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FIRST RESULTS OF LONG-TERM MONITORING OF PORTICO VARANO IN THE CAMERINO DUCAL PALACE (ITALY)

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Abstract

Portico Varano in the Ducal Palace of Camerino (Italy) is a Renaissance monumental quadriporticus that was severely damaged by the Central Italy earthquakes in 2016. Within the field activities for saving cultural heritage foreseen within a recent European research project, a long-term static and dynamic monitoring system was installed in October 2020. Through a series of accelerometers, the monitoring system allows to track the evolution of the modal parameters of the structure, namely frequency, damping ratio and modal shapes, and investigate the effects of environmental conditions on the building dynamics. Furthermore, a series of displacement transducers installed on the vaults of the courtyard allows controlling the evolution of the crack patterns. In this paper, the design and installation of the monitoring system as well as some first results are presented and discussed.

Keywords: Operational Modal Analysis, Structural Health Monitoring, Cultural Heritage Buildings, Ambient Vibrations, Dynamic System Identification.

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1 INTRODUCTION

The Italian architectural heritage is constituted by a wide number of historical masonry constructions such as churches, towers, buildings, and fortresses, characterized by both structural and typological vulnerabilities, which are often responsible for their poor seismic performance, e.g. [1-3]. Such situation is unfortunately periodically confirmed by the damage observed after the occurrence of seismic events, inevitable reminders of the high seismic risk of the Italian peninsula.

The analysis of the seismic vulnerability of architectural heritage requires an integrated approach where different disciplines provide indispensable contributions: historic investigations of the construction evolution; survey of the construction; in situ experimental testing and characterization of the materials; structural modelling and seismic analysis. Such contributions do not necessarily have a predetermined chronological sequence, given that the results of one of them influence the development of the investigations of the other three [4]. Among the various possibilities for experimental testing, dynamic testing under service conditions, commonly referred as Operational Modal Analysis (OMA), e.g. [5], constitute a very effective tool for structural identification and model updating, essential tools to support model-based simulation for the prediction of the seismic response of heritage constructions as well as for the calibrations of advanced seismic upgrading interventions, e.g. [6]. Examples of recent structural monitoring studies in the Italian architectural heritage include: the Consoli Palace in Gubbio [7], the church of Santa Maria in Collemaggio in L'Aquila [8], the San Pietro bell-tower in Perugia [9], the Milan Cathedral [10], the San Vittore bell-tower in Arcisate [11], and the Rubbianello Bridge [12].

This paper adds to the above list and presents the first results from a structural monitoring system installed in the quadriporticus of the Ducal Palace in Camerino, within the field activities planned in the European research project named ARCH (Advancing resilience of historic areas against climate-related and other hazards - https://savingculturalheritage.eu/) funded in the Horizon 2020 framework for the years 2019-2022. The objective of the ARCH project is the evaluation of the resilience of the historical centres and the risk management related to climate change and other natural disasters.

2 THE DUCAL PALACE IN CAMERINO

The Ducal Palace (Figure 1) is one of the main Renaissance monuments of the city of Camerino, located in Central Italy in the inner Apennine area of the Marche Region, about 65 km from the Adriatic Coast, 70 km from the city of Perugia and 190 km from Rome. The building hosted the headquarters of the University of Camerino before the 2016 Central Italy seismic events. The nucleus has ancient origins, remodelled at the end of the XIV century and completed in the second half of the XV century under Giulio Cesare da Varano. Over the centuries, the layout of the Palace underwent many modifications thanks to acquisitions that led to the incorporation of other surrounding buildings. These caused a continuous structural reorganization and maintenance works, resulting in a very complex and densely stratified palace. Continuous interactions between the building and the city led to architecture and urban spaces that were mutually conditioned. For this reason, the Ducal Palace is also defined as “part of the city”.

