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A BIM-Based Model for Structural Health Monitoring of the Central Body of the Monserrate Palace: A First Approach

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Abstract: The preservation and safeguarding of built cultural heritage is a permanent concern for institutions. These structures were generally poorly prepared for movement triggered by natural disasters, a situation further complicated in the case of earthquakes, as each building has a unique structural dynamic linked to its geometry, materials, method of construction and environmental conditions. The use of structural health monitoring (SHM) systems integrating monitoring techniques as well as inspection and structural analyses has gained great relevance in the appearance of low-cost IoT (Internet of Things) sensors on the market. In this paper, an IoT BIM-based solution is presented for real-time monitoring using low-cost sensors in the scope of building SHM systems. The case study takes place at the central body of the Palace of Monserrate, one of the most distinguished elements of the Cultural Landscape of Sintra. An H-BIM model was created in Autodesk Revit® software (version 2022 and 2023) based on a point cloud, and used as the basis for the numerical model developed in 3MURI. A MeM low-cost sensor was installed on the third floor of the central tower of the Monserrate Palace in Sintra, and the data gathered were recorded in the H-BIM model. The capacity to acquire real-time information on a structure's vibration, both during normal operation and after an extraordinary occurrence, could allow the application of more effective maintenance and repair practices, resulting in lower operating costs and allowing for the best management of built cultural heritage.

Keywords: H-BIM; TLS; GPR; structural health monitoring; digital twin; low-cost sensor

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1. Introduction

Preserving heritage buildings, such as historical masonry constructions, is relevant to the individual and collective identity of countries, as well as to fuel tourism. In line with the need for the preservation and conservation of historical constructions, the number of designed and applied structural health monitoring (SHM) systems has increased significantly in the last two decades. The final aim is to assess their structural behavior, especially regarding seismic performance, integrating monitoring techniques, inspections and structural analyses.

Historical masonry constructions have been shown to be vulnerable to natural disasters, such as earthquakes, mainly due to their intrinsic fragility. Portugal's seismic hazard puts a high number of historical constructions at risk of damage and collapse, namely, most of the old masonry constructions, which are particularly vulnerable to seismic activities. For the seismic assessment and strengthening of historical constructions, a multi-disciplinary approach is required [1,2]. This approach is a step-by-step procedure, starting with the knowledge process of the historical constructions under study, and should include, among others, the following steps: (i) the research, compilation and analysis of relevant historical data for the generic characterization of the construction and (ii) the definition of a plan for experimental campaigns.

For most historical constructions, it is recommended that the experimental campaigns include: (i) the acquisition of geometry; (ii) static and dynamic monitoring systems; (iii) experimental tests for the mechanical characterization of materials and/or structural elements; and (iv) ambient vibration tests for the dynamic identification of the structure.

According to the characteristics of the building (e.g., the irregularity or dimension of objects), there are many alternatives for the acquisition of geometry using more conventional methods, such as the classical methods of topography [3], photogrammetry [4] or terrestrial laser scanning (TLS) [5], which produce a three-dimensional point cloud. TLS allows for the rapid collection of data from geometry with a high level of detail [6].

The mechanical characterization of materials and/or structural elements can be conducted through different types of tests, taking into account the in situ limitations and available resources. These can be semi-destructive and non-destructive tests, such as the removal of masonry samples, flat-jack tests, ambient vibration tests and ground-penetrating radar (GPR) tests [7].

Experimental dynamic characterization is essential for the obtainment of an accurate portrayal of the current state of structures, the calibration of the numerical models of the constructions to be utilized for seismic structural assessments and the design of retrofitting works [8,9], and the structural health monitoring of the building by observing changes of its dynamic behavior over time [10].

The building information modeling (BIM) approach uses a centralized database that allows access to information in accordance with a users' profile. This brings benefits at each stage of this type of work, namely, due to its adaptability to project modifications or the easiness in communicating between all specialties involved in the design and construction process, reducing the costs and time of planning and construction and, consequently, making the process more efficient. One of the emerging fields of BIM application is in monuments and buildings with heritage value, usually referred to as an H-BIM. According to Biagini et al. [11], the major difference between a BIM model and an H-BIM model is the need to consider not only the information regarding the objects and their properties, but also their history and cultural identity. Additionally, the level of complexity of the representation of elements in an H-BIM needs to consider not only its function, but also future analyses intended for the element; as such, it is important to determine the geometric detail during the modeling and to establish the relevant information associated with the object [12]. As in the case of the Basilica of Collemaggio, reported on by Brumana et al. [12], several configuration levels of detail, geometry, accuracy and information were tested to establish modeling protocols and guidelines to support the BIM-based management. There are other applications and considerations regarding the use of an H-BIM, such as: conducting a structural health assessment through a point cloud BIM-generated element, simplified and meshed, for the creation of a finite element model that fulfills the structural analysis requirements [13]; the creation of a unique model that serves all stakeholders involved in the conservation and rehabilitation of a damaged monument [14]; the uses of an H-BIM model as a digital platform to support tests of construction solutions to achieve the final solution of the rehabilitation process [15]; or the use of an H-BIM as a central database for facility management [6].

One of the great challenges in the implementation of H-BIMs is the non-existence of information (graphical and non-graphical). Heritage buildings are often complex and irregular, with absences of documentation concerning the material (and their properties) when compared to young buildings. Buildings with heritage value do not have monitoring systems installed and follow strict rules concerning their installation, preventing the acquisition of relevant data for SHM systems.

Through the identification of this gap, the main objective of this work is to present a BIM-based solution that enables real-time structural monitoring based on low-cost sensors. The central body of the Monserrate Palace is used as the case study, in which the geometry and description of the materials of the structural elements are defined and stored in an H-BIM model. Thus, this work is divided into the following main parts: (i) data collection and geometric modeling, (ii) real-time structural monitoring based on low-cost sensors, (iii) numerical modeling and calibration and (iv) the proposal of a SHM for the central body of the Monserrate Palace.

2. Literature Review

SHM is a procedure that aims to estimate a structure's condition through the evaluation of measured physical features involving three stages: signal collection, processing and interpretation.

The first stage can utilize a varied range of sensors to measure the physical properties of structures, and is divided into: kinematical (displacement, velocity and acceleration), mechanical (forces, deformations and stress) and ambient (wind and temperature) [16]. Combining various sensing technologies with data acquisition and processing capabilities plays a significant role in assessing the condition of structures [17].

Kinematic sensors in SHM applications measure the motion induced by external forces, ranging from moderate or strong winds to seismic waves, traffic and human-induced vibrations, among others [16]. By measuring the acceleration of the in-test structure through the application of accelerometers, the study of the resulting building vibrations has several fields of application, including the analysis of environmental vibrations and their effects on the comfort and safety of these structures. An accelerometer is an electro-mechanical device that measures the acceleration forces acting on or being exerted onto an object. There are various types of accelerometers that diverge in operation mechanisms, including: piezo-electric, which uses the piezo-electric effect of a specific material and transforms a type of energy into another, which then produces an electrical signal in response to the parameter being measured; force balance, where the relative displacement can be measured with a capacitive gauge or a transducing material (piezo-electric ceramic) fixed onto the compliant element (best for lower frequencies); piezo-resistive, which generates resistance changes in displacement sensors, which are a part of accelerometer systems (best option for measuring the impulse where the amplitude and frequency range are high); and the capacitive micro-electro-mechanical system (MeMs), which works according to capacitance changes in a seismic mass under acceleration [18,19]. With the increasing demand for more efficient and lower-cost sensors for monitoring buildings, coupled with the fast increase in micro-sensor technology and jutting micro-controllers (e.g., Arduino and Raspberry), the increased application of low-cost sensors (encompassed in the MeM category) has been founded in the literature, as reflected in the work of Komarizadehasl et al. [20–22], which demonstrates how to design and set up low-cost sensors of structural vibrations and inclinations. This solution could be the starting point for reducing the uncertainty of building monitoring by increasing the density of measurement points. This new technology, linked with the higher processing power of computers (that allow for the processing of substantial amounts of data) enables the spread of the application of embedded intelligence in buildings, i.e., "smart buildings", through IoT (Internet of Things) solutions. The application of the IoT allows for the permanent monitoring of buildings with real-time readings accessible at a distance. Although the permanent monitoring of buildings for indoor environment data with low-cost sensors can be easily found in the literature, as exemplified in the works applied to historic buildings by Casillo et al. [23], in museums of Chianese et al. [24] and Amato et al. [25] and in the facility management of Valinejadshoubi et al. [26], for dynamic data, permanent readings with the support of the IoT in buildings have been less expressed in research papers; however, there has been an increase in applications, as is the case of Pierleoni et al. [10]. However, in heritage, due to the severe restrictions to which the buildings are subjected to, the application of such monitoring has had minor presence in practice according to Mobaraki et al. [19]. As for applications of wireless sensor networks (WSNs) linked to BIM approaches, such solutions have gained prominence within the management of built environmental assets post-construction, with a focus on environmental data, as described in the work of Mataloto et al. [27,28], applied to energy saving.

Currently, the implementation of IoT solutions for continuous SHM is underway in the scientific community; however, such works have yet to reach significant volume. This direction of research could allow for quick decision making due to real-time data availability in a post-occurrence instance, leading to a shorter time for the recovery of essential utilities, mitigating downtime and associated financial costs. According to Kim and Frangopol [29], continuous monitoring over a long-term period can increase the reliability of the assessment and prediction of structural performance. Gentile et al. [30] described the largest monitoring system in a cultural heritage monument with an implementation of a wired sensor network with a semi-manual data export IoT solution, demonstrating the potential of such surveillance systems during the life cycle of a building. Recently, the work of Li et al. [31] demonstrated the implementation of a multi-sensor solution monitoring structures for guiding maintenance works by measuring safety during the process, demonstrating the importance of surveys with an IoT solution for data management and concluding the importance of a WSN for future works. As such, the apparent future path of research efforts is implementing low-cost MeM WSNs with IoT systems for heritage SHM, notwithstanding monitoring with better-established methods.

