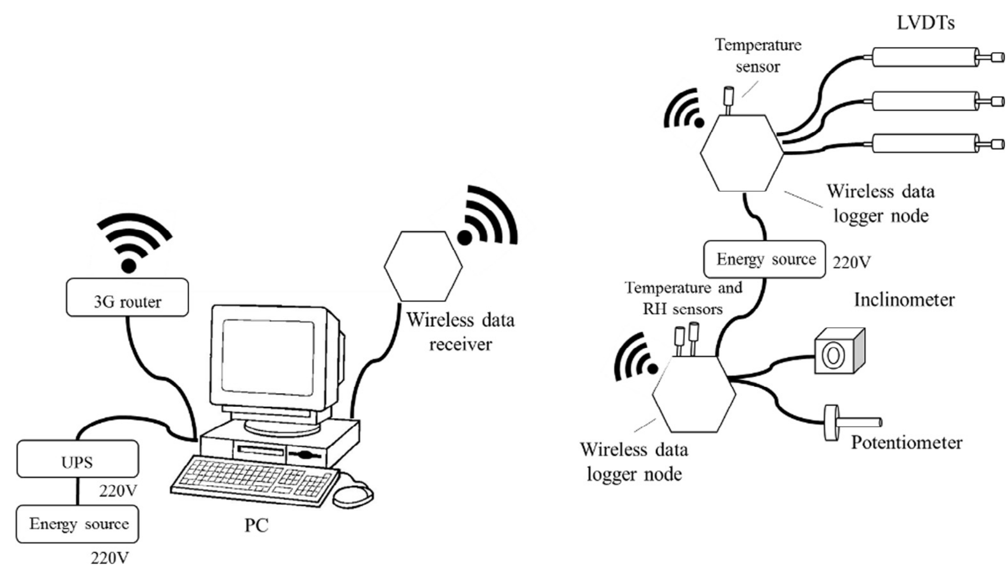

Fig. 6. Setup of the SHM system implemented at Foz Côa Church.

The data acquisition system (W1 and W2) was composed by two HOBO® wireless data logger's node, namely Zw-007 and Zw-006, one HOBO® wireless data receiver, ZW-RCVR, a 3G router and a desktop computer. An illustrative scheme of the complete SHM system is presented in Fig. 6.

All the sensors were connected to the data logger's node, assigned as W1 and W2 in Fig. 5, that provide the data transmission to a data receiver node ZW-RCVR connected to a computer, placed at the high choir of the church. Through an HOBO® software installed on the computer, the acquisition parameters as sample rate, transmission rate, measuring range of the input signals and sensors scaling of the nodes were configured. It was defined a sample rate of 1 min and a transmission rate of 2 min. All data received from the nodes is stored on a data base for management, processing and display. Moreover, alarms were created with warmings through email, and the data storage daily were send through email and FTP protocol to a remote server in LESE/FEUP. To allow internet access, a 3G router was installed and connected to the computer. The complete scheme of the sensors distribution along of the Foz Côa Church can be seen in Fig. 5c.

The wireless sensor network is not fully wireless, from each sensor location to a nearby wireless node, it is cabled. Nonetheless, the use of wireless nodes, reduces significantly the cabling, especially across the structure, which is of the upmost importance in open to the public HC, such as the one studied here. The used nodes, AC powered with long duration backup batteries (1 year battery life logging at 15-min intervals) can communicate with the wireless receiver (linked through cable to the computer with the 3G router) up to a distance of 100 m, additionally, although we only used two wireless nodes, such scheme can be used with up to one hundred nodes, being able to deal also with kHz dynamic measurements. The instrumentation uses the wireless data standard - IEEE 802.15.4 2.4 GHz band, offering efficient, lower-cost, lower-speed ubiquitous communication between devices. Although the masonry structure can reduce significantly the signal from the wireless node to the receiver, it is still possible to use them efficiently in most of

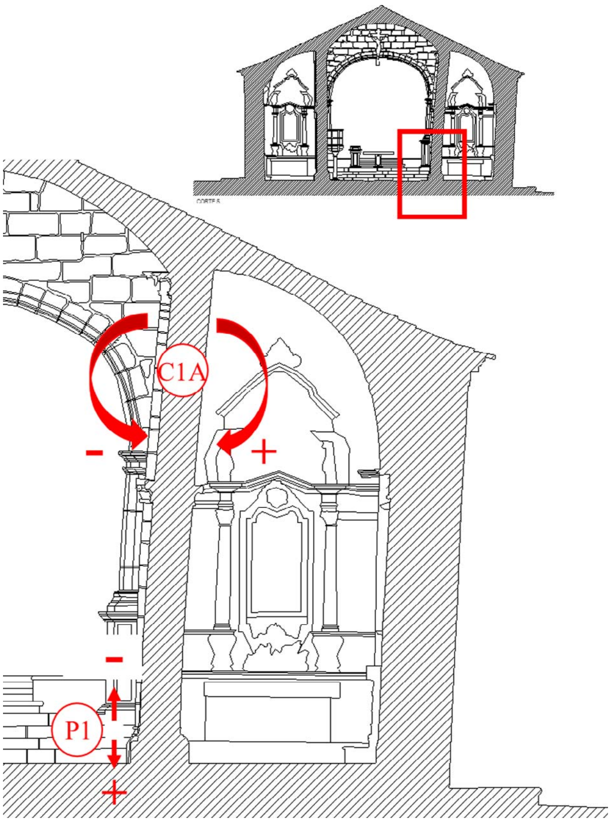

Fig. 7. Schematic view of the movements and orientations monitored through sensors C1A and P1.

