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Preliminary results in the automated detection of operational modal properties of the Portico Varano in the Camerino Ducal Palace

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Abstract

Portico Varano in the Ducal Palace of Camerino (Italy) is a renaissance monumental quadriporticus that was damaged by the 2016 Central Italy seismic sequence. Within the field activities for saving cultural heritage foreseen within a recent European research project named ARCH, a long-term monitoring system, comprising different types of sensors, such as accelerometers, displacement transducers, environmental sensors, and a weather station, was set up to achieve comprehensive measures of its operational behaviour and the evolution of the damage. The monitoring system, installed in October 2020, is currently operating, providing valuable information on the experimentally observed dynamic behaviour, also considering changes in the environmental conditions. Starting from the results of the dynamic characterization of the structure and after the optimization of the position of the sensors, this paper shows and discusses the efforts made to track over time the modal characteristics of the Portico Varano in order to detect changes in its conditions. In addition, a procedure has been proposed and implemented combining information available from Italian National Institute of Geophysics and Volcanology (INGV) to identify recorded data related to seismic events relevant to operational conditions.

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

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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., Doglioni et al. 1994, Canuti et al. 2016, Despotaki et al. 2018, Pavia et all 2021.

The analysis of the seismic vulnerability represents a fundamental step for identifying and designing proper retrofitting strategies, e.g., Gioiella et al. 2018a, Castaldo et al. 2021, Gioiella et al. 2018b. In the case of architectural heritage, seismic vulnerability analysis requires an integrated approach where different disciplines provide essential contributions: historic investigations of the construction evolution; geometric and material survey of the construction; in situ experimental testing and characterization of the materials; structural modelling and seismic analysis, e.g., Dall'Asta et al. 2019. Given the intrinsic difficulties that structural engineers must face when modelling heritage buildings, non-invasive experimental testing methods are valuable tools to provide support in the identification of the structural characteristics of a building. Among the various possibilities for experimental tests, dynamic testing under service conditions, commonly referred as Operational Modal Analysis (OMA), e.g., Brinker and Ventura (2015), Ranieri and Fabbrocino (2014), is a very effective tool for structural identification and model updating 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., Pavia et al. 2021. In the past, OMA was used especially in bridges and new structures, but lately various applications appeared in architectural heritage, e.g., Kita et al. 2019, Potenza et al. 2015, Ubertini et al. 2016, Gentile et al. 2019, Cabboi et al. 2017, Scozzese et al. 2019, Arezzo et al. 2021.

Among OMA techniques, automatic OMA analysis, e.g., Magalhaes et al 2009, is very appealing in supporting seismic assessment, as it identifies seismic events within the environmental noise recorded, to evaluate changes in the dynamic response of the structure before and after them. For this reason, an automated procedure was developed in this study to identify seismic inputs in the data acquired through continuous monitoring combining data available from Italian National Institute of Geophysics and Volcanology (INGV) relevant to seismic events. To this end, a monitoring system was installed, and an automated procedure implemented in the quadriporticus of the Ducal Palace in Camerino.

The Ducal Palace was chosen as case study within the field activities planned in a 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, whose main goals were the evaluation of the resilience of the historical centres and the risk management related to climate change and other natural disasters. As selection of preliminary results in the case of seismic risk is presented in this paper.

1.1. Case study

The Ducal Palace (Fig. 1) is one of the main monuments of Camerino, a city 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 Renaissance building hosted the headquarters of the University of Camerino until the 2016 Central Italy seismic events. The nucleus has ancient origins, it was 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, which caused a structural reorganizations and maintenance works. This way, the palace results a very complex and densely stratified place and such 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 (Fig. 1a- f), also called Portico Varano or Sottocorte, is the central architectural element around which the palace is organized. Until the damages followed 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.

After the seismic sequence that struck central Italy from August 2016 to January 2017, the structural vulnerabilities of the Ducal Palace strongly emerged, with damages observed both in the elevation structures and at the floor levels. The damages suffered by the vault of the quadriporticus, and by the perimeter walls interdicted the public access to the Ducal Palace and required safety securing measures. In addition, important damages concerned also non-structural elements were detected, with detachment of internal plaster and cracks located in the “camorcanna” ceilings, some of them decorated with fresco paintings.