The quadriporticus courtyard (Figure 1a,e), also called Portico Varano or Sottocorte, probably designed by the great military architect Baccio Pontelli, is the central architectural element around which the palace is organized. Before the damages following the 2016 Central Italy earthquakes, the quadriporticus courtyard played a key role in the social life of the academic community of the University of Camerino.

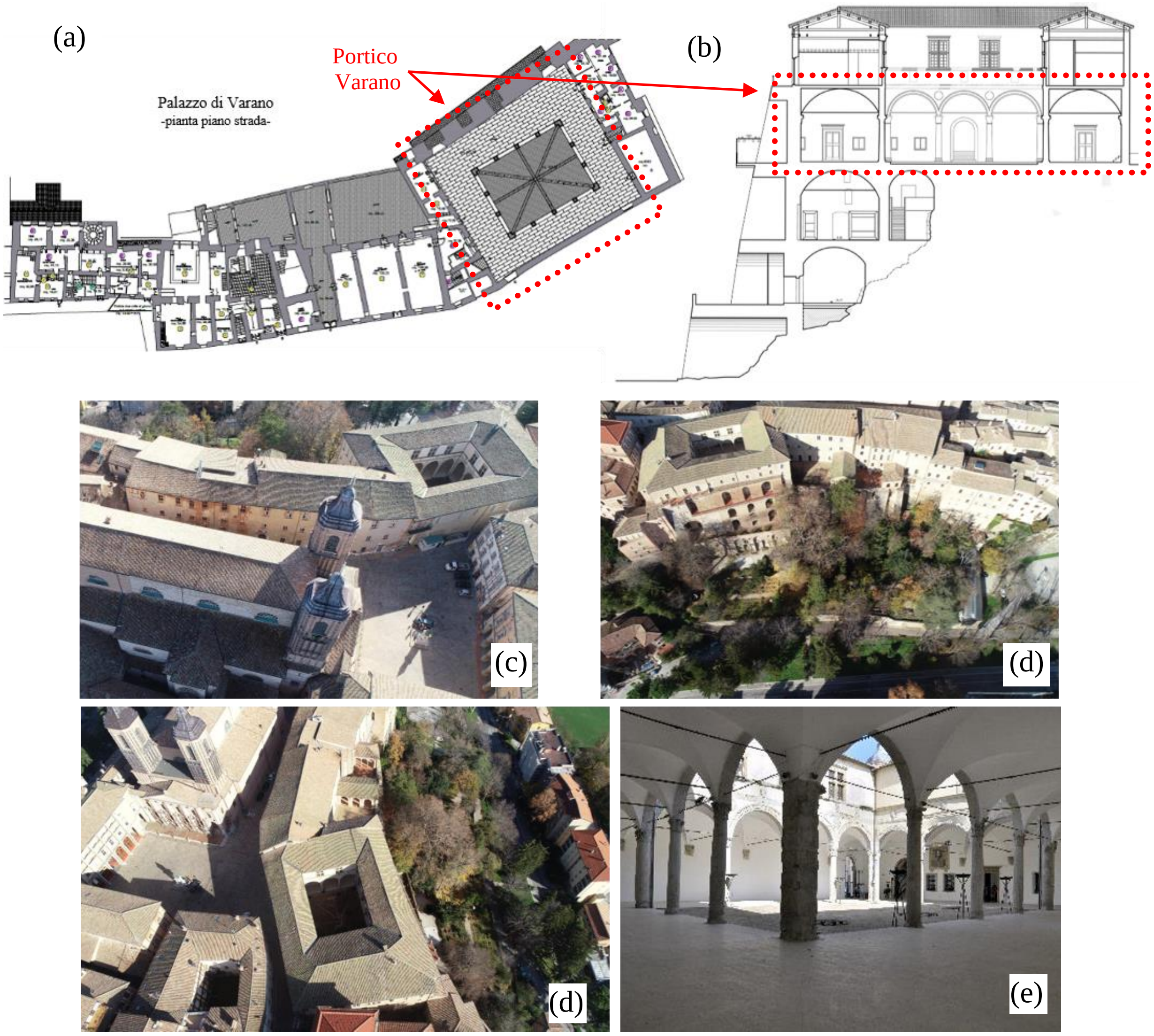


Figure 1: Ducal Palace Camerino, Italy (a) layout at the street level; (b) vertical section; (c) aerial view from the North-West side (d) aerial view from South-East; (d) aerial view from South-West; (e) view of the inner courtyard from the North corner of the quadriporticus.