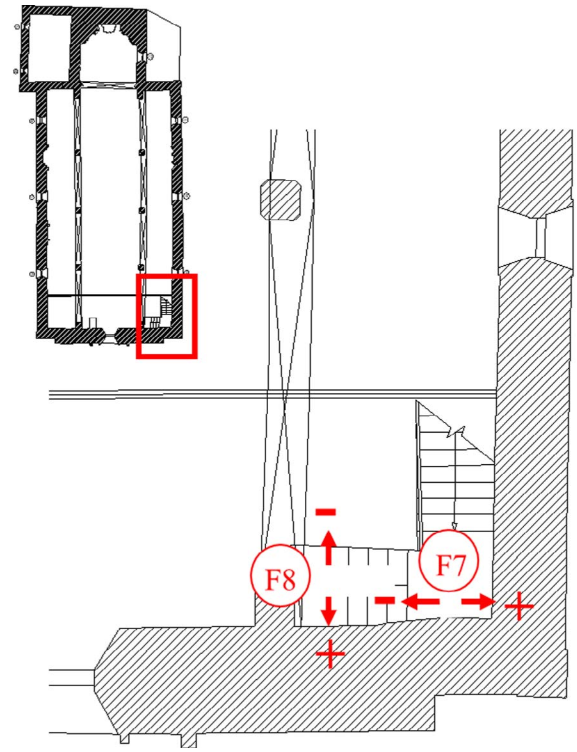

Fig. 8. Schematic view of the movements and orientations monitored through sensors F7 and F8.

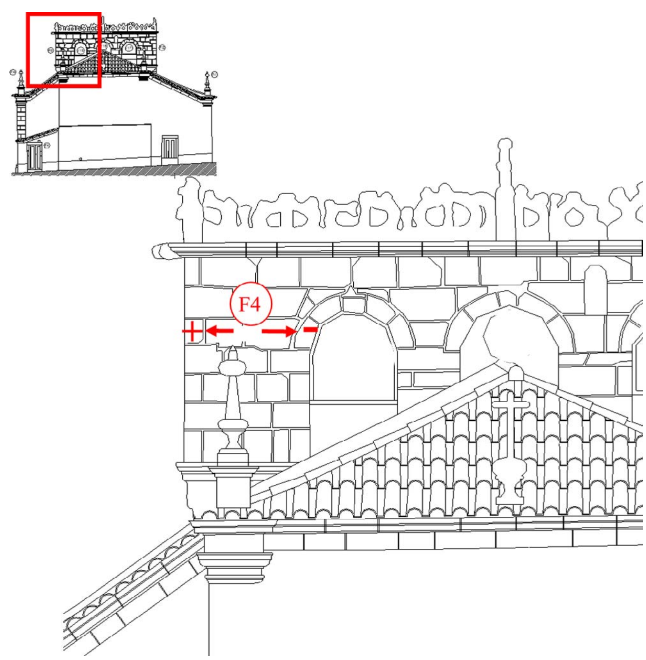

Fig. 9. Schematic view of the movements and orientations monitored through sensor F4.

the HC structures, with advantages over other network sensing technologies, such as energy efficiency, cabling reduction, portability, installation versatility, lower visual impact, among others.

Fig. 7 shows in detail the displacement parameters monitored on column 2, one of the most damaged elements inside of the Foz Côa Church. The C1A sensor was positioned to collect displacements concerning inclination along column 2, where the positive values indicate displacement of the column 2 to the interior side of the right lateral nave, while the negatives values evidence the column 2 inclination in the direction of the Central nave. Additionally, the P1 sensor was positioned to measure the relative displacements on the bottom of the column 2, where the positive values recorded indicate movements in the down direction while the negative values indicate movements in the opposite direction. In other words, the recorded positive values of displacements in the basis of the column 2 can be understood as compression movements, while the negative values can be interpreted as tension.

Concerning the sensors F7 and F8 positioned aligned with the façade stone walls (from interior side of the church), as shown by Fig. 8, they measure relative displacements at transversal and longitudinal direction of the façade, respectively. The positive and negative directions indicate movements out-of-plane, where positive displacements can be understood as movements to exterior of the church and the negative displacements indicate that the movements are occurring to the interior of the church. The F4 sensor was placed on the top of the main façade, inside the bell-tower, to measure the relative displacements along the transversal direction of the church, as shown in Fig. 9, where the positive values correspond to the movements towards the left while the negative values correspond to the movements towards the right.

