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Preventive Preservation of Rammed Earth Historical Heritage Through Continuous Monitoring, Architectural Inspections, and Data Fusion

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Abstract: Rammed earth construction, an ancient and sustainable building technique, faces significant preservation challenges, particularly in historical contexts. This study aims to enhance the preventive preservation of rammed earth historical heritage through a comprehensive methodology combining continuous monitoring, architectural inspections, and data fusion. By integrating nondestructive testing techniques such as ultrasound, thermography, and ground-penetrating radar with operational modal analysis and modeling, the proposed approach allows for early detection and assessment of structural vulnerabilities. This methodology was applied to the Tower of Muhammad in the Alhambra of Granada, Spain, demonstrating its effectiveness in identifying and quantifying damage and predicting structural health. Using multi-source data (documentation, inspections, nondestructive tests, and continuous monitoring), a finite element model was built, calibrated (achieving an avg. error in modal frequencies of 1.28% and a minimum modal assurance criterion value of 0.94), and used to develop a surrogate model able to predict the modal properties of the tower in 0.02 s, becoming compatible with continuous system identification. The presented results highlight the importance of continuous data acquisition and advanced diagnostic tools for safeguarding rammed earth structures against environmental and anthropogenic threats. This study advocates for the adoption of digital twins in historical preservation, facilitating informed decision-making and sustainable management of cultural heritage.

Keywords: rammed earth; architectural heritage; continuous monitoring; nondestructive testing; data fusion; structural vulnerability

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1. Introduction and Background

Architectural heritage is a substantial part of our cultural and historical heritage, and its sustainable management is a strategic decision for 21st-century societies [1]. The Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage of the International Council on Monuments and Sites (ICOMOS) [2] highlight the necessity of architectural heritage management. This document states that data collection and treatment must be carried out in a balanced, prudent, and thoughtful manner, with the aim of establishing a comprehensive action plan proportional to the actual problems of structures. A rational analysis of these buildings is necessary and should be based on research methods that can use both qualitative and quantitative techniques. Also, the Committee of Ministers of the Council of Europe, through the document "Recommendation on the Protection of the Architectural Heritage Against Natural Disasters" [3], emphasized the need to assess risks as part of the maintenance program of architectural heritage, quantifying and evaluating their probability of occurrence and promoting mitigation strategies. Among the current priorities is the implementation of good practices on integrating cultural heritage into disaster risk reduction strategies, with the necessity to develop early warning systems and damage models to safeguard endangered assets, and undertake the creation of a database on the criticalities of cultural heritage and intervention priorities [4].

The development of models for the structural condition analysis and damage assessment of architectural heritage must be carried out by considering the specific characteristics of each building and taking into account factors such as the construction techniques used and the materials employed. The present study is focused on a traditional building technique, widely used in several countries all over the world, that has experienced a notable resurgence today due to its minimal environmental impact and the growing interest in sustainable construction: rammed earth (RE). Rammed earth is a modular construction technique that consists of pouring a mixture of earth (mostly clayey sand) with a certain moist content between temporary formwork, sometimes also including mineral additives (e.g., cement, lime) or fibers [5]. The growing interest of the scientific community in RE construction can be seen in the increasing number of published studies on the topic, as shown in Figure 1.

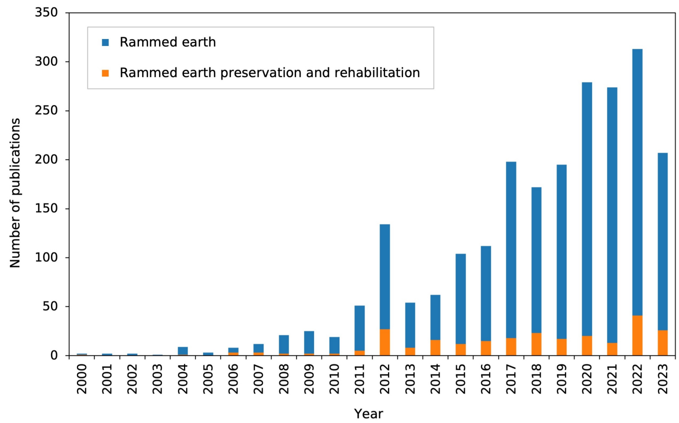


Figure 1. Publications in Web of Science per year since 2000 with the topic "rammed earth" and "rammed earth" AND ("preservation" OR "conservation" OR "rehabilitation").

Despite the widespread international presence of RE construction, its use in traditional building practices across numerous countries, and the growing interest in recent years, there are few construction and testing standards related to this kind of structure [6–8]. Most documents refer to testing procedures, primarily on erodibility, wetting/drying cycles, and compressive strength. In several countries, the use of the rammed earth technique is not prohibited, but a technical justification of the structural performance and safety of the building is usually required, leaving all the responsibility to the designer, who lacks sufficient technical standards to rely on. Moreover, the state of the art concerning the conservation of RE buildings is very limited, with periodic visual inspections remaining the most widespread maintenance scheme. However, the limitations of these schemes are well documented in the literature [9–11], being efficient only for corrective interventions when the pathology is identifiable on the surface and, therefore, severe enough to compromise the life of the building.

The integrity of RE structural elements can be threatened by the presence of pathologies related to cracks, mass loss, vertical misalignment, bulging, foundation problems, and lack of material cohesion. These pathologies can be exacerbated by external actions that represent a significant threat to rammed earth architectural heritage, such as earthquakes, water action, wind, and long-term climatic effects. Additionally, several heritage buildings are affected by inadequate interventions.

Water action particularly affects the base and top areas of the rammed earth walls, in the first case, through capillary infiltration or flooding, and in the latter, due to rain action. Over time, these actions can not only erode the surface but also cause material losses that affect the structural integrity. Wind action can also negatively influence the load-bearing capacity of RE walls if it exceeds a limit value, causing local mechanical damage (wind erosion) or, in extreme events, leading to collapse [10]. Moreover, earthquakes are among the natural disasters with the most significant impacts on the structural behavior of buildings. Rammed earth constructions, in particular, have some characteristics that make them especially vulnerable to earthquakes: due to their large mass, the walls experience significant inertial forces during a seism, which they cannot adequately resist due to their low tensile strength [11,12]. The seismic vulnerability assessment of RE structures is particularly interesting considering that many of them are located in areas with significant seismic hazards [7,13].

In general, methodologies for the evaluation of structural vulnerability can be classified into two main categories: empirical/statistical assessment and numerical/mechanical-based assessment [14]. The first one is relatively simple and easily applicable, as it relies on the visual inspection of structural damages and material degradation, as well as historical and archaeological research. It is usually limited to simple or standard building types. In the literature, there are some publications that used this approach to analyze the vulnerability of historic masonry [15] or timber structures [16], while the number of studies applying methodologies based on qualitative analysis for obtaining the risk associated with the vulnerability of rammed earth buildings is still very limited [17,18].