Additionally, considering the influx of large quantities of data, methods of monitoring data analysis and structural state assessment have expressed a concern. As Mondal and Jahanshashi [32] stated, the processing of procured data enabling real-time decision making remains an impediment. Therefore, in the literature, some solutions have been proposed to deal with large sets of data, such as the application of machine learning in the interpretation of photographic data [32], with prediction models having been applied through algorithms [29,33,34].

3. Materials and Methods

Extensive research of relevant historical data was the first step to better understanding the heritage buildings. In parallel, in situ tests were performed (GPR and ambient vibration tests) for the characterization of the structural elements, together with field surveys to acquire geometric information carried out to obtain the geometry of the buildings using total station and TLS in conjunction with targets that were previously coordinated with the use of a global navigation satellite system (GNSS). The final point cloud was used as the basis for the 3D modeling in the BIM environment, and the database was enriched with information concerning the building materials and their properties. Based on the H-BIM model, a numerical model was developed using 3Muri software (version 13) [35], for which a dynamic modal analysis was conducted; the numerical model was calibrated according to the results of the in situ tests. In complement, static and dynamic monitoring was performed. For the latter, two types of sensors are used, including highly sensitive force balance accelerometer equipment for periodic monitoring, utilized for the structural assessment of the buildings and model calibrations, and a micro-electro-mechanical system (MeM) low-cost sensor was employed for both unique (10 min reading) and continuous (4-month reading) monitoring.

3.1. Case Study Description

The Monserrate Palace belongs to the Cultural Landscape of Sintra (Figure 1), classified as a World Heritage Site by UNESCO since 1995, and is characterized by its unique identity and the progress of architecture and technology in landscape and project planning. These topics alone are an indication of its heritage value, emblematic identity and consequent relevance for the research and preservation of the palace and its surroundings.

Monserrate's history progressed through cycles of greatness and ruin (Figure 2), starting with the chapel devoted to Our Lady of Monserrate, after whom the palace was named, dating back to 1540. In 1718, the property was bought by the Mello e Castro family and administrated through third parties. As the earthquake of 1 November 1755 devastated the area, destroying the houses on the grounds of the current palace, De Visme (tenant) took care of the recovery of Monserrate and built a neo-gothic castle with special attention to characteristics such as symmetry, proportion and balance. This building followed guidelines quite common in England, and set the tone for what would be the structure of the palace throughout the centuries: three towers, where the central one would have a square base and two floors from which two wings led to each end of the palace with circular towers. De Visme left the property abandoned from 1791 to 1794, after which William Beckford, an English aristocrat and art connoisseur, took the lease and carried out restoration work. Due to the war climate in 1799, he returned to England, and Monserrate was left, once again, to abandonment.

Figure 1. Location of the case study: Portugal (**left up**), Lisbon (**center up**), Monserrate Park and palace (**right**), Monserrate Palace (**left down**).

During this cycle, the property was vandalized and received different visitors, one of which was Francis Cook, an English art appreciator, who, during his Grand Tour in 1856, became a tenant, and in 1863 becoming its most notorious owner. It was during Cook's period as an owner that Monserrate came closest to what it is known as today: a palace with gothic, Indian and Moorish influences, with ornaments that extended to the outside of the palace, showing how important it was to be in harmony with the surrounding nature and preserving the memory of the previous owners by preserving the plan of the house, with it later being the scene for large parties, dinners and balls [36].

Due to World War II and the resulting crisis, the Cook family had to sell the palace to Saúl Saragga (an antique dealer), who sold the house to the Portuguese state, after which it was handed over to the management of the park to Parques de Sintra—Monte da Lua S.A. (PSML) in 2007.

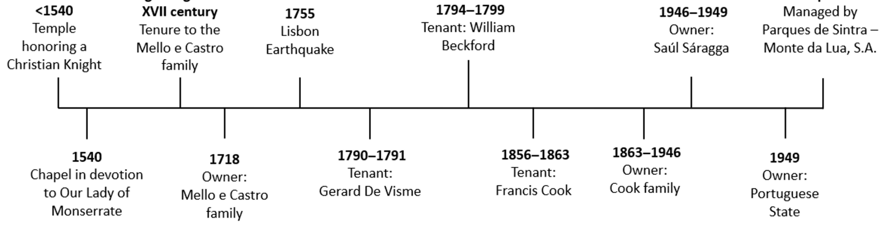


Figure 2. Chronogram of Monserrat, showing who it belonged to and the different occupants.

The current iteration of the building rests on a raised platform with a longitudinal symmetrical plan composed of a rectangular central body with two circular plan towers at the ends. The building is 60 m long by 20 m wide, with 5 floors in total. Most of the floors comprise wood flooring supported by wooden beam structures, with a few exceptions of tile flooring over brick vaults supported by steel beams. The exterior (structural) walls of the building appear to be of rubble stone masonry and air lime mortar, with the interior walls appearing to be "tabique" partition walls. In the central body, the walls that support the interior dome appear to have a mixed structure, being part rubble stone masonry for the first 2 floors and the rest having been built with brick masonry. However, due to the lack of detailed records, the composition of all existing elements is not evident; for the extensive characterization of the monument, it would be necessary to execute non-destructive tests to ascertain particular elements.

For the case of the present work, the central rectangular body was chosen as the focus, due to the symmetrical quality of the building. Specifically, the experimental campaign was started on the third floor of the central body, since this floor was not visitable by the public, allowing the campaign to be performed with reduced external impact (such as uncharacteristic vibrations of the structure due to the walking of visitors) and ease of access to areas for the placement of sensors near the outer walls that define the body. In the future, continuous monitoring should first be extended to the whole central body (Section 4) and then to the entire palace.

3.2. Data Collection

3.2.1. Geometrical Data Acquisition

Regarding the geometric data acquisition, 336 scans were carried out with TLS to obtain geometric information about the Monserrate Palace. Of this total, 205 scans corresponded to the rooms of the central body and side wings, which were the object of the study. These scans were acquired with a Faro Focus S70 laser scanner starting in April 2021. For each scan, a combination of parameters was selected, considering the amount of information that was needed from each room of the palace and finding a balance between collected information and the duration of its acquisition. The detailed point cloud was processed in Autodesk ReCap® [37], and was the basis of the geometric model (Figure 3). To geo-reference the model, a topographic survey was carried out with a GNSS receiver and total station with the support of topographical targets located at strategic points (Figure 4). The coordinates (M, P) are relative to the PTTM06/ETRS89 system, and the H coordinate, orthometric altitude, is in relation to the Cascais tide gauge.

Figure 3. Point cloud perspective view.

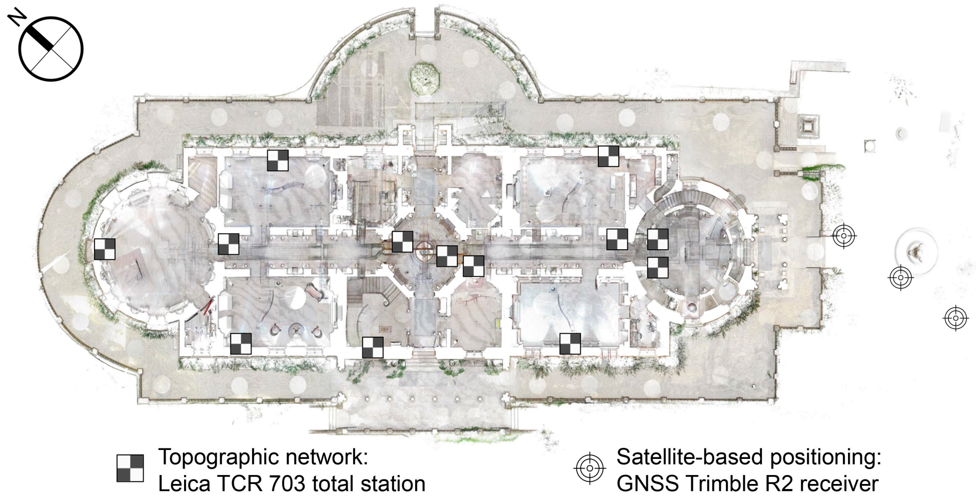


Figure 4. Location of the topographic network support targets. Plan view of point cloud in Autodesk ReCap®.

3.2.2. Characterization of the Structural Elements

Due to the scope of the work, a clearer comprehension of structural composition was required whilst maintaining the physical elements of the palace; as such, non-destructive tests were applied. Therefore, in areas where the construction technique applied was unknown, ground-penetrating radar (GPR) surveys were conducted by a team from Morph Geociências Lda [38] and coordinated by the IST team. Through the emission and reception of electro-magnetic waves in the object, it was possible to decipher cavities and alterations in materials, which allowed for a better understanding of the constitution of the elements. In total, we obtained 22 polygons of a 3D inspection with a 1.6 GHz geo-radar, 4 discrete profiles with a 1.6 GHz geo-radar in the columns, 2 discreet profiles with a 500 MHz geo-radar on the pavement and 3 discreet profiles with a 500 MHz geo-radar in the wall. Of which, for the central body, there are 14 polygons of 3D inspection and 2 discrete profiles in the columns. The survey helped to identify the construction apparatus in several walls that were previously mis-categorized, such as the walls on the higher floor in the central tower, which turned out to be composed of masonry instead of brick (Figure 5c) as originally expected, as well as the opposite seen in the ground floor corridor niche (Figure 5a,b). For the remaining elements, the construction technique was inferred from the surveys or exposed elements, such as the walls viewed from the foundation level.

3.2.3. Static Monitoring of the Main Crack

Due to the good conservation of the Monserrate Palace, no cracking state was generally acknowledged. Only one major crack was identified indoors in the west workroom over the window on the third floor of the central body of the palace (Figure 6). As no other cracks or inclinations in the walls were surveyed, it was decided to only place crack meters along this crack to periodically monitor and control any movement that occurred instead of displacement transducers.