2. Description of the Monitoring System

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 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 with NI 9234 analogue-to-digital converters) controlled through a Dell Precision 7540 laptop running National Instruments Signal Express software. For further details about the configuration of the sensors and the post-processing parameters refers to Cipriani et al. (2021).

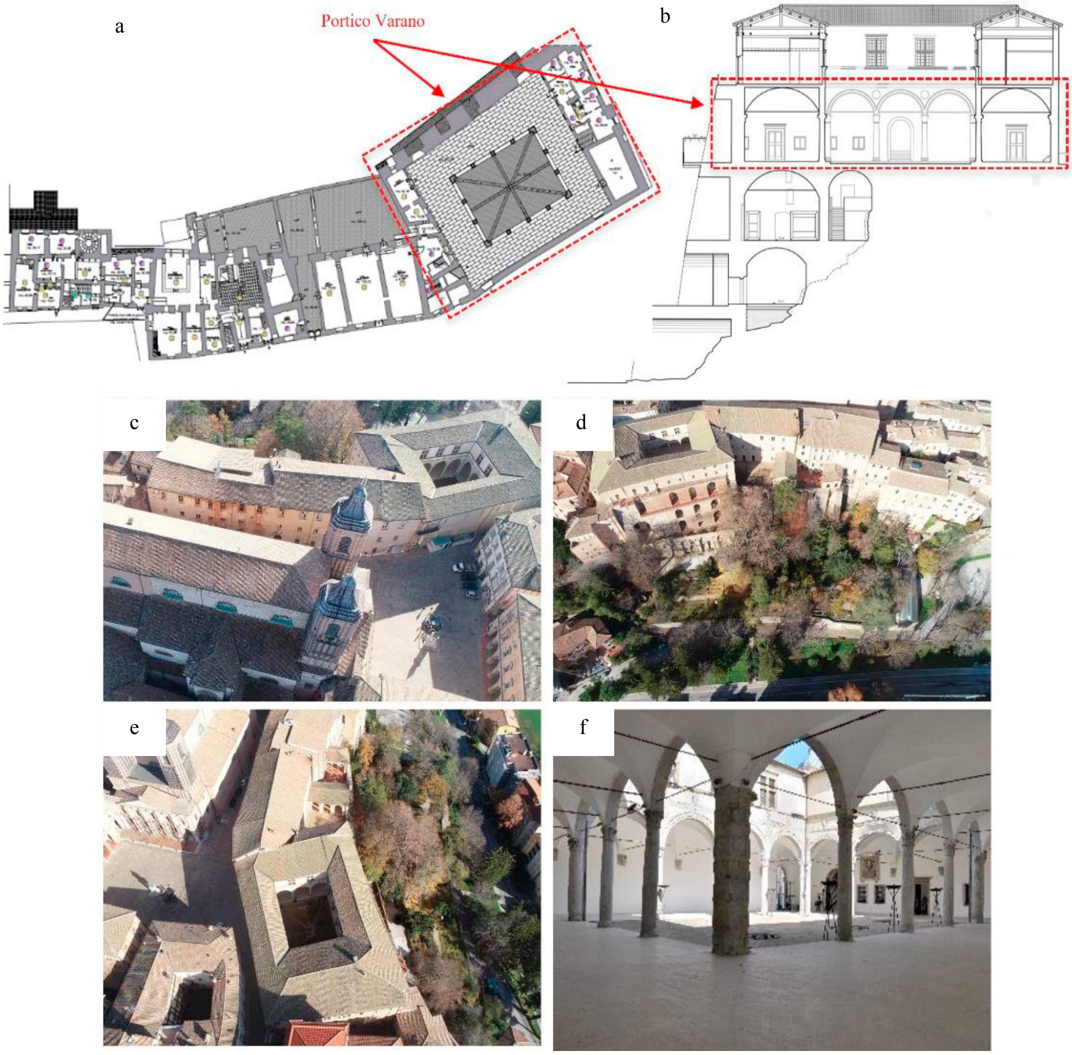


Fig. 1 Ducal Palace in Camerino, Italy: (a) layout at the street level; (b) vertical section; (c) aerial view from the North-West side (d) aerial view from South-East; (e) aerial view from South-West; (f) view of the inner courtyard from the North corner of the quadriporticus.

