



The effect of existing damage on the seismic performance of a historical masonry structure: a site-specific assessment

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Received: 27 March 2026 / Accepted: 10 May 2026 / Published online: 26 May 2026
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Abstract

This study comprehensively evaluates the structural integrity and seismic performance of a historic masonry mosque, exhibiting significant settlement cracks, through an integrated approach combining field measurements and advanced numerical analyses. The Operational Modal Analysis (OMA) conducted to determine the dynamic characteristics of the structure. Field measurements revealed that the environmental vibrations originating from a nearby tram line causes significant amplitude increase in one of the main columns. The dynamic characteristics of the structure obtained from field experiments are used to calibrate the numerical model via the Particle Swarm Optimization Algorithm. The calibrated numerical model, taking into account the existing cracks in the structure using contact elements, was subjected to nonlinear analysis in the time domain under 11 site-specific ground motion records selected in accordance with the procedures of the Turkish Building Seismic Code. This analysis examined the seismic performance and damage mechanisms of the structure. The findings revealed that while existing settlement cracks contribute to seismic energy dissipation through frictional sliding and gap opening mechanisms, they may also serve as potential failure initiation points under strong ground motions. This study's integrated approach, combining dual-purpose OMA application and explicit crack modeling with contact elements, constitutes a novel methodological framework for the realistic seismic assessment of historic masonry structures with pre-existing damage.

Keywords Seismic assessment · Operational modal analysis · Model calibration · Existing damage · Masonry

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1 Introduction

The preservation of architectural heritage is a fundamental obligation, ensuring that the aesthetic and technical heritage of the past is safeguarded for future generations. Historical masonry structures, particularly monumental ones like masonry mosques with their large domes and monolithic walls, serve as cultural landmarks that shape societal identity. However, preserving these structures presents complex engineering challenges, including material uncertainties, age-related deterioration, and the need for non-invasive interventions (Krentowski et al. 2023; Kocaman and Kazaz 2023a, b). Consequently, ensuring their structural safety requires a comprehensive approach that integrates non-destructive testing (NDT) with advanced numerical analysis. Nevertheless, miscalculated or inappropriate interventions can compromise structural integrity, highlighting the need for rigorous evaluation methodologies tailored to the unique characteristics of each structure. In this context, recent studies utilizing NDT techniques on historical masonry structures have significantly advanced the field of structural assessment and heritage preservation. These methods are crucial for assessing the condition and durability of aging masonry while minimizing the risks associated with traditional invasive testing techniques, with various applications emerging that range from evaluating mechanical properties to assessing structural integrity, all aimed at preserving the cultural significance of these structures.

A notable study conducted by Grazzini and Lacidogna (2021) demonstrated how non-destructive techniques can effectively estimate the mechanical strengths of masonry materials without requiring destructive sampling, which is particularly useful for preserving the historical integrity of structures, with their work focusing on in situ tests at the St. Agostino Church in Amatrice, Italy. Similarly, Luo et al. (2021) emphasized the necessity of robust NDT techniques for protecting historic structures, summarizing various damage and repair measures facilitated by non-destructive evaluations. The integration of NDT with advanced technologies has led to innovative approaches in structural assessment; for instance, Solla et al. (2020) merged building information modeling (BIM) with geospatial data acquired through terrestrial laser scanning (TLS) to enhance the documentation and preservation of cultural heritage, while Azar and Sari (2023) focused on modern tools such as Faro laser scanning and impulse sound testing for evaluating historical arch bridges, underscoring the importance of non-invasive methodologies in restoration projects. Moreover, the use of dynamic identification techniques in historic structures has gained traction, as evidenced by Luger et al. (2025), who conducted a field investigation employing NDT methods to characterize the masonry properties of the Castle of Lanjarón in Spain, with their results contributing to the calibration of finite element models and addressing dynamic responses crucial for seismic assessments. The study of Bozyiğit and Acikgoz (2025) further highlighted the use of rapid post-earthquake assessment methods to estimate vibration frequencies of historical masonry structures, demonstrating the utility of NDT in assessing structural vulnerabilities under seismic actions. Additional research has reported the effectiveness of advanced NDT techniques like ambient vibration tests and acoustic emission monitoring; for instance, Sunara et al. (2023) utilized ambient vibration testing to identify modal properties of a historic bell tower, providing insights into structural behavior necessary for preservation efforts, while Verstrynghe et al. (2021) reviewed acoustic emission monitoring, noting its potential for detecting damage in masonry structures through non-invasive methodologies, which aligns well with the unique characteristics of historical materials. Thus,

the application of non-destructive testing methods facilitates the preservation of historical masonry structures and contributes to a deeper understanding of their material properties, with these technologies increasingly enhancing conservation methodologies as they continue to evolve.