3.2.4. Ambient Vibration Tests and Unique Dynamic Monitoring

Comparison between Sensors

For the ambient vibration tests, using the unique dynamic monitoring, two types of accelerometers were placed in situ with different typologies and basic characteristics (Table 1 and Figure 7b). The first was a piece of force balance vibration measuring equipment (EpiSensor ES-T triaxial measuring and digital recording unit) from Kinemetrics Inc. (Pasadena, CA, USA) The Etna2 was capable of recording a series of accelerations observed in three orthogonal directions (two horizontal and one vertical). Their communication was performed using a laptop computer connected with a GPS/GNSS antenna (global position system/global navigation satellite system). The units were configured with the highest available sensitivity of ±1 g at full-scale with a 24-bit resolution (accelerations ranging from 5.96×10^{-8} g to 1 g) for a frequency of 200 Hz, and each assay lasted for a duration of 660 s.

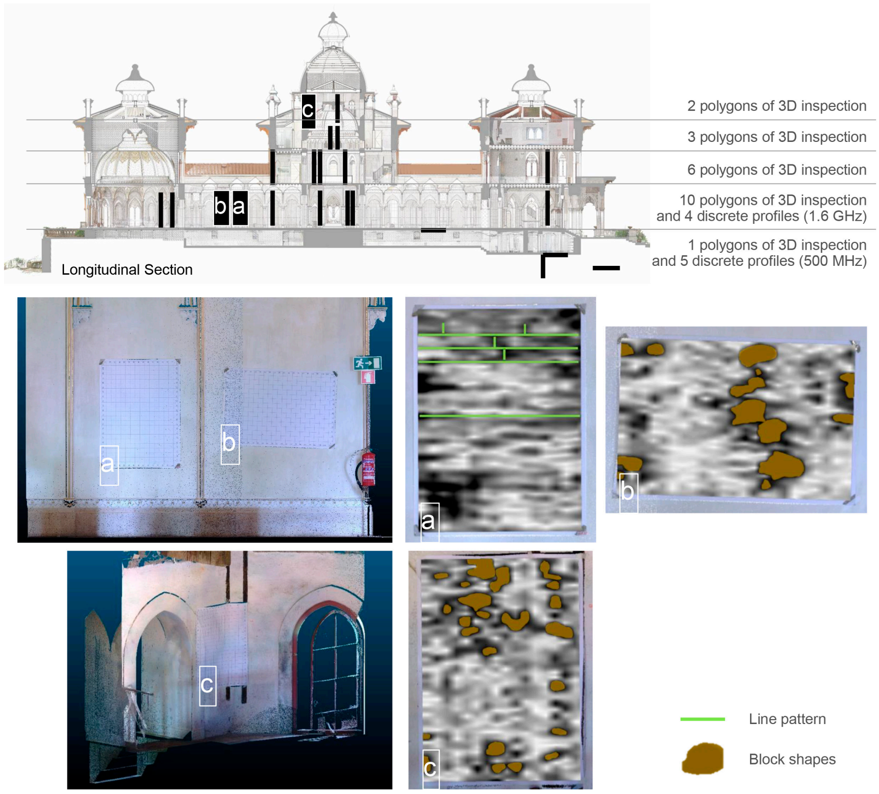


Figure 5. Location of GPR windows in longitudinal section of the palace (top) and 3D view (left): (**a**) window at ~0.091 m deep displaying a line pattern consistent with brick masonry; (**b**) window at ~0.17 m deep displaying block shapes consistent with rubble stone masonry; and (**c**) window at ~0.12 m deep displaying block shapes consistent with rubble stone masonry.

Figure 6. Location of the cracks in the west workroom over and below the window on the third floor: view of crack meters (**left**); photo of the cracks in relation to the wall (**middle**); location in plan view (**right**).

Alongside the low-cost MeM accelerometer sensor, we also used the Bosch BMA280 sensor (Gerlingen-Schillerhöhe, Germany), encompassed in the Bosch XDK110 kit that includes environmental and dynamic sensors and a wireless connection. To characterize the low-cost sensor that would be employed for the continuous monitoring, a comparison of accelerations acquired with the MeM device and Etna2, with an equivalent frequency of 0.005 s, was conducted. The available and applied sensitivity was lower than that for the opposing equipment, with a 14-bit resolution at ±2 g full-scale with 4096 LSB/g (accelerations ranging from 2.44 × 10^{-4} g to 2 g). This sensor allowed for the creation of a record log either via a Wi-Fi connection to an online platform (e.g., Microsoft Azure®) or via a USB cable to a laptop computer using the XDK-Workbench program interface to program and record the readings, programmed using the C language. Due to the high frequency of records and low period of time, the USB connection was utilized.

Table 1. Characteristics of ETNA2 and Bosch BMA280 sensors.

		ETNA2	**Bosch BMA280**
Sensor Performance	Typology	Force Balance	MeM
	Resolution	24-bit	14-bit
	Sensitivity	1 g/2^24 = 1 g/16,777,216 = 59.6 ng 2 g/2^24 = 2 g/16,777,216 = 119.2 ng * 4 g/2^24 = 4 g/16,777,216 = 238.4 ng *	±2 g: 4096 LSB/g = 0.244 mg ±4 g: 2048 LSB/g = 0.488 mg * ±8 g: 1024 LSB/g = 0.977 mg * ±16 g: 512 LSB/g = 1.953 mg *
	Voltage	9–28 (VDC)	1.62–3.6 (VDD)
Environmental Restrictions	Temperature and humidity range for correct operation	−20 °C to 70 °C 0–100% RH (non-condensing)	−40 °C to +85 °C (0.015%/K sensitivity temperature drift)
	Size of sensor	15 cm × 15 cm × 7.5 cm (1.5 kg) (per unit)	60 mm × 40 mm × 22 mm (54 g) (XDK110)
Economic Issues	Sensor cost	EUR~6300	EUR~300 (XDK110)
	Market availability	Y	N
	Easy installation	Y	Y
	Need for accessories, such as data acquisition systems, electric current, wiring, etc.	Y (must have electric current and cable connection between units and antenna)	Y (due to limited battery life)

* Other modes of registration not used in this work.

For this comparison, the accelerometers were placed on the floor in the corners of three of the workrooms on the third floor (Figure 7a,b for the identification of position S1) and leveled with the integrated support system, ensuring that they were in a horizontal plane at points where the largest displacements were expected to occur without the need to fix the accelerometers to the walls, which would damage the property. In total, 4 phases of measurements were performed. In each measurement phase, the accelerations were recorded 2 times for 10 min each to ensure that at least one reliable record was obtained. Four records were obtained with the "master" and two records with each "slave". The in situ testing was conducted on 18 January 2022, and, according to the weather data from "Humberto Delgado" airport, the day temperature varied from 6 to 14 degrees Celsius.

For the comparative test, the rough data from the XDK sensor and treated data from Etna2 were imported into ARTeMIS Modal software (version 7.2.2.3) [39] in an attempt to find the same vibration frequency for both sets. Longitudinal and transverse data for the first "slave" (S1) placement were utilized, ignoring the vertical component. As such, for the XDK dataset, the frequency found for the frequency domain decomposition (FDD) in the X and Y directions was fx = 2.393 Hz and fy = 3.906 Hz, with a complexity of 0.501% and 4.144%, respectively, and a modal assurance criterion (MAC) value of 1. For Etna2, the single point frequency was set to fx = 2.734 Hz and fy = 3.955 Hz, with a complexity of 0.055% and 17.112%, respectively, and a MAC value of 1 (Figure 8). However, though similar vibration frequencies were found, the data with higher sensitivity had clearer "peaks" that would allow us to easily identify frequencies (or periods) and correspondent modes of vibrations. Something that also became evident during the campaign was the instability of the XDK-Workbench program for data recording, resulting in the loss of data after a forced shutdown of the program due to the computer RAM capacity failures (due to the sheer number of entries kept in temporary memory).

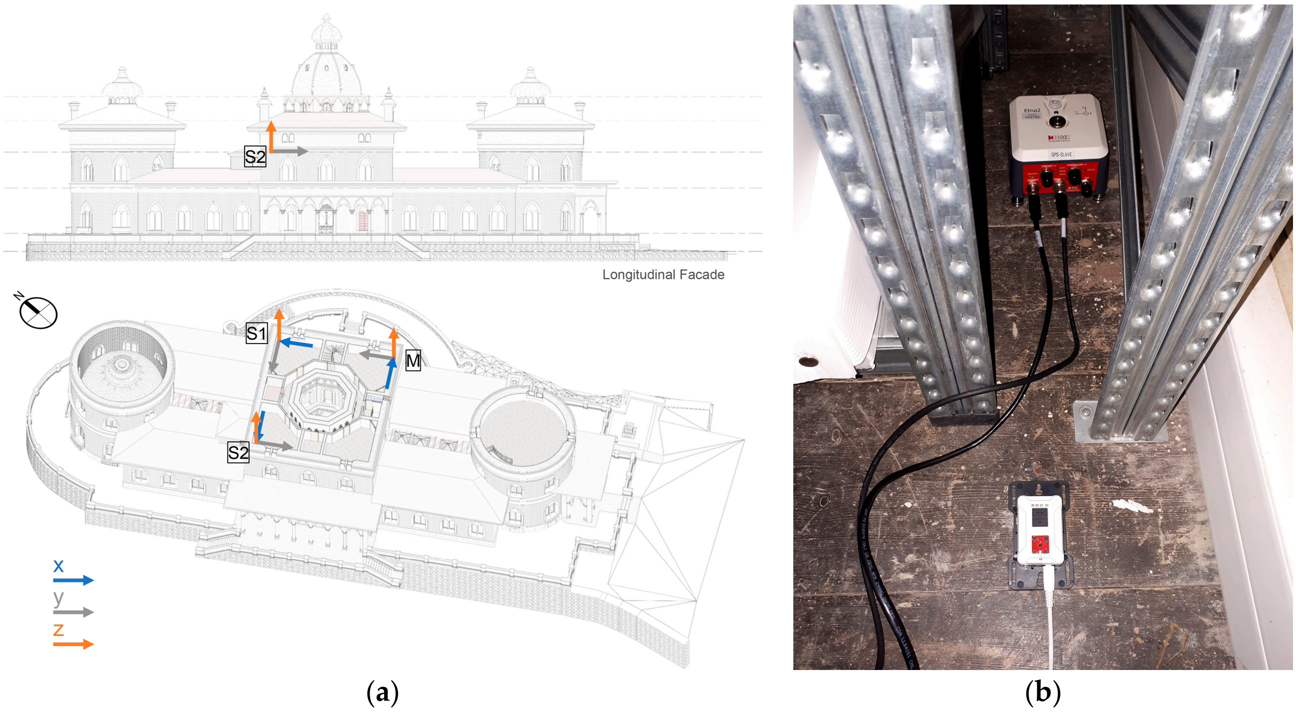


Figure 7. Equipment in situ survey: (**a**) position and orientation of the accelerometers; (**b**) S1 position: Etna2 (top) and XDK110 (bottom).