The second methodology, numerical-based vulnerability assessment, is more precise and generic, although it requires greater knowledge of the material properties and the performance, as well as advanced structural simulation methods. Traditionally, the assessment of the mechanical properties of construction materials is carried out through destructive tests, but these are usually inapplicable to historic and heritage structures. An alternative for these cases is the use of nondestructive testing (NDT) techniques with minimal impact on the historical/artistic value and the normal functioning of RE structures. In particular, NDT techniques based on wave propagation (ultrasound or seismic) provide direct information on the material properties at low deformation. Multiple studies have correlated the velocity of ultrasonic pulse velocity (UPV) with the compressive strength of unstabilized [19,20] and lime-stabilized [21–24] RE materials. Another technique successfully employed by diverse researchers to estimate material properties is the spectral analysis of surface waves (SASW), which allows the material stiffness of layered media to be assessed based on the dispersive behavior of Rayleigh waves. It has been used by several authors in various types of materials, such as concrete [25,26], stone masonry [27], or asphalt pavements [28].

These techniques can be complemented by other diagnostic techniques, such as optical (e.g., laser scanning and thermography) and electromagnetic (georadar) methods [29]. Laser scanning is a method that allows the automatic acquisition of the three-dimensional geometry of surfaces using light detection and ranging (LiDAR) technology and is essential for analyzing the structure at the time of measurement to compare the evaluation and identify deformations, movements, modifications, etc. Thermography involves capturing temperature mapping obtained by an infrared camera that converts it into a color scale, allowing researchers to distinguish different material types, as well as heterogeneities, cavities, moisture variations, and defects. Ground-penetrating radar (GPR) is a pulse reflection electromagnetic method based on principles similar to seismic reflection and is useful for characterizing the internal composition of structures, estimating wall thicknesses, and detecting moisture, material heterogeneities, cracks, and voids [30].

Finally, local NDT can be complemented by operational modal analysis (OMA) techniques, which are nondestructive global evaluation techniques that allow for obtaining the dynamic characteristics of structures (e.g., damping ratios, natural frequencies, and mode shapes) by recording the vibrations experienced by the structure under normal operating conditions when excited by environmental loads (microseisms, wind, traffic, etc.). These techniques have been widely used in heritage buildings in recent years [31–33], but they have barely been employed in rammed earth constructions [34]. All of these nondestructive techniques form the paradigm of preventive structural maintenance and structural health monitoring (SHM), which, unlike traditional corrective maintenance techniques based on periodic inspections, advocate for developing maintenance plans based on the characterization of the structural integrity of the asset under evaluation [35]. This allows for the development of decision-making techniques based on the analysis of the recorded data and planning interventions according to quantitative criteria.

It is important to note that this approach requires the adoption of techniques that can relate experimental measurements to the structural health of the building, specifically the presence of potential pathologies. The damage identification problem can be structured into a four-level hierarchical process, with each level increasing in complexity: detection (Level I), localization (Level II), quantification (Level III), and prognosis (Level IV) [36,37]. While adequately processing data acquired through NDT techniques may be sufficient for detecting certain pathologies, higher levels of damage identification often require the use of theoretical models to link failure mechanisms with potential anomalies observed during inspection [38].

In this context, the finite element method (FEM) is the most widely used numerical method for simulating structural behavior. Once the numerical model is built, damage identification can be achieved through inverse calibration of certain parameters that are sensitive to damage, aiming to reproduce the experimental measurements. These techniques, also known as model updating techniques, can be carried out using deterministic or Bayesian approaches [39]. Bayesian methods have generated significant interest in recent years due to their ability to incorporate sources of uncertainty into the model parameters and to obtain statistical probabilities in structural damage characterization. In historical heritage structures, they have been successfully used to determine structural damage, primarily through dynamic characterization measurements [40]. The combination of permanent or quasi-permanent monitoring systems and model updating techniques leads to the development of so-called digital twins [41], defined as a virtual representation of the real monitored structure. Digital twins are fed with experimental data, allowing the evaluation of the structural integrity of the actual physical system and the planning of conservation interventions. This innovative concept has started to be applied in recent years, especially in mechanical engineering, and only very recent publications report its application to historical (masonry) structures [42–44]. The implementation of all these advanced SHM techniques to rammed earth structures is practically nonexistent, and only a few studies on calculating vulnerability in rammed earth using FEM can be found in the scientific literature [45,46].

In light of this situation, the present study aims to develop a methodology for assessing the structural health of rammed earth constructions based on the combination of dynamic identification and nondestructive testing techniques, enabling the preventive preservation of heritage RE structures. Taking into account the limitations observed in the literature, where little attention is given to earthen constructions and the focus is primarily on specific case studies or single data sources, this study seeks to provide a comprehensive methodology for the integration of multiple complementary techniques for the condition assessment of heritage RE buildings. These techniques include documentation analysis, field inspections, NDT, long-term structural monitoring, structural digital twins, and nonlinear FEM simulations for the holistic assessment of the structural integrity of the structure. The following sections describe and justify the proposed methodology and analyze the experiences and results obtained to date from a specific case study, the Tower of Muhammad in the Alhambra of Granada (Spain), analyzing data from a continuous monitoring campaign conducted between January and March 2022.

2. Methodology for the Vulnerability Assessment of Historical RE Buildings

To address the need to preserve the abundant architectural heritage built in rammed earth, a methodology specifically designed for analyzing the vulnerability of these structures is proposed. The general approach of this methodology involves collecting available architectural and structural information, continuously and periodically gathering data, creating models for damage detection and prevention by combining all available data, and, finally, assessing the vulnerability of the structure under analysis. The goal is to ensure the preservation of RE structures and extend their lifetime while sustainably managing available (limited) resources.

Considering the above, the steps of the proposed methodology are represented in Figure 2 and itemized as follows:

1. Existing data collection;
2. Periodic inspections;
3. Continuous monitoring;
4. Numerical modeling and digital twin creation;
5. Damage identification and vulnerability assessment.