4. Influence of the temperature on structural displacements

The time evolution of the internal and external temperatures and the relative humidity recorded by the monitoring system are shown through the data in Fig. 10, whereby the maximum and minimum values of measured temperature were over around 39 °C and 0 °C, respectively, while the maximum and minimum values of relative humidity were of 88% and 25%, respectively. It should be noted that the temperature measurements recorded by the T1C sensor, placed inside

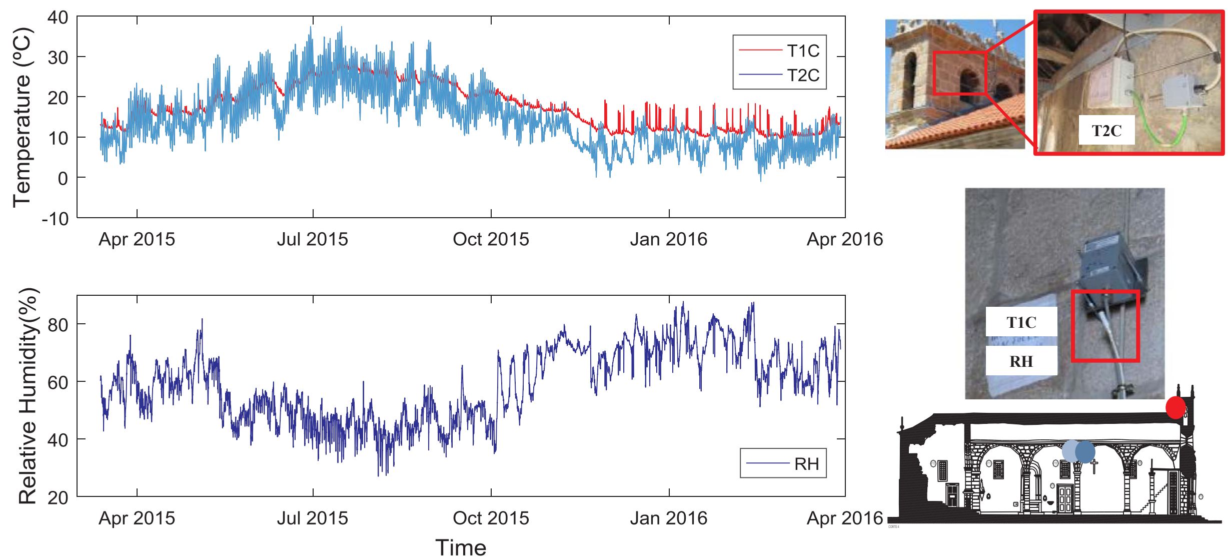

Fig. 10. Time evolution of the internal and external temperatures and relative humidity monitored at Foz Côa Church.

the church, present significantly less variation (ranging from 9 °C to 29 °C) than the values of temperature collected by sensor T2C, that vary from −1 °C to 37 °C, as can be observed in Fig. 10.

To investigate the influence of the internal temperature on the displacement parameters monitored in the present work, the values of the temperature collected by sensor T1C were used to estimate a correlation between temperature and relative displacements, and subsequently, the correspondent correlation function was used to remove the thermal effects from the displacement values of originally collected.

The correlation functions between temperature and the relative displacements were obtained through polynomial interpolation, as well as their respective correlation coefficient (R^2). While the R^2 obtained from the T1 temperature analysis *versus* relative displacements, measured by the sensorial system presented values higher than 0.80, the R^2 obtained for T2 temperature values *versus* relative displacements presented a correlation coefficient lower than 0.60, which is not useful in this study. Only T1 temperature values were used to obtain the correlation functions presented in this paper.

The effects of a potential differential temperature distribution into the church were excluded in this study because, the main monitored column is not directly connected with external walls or other external elements. The minimum distance between the column and a lateral stone masonry is, at least, 3 m. Also, stones masonries do not present significant heat transfer capabilities, reducing any external temperature gradients, on the external elements, influence in this internal column displacement.

From the analyses of the inclination time evolution data, of the column 2, plotted in mm/m, it can be noticed that high temperatures are more influencing than low temperatures. In general, when the average temperature values are close to 38 °C, the inclination reach values around 0.320 mm/m. In contrast, during the winter, when the average temperature values are around 5 °C, the inclination measured values are close to 0.100 mm/m, in the opposite direction from the movement observed during the summer (see Fig. 11).

Through a correlation between the T1 temperature values and the inclination acquired by sensor C1A, it was possible develop Eq. (1), where $D_{C1A}(t1)$ is the inclination as a function of the T1 sensor temperature in [mm/m]/°C, and x is the temperature in °C. The thermal influence from the monitored inclination can be removed, as can be seen by the data in Fig. 11. The correlation coefficient (R^2) value for the $D_{C1A}(t1)$ function is presented in Table 1.

$$D_{C1A}(t1) = -8.1448^{-4}x^2 + 4.3725^{-2}x - 4.4386^{-1} \quad (1)$$

Removing the temperature effect from the inclination values recorded by sensor C1A, the curve can be fitted by a line (see Fig. 11). The inclination movements evolution over 1-year monitoring on the Column 2, without the temperature effect compensation shows maximum value of inclination of 0.320 mm/m (ranging from 0.320 mm/m to −0.200 mm/m), and with compensation a maximum value of 0.210 mm/m (in a range between 0.210 mm/m to −0.180 mm/m) was estimated. Therefore, a 34.4% difference was calculated between the maximum inclination values, estimated with and without compensating the thermal effects.