One of the most critical issues identified through such assessments is the response of masonry structures to foundation settlement, as the assessment of structures subjected to varying levels of settlement is a primary concern given that differential settlement can lead to severe structural distress. Settlement can lead to various structural issues, including cracks that compromise integrity; this is especially true in cases of differential settlement Marina et al. (2026), where different parts of a structure settle at varying rates, thereby exacerbating stress concentrations. Understanding the mechanisms of settlement-induced damage and accurately modeling these effects are essential for determining appropriate remediation strategies and ensuring the longevity of masonry structures. Recent studies have utilized various numerical techniques to simulate the behavior of masonry under differential settlement conditions; Gagliardo et al. (2019) explored both rigid block and finite element methods to analyze the failure mechanisms in historic masonry panels subjected to settlement-induced damage, emphasizing the importance of modeling the masonry shape and settled zones, as these factors significantly influence the resulting crack patterns. When addressing crack propagation in masonry structures, various modeling techniques have been developed to predict crack formation and progression accurately. Bejarano-Urrego et al. (2018) conducted numerical analyses comparing discrete and smeared crack modeling approaches, with their findings indicating that while smeared crack models benefit computational efficiency, they require careful approximation of joint interface behavior to capture the nonlinear characteristics affecting crack propagation, which is particularly relevant for settlement-induced cracking analysis. Additionally, Casalegno et al. (2013) performed a comparative analysis of homogenized and heterogeneous modeling strategies for masonry subjected to differential vertical displacements, demonstrating how the choice of modeling approach influences the predicted structural response, with heterogeneous models providing more detailed descriptions at the cost of computational efficiency. This consideration is vital, as the mechanical response of masonry can vary significantly based on the interaction of its components, influenced by factors such as the orientation and bond quality of the masonry units. Consequently, integrating robust numerical modeling with modern monitoring strategies offers a comprehensive framework for evaluating settlement-induced damage. However, the reliability of these numerical models depends heavily on the accuracy of input parameters and validation against real-world behavior.

In this context, Operational Modal Analysis (OMA) has emerged as a vital technique for validating numerical models and assessing structural integrity. This analytical method focuses on determining the dynamic characteristics of structures—such as natural frequencies, mode shapes, and damping ratios—using ambient vibrations without the need for controlled excitation forces; because of that, OMA became suitable for assessing structures where traditional forced vibration testing may not be feasible or would pose risks to structural integrity (Azzara et al. 2017; Meoni et al. 2024). One of the key advantages of OMA is its ability to analyze the structural behavior in its operational environment, thus capturing the effects of various dynamic loads that a structure experiences over time, which is particularly relevant for historical buildings that often endure additional stresses due to their unique compositions, age, and surrounding urban conditions. The method facilitates

continuous monitoring of the dynamic response of structures, allowing for timely detection of any significant changes or deterioration in structural performance. For example, Ramírez et al. (2022) used this method with long term measurements to identify modal properties of how structures get affected by environmental conditions. Koçak et al. (2019) studied on the determination of characteristic parameters of masonry structures through OMA, demonstrating how this technique can assist in understanding the response of masonry elements to dynamic loading, while Scozzese et al. (2019) utilized OMA for detecting variations in modal properties of masonry arch bridges, emphasizing the method's effectiveness in identifying changes due to external actions such as scour. In practical scenarios, researchers have successfully applied OMA to assess damages induced by environmental factors, such as earthquakes; for instance, Hökelekli et al. (2020) employed OMA to investigate the seismic performance of a historical masonry minaret, facilitating model updates to account for observed dynamic responses under various ground motion conditions, while García-Macías et al. (2020) demonstrated the synergistic application of operational modal analysis and ambient noise deconvolution interferometry for structural and damage identification in historic masonry structures, particularly for localizing damage after seismic events. Furthermore, research by Masciotta et al. (2025) suggests that structural health monitoring serves as a critical component during the restoration phase following seismic activity. This ability to integrate real-world observations into predictive models underscores OMA's role as an essential tool in the field of structural health monitoring.