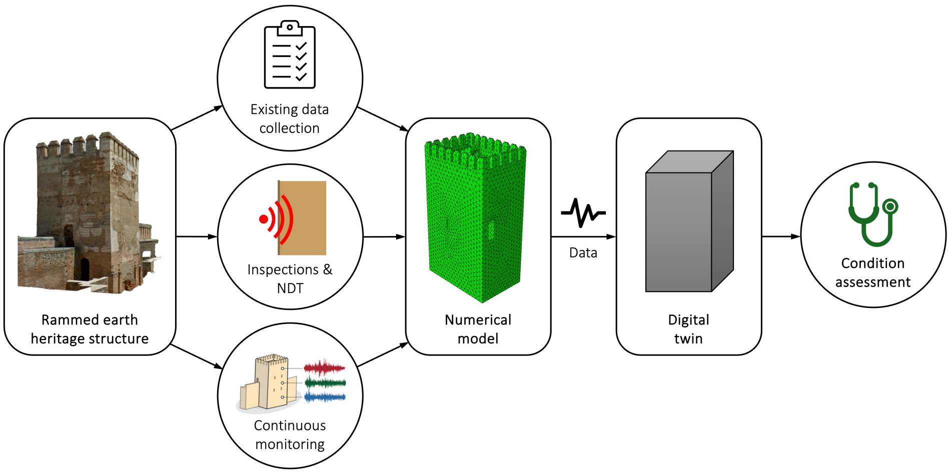


Figure 2. General workflow of the proposed vulnerability assessment methodology.

Existing data collection should always be the first step in any study, especially when dealing with historic buildings that have often undergone numerous modifications and have experienced various pathologies over the years or centuries. In these structures, particular attention must be paid to information documented in historical texts, as well as the more recent scientific literature analyzing structural aspects of the building or other relevant or side factors. Therefore, an exhaustive literature review will be conducted, critically analyzing the available information and selecting data deemed essential for assessing structural integrity (e.g., structural properties, extreme events experienced, known damage, and material properties). All the collected information has to be properly organized and stored for future consultation in the form of more traditional databases or by creating a heritage building information model (HBIM) [47,48], which allows the collected data to be stored within a three-dimensional geometric model.

Periodic inspections of the structural and damage conditions of historical buildings include the traditional approach based on visual inspections and simple measurements (e.g., crack width) and more complex evaluation techniques. Particular attention is paid in this study to NDT techniques due to their capacity to provide significant information about the material properties and to locate damage in the structure causing minimal or no impact on the heritage building under assessment. The present methodology is not limited to any inspection technique in particular, as long as its effectiveness in assessing the properties of RE or detecting damage is proven. In this regard, good results have already been obtained using UPV tests (both for unstabilized [19,20] and lime-stabilized [21–24] rammed earth) and rebound hammer tests [20]. It is recommended that periodic inspections include not only local tests but also methods that can evaluate the building from a more global perspective, like laser scanning, photogrammetry [49,50], and infrared thermography [20].

Continuous monitoring involves the implementation of long-term monitoring systems to continuously assess the health condition of the structural system. These methods facilitate the early detection of structural pathologies, enabling condition-based maintenance strategies to extend the lifespan of the monitored asset. Among the numerous SHM methods available, vibration-based approaches through OMA have become particularly popular for the preservation of historical buildings. These methods operate with minimal impact on the architectural and aesthetic values, providing global damage assessment without disrupting the normal use of the asset. These techniques involve extracting the modal signatures of the asset through the post-processing of ambient vibration data collected by strategically placed sensors under normal in-operation excitations [38]. This approach has been successfully applied to heritage structures, primarily masonry buildings [51], and shows significant potential for application in rammed earth constructions.

Numerical modeling and digital twin creation is the next essential step for structural vulnerability analysis and involves the development of computational models that can replicate the structural behavior of the analyzed structure using the data obtained from inspections and monitoring. FEM models can be developed to evaluate specific structural aspects or load conditions, but they are typically very complex, involving a high computational cost, making real-time SHM schemes impractical [52]. Therefore, damage identification through supervised learning techniques often relies on the development of computationally efficient surrogate models. These models, defined as physics-based or machine learning models, continuously exploit monitoring data to infer and classify the health condition of the physical asset, acting as a structural digital twin [53–55]. These digital twins can be continuously fed with data obtained from continuous monitoring and periodic inspections and tests to infer the health condition of the asset in the following step.

Damage identification and vulnerability assessment imply the application of numerical models to identify potential damage in the building. The present methodology proposes a two-step damage identification approach. The first step is purely data-driven, using novelty detection analysis through statistical pattern recognition methods to detect structural abnormalities that may be indicative of damage. Upon detecting a novelty, model updating is used to fully identify the location, extension, and severity of the damage [56,57]. When numerical models indicate damage, it is recommended to conduct further visual inspections and in situ testing to fully characterize the pathology. This information is then processed to evaluate its impact on the structural condition and vulnerability of the building [40].

3. Experiences in the Tower of Muhammad

The methodology presented in this study has been developed based on a series of experiments conducted since 2019 in the Tower of Muhammad in the Alhambra of Granada, Spain. These experiments follow the workflow of the proposed methodology, including an architectural and structural analysis of the tower using available historical and scientific information, site visits and local tests, vibration-based continuous damage identification through a digital twin, and seismic vulnerability analysis using FEM analysis. The specific methodology implemented for this case study is summarized in Figure 3.

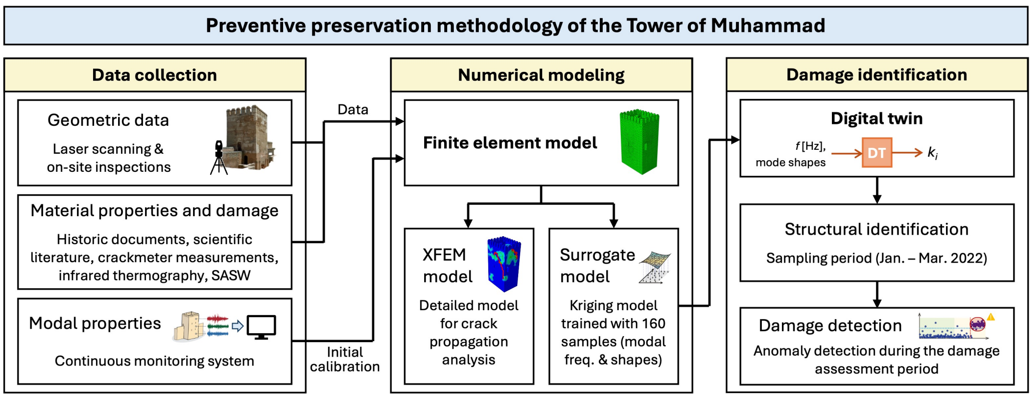


Figure 3. The workflow of the preventive preservation methodology implemented in the Tower of Muhammad.

3.1. Architectural and Geometrical Characterization

The Tower of Muhammad (Figure 4), also referred to as the Tower of the Hens due to its use as a chicken coop in the 19th century, was constructed in the 13th century, during the early Nasrid period [58,59]. Located in the north wall of the Alhambra fortress, it occupies a strategic defensive position between the Alcazaba fortress and the Royal Palaces. The tower was built in rammed earth stabilized with lime [60–62], and, over the centuries, it has undergone numerous alterations and modifications, some of which have compromised its structural integrity.