Ambient Vibration Tests

With the ambient vibration tests, it was possible to define the main dynamic characteristics of the buildings (frequency/periods and vibration modes), which were then compared with the dynamic characteristics obtained through the numerical model simulation based on the performance of the modal analysis (Section 3.4).

The vibration-measuring equipment used for the ambient vibration tests consisted of two autonomous triaxial Etna2 units, with communication carried out using a laptop computer. In the equipment software, it was possible to configure the type and parameters of the readings and order simultaneous recordings. Two different set-ups were defined; set-up 1 included the master sensor M and slave sensor in position S1, and set-up 2 included the master sensor M and slave sensor in S2 (Figure 7a). For each setup, two different records of 10 min were performed.

Then, the Etna2 records were used and the data were processed with ARTeMIS Modal software, dis-aggregated in the respective orthogonal directions and reduced to 600 s in order to "clean" the signal. From the results, a Fourier spectrum was defined that allowed for the discovery of the frequencies for the X and Y directions, which were fx = 3.95 Hz and fy = 4.065 Hz, respectively. These frequencies and corresponding modes of vibration along the two directions were those expected to govern the seismic response of the central body of the Monserrate Palace; thus, they were of primary interest in the seismic analysis of the central tower.

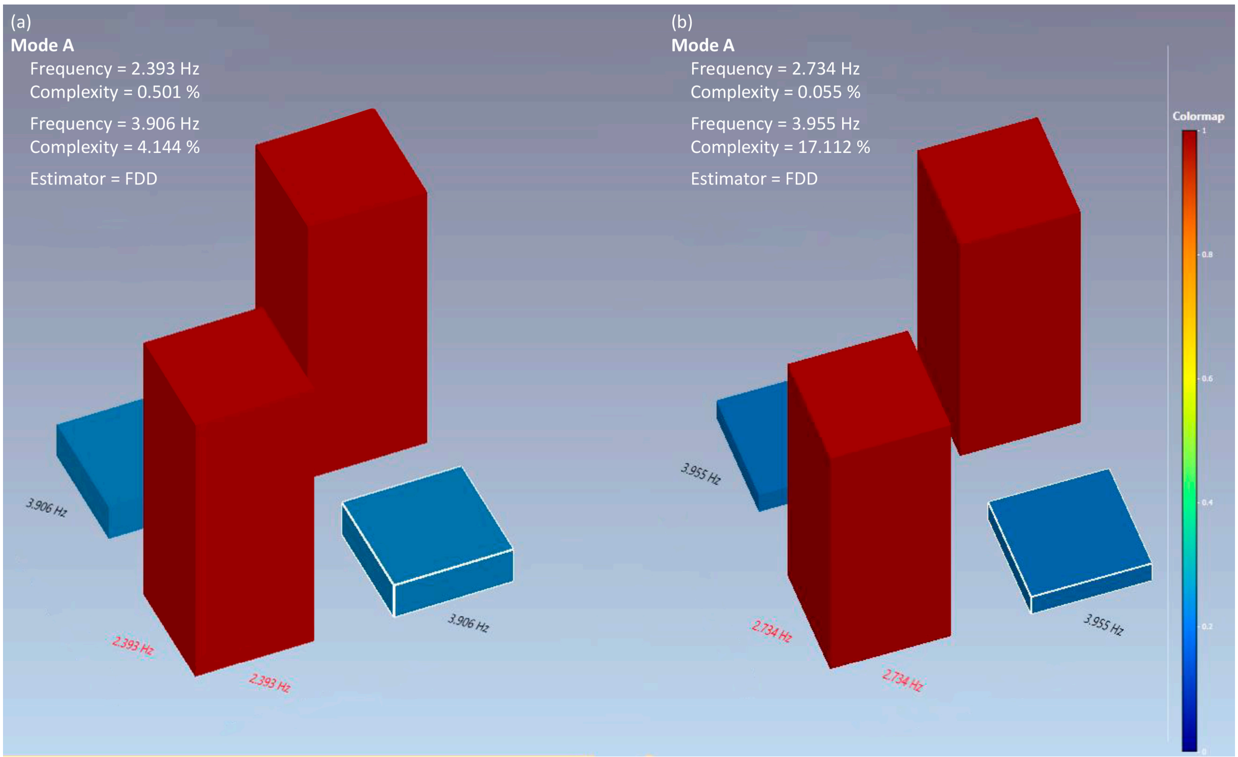


Figure 8. ARTeMIS modal assurance criterion, in S1 position, for XDK (**a**) and Etna2 (**b**).

3.3. H-BIM Modelling

The H-BIM model was developed in Autodesk Revit® software [40]. The geometric representation of the building needed to be compatible with its intended use at an adequate detail level. For heritage buildings, in a conservation context, information concerning materials and elements must be registered with a high level of detail, either in attributes or in geometry. For the case of BIM-based management, the level of detail can be simplified, while the attributes should enable operations along a building's life cycle. As for the structural analyses, the structural apparatus elements needed to be properly represented, having a greater value than decorative and simple architectural elements.

Since the present model had more than one intended use, encompassing the future monitoring aspects (pertaining to management), as well as a basis for the structural model, the elements represented were modeled assuming some simplifications while maintaining the overall shape and function, but ignoring the highly decorative elements while maintaining the point cloud alignments and geometric overall shape. During the modeling process, several approaches were considered to find a balance between both intended uses. As such, the structural floor system was based on floorboards laid over beam systems that were possible to observe in the access to the boiler room. Due to the complexity of the domes, the option Model in Place was used to sketch the overall details maintaining the identity, but simplifying the support system, since they did not have structural relevance. For the doorways, simplified families of doors and windows were created to retain the overall atmosphere in conjunction with the desired geometry (as the 3Muri software only required basic opening information), and for the columns, a family was created, allowing for the repletion and tally of elements. The final model is illustrated in Figure 9. To thoroughly utilize the qualities of the H-BIM, information pertaining to the in situ testing was also added to the pertinent elements. To this purpose, new parameters were created in the wall elements, allowing us to identify the areas surveyed and corresponding report information. Information pertaining to the mechanical properties of the walls, described in the following chapter, were also added as attributes to the corresponding family types as new parameters.

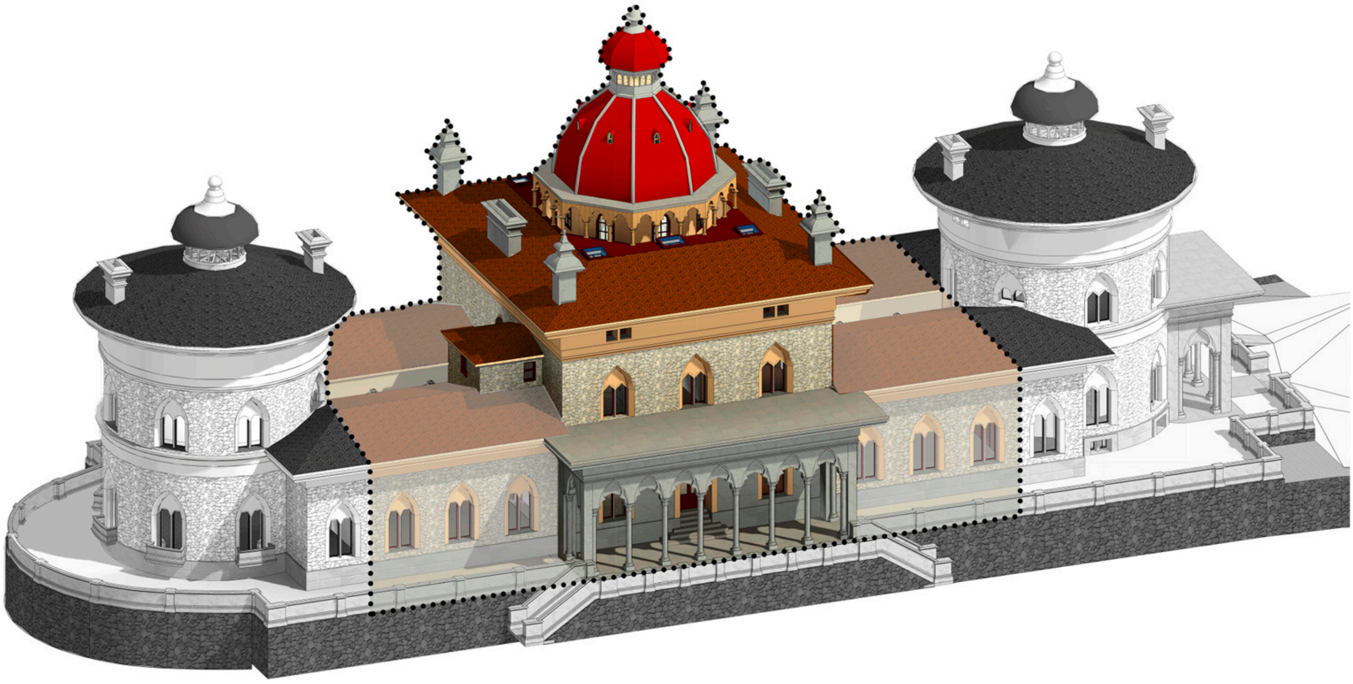


Figure 9. H-BIM representation of the palace: area of study in strong color. The light and strong colors identify the parts numerically modeled.