Once the dynamic characteristics are identified via OMA, they serve as a benchmark for calibrating numerical models. In recent years, optimization algorithms or numerical methods have gained prominence in model calibration processes aimed at enhancing the accuracy and reliability of numerical models. In this context, Ergün and Tayfur (2024) used Tabu Search Algorithm; again Ergün et al. (2026) used Teaching-Learning Based Optimization and Salachoris et al. (2024) used Genetic Algorithm to reduce discrepancies between analytical predictions and experimental outcomes. Beyond these deterministic algorithms, Bayesian inference has recently emerged as a prominent and differentiating tool in this field for explicitly quantifying and mitigating uncertainties. Specifically, Bayesian updating has proven highly effective in managing multiple uncertainty sources to enhance the predictive capabilities of historical masonry tower models (Monchetti et al. 2022). Comparative studies have evaluated its computational performance against surrogate-assisted deterministic approaches (Ponsi et al. 2022), while recent advancements have introduced more flexible likelihood-free techniques, such as Approximate Bayesian Computation, for dynamic identification (Monchetti et al. 2024). Building on these developments, a contemporary study by Monchetti et al. (2026) further indicates that Bayesian optimization is highly instrumental in mitigating such structural uncertainties. Furthermore, updating numerical models based on experimental dynamic characteristics is a fundamental step to reliably perform nonlinear dynamic analyses and predict potential failure mechanisms of historical structures (Nohutcu 2019; Sakcali et al. 2022). Historical masonry structures, characterized by complex geometries and material properties, necessitate meticulous modeling efforts, and the use of optimization algorithms in model calibration often integrates ambient vibration data to extract dynamic properties, which can inform subsequent model adjustments and enhance parametric sensitivity analyses (Bianconi et al. 2020). The methodologies applied range from traditional finite element methods to more sophisticated hybrid approaches that incorporate machine learning techniques; for example, artificial neural networks trained on

material and geometric descriptors to predict the compressive strength of historical masonry buildings (Onat and Yön 2019), or clustering-based algorithms developed to automate the interpretation of OMA results on masonry arch bridges (Civera et al. 2022), thereby supporting more robust predictions of structural integrity under various loading scenarios. This approach is bolstered by continuous advancements in computational capabilities that support detailed parametric comparisons of finite element modelling strategies for unreinforced masonry (Ravichandran et al. 2021), as well as the derivation of fragility curves that quantify how pre-existing light damage influences the seismic response of masonry walls (Kor-swagen et al. 2022). Openly available software frameworks further assist in systematic vulnerability analysis workflows (Martins et al. 2021). These techniques enhance the fidelity of numerical models while providing a framework for dynamic updating, allowing for the assessment and recalibration of models in response to real-time monitoring data. Consequently, the integration of optimization algorithms into model calibration aids in safeguarding historical masonry while playing a pivotal role in restoration and preservation efforts, ensuring that these invaluable cultural artifacts are maintained for future generations, and by leveraging these advanced technologies, structural engineers can more effectively address the inherent challenges associated with the aging and unique architectural features of historical masonry constructions.

Beyond the optimization of model parameters, accurate simulation of masonry behavior under complex loading requires advanced constitutive models. While the Mohr-Coulomb model is widely used due to its simplicity, it often fails to capture the complex stress paths and confinement effects typical of masonry structures; in contrast, the Drucker-Prager model offers a more robust framework for representing the yield behavior of pressure-dependent materials, with its ability to account for hydrostatic pressure effects and material hardening/softening making it particularly suitable for simulating the nonlinear response of historical masonry under seismic loads (Resende and Martin 1985; Avossa and Malangone 2015). A critical aspect often overlooked in standard finite element analyses is the explicit modeling of existing cracks, as smeared crack models, while computationally efficient, often fail to capture the discrete nature of crack opening and sliding mechanisms, which are vital for accurate seismic assessment. The use of contact elements addresses this limitation by explicitly modeling the interaction between crack surfaces, allowing for the simulation of frictional sliding and gap opening, and providing a more realistic representation of the structure's energy dissipation capacity and potential failure mechanisms (Ferrante et al. 2021; Pulatsu and Tuncay 2024; Schiavoni et al. 2026). In the broader context of numerical approaches to cultural heritage structures, DEM-based models inherently represent the discontinuous block mechanics of masonry, capturing the large relative displacements between blocks under quasi-static and impact loading conditions (Pulatsu et al. 2021) as well as the continuum-to-discontinuum transition that governs collapse mechanisms in multi-block masonry assemblies (Smoljanović et al. 2015), while hybrid finite-discrete element formulations have combined the advantages of both frameworks for problems involving settlement-induced failure in historic masonry (Ou et al. 2022). For crack propagation simulation within the FEM framework, tracking algorithms have been developed for masonry structures under monotonic and cyclic loading (Saloustros et al. 2019), and continuum damage formulations have proven effective for the seismic assessment of complex historic masonry geometries (Kujawa et al. 2020). The present study adopts a FEM-based approach with explicit contact elements for pre-existing cracks, which captures the discrete nature of iden-