Essentially, the inclination movements collected over 1-year demonstrate that the increase of the temperature observed between March/2015 to the beginning of August/2015 are influent in the inclination value increase on column 2, to right lateral nave direction, while between August/2015 to beginning of March/2016, the inclination tends to go in the opposite way, namely to direction of the main nave. After the thermal effects removal, it was noticed that the inclination is not related with structural movements, only with annual thermal cycles.

Concerning the displacements measured on the bottom of the column 2 by the potentiometer sensor P1, its time evolution is presented in Fig. 12. To identify the thermal effects on the relative displacement collected, a correlation between the displacements and the temperature evolution (t_1) was done and Eq. (2) was obtained, where $D_{P1}(t_1)$ is the relative displacements in function of the temperature T1C, in mm, and t_1 represents the temperature value, in °C. The respective correlation coefficient (R^2) is shown in Table 1.

$$D_{P1}(t1) = -4.0484^{-3}t_1 + 5.6881^{-2} \quad (2)$$

Through the time evolution analysis, while the temperature stimulus induces a displacement, acquired by sensor P1, varying from −0.078 mm to 0.020 mm, the displacement behavior without the thermal effects vary from −0.040 mm to 0.020 mm, evidencing the temperature influence at the base of the column to the up direction, in this case, assigned as the negative values. Essentially, these relative displacements, related with the temperature increases, can be due to the inclination movements, collected by C1A, as well. In fact, the temperature increases can induce the base of the column 2 to move, aggravating the emergence of tension on it.

Making a comparison between the maximum overall displacement values collected and the maximum displacement estimated removing the effect of the internal temperature (t_1), a variation from −0.078 mm to −0.040 mm, was observed, for the maximum displacement with and

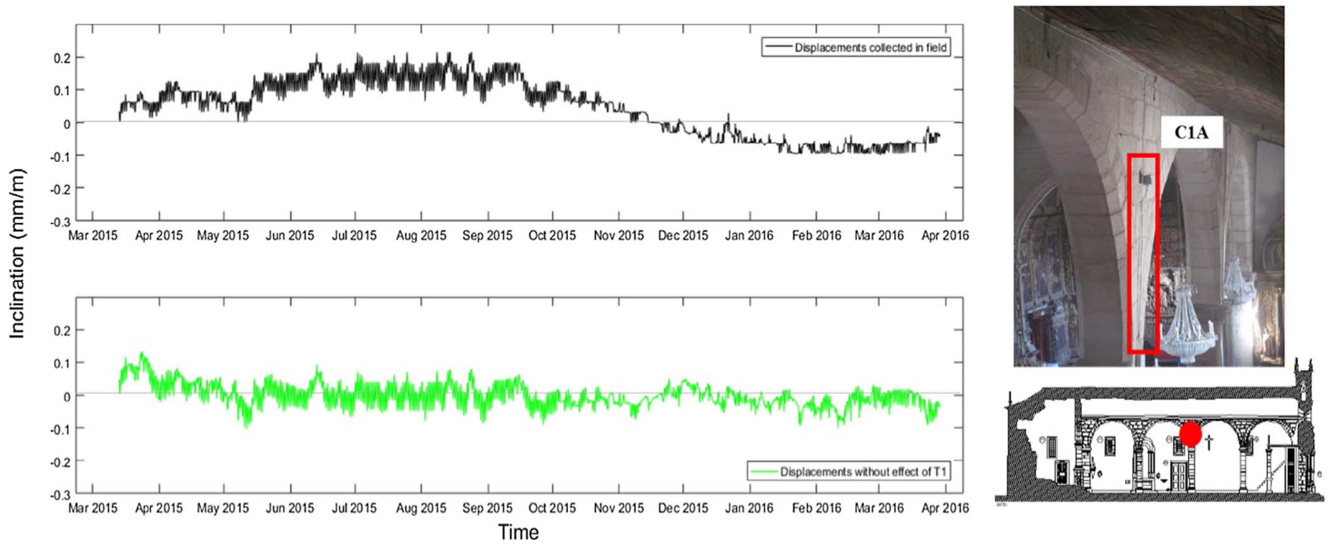

Fig. 11. Time evolution of the inclination measured by sensor C1A on column 2 with and without the temperature effect.

Table 1
Determination coefficient (R^2) between temperature T_1 and the displacement monitored at sensors C1A, P1 and F8.