3.4. Numerical Modelling and Calibration

As previously mentioned, based on the BIM model, the numerical model of the central body of the Palace of Monserrate was developed using 3Muri software [35], which uses the equivalent frame method—EFM [41]. The numerical model was calibrated according to the results of the GPR (see Section 3.2.2) and ambient vibration tests (Section 3.2.4).

The inter-operability between Autodesk Revit® and 3Muri was not automatic; therefore, it was necessary to re-model the structural materials and their characteristics for the structural assessment calculation, using the BIM model as a working basis. To facilitate the process of adapting the plans, average thicknesses and the locations of openings, the plans were exported in a .dxf format to Autodesk AutoCAD® [42] and, after making the necessary changes and simplifications (e.g., imposing that nodes were not too close to each other and that the midline of the wall was coincident in height), the plans were imported into 3Muri. The plans used with the assumed simplifications are illustrated in Figure 10a. The simplifications were performed because the structural program could result in conflicts when modeling and predicting the behavior of different macro-elements due to the mesh created.

After this process, the numerical modeling took place by dividing the structure into 6 levels (Figure 10b) to ensure that all structural elements with different characteristics were defined without major approximations. The mechanical properties of the materials, the geometry of the structural elements and the loads applied were defined based on a previous research work by Candeias et al. [43]. These mainly included stone masonry (regular and irregular) and Portuguese pine wood used in the floors, roofs and partition walls, known as "tabique" walls. The mechanical characteristics of the materials were defined after an iteratively processed development based on the results of the calibration using the results from non-destructive experimental in situ tests and the results obtained with the numerical model by performing a dynamic modal analysis (Table 2).

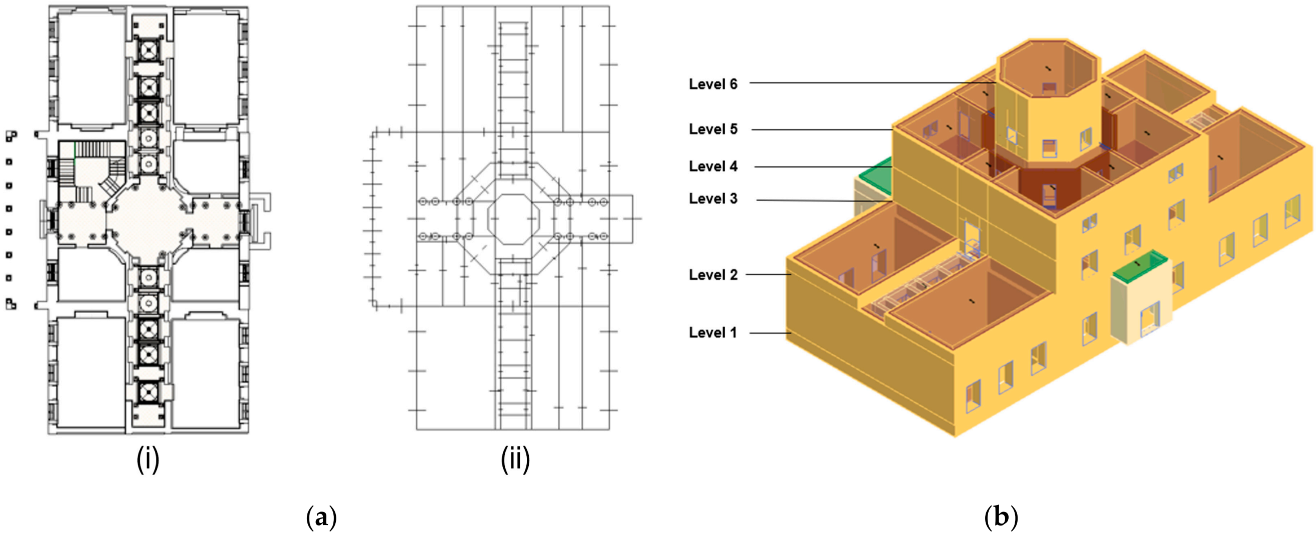


Figure 10. From Revit to 3Muri: (**a**) model in Autodesk Revit® (i) and simplified wireframe plan with all structural elements of all floors superimposed (ii); (**b**) identification of levels in 3Muri.

Table 2. Mechanical properties of wall materials.

	Elasticity Modulus E (GPa)	Distortion Modulus G (GPa)	Shear Strength τ (MPa)	Compressive Strength fc (MPa)	Volumetric Weight w (kN/m^3)
Irregular ordinary masonry with good adhesion	1.70	0.60	2.60	0.08	21.00
Regular stone masonry of quality	2.80	0.90	6.00	0.08	22.00
Partition	0.060	0.0035	0.075	1.000	14.000

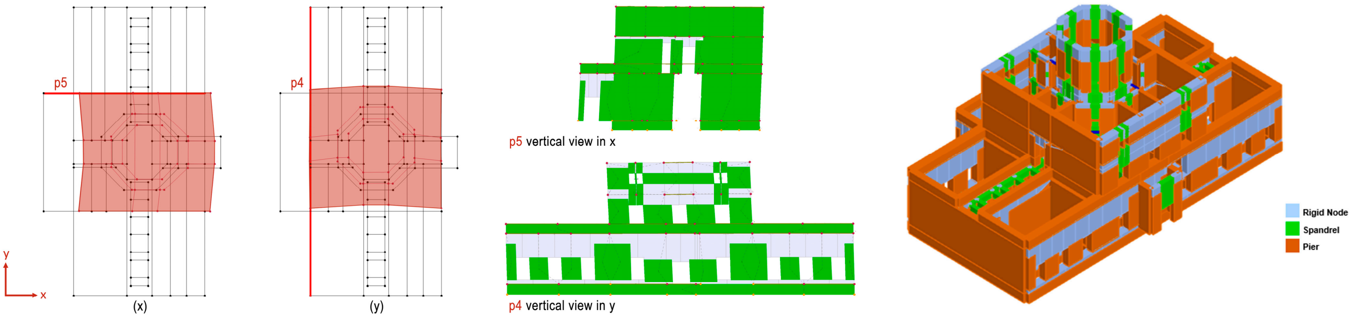
It is worth mentioning that to obtain an adequate numerical model of the central body of the Palace of Monserrate, it was necessary to account for the constraints imposed by adjacent parts of the palace, the ones necessary to obtain the correct dynamic characteristics of the body under analysis. Thus, the numerical model accounted for the central tower and the two wings (Figures 9 and 10b).

In 3Muri, it was possible to perform a modal analysis and obtain the main dynamic characteristics: periods, vibration modes and mass participation factors. After many iterations and changes to the material properties and types of walls in the 3Muri software, the results presented in Table 3 showed the dynamic global response of the calibrated model, and were in accordance with the results obtained in the in situ tests (with an error margin of 9.5% and 6.9% for the fundamental frequencies in the X and Y directions, respectively). The first fundamental vibration mode had a frequency of 3.579 Hz and corresponded to a pure translation in the transverse direction (X direction). The second mode of vibration was a pure fundamental Y-translation mode and corresponded at a frequency of 3.784 Hz in a longitudinal direction. These two fundamental vibration modes can be seen in Figure 11a.

It was noted that the fundamental modes of vibration corresponded to close frequencies, which was a result of the symmetry of the central tower from the first floor up.

The mechanical properties of the wall materials adopted after the calibration are listed in Table 2.

The final numerical calibrated model is depicted in Figure 11b. This model was ready for the seismic structural assessment of the central body of the palace to identify potential vulnerable structural elements and to support the design of retrofitting interventions.



(**a**) (**b**)

Figure 11. 3Muri analyses: (**a**) main vibration modes represented in vertical and plan view, (x) pure X-translation with a frequency of 3.579 Hz and (y) pure Y-translation with a frequency of 3.784 Hz; (**b**) final model of 3Muri with rigid nodes, spandrels and piers represented.

Table 3. Values of periods, frequencies and mass participation factors for the main vibration modes.

Modes of Vibration	Numerical			Experimental	Error (%)
	Frequency (Hz)	Mass Participation Factors		Frequency (Hz)	
		M_x (%)	M_y (%)		
1	3.579	35.85	0.03	3.95	9.5
2	3.784	0.08	17.03	4.065	6.9

3.5. Continuous Real-Time Structural Building Monitoring

Continuous monitoring was implemented to determine its significance for the management and preservation of the palace. As previously mentioned, SHM systems have previously been implemented with success using sensors such as accelerometers to track the structural health of historical masonry structures. These systems have also shown that structures exhibit seasonal variation in response to variations in ambient conditions (temperature and relative humidity) [44]. As such, the Bosch XDK110 kit was programmed to register environmental (Bosch BME280) and dynamic data in a continuous mode, measuring at 1 s intervals while depositing the average data at 3 min spans through a Wi-Fi network using the Microsoft Azure® platform, encompassing the IoT solution. The 3 min span was selected due to limitations of the volume of data available in the Microsoft Azure® platform package. The data were registered and visualized in the Azure platform in real time, allowing for the conductance of a consultation at any point through an internet connection. For the position, as previously determined in Section 3.2.4, the third floor west workroom corner was chosen (Figure 12). The data present in the Azure platform were, subsequently, exported to a Microsoft 365 Excel® spreadsheet, aggregating all the records. For creating an active connection with the Revit model, a generic element representing the sensor format and location was created. In the spreadsheet, a VBA script extracted a series of statistics, e.g., the last value of each parameter or their daily average, storing these values and connecting them to the BIM model (see Section 3.3) through the DiRoots® plug-in for Autodesk Revit®. This allowed for an interpretation of the data connected to its geometric position, as well as all other relevant data pertaining to the affected area stored in the model.