The results of this preliminary experimental campaign (Table 1) gave a first knowledge of the behaviour of the structure and allowed to optimize both the sensor layout. (Fig. 2), reports the location and typology of the sensors chosen after the optimization of the monitoring system: (i) four uniaxial high sensitivity accelerometers (PCB model 393B31) in the internal middle sides of the quadriporticus; (ii) three uniaxial high sensitivity accelerometers (PCB model 393A03) in the middle of the tie roads across the vaults; (iii) two triplets of displacement transducers (Gefran PZ67-A) across the cracks in the cross vaults (for further details about the configuration of the displacement transducers, refers to Cipriani et al. 2021); (iv) two wireless sensors for internal temperature and relative humidity (Elitech RC-51H); (v) a weather station for temperature, relative humidity, wind speed and direction (WatchDog 2700) located in a balcony at the first floor.

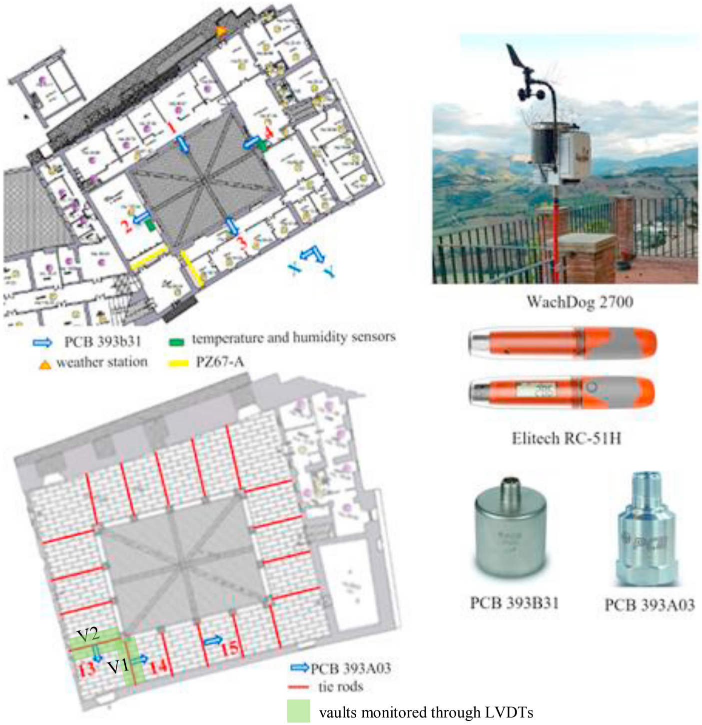
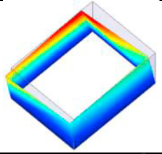
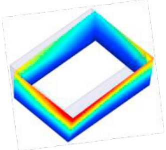


Fig. 2 Type of sensors and related configuration used in the Monitoring System.

Table 1 Results about the AVT ambient vibration testing.

Mode	Method	Frequency [Hz]	Damping ratio [%]	MAC	Modal shape
1st translation in X	SSI/Cov	3.36 Hz	1.86 %	100 %	
2nd translation in Y	SSI/Cov	4.52 Hz	3.71 %	100 %	

The acquisition procedure was developed in the cRIO 9045 using the programming environment National Instruments LabView to control the entire process. The initial configuration (October 2020 to May 2021) used a continuous data logging with a fixed time step of 30-minute time logging every 2 hours. Nevertheless, this configuration was not able to take the time history of a seismic event if it would happen close to the site but outside the recording-windows.