	C1A	P1	F8
t_1	0.82	0.92	0.84

without the effect of the temperature, respectively. Therefore, a decreasing of −48.7% on the displacement value recorded by sensor P1, was estimated.

Especially during the summer period, the relative displacements recorded through P1 achieved higher values. This way, the temperatures and the relative displacements recorded in July and August of 2015 are presented in Fig. 13, allowing to observe the day-by-day thermic cycles, and its correspondent effects on the relative displacements evolution. After removing the temperature effect, the relative displacements tend to stabilize around zero, supporting our finding of absence representative structural movements.

The displacements data, collected by sensor F8, with and without the effect of the temperature t_1 is shown in Fig. 14. The correlation function between relative displacements and the temperature values was stated based on Eq. (3), where $D_{F8}(t1)$ represents the displacement in function of the temperature t_1, in mm, and t_1 is the temperature value, in °C.

$$D_{F8}(t1) = 2.8543^{-3}t_1 - 3.7782^{-2} \tag{3}$$

Based on the evolution of the measured linear displacements at the sensor F8 location, after the removal of the thermal effect (t_1), the amplitude of the relative displacement along the longitudinal direction decreased. In July 22, 2015, for instance, the displacement curve with the temperature effect presented a maximum of 0.05 mm, while after the removal of the internal temperature effect (t_1), the maximum displacement found was 0.02 mm, in other words, the internal temperature effect virtually increased the displacement up to 250%.

5. Combined effect of the temperature and relative humidity on structural displacements monitored

The previous section demonstrates how temperature can affect the structural movements of the monitored elements of the Foz Côa Church. However, the Relative Humidity (RH) may constitute an amplitude constraint of the observed movements. Therefore, the present section is devoted to the combined effect of the temperature and relative

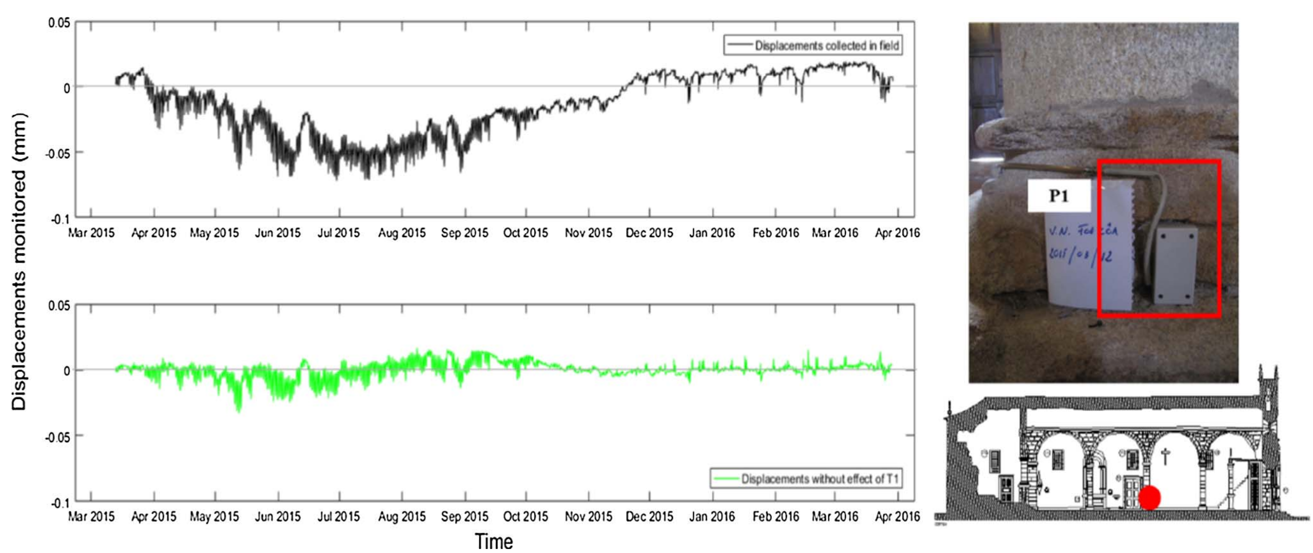

Fig. 12. Time evolution of the displacements measured by sensor P1 on the bottom of the column 2 with and without the temperature effect of t_1.