After the latest seismic sequence that hit central Italy from August 2016 to January 2017, the structural vulnerabilities of the Ducal Palace were exposed, with damage observed both in the elevation structures and in the floors (for example some sample photos are shown in Figure 2). Damages in the vault of the quadriporticus, and in the perimeter walls interdicted the public access to the Ducal Palace and required safety measures (Figure 2). In addition, important damages concerned non-structural element with detachment of internal plaster and cracks in the “camorcanna” ceilings, some of them decorated with fresco paintings.

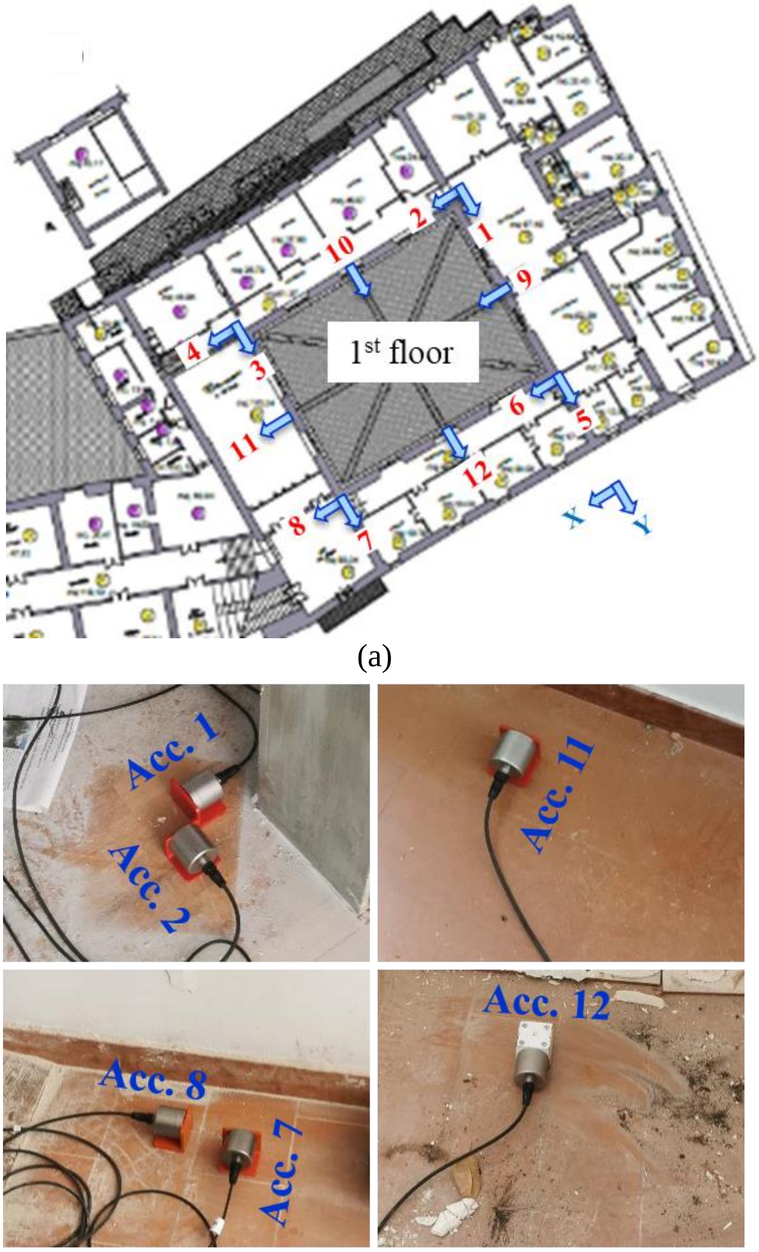
Figure 2: Examples of the damages in "Portico Varano" after the 2016 Central Italy earthquakes.