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

Figure 4. Tower of Muhammad: (**a**) location and (**b**) southwest view.

There have been no specific investigations to assess the mechanical properties of the rammed earth used in the tower, although they must be reasonably similar to those measured by Gonzalez Limón et al. [60]. Those authors conducted destructive laboratory tests on samples extracted from the Tower of Comares, which was constructed a few decades later using the same building techniques and materials [62,63]. Their experimental campaign included tests for the determination of the apparent density, porosity, and capillarity according to UNE 83312:1990 [64] and uniaxial compression tests on 11 RE samples according to UNE 83304:1984 [65]. These mechanical properties, listed in Table 1, have been employed in finite element models of the Tower of Comares in prior studies [66–68]. The results are very significant, as they stem from the latest destructive testing campaign conducted on the rammed earth material of the Alhambra towers. However, it is important to consider that the age of the data (from 1997) introduces a significant source of uncertainty. Therefore, the calibration of the model using experimental data, as described in Section 3.4, becomes essential.

Table 1. Mechanical properties of rammed earth in the Tower of Muhammad, according to [60].

Parameter	Value
Density	2250 $kg\,m^{-3}$
Compressive strength	2.45 MPa
Tensile strength	0.30 MPa
Elastic modulus	0.92 GPa
Poisson's ratio	0.30

The original structure of the tower has undergone several extreme loading episodes, such as the July 1431 earthquake, which destroyed several walls and buildings in the fortress [69,70], or the explosion at a nearby gunpowder factory in 1590, which severely damaged many constructions within the Alhambra complex, likely including the Tower of Muhammad [61]. Its structural condition further deteriorated in the following centuries due to a lack of maintenance and various wars [61,70].

Since the 20th century, several interventions have been carried out to prevent the collapse of the tower. The need for restoration was already highlighted in the Conservation Plan of the Alhambra of 1917 [71], and the first works began in 1929, with the restoration of the north wall adjacent to the tower [72]. The majority of the restoration works on the Tower of Muhammad, however, were carried out by the architect Prieto-Moreno y Pardo in the latter half of the century [59], including the underpinning and reinforcement of the foundations of the tower, completed in 1975 [73]. Despite these interventions, the tower is still in a precarious situation, as detailed in the Emergency Technical Project for the Consolidation of Battlements and Walls of the Tower of the Hens [74] developed by Lopez Osorio in 2021. The tower presents several visible cracks on all its faces, and the different materials used in various maintenance and restoration interventions are clearly observable.

The most accurate information about the geometry of the Tower of Muhammad can be found in the most recent restoration projects [74] and in the pictures and architectural blueprints developed in the second half of the 20th century and preserved in the Archives of the Alhambra, like the ones shown in Figure 5. These data can be complemented and updated with in situ measurements. As a result of all the above, it can be said that the Tower of Muhammad has a trapezoidal plan, with the north and south walls measuring approximately 9 m in length, while the west and east walls are 6.6 and 6.0 m long, respectively. The tower stands 15.9 m high, including 1.2 m tall battlements, and the wall thickness varies between 1.45 m and 1.80 m.

(a) (b) (c)

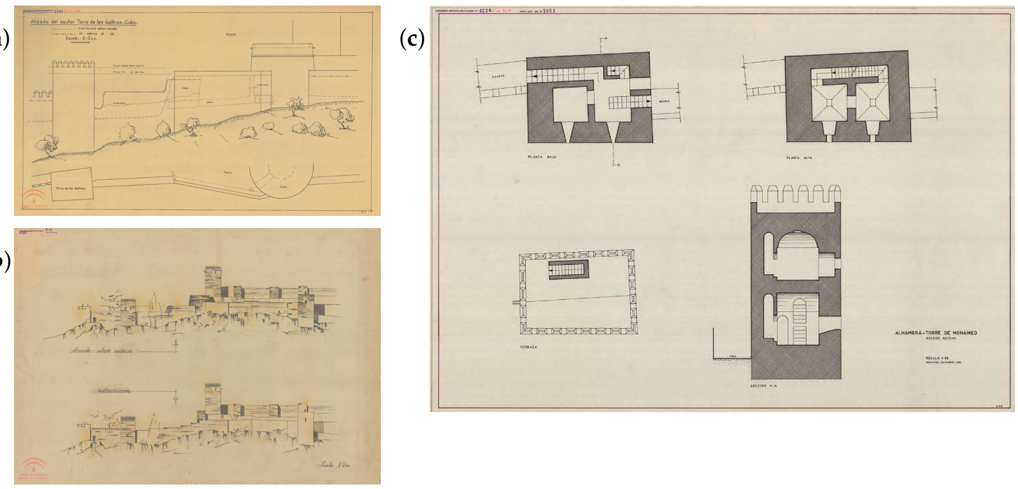


Figure 5. Architectural blueprints of Tower of Muhammad: (**a**) side view, 1954 [75]; (**b**) side view pre- and post-restoration, 1957 [76]; (**c**) plan view, vertical and horizontal sections, 1985 [77].

3.2. Inspections and Nondestructive Testing

As described in the methodology, periodic inspections are needed to address the conservation state of the building under evaluation. At least one inspection has to be carried out at the beginning of the process, and then future visits can be planned periodically, including emergency inspections if the monitoring system detects anomalies.

In the initial visit to the Tower of Muhammad in 2019, within the framework of the project "Seismic vulnerability assessment service for the Tower of the Hens" (University of Granada—Council of the Alhambra and the Generalife), the following pathologies were detected, later confirmed by the 2021 emergency consolidation project [74]:

- Humidity causing salt efflorescence.
- Degradation of the lime plaster with material loss (Figure 6a).
- Biodeterioration due to the growth of parasitic vegetation, leading to cracking and partial loss of the lime plaster (Figure 6b).
- Pollution and other anthropogenic factors.
- Inadequate restorations.
- Fissures and surface cracks, without the separation of parts (Figure 6c).

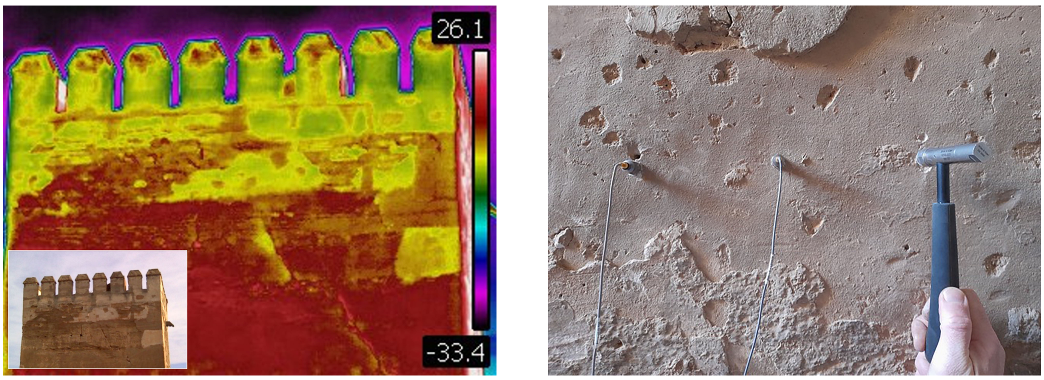
- Deep cracks, with the separation of parts.
- Exfoliation, the separation of layers.