Therefore, a new system configuration where the data logging was continuous in the 24 hours with a data package of 10-minute, 1200 seconds, and a frequency resolution of 0.017 Hz, was adopted. Once acquired the recorded data, the automatic procedure organizes them, selects the signal to process and performs the identifications of main dynamic properties of the structure, i.e., natural frequencies, damping ratios and modal shapes.

3. Automated detection of dynamic properties

3.1. Description of the proposed procedure to auto menage and process the data acquired

In the proposed procedure, the algorithm identifies recorded data related to seismic event relevant to operational conditions through the subsequent steps: (i) daily downloads the extreme events occurred near the site of Camerino from the INGV website; (ii) chooses the data to be kept by the attenuation relationship law of Sabetta and Pugliese, e.g., Sabetta et al 1996, plus the data necessary for monitoring, these latter chosen by the operator (with reference to the parameters of the attenuation law necessary to predict the peak ground acceleration in the site of interest, they were calibrated by a statistical approach, starting from the data of seismic events occurred within the last ten years); iii) post-processes the data with a machine learning toolkit “the hierarchical clustering” that starting from the outcome of the dynamic identification algorithm, the SSI/cov, e.g., Peeters et al 1999, groups the real pole into clusters and automatically assesses the dynamic parameters of the structure; (iv) tracks the variation of the natural frequencies over time and evaluates their possible fluctuation with the environmental conditions; (v) takes information about the modal shapes with the MAC parameter between those identified from the ambient vibration tests and the modal shapes identified during the monitoring period.

3.2. Discussion about the results after an event occurred close to the site of Camerino

From the seismic events database acquired from the INGV website for the Camerino site, a particular event (whose location and features are reported in (Fig. 3) is chosen and used as “tester” for evaluate the effectiveness and efficiency of the automatic procedure proposed. This latter was implemented to save every event characterized by a magnitude higher than 2, which is chosen as threshold for the intensity, with an epicentral distance lower than 30 km from Camerino. Once stored an event having the desired features, the procedure calculates the Peak Ground Acceleration (PGA) according to the mentioned Sabetta-Pugliese attenuation law. The calculated PGA is compared to a PGA threshold equal to 0.001g and if the value is lower, then the recorded event is disregarded, otherwise the data acquired are used for the system identification procedure. The evaluation of the procedure is articulated in the following points: (i) from the overall data logged, a time windows of 10 minutes before and after the event is selected and considered; (ii) OMA is performed with reference to the selected time windows, and repeated one and two hours after the event; (iii) the natural frequencies and the modal shapes identified with reference to the selected event are compared with those previously identified, that is the day before the event.

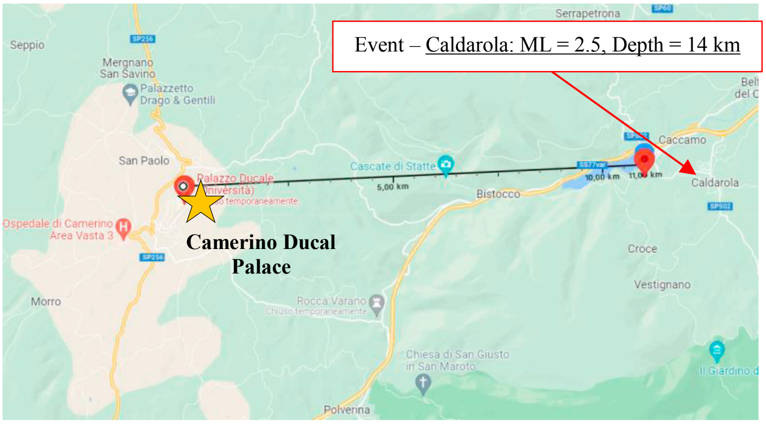


Fig. 3 Event to be analysed from the recently seismic events occurred within 30 km from Camerino.