3 MONITORING SYSTEM AND FIRST RESULTS

3.1 Preliminary monitoring system and dynamic characterization

The Ducal Palace is a very complex case study and reliable structural models were not available in the first stage of the field activities foreseen in the ARCH project. For this reason, preliminary structural monitoring tests were made in June 2020 in order to provide a characterization of the dynamic behaviour of the quadriporticus under ambient-induced vibrations to support the first evaluations on its structural behaviour.

The instrumentation adopted during this preliminary experimental campaign consisted of 12 uniaxial high sensitivity piezoelectric accelerometers (PCB model 393B31) connected through high-quality shielded coaxial cables to the acquisition system (National Instruments cDAQ-9178 installed with NI 9234 analogue-to-digital converters) controlled through a Dell Precision 7540 laptop running National Instruments Signal Express software. The accelerometers were placed on the first floor as depicted in Figure 3 in order to provide a comprehensive description of its horizontal motion, given that such floor cannot be realistically modelled as a rigid diaphragm due to its geometry and materials. The adopted configuration was possible given that the interested portions of the first floor were safely accessible. Other configurations keeping some of the accelerometers as fixed (reference sensors) and the other as roving sensors, e.g. [5], were not explored given the major difficulties in a safe accessing other areas of the same floor and the impossibility of a safe access to the roof level just above the first floor. Data acquisition was performed at 2048 Hz for about 30 minutes. This duration corresponds to more than 4000 times the fundamental period of the building, as suggested in [7]. Afterwards, the signals were pre-processed to remove the linear trend by subtracting the logged signal with a zero-degree polynomial, filtering with a low-pass filter with a cut-off frequency of 49 Hz, and a resampling at a frequency of 102.4 Hz to reduce the amount of data and to make subsequent analyses faster.



(a)

(b)

Figure 3: Configuration of the installed 12 accelerometers in preliminary monitoring: (a) position of sensors; (b) example of installations.

The identification of the modal parameters (frequencies and damping ratios) was carried out by the Covariance data driven - Stochastic Subspace Identification (SSI/Cov) [5]5[14]. Figure 4 shows the stabilization diagram obtained from the tests, where the identification of the stable modes indicated on the graph by a solid black circle, was carried out considering a difference less than 1% in frequency and a MAC greater than 95% on mode shape. The first mode is essentially a translational mode along the X-direction and has an estimated frequency 3.36 Hz (period 0.298 s) and damping ratio 1.86%. The second mode is essentially a translational mode along the Y-direction and has an estimated frequency 4.52 Hz (period 0.221 s) and damping ratio 3.71%.

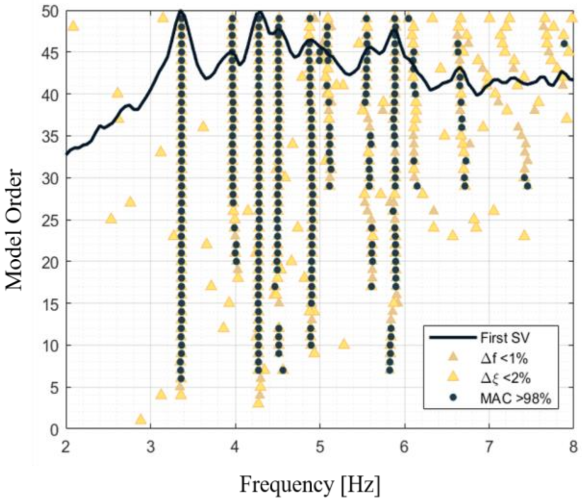


Figure 4: Results of preliminary monitoring (June 2020): Stabilization diagram.