As for data, the sensor collected data from December 2022 (four months of data). Due to the acquisition rate, a detailed modal analysis could not be achieved with these acceleration data due to the low frequency of vibrations in the building (established in Section 3.2.4). Namely, for continuous monitoring, the period of registration was 3 min, in contrast to instant monitoring, which has a period of registration of 0.005 s. As such, the continuous monitoring over the 4 months did not allow us to record the vibrations previously established. However, through the analysis of the vibrations, changes in the structure of the building could be observed. In Figure 13, for the acceleration data, a shift was detected in the vibrations, which was later established to be due to the roof rehabilitation of the central tower. As such, with the work reaching a higher level of intervention on 23 January, a clear change in transverse vibrations was observed. At this time, most of the work had already been completed. Nevertheless, some interventions were still taking place, and that was reflected in the graph, displaying a slow recovery to the previous vibration period, though not yet stabilized.

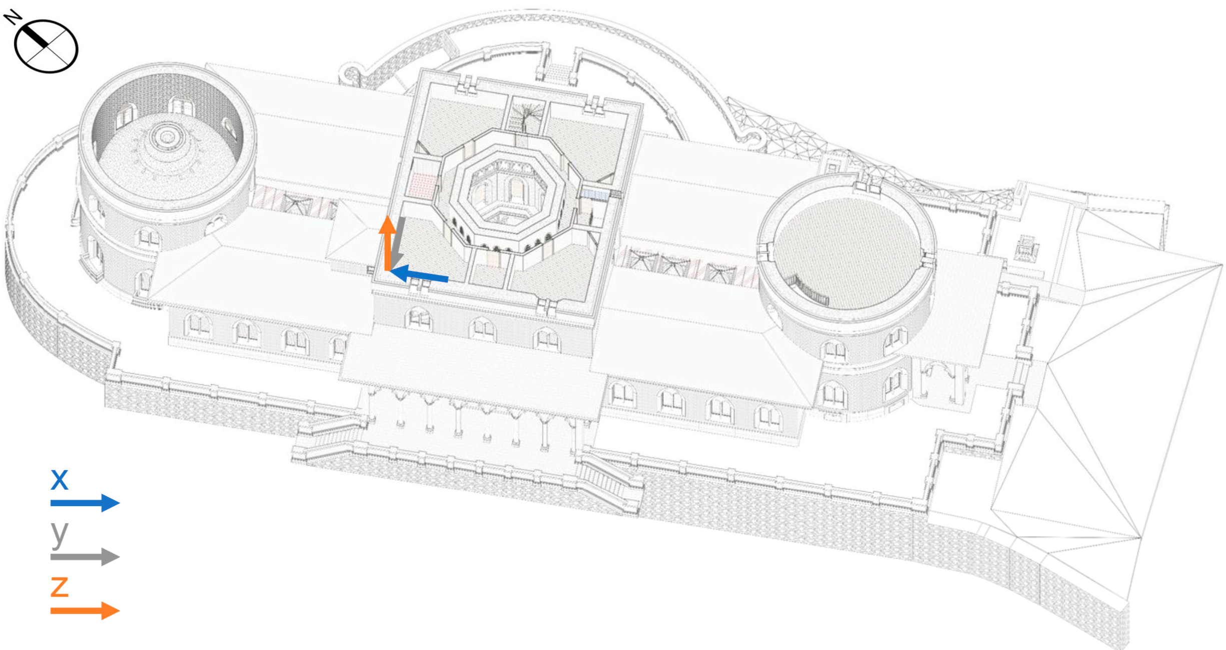


Figure 12. XDK sensor for continuous monitoring: position and orientation.

Regarding the temperature data, an impact study of temperature on the structure could not be conducted due to the intervention work that skewed the stated data, as well as the uniform distribution of temperature to the time frame in question. Nonetheless, to determine the importance of in situ temperature measurements, in Figure 14 on the right, temperature data by day were extracted from the closest weather station in Colares, Sintra (4 km distance to the Palace), published by the "Instituto Português do Mar e da Atmosfera" (IPMA), to compare to the collected information inside the building. As was expected, the recorded temperature amplitude varied greatly between the two, as the weather station measured outside at an 11 m elevation, while the palace sensor was inside the building; thus, the weather station values varied between −2 and 31 degrees, while the palace room readings varied from 12 to 22 degrees Celsius.

Figure 15 shows the indoor humidity registered with the same sensor for the same period of time, as well as the rainfall recorded by the IPMA in the closest weather station in Colares, Sintra. The results showed that, for most of the cases, high values of humidity occurred with high values of rainfall. Nevertheless, on some particular days, there were some unexpected high values of amplitude of humidity (difference between maximum and minimum values), which did not correlate with the level of rainfall. However, this may have occurred due to the maintenance works being conducted on the roof in the same period.

In the future, variations in the fundamental frequencies (fx, fy) identified from the periodic ambient vibration recordings should be assessed, and the potential shifts due to the temperature and humidity variations should be analyzed. Based on previous studies [45], the following was expected: (i) a positive correlation between frequencies and temperatures so that an increase in temperature would correspond to an increase in natural frequency; (ii) a weaker correlation with frequency variations and humidity.

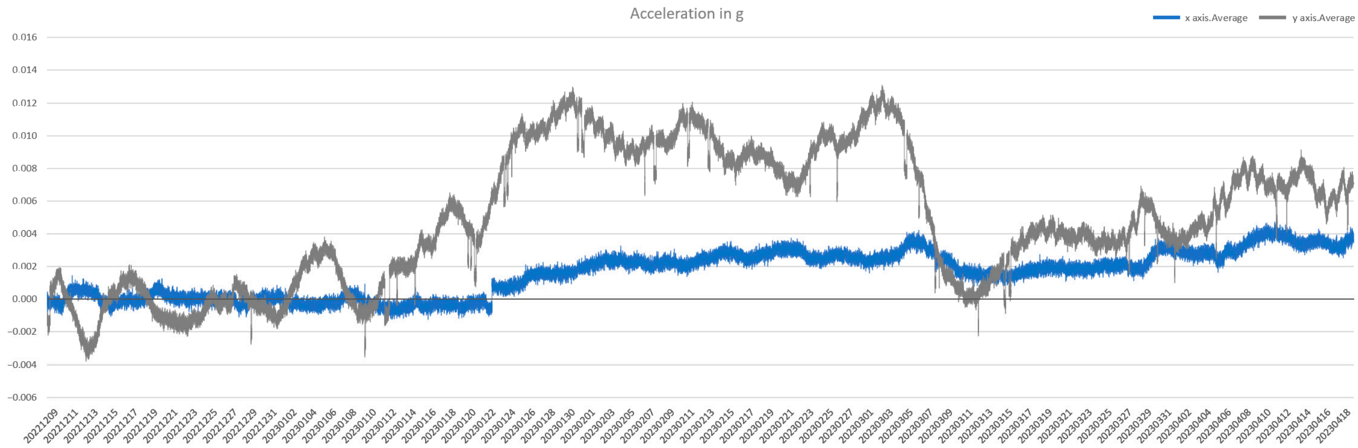


Figure 13. Continuous monitoring data (for four months) of acceleration in g for XDK; measurements without detrending and filtering of 3 min average of the 1 s measures.

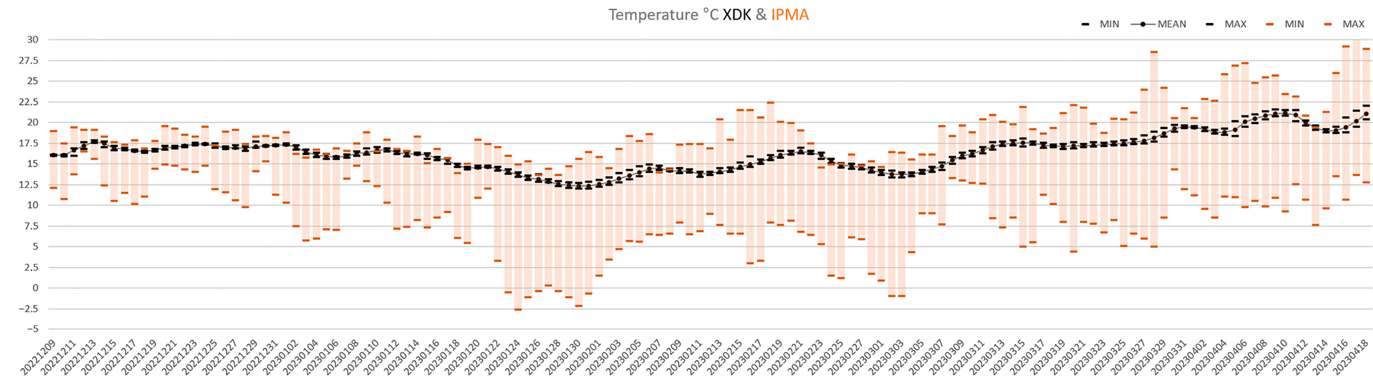


Figure 14. Continuous monitoring data (for four months) of temperature in °C XDK in black (mean, max and min by day) and IPMA day temperature in °C max and min values for Sintra.