As a first result, one of the four accelerometers time history is shown in (Fig. 4a) reports the overall 30 minutes time window recorded, while (Fig. 4b) provides a close-up view in the nearby of the occurrence of the event (nearly 4 minutes). From the figures it can be observed that the automatic procedure is able to identify the seismic event chosen as tester also confirming the goodness of the limits chosen for the parameters (magnitude, epicentral distance and PGA). The red line in the (Fig. 4), represents the time event in the INGV website, whereas the green line represents the instant in which the event it was recognized by the accelerometers installed on the first floor of Portico Varano. There is a delay, indeed, between the time of the event recorded by the INGV and the one seen by the accelerometers.

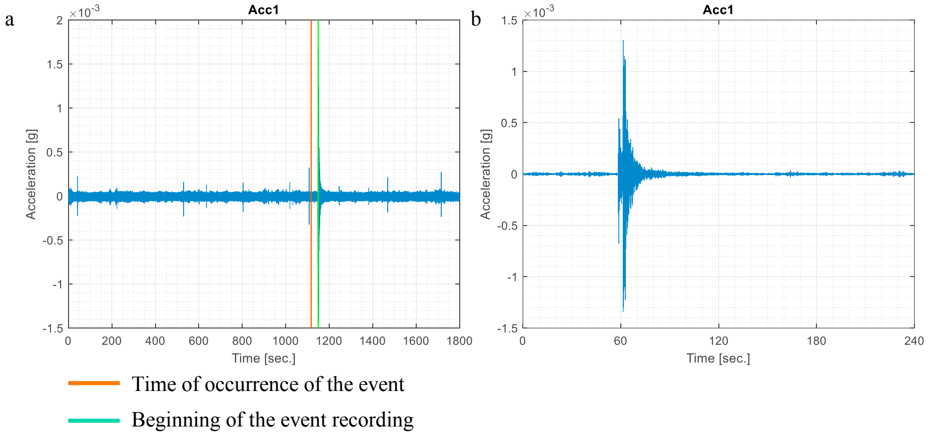


Fig. 4 Time history of the Caldarola seismic event recorded by Accelerometer 1: (a) 30 minutes time window and (b) close-up view in the nearby of the event occurrence.

Fig. 5 shows the evolution of the natural frequencies of the main modal shapes (1st translational in X direction and 2nd translational in Y direction) over time, derived by the OMA carried out from the data acquired. It is worth to note that the natural frequencies tracking refers to a time interval spanning from the day before to the day after the event. The results show that automated procedure to detect the modal parameters of the structure by a hierarchical clustering about the stabilization diagram poles, is able to find the main natural frequencies of the structure. Moreover, these parameters seem to have a linear trend over time except for some acquired data (i.e., 14 April 2022 9 p.m. and 15 April 2022 9 p.m.) where only the 1st modal shape translational in X is recognized.

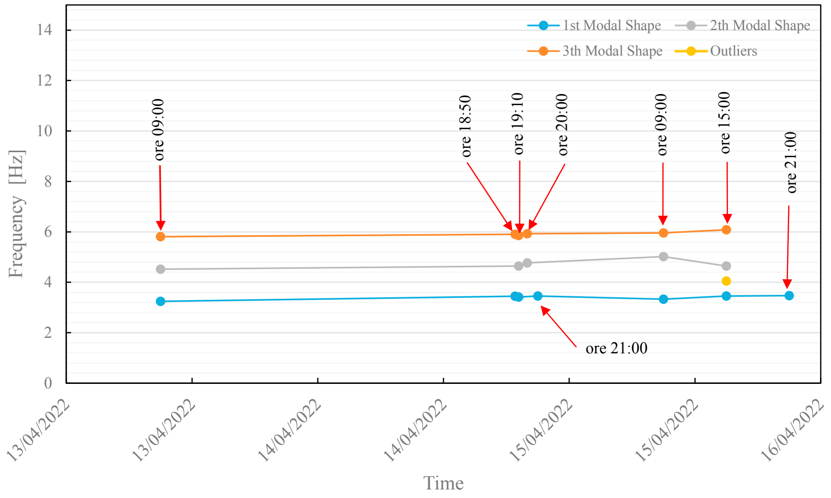


Fig. 5 Evolution of the natural frequencies of the main modal shapes in a time interval spanning from the day before to the day after the event.