3.2 Long-term monitoring system and first results of continuous monitoring

The results of the preliminary structural monitoring made in June 2020 provided the support for the definition of a simpler configuration using a limited number of accelerometers in order to reduce the data to be stored and processed. Given that the larger accelerations were measured in points 9, 10, 11 and 12 (according to Figure 3) and that such sensors were able to identify the first modes, the selected configuration for long-term monitoring uses four accelerometers located as depicted in Figure 5a. The adopted accelerometers are uniaxial high sensitivity piezoelectric accelerometers (PCB model 393B31). Environmental parameters are monitored using an independent system comprising two wireless sensors for internal temperature and relative humidity (Elitech RC-51H) as well as a weather station for temperature, relative humidity, wind speed and direction (WatchDog 2700) located just outside the Ducal Palace (Figure 5b). In addition, a triplet of linear potentiometers (Gefran model PZ67-A) were installed across the cracks in the cross vaults in order to measure their movements (Figure 5a). The configuration of the displacement transducers is composed by three linear potentiometers placed across the vaults connected by two galvanised metal sheets (2 mm thickness) to follow the curvature of the vaulting. Each pair of linear potentiometers forms an angle of 60 degrees. Such configuration permits to evaluate every motion of the cracks, such as side scrolling or stretching movements leading to an opening of the crack itself (Figure 6). Besides, image-based monitoring, e.g. [15], is being evaluated to possibly complement contact sensors.

Both accelerometers and linear potentiometers were connected through high-quality shielded cables to the acquisition system (National Instruments cRIO 9045 installed with NI 9234 analogue-to-digital converters for acquiring accelerometers and NI 9209 for acquiring potentiometers). The acquisition procedure was developed in the cRIO 9045 using the programming environment National Instruments LabView to control the entire process, i.e., 30-minute time logging every 2 hours, local data storage, data transfer on cloud storage accessible for remote verifications. The procedure is characterized by a continuous data acquisition of the data and a timing control that activate the logging data; within the logging cycle there is another timing control that stops the logging procedure when the assigned time elapsed. To optimize the accelerometers and linear potentiometers acquisition, the physical channels definition were divided into two parallel cycles with specific sample clock to synchronize the analogue to digital converters modules (Figure 7).