tified crack surfaces while retaining the computational advantages of the continuum formulation for the undamaged portions of the structure. While these modeling techniques offer detailed insights into the nonlinear seismic response of pre-damaged masonry structures, their accuracy is contingent upon rigorous definition of contact surface parameters and constitutive material inputs, which are systematically addressed in the methodology presented herein.

This study presents a comprehensive seismic performance assessment of a 500-year-old historic mosque whose condition is structurally singular in its combination of features: an advanced pattern of pre-existing settlement cracks coexisting with continuous low-amplitude dynamic loading transmitted from an adjacent urban tram line. This coexistence of severe pre-damage and persistent environmental excitation in a monumental masonry setting is rarely documented as a single case in the literature, and the structural uniqueness of the case principally motivates the present work. An integrated assessment methodology is developed for this specific setting, combining experimental field studies (UPV, OMA), optimization-based numerical model updating, and nonlinear seismic analysis in the time domain. The operational vibration measurements, originally conducted only for modal identification, unexpectedly revealed during processing a strong correlation between tram passage times and amplitude amplifications in one of the main columns; this finding (which was not anticipated at the outset of the measurement campaign) was subsequently incorporated into the assessment and is reported here as an environmental loading factor that is seldom documented for historic masonry structures in urban operational settings. Alongside this observation, the study contributes a cohesive assessment framework for structures of this kind: (i) pre-existing settlement cracks are modeled explicitly through contact elements rather than through smeared stiffness reduction, providing a physically consistent representation of the actual damage state; (ii) a fully automatic Particle Swarm Optimization (PSO)-based updating procedure reconciles the heterogeneous material distribution with the experimentally identified frequencies; and (iii) the calibrated model is assessed under 11 site-specific ground motions selected in compliance with the Turkish Building Earthquake Code (Disaster and Emergency Management Authority 2018). The analyses revealed that the existing cracks exhibit a dual mechanical role: while they contribute to seismic energy dissipation through frictional sliding and gap opening mechanisms—with crack surface separations reaching up to 15 mm and frictional stresses up to 9 MPa—they simultaneously represent potential vulnerability zones where severe damage may initiate under strong ground motions. To the authors' knowledge, this particular combination of conditions and methodological elements has not been previously reported in the literature on historic masonry assessment. Thus, the contribution of the present work therefore resides primarily in the structural singularity of the case and in its case-specific integration of the adopted methods, rather than in any individual technique considered in isolation.

2 Overview of the historical Karatay Sultan Selim Mosque

In this section, architectural and geometric properties, historical background, and existing damage conditions of the Karatay Sultan Selim Mosque are presented. In addition to the above information, the results of the non-destructive field tests are also given in this section. Images of Karatay Sultan Selim Mosque can be seen in Fig. 1. The structure is located in the



Fig. 1 Karatay Sultan Selim Mosque



Fig. 2 Location of the Mosque

city center of Konya, Türkiye. The Mevlana Tomb is located almost adjacent to this unique structure. Due to its location, the mosque has a high potential for being visited by both local and foreign tourists. The satellite image of the mosque is given in Fig. 2 (Google 2025).