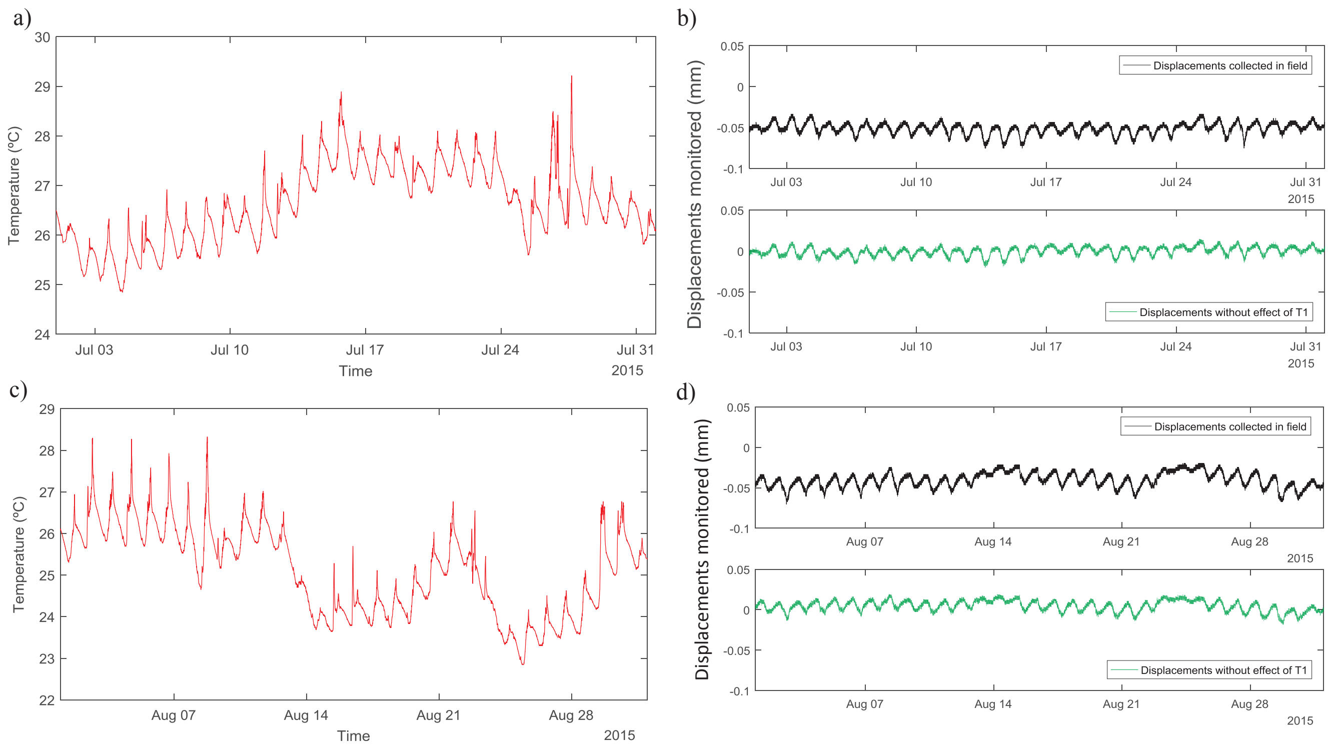

Fig. 13. Time evolution of the temperature and displacements measured on the bottom of column 2: (a) temperature measured at the sensor T1C location from July 1st to 31th, 2015 and correspondent (b) displacement measured on sensor P1 with and without the temperature effect; (c) temperature measured at sensor T1C location from August 1st to 31th, 2015 and correspondent (d) displacement measured on sensor P1 with and without the temperature.

humidity on structural displacements observed on the Column 2, namely inclination and relative displacements at the basis, as well as the relative displacements of the longitudinal section of the main façade, measured through sensor F8, as shown in Fig. 8. This study was limited to the data collected through sensors C1A, P1 and F8, excluding the data collected on sensors F4 and F7 due to their measured relative displacements didn't allow to estimate an adequate correlation coefficient R^2.

The correlation between the temperature (collected through sensor T1C) and the relative humidity values and the inclination measured at C1A sensor location, is shown in Fig. 15, with an estimated correlation coefficient, R^2, of 0.86.

The results confirmed that the combination between a relative humidity (around 80%) and temperature increase (around 10 °C) can aggravate an inclination movement of the column 2 of roughly 0.150 mm, in the main nave direction of the Church. Otherwise, a low relative humidity (between 50% and 60%, for instance) can constrain the column 2 inclination for the same level of temperature variation. The inclination movement in the opposite situation, namely in the direction of the right lateral nave, occur when the values of temperature are near or higher than 20 °C for all levels of relative humidity.

Concerning the combined effect of the temperature and relative humidity on the relative displacement observed at the column 2 base, the results are presented in Fig. 16, with an estimated correlation coefficient, R^2, of 0.92.