As described in Cipriani et al. (2021), this is due to the level of environmental noise, which is very low in historical centre of Camerino during the evenings and nights because the area was still restricted (red zone) because of the major damages after the 2016 Central Italy earthquakes and consequently the acceleration input is very low with respect to the instrument noise.

Fig. 6 shows the evolution of the displacements recorded by the two triplets of displacement transducers installed in a diagonal configuration across the cracks of the vaults 1 and 2 (Fig. 2) in a time interval spanning from the day before to the day after the event of Caldarola. It can be observed that, in general, the event does not provide significant increments of the damaging already identified in the vaults. The displacements, indeed, remain the same for the linear transducers 2 and 3 of vault 2 and for the transducers 2 and 4 of vault 1 during the observed time interval. While only a slight change is detected in the acquisition performed ten minutes before the occurrence of the event in the transducers 1 (vault 2) and 3 (vault 1), towards the zero configuration which corresponds to their first installation. These little changes are, therefore, independent form the event. Moreover, the results agree with those achieved in the tracking over time of the natural frequencies, which did not suffer significant modifications. Consequently, the Caldarola event was correctly recognized and processed by the proposed procedure without increasing both the crack patterns of the quadriporticus and the damages of the Ducal Palace.

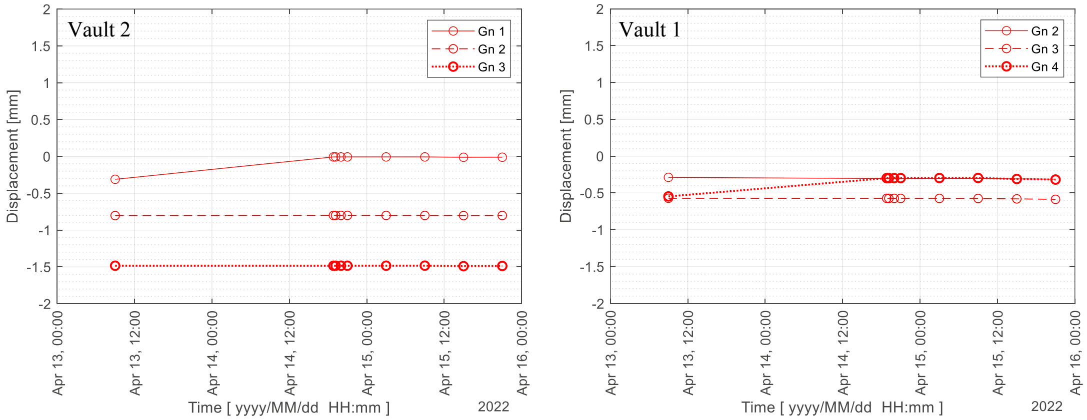


Fig. 6 Evolution of the vault displacements recorded by the two triplets of transducers in a time interval spanning from the day before to the day after the event.

4. Conclusions

In this paper an automated procedure for automated management and post-processing of data acquired through a permanent monitoring system is proposed. The data acquired through ambient noise vibrations may encompass measurements of different sensors like accelerometers, displacement transducers and data related to environmental conditions. The post process provides information regarding the modal properties of the building, i.e., the natural frequencies and the modal shapes. The automated procedure can be particularly useful for architectural heritage and monumental buildings vulnerable to natural hazards such as earthquakes. The procedure provides a daily control of the modal parameters of the monitored building and consequently the opportunity of investigating more in detail the eventual changes detected and, if necessary, provide an alert. Moreover, once established proper thresholds in terms of magnitude, epicentral distance and PGA with reference to the site where the structure under investigation is installed, the procedure is also able to recognize and acquired data related to a seismic event that can be significant for the building. The data related to the seismic event are automatically processed and the related results compared with the modal properties in the operational conditions. The proposed procedure, that can be suitable not only for buildings but also for a wide range of civil structure and infrastructure, was applied to the case study of the Ducal Palace of Camerino and its quadriporticus. Preliminary results related to both the operational conditions of the building and the data acquired after a near seismic event shown to be very promising.

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