2.1 Historical background

The exact construction date of the Karatay Sultan Selim Mosque is not known. However, some archive documents and architectural properties of the structure indicate that it was built in the 16th century (Özyalvaç 2020). The architectural design of the mosque bears notable similarities to the Fatih Mosque in Istanbul (a structure that has previously been the subject of a seismic structural-identification study by Beyen (2008)), which was constructed a few decades earlier, suggesting a shared architectural tradition and influence from the classical Ottoman period. The structure underwent several restorations throughout its history. As known from local sources, the foundation of the structure also had some interventions in the recent past due to settlement problems. The city of Konya is located in an area of moderate seismic risk in Türkiye (Aksoy and Demiröz 2012). However, historically, earthquakes occurring along the surrounding fault lines have caused significant damage to structures in the region. Reports mentioning destructive earthquakes in Konya date back to the Ottoman period (Boğaziçi University Kandilli Observatory and DAE Regional Earthquake-Tsunami Monitoring and Assessment Center 2023). In addition, the city has a continental climate. Therefore, it experiences heavy snowfall in winter and high temperatures in summer. Con-

sequently, the structure is situated in a location that necessitates careful consideration of environmental conditions.

2.2 Geometric configuration and structural components

The mosque is a representative example of classical Ottoman architecture, with its central dome, symmetrical plan, and well-proportioned structural elements. The structure has an almost square footprint with measurements roughly 37.65 m by 37.24 m, while the rectangular portico extends approximately 10.5 m outward, functioning as a covered transition zone between the courtyard and the main prayer hall. The minarets reach up to about 32.2 m (without spire), while the central dome rises to 24.17 m above the ground. The central dome sits at the center of the structure, supported by four large piers connected through pendentives, structural transition elements that transfer the dome loads from the circular base to the square pier layout. Around this central dome, smaller semi-domes and additional domes contribute to the lateral stability of the central dome by providing intermediate thrust paths toward the outer walls; this hierarchical dome arrangement is a characteristic structural system of classical Ottoman mosque design, in which the lateral thrust of the central dome is progressively transferred through a sequence of semi-domes and buttressing elements. Additionally, the central dome is laterally supported by a system of eight arches that transfer dome thrust to the piers and exterior walls. The solid model of the structure and its main geometric features are shown in Fig. 3.

At the front, the portico features a series of arches supported by slender columns, with each section capped with its own small dome, while the two minarets are positioned symmetrically on either side of the main entrance. The architectural plan is organized symmetrically around the central domed hall, with the surrounding smaller domed bays providing both spatial subdivision and distributed lateral support to the exterior walls. The structural system integrates load-bearing walls, arches, and domes in a hierarchical arrangement in which vertical loads are channeled through the dome-pendentive-pier-wall sequence to the foundations. The domes, arches, and vertical elements collectively form a statically coherent system that combines formal symmetry with structural continuity, characteristic of the classical Ottoman structural tradition.

2.3 Visual inspection and damage status

Detailed visual inspections of the structure revealed continuous cracks, particularly at the dome skirt, window openings, and above the door lintels (Fig. 4). The majority of these cracks extend vertically, exhibiting a pattern that continues downwards along the wall, indicating stress accumulation in the load-bearing wall elements and suggesting potential settlement or differential settlement effects. The cracks observed at the dome skirts originate from the arch-slab connection regions, progressing towards the wall surface and concentrating at the upper levels of the window openings; these cracks are generally acceptable and distinct within the plaster layer, however, in some sections, they are observed to penetrate the load-bearing masonry. The vertical orientation of the cracks around the window openings indicates that these regions, which constitute weak sections, are subjected to stress concentrations due to differential settlement.