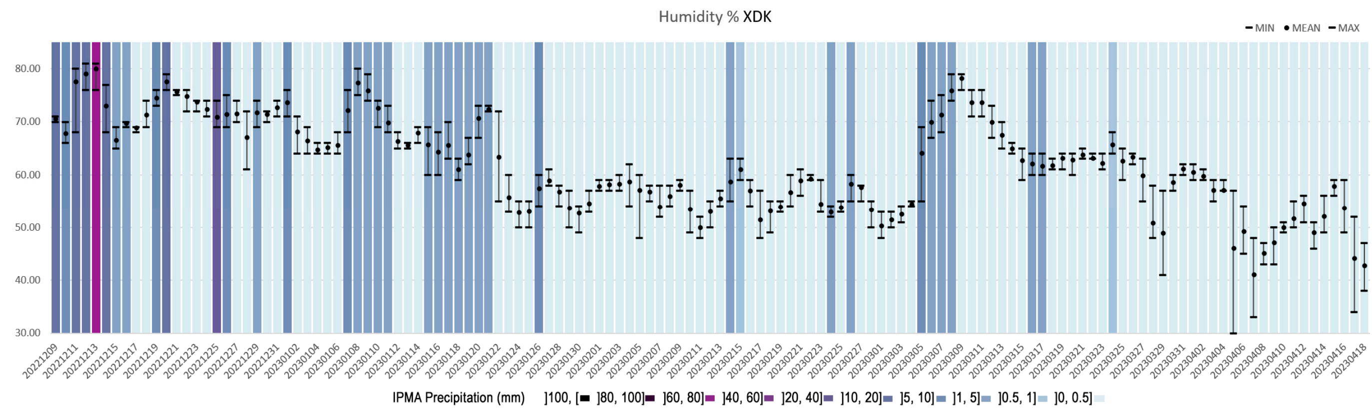


Figure 15. Continuous monitoring data (for four months) of humidity in % XDK in black (mean, max and min by day) and rainfall from Sintra IPMA.

4. Results and Discussion

In this paper, a first approach for a BIM-based model for structural health monitoring was presented, with the central body of the Palace of Monserrate selected as the case study due to the palace's status as a UNESCO World Heritage building since 1995. To support the definition of a BIM-based solution for real-time structural monitoring of the case study, two models were developed: a geometric one and a numerical one.

Particularly, in the case of old heritage buildings where the lack of geometric and non-geometric information is very frequent, the use of historical data can be a valuable source of information regarding the geometric and constructive changes to which the building was subject throughout its existence.

Concerns relative to an accurate geometric representation led to the acquisition of geometric and physical data relating to the construction system and ambient vibrations. Among them, a topographic survey made it possible to obtain the real coordinates of the palace and a survey using TLS technology, which, after data processing, allowed us to obtain the representative point cloud of the palace that later served as the basis for the H-BIM modeling in Autodesk Revit software. GPR surveys were also conducted to characterize the structure better, as semi-destructive or destructive techniques could not be used due to the historical value of the site.

The capacity to acquire real-time information on a structure's vibrations, both during normal operation and after an extraordinary occurrence, can allow for the application of more effective maintenance and repair practices, resulting in lower operating costs. This paper presented an IoT system for real-time monitoring data shared over the Microsoft Azure® platform. In the future, the suggested system could monitor a structure's health by analyzing, periodically or just after an extraordinary occurrence, its dynamic characteristics, including tracking the evolution of modal characteristics such as fundamental frequencies. During the study, the system worked continuously on the third floor of the central tower of the Monserrate's Palace in Sintra, and the data gathered were recorded in the H-BIM model, which could allow for further studies to best manage the heritage building regarding conservation concerns of the structural health status of the monitored building. It is worth mentioning that the implemented sensor was a low-cost MeM, which, in this work, was proven to be reliable in obtaining the vibrations of the structure and defining its dynamic characteristics when the monitoring period replicated the structure's modal characteristics. Due to limitations with the server platform that hosted the data, 3 min (average of the 1 s measures) was the lowest possible measurement report available. Although the data did not allow for a dynamic characterization, the monitoring was conducted to evaluate if even with this lower sampling any conclusions on the structure could be extracted, which was corroborated when the intervention on the roof for maintenance was noted in the surveyed data.

Despite the challenges in the construction of the H-BIM model, its implementation showed several advantages, such as being a central database on which geometric and non-graphic information regarding each BIM element was stored. As such, generic models representing the used surveyed equipment were added to the corresponding surveyed position on the model and through a new parameter on which the data files could be accessed. For the specific case of the generic model representing continuous monitoring, a parameter was created that connected to the Azure platform's URL for the obtainment of real-time data, another parameter that connected to previously observed values and a third parameter that reported a value in the model that summarized the last day in the records. This last connection was achieved by using the DiRoots® plug-in for Autodesk Revit®, which needed to be selected upon opening the model, through which a VBA script enabled the data stored in an Excel spreadsheet to be called into the H-BIM model. Based on the H-BIM, a numerical model was developed with 3Muri software and calibrated based on the in situ test results.

The H-BIM capacity to store real-time information on a structure's vibration, together with a calibrated numerical model, could be a valuable support for the quick structural health assessment in a general framework of decision-making processes regarding the safety evaluation of the palace post an extraordinary event, such as a post-earthquake emergency scenario. This model was ready to analyze and assess the structural health and damage of the central tower of the palace due to the occurrence of extraordinary events, such as an earthquake. Moreover, it can be easily changed if some structural elements are damaged or collapse due to external actions. In the rigorous context of heritage, a general framework was established (the assessment of the dynamic behavior, details concerning the installation and configuration of the low-cost sensor and its subsequent calibration) that could be replicated in a similar context.

5. Final Comments

In the near future, an extended WSN is intended to be implemented with a permanent sensor layout of the central body of the palace represented in Figure 16; this layout would include a sensor at the base of the building, measuring the ground motion, whereas the other sensors would be fixed directly onto the structure, measuring the continuum of its vibrations, as well as the temperature and humidity. If an earthquake were to occur, the monitoring system would be able to register the seismic action and the seismic response.

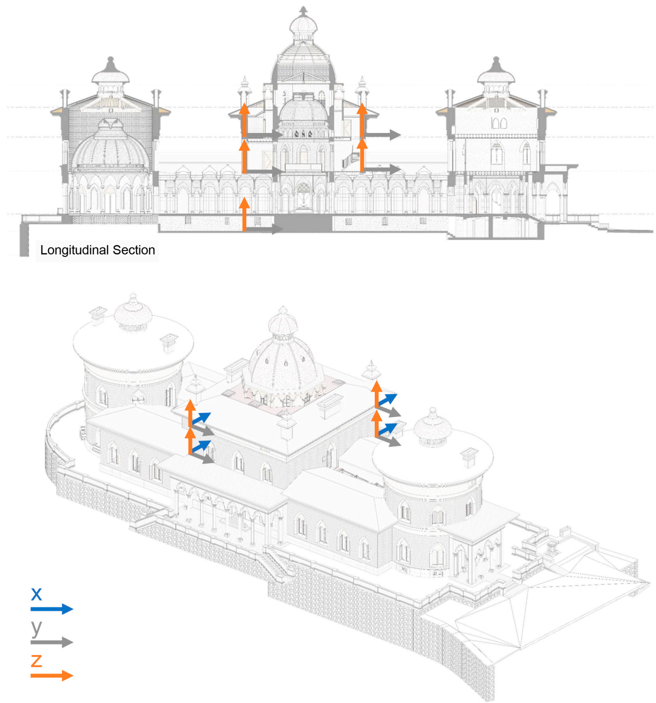


Figure 16. Future WSN layout of the central tower.

The final goal of this research work, which started in 2021, was to define a BIM-based solution that enabled real-time structural health monitoring based on a wireless low-cost sensor network of the whole palace.