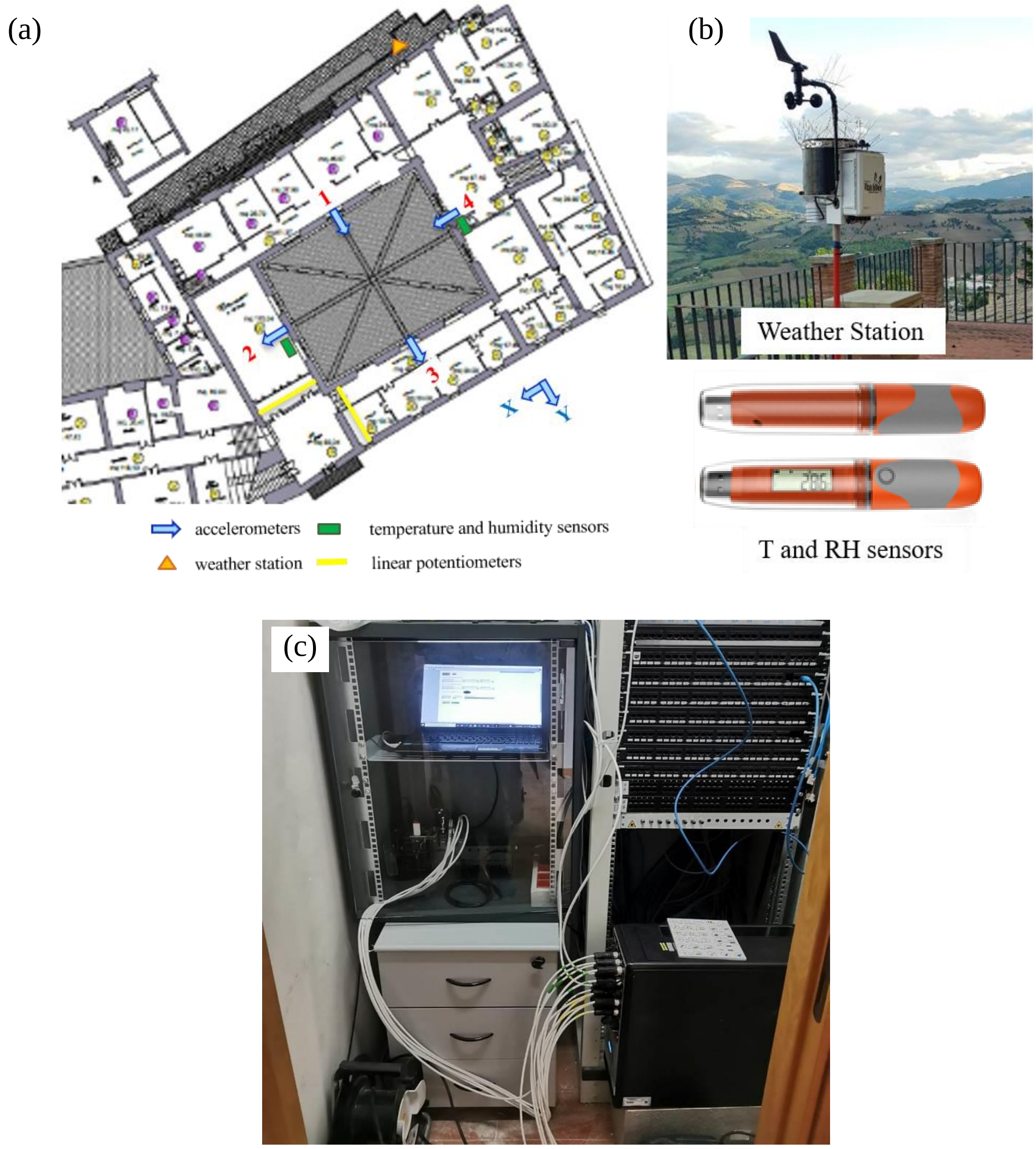


Figure 5: (a) configuration of the sensors position; (b) environmental sensors; (c) acquisition system (laptop, data acquisition module with AD converters, and signal conditioner for linear potentiometers).

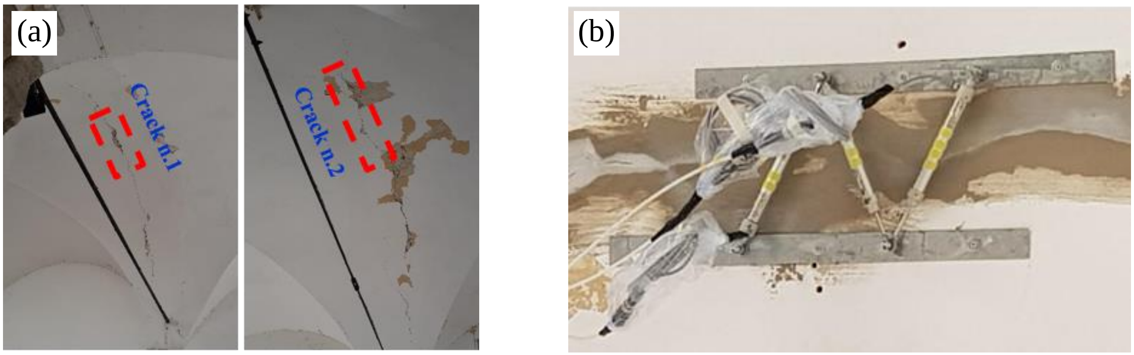


Figure 6: (a) survey of the monitored cracks; (b) arrangement of the triplet of linear potentiometers.