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

Figure 6. Pathologies found in the Tower of Muhammad: (**a**) degradation of plaster, (**b**) biodeterioration, and (**c**) surface cracking.

The detection of pathologies was first performed via visual inspection, as several defects were clearly visible on the walls. A crackmeter was used to measure the displacements across surface cracks and joints. Additionally, to locate further structural alterations on the walls and measure the crack depth, an infrared thermography study of the tower was conducted (Figure 7a) using a FLIR T420bx infrared camera, with thermal sensitivity below 0.045 °C and a 320 × 240 MSX sensor.

With the aim of mechanically characterizing the structural materials of the tower, the testing campaign on the tower was complemented by nondestructive SASW tests. These tests (Figure 7b) were conducted on the walls across all three levels of the tower, enabling the identification of three distinct zones with similar elastic properties, which were used in the numerical analyses described in the following section.



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

Figure 7. NDT on the Tower of Muhammad: (**a**) infrared thermography and (**b**) spectral analysis of surface waves.

3.3. Operational Modal Analysis

To assess the current state of the tower, in addition to periodic on-site inspections, a continuous monitoring system was installed in January 2022. The system consists of eight high-sensitivity piezoelectric accelerometers, model PCB393B31 (μ 5% 10.0 V g^{-1}, wideband resolution 1 µg rms, and measurement range 0.5 g pk). The sensors, protected by waterproof metal cases placed directly on the ground, were installed on the three levels of the tower, as shown in Figure 8. Accelerometers A1 and A4 were positioned at the northwest corners of levels 3 and 2, respectively, in a unidirectional configuration, while the remaining sensors were placed in pairs (in a bidirectional configuration) at the northeast corners of all three levels of the tower. The sensor placement was determined based on the authors' experience following a preliminary inspection of the tower.

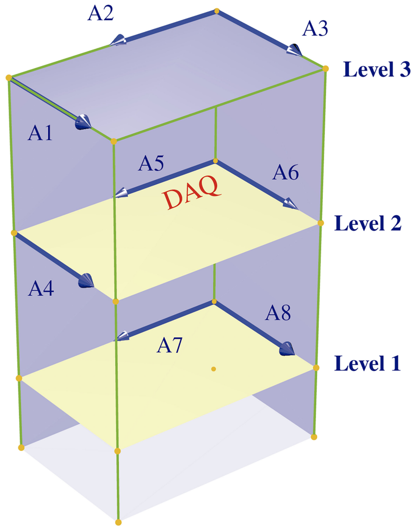


Figure 8. Sensor placement in the tower [78].

The sensor measurements were collected by an LMS SCADAS acquisition system located on the second floor of the tower. Additionally, every 10 min, information on environmental conditions, including ambient temperature, relative humidity, wind speed, and atmospheric pressure, was recorded by a weather station situated in the Albayzin neighborhood, just 300 m from the tower.

3.4. FEM Modeling and Vibration-Based Damage Identification

The surrogate model for damage identification of the tower, using the data from the OMA, is explained in detail in García-Macías et al. (2022) [34]. Signal processing was conducted using the MOVA/MOSS signal preprocessing module [31], a software solution developed by some of the authors for analyzing ambient vibration and long-term dynamic structural health monitoring. To minimize noise effects and abnormal events in the acceleration records, the signals were processed using a trend elimination filter and a high-pass Butterworth filter with a 2 Hz cutoff frequency. Based on the continuously measured ambient vibration signals recorded in separate 30-minute-long records, the modal parameters of the tower were identified using an automated version of the covariance-driven stochastic subspace identification (Cov-SSI) method [79].

As reported in our previous work [34], although up to eight modes were clearly identified in the frequency broadband up to 60 Hz, only the first three modes exhibit clear global motions of the tower, while the others are hypothesized to represent local modes of the battlements. These first three modes represent first-order bending in the two main directions of the tower (F_X and F_Y), while the third one represents a first-order torsional mode of the tower (T_Z). These first three modes were consistently identified throughout the monitoring period until March 31st, yielding the average modal properties listed in Table 2. Note in this table that the modal properties vary considerably due to fluctuations in environmental conditions (mainly temperature and humidity). These variations are generally much larger than those caused by damage. Therefore, it is essential to implement a statistical pattern recognition approach to minimize benign variations and avoid masking the effects of damage. Interested readers can refer to reference [34], where a Multiple Linear Regression model was used to identify the environmental effects on the tower's resonant frequencies.

Table 2. The average values of the modal properties for the first three modes during the monitoring period.

Mode	Frequency [Hz]	Damping Ratio [%]
1 (F_X)	4.44 (±4.07%)	4.49 (±31.67%)
2 (F_Y)	7.38 (±4.42%)	4.39 (±47.46%)
3 (T_Z)	9.95 (±6.19%)	2.46 (±92.11%)

To create a structural digital twin of the tower, a three-dimensional finite element model was developed using ABAQUS software (Figure 9). The model's geometry was constructed using information from available blueprints and in situ inspections. The vaulted floors, openings, interior stairs, and battlements were included in the model. Additionally, sections of the adjacent walls of the Alhambra were also included. To balance computational efficiency and accuracy, only small sections of the walls, each 15 m long (determined by a preliminary sensitivity analysis), were included in the model. The foundations of the walls and the tower are considered fixed, while the lateral interaction with the ground for the buried portion of the tower and adjacent walls is modeled using elastic springs. The model uses four-node linear tetrahedral elements (C3D4) with an average size of 0.50 m, determined through a convergence analysis that increased the mesh density until variations in the resonant frequencies fell below approximately 0.25%, resulting in a total of 70,898 nodes and 345,642 elements.

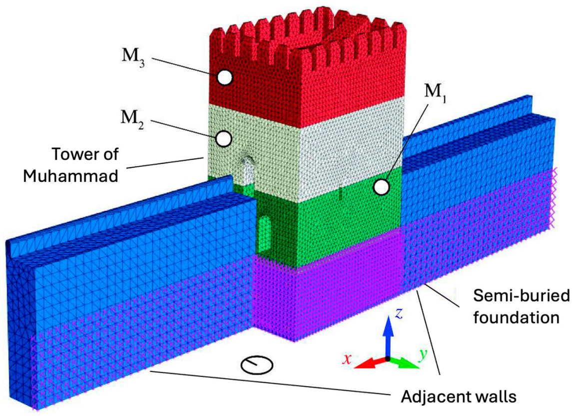


Figure 9. The finite element model of the tower for vibration-based damage identification [78].