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References

1. Bento, R. An Interdisciplinary Approach to the Seismic Assessment of Built Cultural Heritage: Case Studies in Lisbon and Outskirts. In *Structural Analysis of Historical Constructions*; Aguilar, R., Torrealva, D., Moreira, S., Pando, M.A., Ramos, L.F., Eds.; RILEM Bookseries; Springer: Berlin/Heidelberg, Germany, 2019; Volume 18, pp. 3–18. [CrossRef]
2. Masciotta, M.G.; Roque, J.C.A.; Ramos, L.F.; Lourenço, P.B. A multidisciplinary approach to assess the health state of heritage structures: The case study of the Church of Monastery of Jerónimos in Lisbon. *Constr. Build. Mater.* **2016**, *116*, 169–187. [CrossRef]
3. Zrinjski, M.; Tupek, A.; Barković, Đ.; Polović, A. Industrial masonry chimney geometry analysis: A total station based evaluation of the unmanned aerial system photogrammetry approach. *Sensors* **2021**, *21*, 6265. [CrossRef] [PubMed]
4. Lingua, A.; Piumatti, P.; Rinaudo, F. Digital photogrammetry: A standard approach to cultural heritage survey. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2003**, *34*, 210–215.
5. Silva, A.; Bento, R. Uma abordagem multidisciplinar para a avaliação sísmica do Edifício dos Brasões, Palácio Nacional de Sintra. *Rev. Port. Eng. Estrut.* **2020**, *Série III*, 97–110.
6. Godinho, M.; Machete, R.; Ponte, M.; Falcão, A.P.; Gonçalves, A.B.; Bento, R. BIM as a resource in heritage management: An application for the National Palace of Sintra, Portugal. *J. Cult. Herit* **2020**, *43*, 153–162. [CrossRef]
7. Ponte, M.; Bento, R.; Vaz, S.D. A Multi-Disciplinary Approach to the Seismic Assessment of the National Palace of Sintra. *Int. J. Archit. Herit.* **2021**, *15*, 757–778. [CrossRef]
8. Oliveira, C.S.; Navarro, M. Fundamental periods of vibration of RC buildings in Portugal from in-situ experimental and numerical techniques. *Bull. Earthq. Eng.* **2010**, *8*, 609–642. [CrossRef]
9. Roia, D.; Gara, F.; Balducci, A.; Dezi, L. Ambient vibration tests on a reinforced concrete school building before and after retrofitting works with external steel "dissipative towers". In Proceedings of the 9th International Conference on Structural Dynamics, EURODYN 2014, Porto, Portugal, 30 June–2 July 2014; pp. 2509–2516.
10. Pierleoni, P.; Conti, M.; Belli, A.; Palma, L.; Incipini, L.; Sabbatini, L.; Valenti, S.; Mercuri, M.; Concetti, R. IoT Solution based on MQTT Protocol for Real-Time Building Monitoring. In Proceedings of the IEEE 23rd International Symposium on Consumer Technologies (ISCT), Ancona, Italy, 19–21 June 2019; pp. 57–62.
11. Biagini, C.; Capone, P.; Donato, V.; Facchini, N. Towards the BIM implementation for historical building restoration sites. *Autom Constr* **2016**, *71*, 74–86. [CrossRef]
12. Brumana, R.; Della Torre, S.; Previtali, M.; Barazzetti, L.; Cantini, L.; Oreni, D.; Banfi, F. Generative HBIM modelling to embody complexity (LOD, LOG, LOA, LOI): Surveying, preservation, site intervention—The Basilica di Collemaggio (L'Aquila). *Appl. Geomat.* **2018**, *10*, 545–567. [CrossRef]
13. Barazzetti, L.; Banfi, F.; Brumana, R.; Gusmeroli, G.; Previtali, M.; Schiantarelli, G. Cloud-to-BIM-to-FEM: Structural simulation with accurate historic BIM from laser scans. *Simul Model. Pract. Theory* **2015**, *57*, 71–87. [CrossRef]
14. Brumana, R.; Oreni, D.; Barazzetti, L.; Cuca, B.; Previtali, M.; Banfi, F. Survey and scan to BIM model for the knowledge of built heritage and the management of conservation activities. In *Digital Transformation of the Design, Construction and Management Processes of the Built Environment*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 391–400. [CrossRef]
15. Machete, R.; Silva, J.R.; Bento, R.; Falcão, A.P.; Gonçalves, A.B.; de Carvalho, J.M.L.; Silva, D.V. Information transfer between two heritage BIMs for reconstruction support and facility management: The case study of the Chalet of the Countess of Edla, Sintra, Portugal. *J. Cult. Herit* **2021**, *49*, 94–105. [CrossRef]
16. Moreno-Gomez, A.; Perez-Ramirez, C.A.; Dominguez-Gonzalez, A.; Valtierra-Rodriguez, M.; Chavez-Alegria, O.; Amezquita-Sanchez, J.P. Sensors Used in Structural Health Monitoring. *Arch. Comput. Methods Eng.* **2018**, *25*, 901–918. [CrossRef]
17. Zhu, L.; Fu, Y.; Chow, R.; Spencer, B.F.; Park, J.W.; Mechitov, K. Development of a high-sensitivity wireless accelerometer for structural health monitoring. *Sensors* **2018**, *18*, 262. [CrossRef] [PubMed]
18. Collette, C.; Carmona-Fernandez, P.; Janssens, S.; Artoos, K.; Guinchard, M.; Hauviller, C. *Review of Sensors for Low Frequency Seismic Vibration Measurement*; CERN-ATS-Note-2011-001 TECH 2011; CERN: Geneva, Switzerland, 2011.
19. Mobaraki, B.; Lozano-Galant, F.; Soriano, R.P.; Pascual, F.J.C. Application of low-cost sensors for building monitoring: A systematic literature review. *Buildings* **2021**, *11*, 336. [CrossRef]
20. Komarizadehasl, S.; Mobaraki, B.; Lozano-Galant, J.A.; Turmo, J. Detailed Evaluation of Low-Cost Ranging Sensors for Structural Health Monitoring Applications. In Proceedings of the Recent Trends in Construction Engineering and Education RTCEE International Conference, Online, 10–11 September 2020; pp. 10–11.
21. Komarizadehasl, S.; Mobaraki, B.; Ma, H.; Lozano-Galant, J.A.; Turmo, J. Development of a low-cost system for the accurate measurement of structural vibrations. *Sensors* **2021**, *21*, 6191. [CrossRef] [PubMed]
22. Komarizadehasl, S.; Komary, M.; Alahmad, A.; Lozano-Galant, J.A.; Ramos, G.; Turmo, J. A Novel Wireless Low-Cost Inclinometer Made from Combining the Measurements of Multiple MEMS Gyroscopes and Accelerometers. *Sensors* **2022**, *22*, 5605. [CrossRef]
23. Casillo, M.; Guida, C.G.; Lombardi, M.; Lorusso, A.; Marongiu, F.; Santaniello, D. Predictive preservation of historic buildings through IoT-based system. In Proceedings of the MELECON 2022—IEEE 21st Mediterranean Electrotechnical Conference, Palermo, Italy, 14–16 June 2022; pp. 1194–1198. [CrossRef]
24. Chianese, A.; Piccialli, F. Designing a smart museum: When cultural heritage joins IoT. In Proceedings of the 2014 8th International Conference on Next Generation Mobile Applications, Services and Technologies, NGMAST 2014, Oxford, UK, 10–12 September 2014; pp. 300–306. [CrossRef]

25. Amato, F.; Chianese, A.; Mazzeo, A.; Moscato, V.; Picariello, A.; Piccialli, F. The talking museum project. *Procedia Comput. Sci.* **2013**, *21*, 114–121. [CrossRef]
26. Valinejadshoubi, M.; Moselhi, O.; Bagchi, A. Integrating BIM into sensor-based facilities management operations. *J. Facil. Manag.* **2022**, *20*, 385–400. [CrossRef]
27. Mataloto, B.; Mendes, H.; Ferreira, J.C. Things2people interaction toward energy savings in shared spaces using BIM. *Appl. Sci.* **2020**, *10*, 5709. [CrossRef]
28. Mataloto, B.; Ferreira, J.C.; Resende, R.; Moura, R.; Luís, S. Bim in *people2people* and *things2people* interactive process. *Sensors* **2020**, *20*, 2982. [CrossRef]
29. Kim, S.; Frangopol, D.M. Optimal planning of structural performance monitoring based on reliability importance assessment. *Probabilistic Eng. Mech.* **2010**, *25*, 86–98. [CrossRef]
30. Gentile, C.; Ruccolo, A.; Canali, F. Long-term monitoring for the condition-based structural maintenance of the Milan Cathedral. *Constr Build. Mater.* **2019**, *228*, 117101. [CrossRef]
31. Li, X.; Xie, L.; Lu, W.; Xue, S.; Hong, C.; Lan, W.; Shi, Q. Structural health monitoring of a historic building during uplifting process: System design and data analysis. *Struct. Health Monit.* **2023**. [CrossRef]
32. Mondal, T.G.; Jahanshahi, M.R. Applications of computer vision-based structural health monitoring and condition assessment in future smart cities. In *The Rise of Smart Cities: Advanced Structural Sensing and Monitoring Systems*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 193–221. [CrossRef]
33. Mondal, T.G.; Jahanshahi, M.R. Modelling and forecasting of SHM strain measurement for a large-scale suspension bridge during typhoon events using variational heteroscedastic Gaussian process. *Eng. Struct* **2022**, *251*, 113554. [CrossRef]
34. Wang, Q.-A.; Wang, C.-B.; Ma, Z.-G.; Chen, W.; Ni, Y.-Q.; Wang, C.-F.; Yan, B.G.; Guan, P.X. Bayesian dynamic linear model framework for structural health monitoring data forecasting and missing data imputation during typhoon events. *Struct. Health Monit.* **2022**, *21*, 2933–2950. [CrossRef]
35. S.T.A. DATA. *3Muri*, V13201; S.T.A. DATA: Turin, Italy, 2022.
36. Neto, M.J. *Monserrate A Casa Romântica de Uma Família Inglesa*; Caleidoscópio: Lisboa, Portugal, 2015.
37. Autodesk. *Recap Pro*, V230; Autodesk: San Francisco, CA, USA, 2023.
38. Morph. Campanha de Prospecção Geofísica. 2011. Available online: https://morph.pt/Campanha-de-Prospeccao-Geofisica/ (accessed on 12 June 2023).
39. Structural Vibration Solutions (SVIBS). *ARTeMIS Modal Pro*, Version 7215; SVIBS: Aalborg, Denmark, 2022.
40. Autodesk. *Revit 2023*, Version 2023; Autodesk: San Francisco, CA, USA, 2023.
41. Lagomarsino, S.; Penna, A.; Galasco, A.; Cattari, S. TREMURI program: An equivalent frame model for the nonlinear seismic analysis of masonry buildings. *Eng. Struct* **2013**, *56*, 1787–1799. [CrossRef]
42. Autodesk. *Autocad 2022*, Version 2022; Autodesk: San Francisco, CA, USA, 2022.
43. Candeias, P.; Correia, A.; Costa, A.; Catarino, J.; Pipa, M.; Cruz, H.; Carvalho, E.; Costa, A. Aspetos gerais da aplicação em Portugal do Eurocódigo 8—Parte 3—Anexo C (Informativo)—Edifícios de alvenaria. *Rev. Port. Eng. Estrut.* **2020**, *Série III*, 99–120.
44. Alarcón, M.; Soto, P.; Hernández, F.; Guindos, P. Structural health monitoring of South America's first 6-Story experimental light-frame timber-building by using a low-cost RaspberryShake seismic instrumentation. *Eng. Struct* **2023**, *275*, 115278. [CrossRef]
45. Sivori, D.; Cattari, S.; Lepidi, M. A methodological framework to relate the earthquake-induced frequency reduction to structural damage in masonry buildings. *Bull. Earthq. Eng.* **2022**, *20*, 4603–4638. [CrossRef]