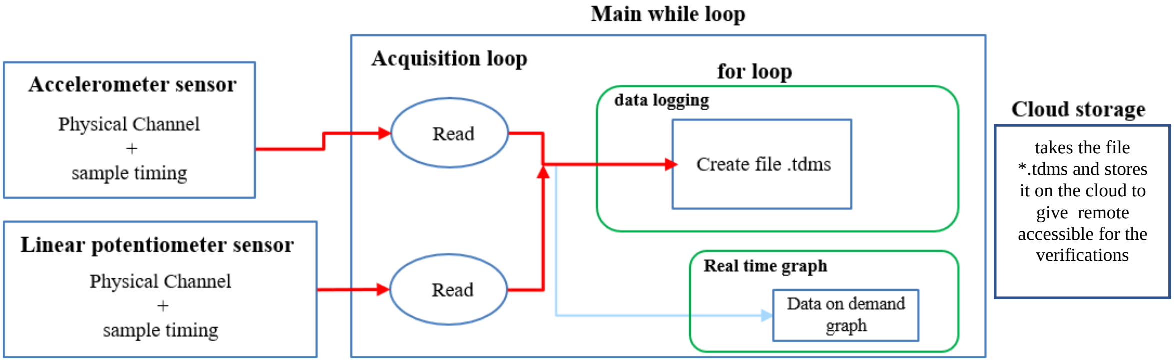


Figure 7: Schematization of the acquisition procedure.

The analysis of the first results is based only on the first month (October 2020) of acquisition of the long-term monitoring system. If attention is focused on the two translation modes identified in the preliminary monitoring described in the previous paragraph, then the results indicate a rather stable trend of the frequencies (Figure 8) with some points missing when the instrument noise was comparable with the background environmental accelerations, making the results of post-processing unreliable. In fact, it should be remarked that the historical centre of Camerino is still a restricted area following the major damages after the 2016 Central Italy earthquakes; this condition makes the area characterized by very low level of environmental noise during the day (a condition possibly exacerbated by the current pandemic restrictions) and even more during the night. At this regard, Figure 9 compares the power spectral density of the signal provided by the same accelerometer in the evening and daytime this highlights the large variation of the signal intensity over the day. Some recordings were excluded in the post-processing because instrument noise was comparable with the environmental accelerations.

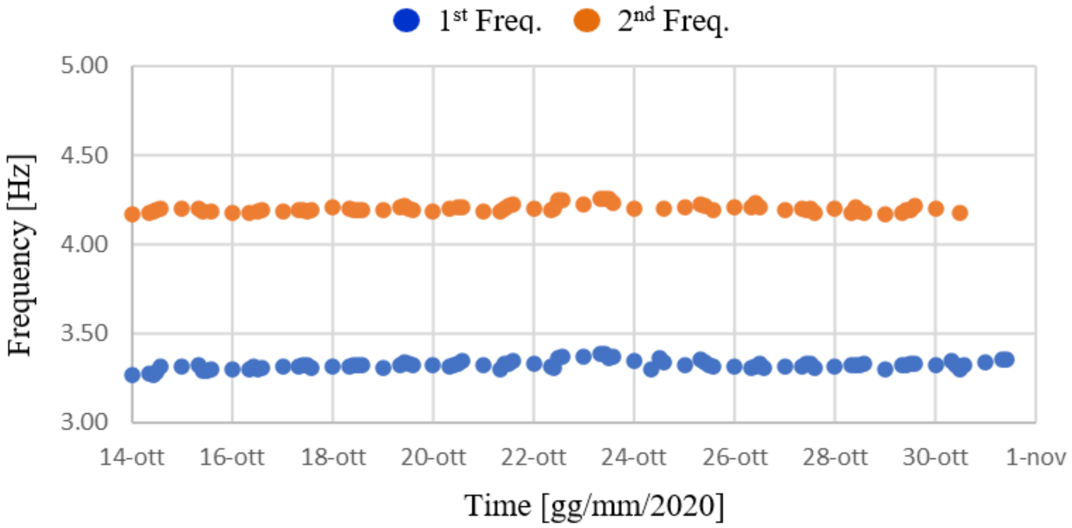


Figure 8: Monitored eigenfrequencies in the first month (October 2020).