Given the uncertainty over the material properties of the tower, the finite element model was inversely calibrated by a simple model updating approach based on linear sensitivity analysis using the first experimental modes (resonant frequencies and mode shapes), resulting in the mechanical parameters shown in Table 3. The calibrated model achieved an average error in frequency of 1.28% and a minimum modal assurance criterion (MAC) value of 0.94. Figure 10 shows a comparison between the first three mode shapes derived from experimental data and those obtained from the numerical model. Interested readers can find further details on the finite element model updating approach in reference [34].

Table 3. Mechanical properties of rammed earth used in the finite element model.

Parameter	Value
Density	2420 kg m^{-3}
Compressive strength	2.45 MPa
Tensile strength	0.30 MPa
Elastic modulus	1.97 GPa
Poisson's ratio	0.30

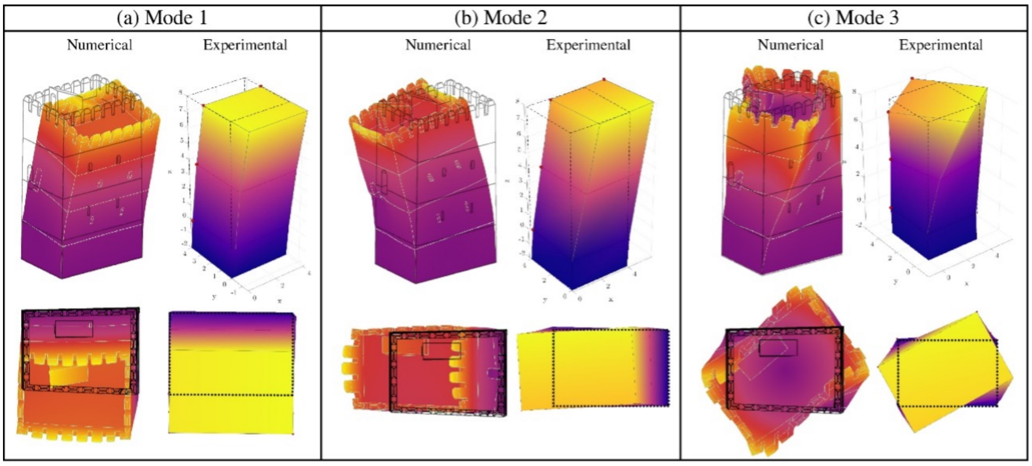


Figure 10. Comparison between numerical and experimental mode shapes of the tower.

Due to the high computational cost of the proposed FEM model, it is not feasible for continuous damage identification. Note that the FEM model takes approximately 5 min to conduct one single linear modal analysis on a standard i7 PC, which results in an overwhelming computational burden when implemented in a FEM model updating using a heuristic optimization algorithm (e.g., genetic or particle swarm algorithms). Therefore, a Kriging surrogate model is used instead, which relates the elastic properties of three macro-elements M_i in the tower, as shown in Figure 9, to the modal properties of the tower. The elastic modulus of each of these three macro-elements is used as a damage parameter in the continuous analysis, assigning each macro-element i a stiffness multiplier k_i. For the construction of the Kriging model, a training population of 160 samples (resonant frequencies and mode shapes) was defined by direct evaluations of the FEM model, achieving a maximum root mean squared error of 6.04×10^{-4} Hz in the prediction of the resonant frequencies of the tower by the Kriging model (over a validation dataset of 200 independent samples). Interested readers are referred to reference [34] for a detailed description of the training procedure and accuracy assessment of the Kriging model. The resulting surrogate model only takes 0.02 s to predict the modal properties of the tower, becoming compatible with continuous modal identification.

Once the digital twin is created, the structural identification procedure is sequentially applied to each dataset from the sampling period (January to March 2022). This procedure involves solving the nonlinear optimization problem of minimizing the objective function considering the differences between experimentally determined vibration modes and their theoretical counterparts (refer to [34] for further details). Time series of identified resonance frequencies, ambient temperature, and relative humidity are shown in Figure 11a,b. Additionally, time series of the stiffness multipliers k_i are presented in Figure 11c. It is observed that environmental effects are also reflected in the adjusted stiffness multipliers. Specifically, the upper macro-element of the tower (k_3) shows particular sensitivity, while k_2 and k_1 exhibit lower sensitivities.

To further analyze the sensitivity of the stiffness parameters, Figure 12 displays the correlation analysis between the adjustment parameters and environmental conditions. In this figure, linear fits are included to illustrate the sign of the correlations. These results confirm the previous analysis, indicating that the upper macro-element (k_3) is the most sensitive. Interestingly, there is a positive correlation between this stiffness multiplier and ambient temperature, while the effect of relative humidity is the opposite. It is important to note that the sensitivity of the modal characteristics of the tower to variations in the upper macro-element is minimal, requiring in-depth calibration analysis (preferably through Bayesian inference) to confirm this behavior. Opposite trends are observed in the correlations for the stiffness parameter of the lower macro-element (k_1). This behavior aligns with the correlations seen for resonance frequencies, which increase with temperature, while increased humidity results in a material stiffness reduction. Notably, the use of the Kriging meta-model allows for inverse calibration in approximately 7 s, making the proposed approach fully compatible with long-term SHM. Lastly, it is important to note that the large variances in the fitting parameters in Figure 12 may hinder the identification of small damages. To address this issue, a proper statistical pattern recognition technique should be adopted to remove benign variations induced by environmental conditions, such as artificial neural networks, nonlinear principal component analysis, or independent source separation techniques. Interested readers can refer to references [80,81] for a comprehensive state-of-the-art review of data normalization techniques for removing environmental effects on SHM data.