However, the surface slope, in Fig. 16 data, demonstrate that the

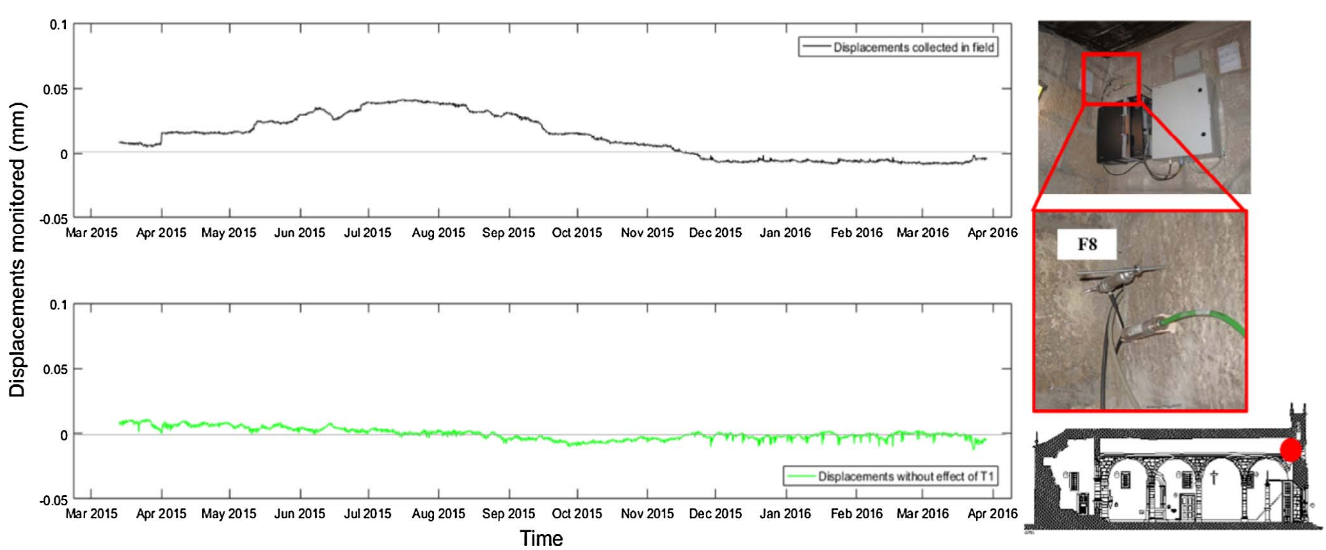

Fig. 14. Time evolution of the displacements measured by sensor F8 on the top of the internal side of the main façade with effect of the temperature and without temperature effect of t_1.

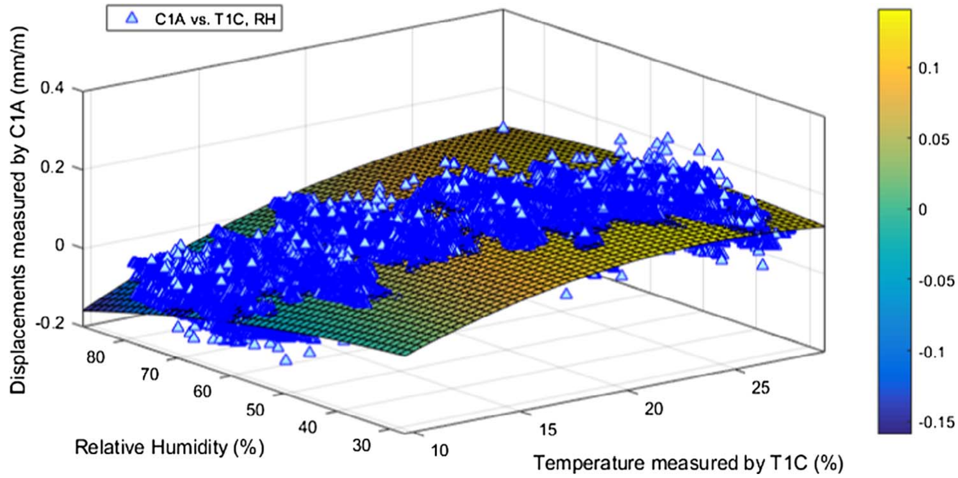

Fig. 15. Influence of the combined effect of the internal temperature and relative humidity on the inclination movements, measured through sensor C1A at column 2.

relative displacement at the basis of the column 2 are mostly influenced by temperature rather than relative humidity changes. Additionally, inclination along the column 2 also has an impact on the relative displacement observed at the basis, contributing for overlapping the relative humidity effect on the structural movement at the basis of the column 2.

Regarding the relative displacement measured on the stone wall, the combination between the temperature (t_1) and the relative humidity effects, in the longitudinal direction, is shown in Fig. 17. The correlation coefficient R^2 was identified as 0.84.

The surface represented in Fig. 17 data present a smooth curvature with higher slope and parallel to the temperature axis. Only in the 60% to 80% RH range, combined with temperature values over 20 °C, incites the wall movement (on the monitored point) to the interior direction of the main nave, otherwise the temperature increase induces a movement in the opposite direction. It was estimated that an 80% RH combined with a temperature value of 10 °C produce an average displacement of 0.02 mm to the interior direction of the main nave.

The relative humidity is directly related with the quantity of water inside the material pores of the components, mainly in the mortar, therefore it may induce small movements. Similarly, changes in the ambient temperature can, besides the thermal expansion, to induce smooth variations on the rigidity of the structural components. To completely understand how the temperature and relative humidity affect the structural movement mechanisms, it is necessary to fully analyze the collected data, to correlate all the known factors, as temperature and humidly changes, and to compensate those in the parameter of interest calculation. That way, it may be used in structural behavior numerical models, and potentially, to identify the damage emergence.

6. Conclusions

This work describes the SHM system implemented on Foz Côa Church (Portugal), as well the main results collected along 1-year monitoring, from 13th March 2015 to 29th March 2016. The sensorial system was composed by temperature, relative humidity and displacements sensors.