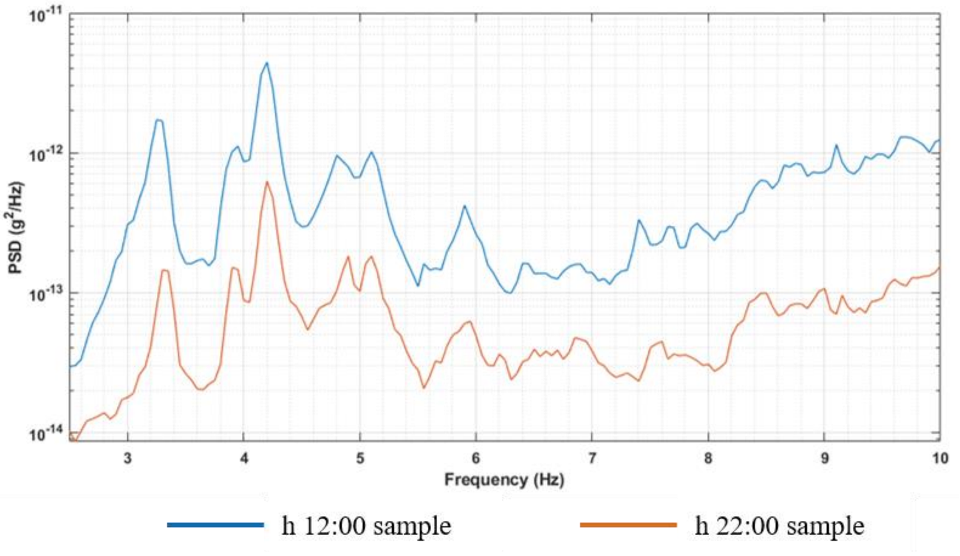


Figure 9: Comparisons of Power Spectral Densities during daylight and at night.

4 CONCLUSION

This paper described the long-term monitoring system designed and installed in the Portico Varano, the quadriporticus of the Ducal Palace in Camerino (Italy), damaged after the 2016 central Italy earthquakes. The system comprises four high sensitivity accelerometers (whose position was selected after preliminary vibration monitoring tests using twelve accelerometers), a triplet of linear potentiometers installed across the most critical crack in the most damaged cross vault, and environmental sensors (temperature, relative humidity, wind speed and direction). The accelerometers permits to observe the natural frequencies of vibration and relevant mode shapes and damping, providing essential information on the evolution over time of the main structural properties and their variation that can be correlated to the level of damage. The displacement transducers complement the information gained through the accelerometer with a direct measure of the variations of the width of the cracks. The environmental sensors allows to separate the contribution caused by the changes in the temperature and humidity to those related to structural damages as well as the relations between wind intensity and induced structural vibrations. Data recording started in October 2020 and some initial results were discussed. It is observed that the low level of measured vibrations due to restricted access to the Camerino city centre (given the safety concerns after the occurred seismic damages and possibly exacerbated by the current pandemic crisis) poses major challenges to long-term monitoring and enforces the use of high-quality and high-sensitivity sensors connected using highly shielded wires. Nevertheless, stable results were observed during the monitoring time window, constituting a first set of data that could be an essential tool to support model-based simulation for the prediction of the seismic response of the Ducal Palace as well as for the optimal calibrations of the required seismic upgrading interventions.

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