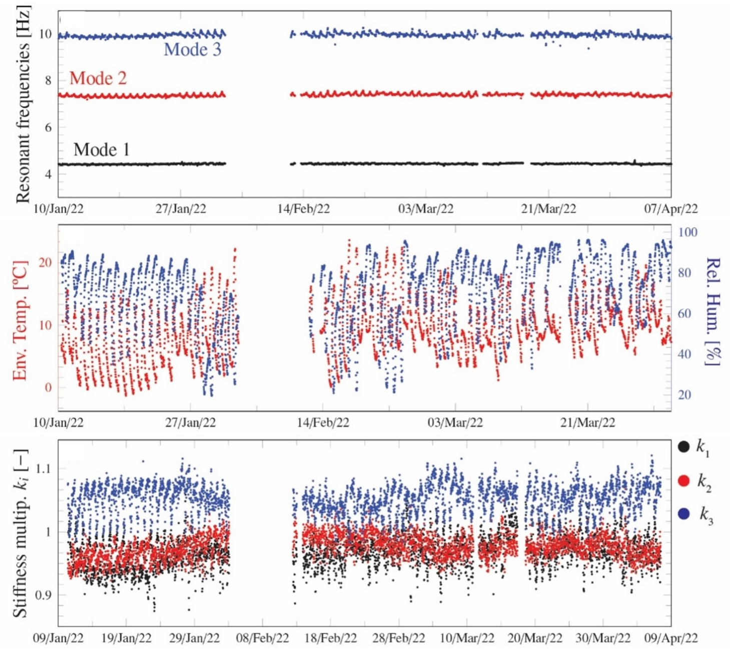


Figure 11. Time series of (**a**) experimental resonance frequencies, (**b**) ambient temperature and humidity, and (**c**) stiffness multipliers k_i adjusted using the surrogate-model-based method.

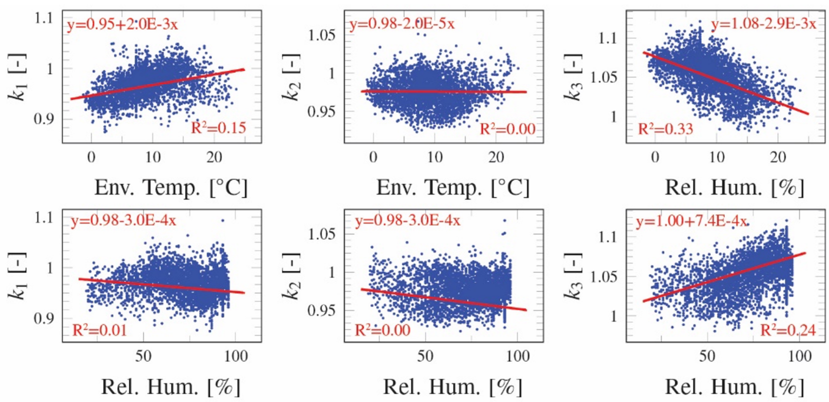


Figure 12. The correlation analysis of the stiffness multipliers k_i for the macro-elements of the Tower of Muhammad, obtained using the surrogate-model-based method.

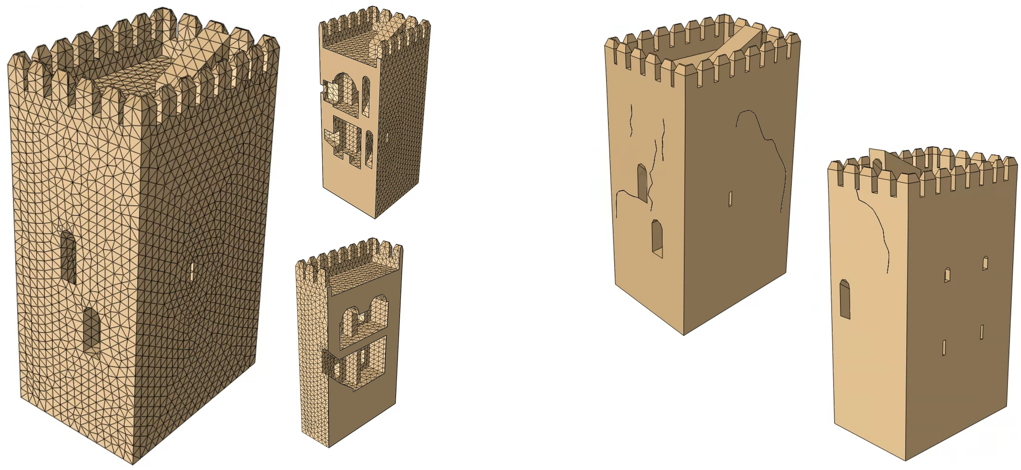
3.5. Finite Element Analysis of Crack Propagation Damage

As mentioned in previous sections, using highly complex, full FEM models is unfeasible for continuous damage identification due to their high computational cost, but they can be very useful for conducting specific damage or vulnerability analyses. In this regard, considering the existence of severe cracks in the walls of the tower, a specific finite element model was developed to evaluate the influence of crack propagation on the seismic behavior of the building, using the extended finite element method (XFEM) to model the cracks [82–84]. The analysis conducted is described in detail in Ávila et al. (2024) [12].

To perform this calculation, a FEM model without cracks was developed for comparison (Figure 13a), together with the XFEM model including the initial pattern of the existing cracks, with an average depth of 0.1 m, in agreement with measurements performed on-site (Figure 13b). Only Level 3 (partial loss of covering, cracking, and moderate spalling) and Level 4 (total loss of covering, cracking, rotation, and large spalling) cracks were considered for the analysis, according to the "Levels of characterization and diagnosis of rammed earth walls with lime plaster (TCA 1)" [85]. The material of the tower was considered homogeneous, with the mechanical properties previously described and following the Mohr–Coulomb plasticity model (Equation (1)), which posits that yielding happens when the shear stress at any point reaches a value that has a linear relationship with the normal stress in the same plane:

$$\tau = c + \sigma \tan \phi, \quad (1)$$

where τ is the shear stress, c is the cohesion (set to 225 kPa), σ is the normal stress, and ϕ is the friction angle (set to 42°). The values for cohesion and friction angle were determined based on the existing literature on lime-stabilized rammed earth [5].



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

Figure 13. The finite element model of the Tower of Muhammad for cracking analysis: (**a**) the FEM model and sections; (**b**) initial crack locations in the XFEM model.

As a first step, a modal analysis of the tower with and without cracks was performed. The results showed that the presence of cracks has a very significant influence on the modal behavior of the building, causing reductions of 8.8%, 13.5% and 4.9% in natural frequencies for the first, second, and third modes, respectively.

The effect of crack propagation under the seismic action was evaluated through a pushover analysis, using a spectrum defined according to the Spanish Seismic Code [86] for the location of the tower (Granada, Spain) for a return period of 500 years and a Type-II soil. The pushover was applied along the north–south direction, the one considered most vulnerable, as the north facade is at the top of the cliff "*Tajo de San Pedro*", which has already shown stability issues [87]. The pushover displacement-based nonlinear static method has been frequently used by diverse authors for the seismic evaluation of heritage structures [88,89] and rammed earth structural elements [90–92], and it is considered a valid method in seismic codes such as Eurocode 8 [93].