Four sensors were installed along a pillar (column 2). Temperature, relative humidity and inclination sensors were positioned on the top, and a potentiometer sensor at the base. Three relative displacements sensors were installed on the main façade, two were placed inside the church to access the displacement in the longitudinal and transversal directions, respectively, and the other was positioned inside the bells-tower, in the top of the main façade, close to another temperature sensor.

The collected data allowed to characterize the structural movements of the column 2, namely the inclination and relative displacements in its base, as well to relate them with the influence of the ambient temperature, consequently to understand how thermal effects influence the column movement.

Additionally, the relation of thermal effects with the column

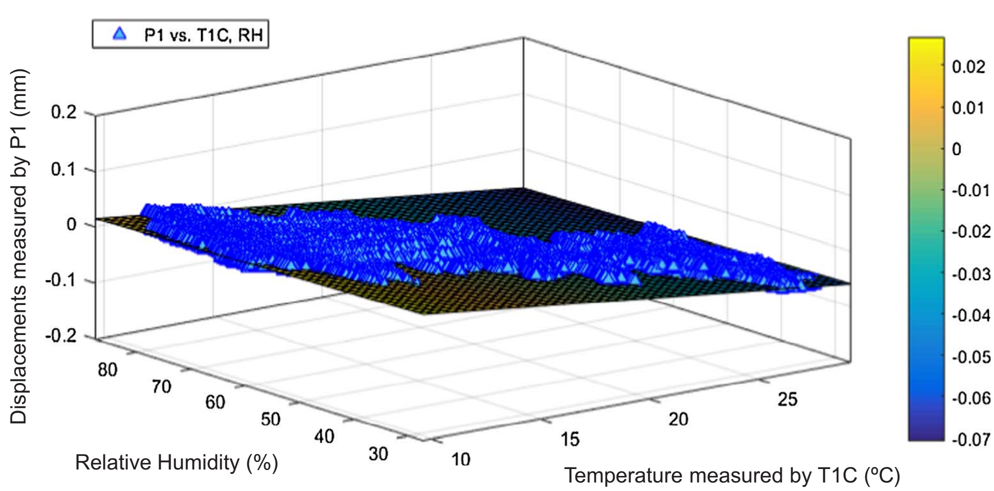

Fig. 16. Influence of the combined effect of the internal temperature and relative humidity on the displacement measured at the bottom of column 2, by sensor P1.

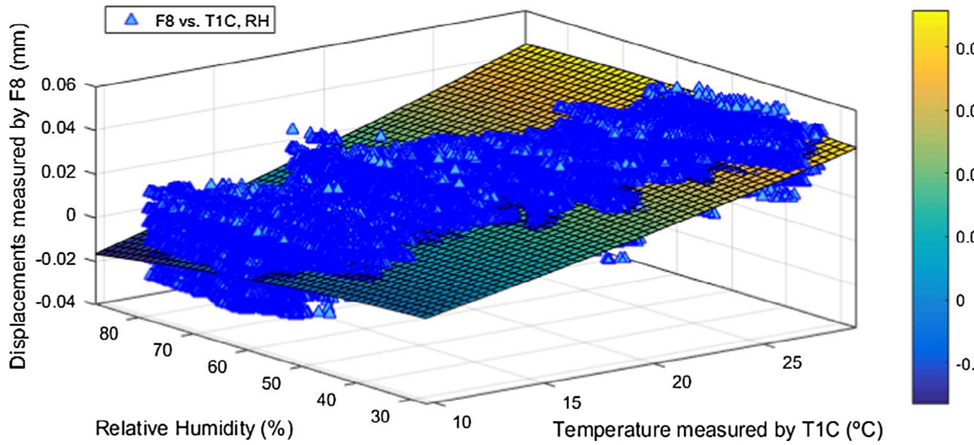

Fig. 17. Influence of the combined effect of the internal temperature and relative humidity on the movements at internal side of the main façade collected by sensor F8.

inclination, and relative displacement, was established allowing to monitor movements other them the ones developed by thermal ambient cycles, namely summer and winter. The same data treatment was performed on the data acquired through the displacement sensor on the main facade.

The subtraction of the thermal effect, as well the study of the combined temperature-relative humidity effect, allowed to conclude that the observed movements on the monitored elements are not related with structural issues. Most likely movements are related with the temperature and relative humidity influence, the later in lower proportion. Nonetheless, the small displacements values observed, over the time evolution series, does not represent any risk condition to the Foz Côa Church integrity.

The employment of SHM allowed to collect accurate and reliable data on the displacements of the structural elements of the Foz Côa Church, and the data management employed provided the basis for an adequate interpretation of the results.

Finally, monitoring of the relative displacements of the Foz Côa Church allowed to state that the structural elements movements and the new cracks emergence are related with the temperature effect. Considering structural stone masonry characteristics and the amplitude of the relative displacements collected over the year, it is possible to state that the church is not under collapse risk.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.engstruct.2018.02.013.

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