The results showed a 28% reduction in the maximum base shear, from 74 MN to 53 MN, due to crack propagation, combined with a significant loss of stiffness and an increase in the top displacement associated with the maximum load. The load–displacement behavior of the tower during the pushover analysis can be observed in detail in the pushover curves in Figure 14. Taking into account the base shear forces obtained and the overall weight of the tower, equal to 1.45 × 10^6 kg, the maximum acceleration reached during the pushover analyses was 3.7 g for the damaged state and 5.2 g for the undamaged state. Considering that the peak ground acceleration for the location of the tower is equal to 0.32 g, according to the Spanish Seismic Code, the pushover results indicate that the structure is far from failure in the event of a potential earthquake.

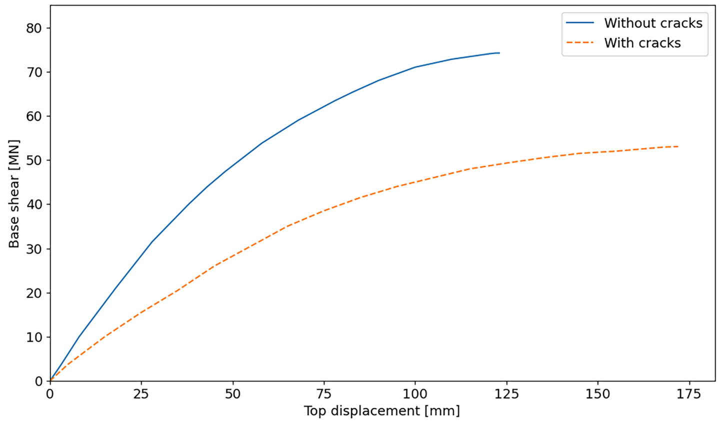


Figure 14. Pushover curves for the FEM model without cracks and the XFEM model with crack propagation.

The progression of cracks during the pushover test can be monitored using the variable STATUSXFEM, which ranges from 0 to 1, where a value of 0 indicates that the enriched element contains no cracks and a value of 1 indicates that the element is completely cracked. The state of this variable at the end of the test is shown in Figure 15, where it is possible to observe damage mainly in the upper part of the tower on all of its sides and in the lower part of the tower, mainly in the north and west walls. The areas with crack propagation damage obtained in the XFEM model coincide with the regions of the tower that show a more precarious state of conservation, presenting cracking and spalling.

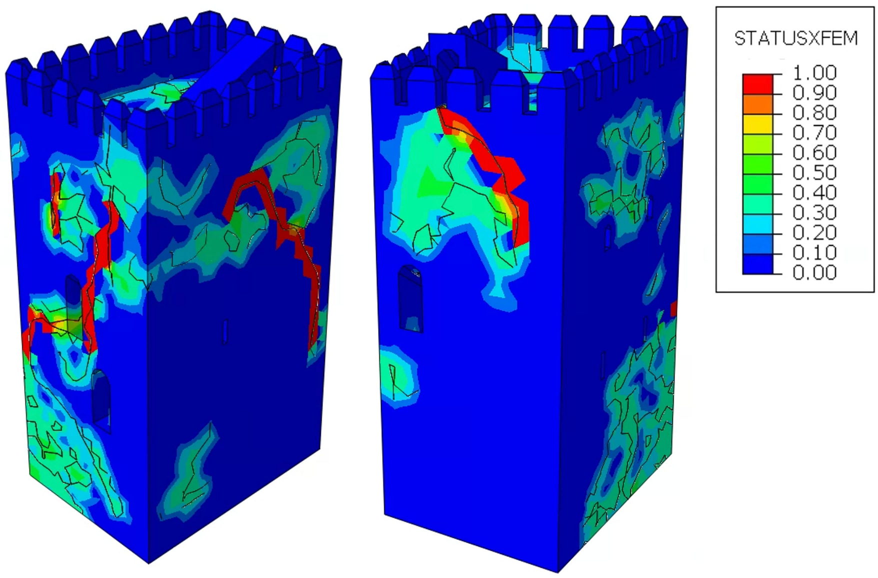


Figure 15. Cracks generated during the pushover analysis of the tower using an XFEM model.

4. Conclusions

The proper preservation of heritage structures with the sustainable management of available resources requires the development of methodologies for continuously assessing their conservation status, detecting potential damage, and evaluating its impact on the structural vulnerability. These methodologies must be specifically designed for the construction type under analysis; their success also depends on their ability to integrate data from diverse sources, including bibliographic information, continuous monitoring, visual inspections, and on-site local tests.

Considering the above, the present study proposes a methodology for the preventive preservation of rammed earth heritage structures through continuous monitoring, on-site inspections, and data fusion. The workflow of the methodology includes data collection from the existing bibliography and studies, periodic on-site inspections (including nondestructive testing), and continuous monitoring. These data are used to develop a numerical model of the building and create a digital twin for the continuous detection of anomalies, which may indicate damage. When damage is detected by the model, further inspections can be carried out, and if necessary, restoration or consolidation work can be planned and executed.

This methodology was applied to a case study, the Tower of Muhammad at the Alhambra (Granada, Spain, 13th century), which is built in lime-stabilized rammed earth, located in a seismic zone, and in a precarious state of conservation. After conducting a bibliographic study of the available historical and structural data, on-site inspections were carried out and confirmed the existing pathologies in the tower. Accelerometers were also installed for continuous monitoring of the building. With these data, a surrogate model was developed to detect damage based on changes in the stiffness of three macro-elements of the tower, as well as an XFEM model that allowed for the analysis of the effect of existing cracks in the tower and their propagation on its seismic vulnerability.

The reported results demonstrate the potential of the proposed methodology to enhance the management of conservation practices for rammed earth structures by continuously detecting damage and facilitating the planning of necessary interventions. Future cases of application of the methodology will allow for the development of specific solutions and recommendations for particular structural types, as well as possible improvements. Based on the results of the present study, the following recommendations for improving the structural health of historic RE buildings can be highlighted:

- Develop digital twins using Bayesian model updating to quantify uncertainties in the calibration parameters.
- Incorporate aging degradation models to predict the expected lifespan.
- Periodically update the digital twins based on the results of regular on-site inspections and nondestructive evaluations.
- Emphasize the importance of pattern recognition models for filtering out environmental effects.

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Abbreviations

The following abbreviations are used in this manuscript:

Cov-SSI	Covariance-driven stochastic subspace identification
DT	Digital twin
FEM	Finite element method
GPR	Ground-penetrating radar
HBIM	Heritage building information model
LiDAR	Light detection and ranging
MAC	Modal assurance criterion
NDT	Nondestructive testing
OMA	Operational modal analysis
RE	Rammed earth
SASW	Spectral analysis of surface waves
SHM	Structural health monitoring
UPV	Ultrasonic pulse velocity
URE	Unstabilized rammed earth
XFEM	Extended finite element method

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