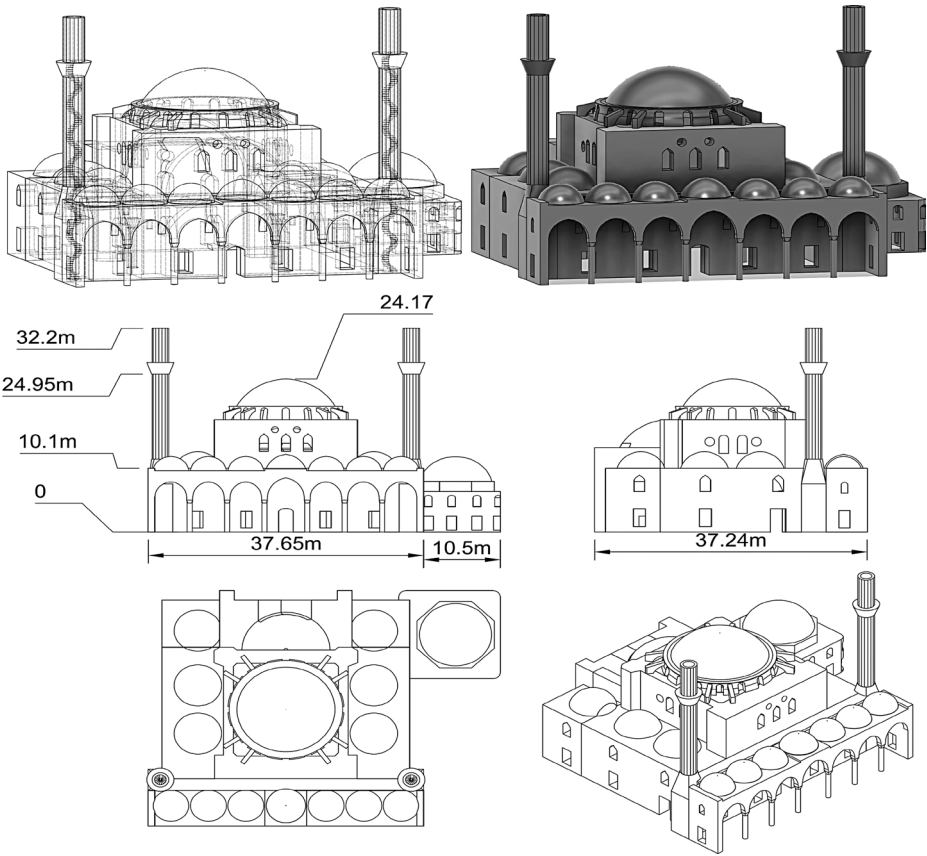


Fig. 3 3D model of the structure

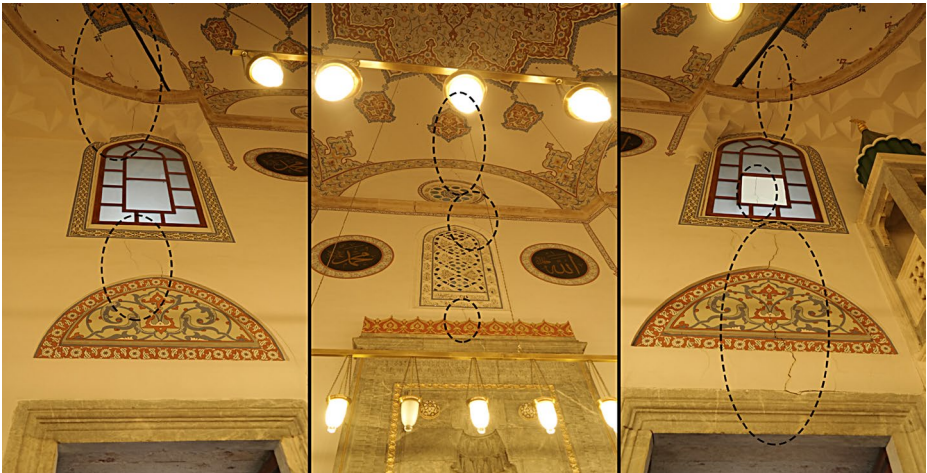


Fig. 4 Cracks on the South Wall

Another notable finding from the visual inspection is the wide cracks located above the door openings, which exhibit continuity through both the plaster and the wall body, extending upwards from both ends of the opening. Such cracks can be associated with shear force effects occurring at the upper parts of the openings and deformations caused by differential settlement. Furthermore, the observation of cracks on the decorative surfaces of the structure indicates that the damage is not limited to the plaster layer but involves stress transfer within the load-bearing wall and arch regions. Consequently, it is evaluated that the existing crack pattern of the structure is of a structural nature and is primarily attributed to differential settlement. In light of these findings, monitoring and mapping the observed cracks, along with their correlation with detailed structural analyses in subsequent stages, are crucial for accurately determining the extent of the damage and potential progression risks.

Short-term vibration measurements performed with accelerometers placed on the four central columns of the structure reveal significant differences in the dynamic behavior of the columns. When the time-domain records presented in Fig. 5 are examined, periodic increases in amplitude are clearly observed, particularly in the series belonging to one specific column, while these periodic amplitude increases are not distinctly seen in the records of the other columns, indicating a deviation from a homogeneous vibration behavior across the structure. The most probable source of this irregular vibration behavior is the tram line passing in the immediate vicinity of the structure; it has been determined that the tram schedules coincide with the minutes of the acceleration records, and a correlation exists between the periodic amplitude increases observed in the records of the aforementioned column and the timing of tram passages. This situation demonstrates that the ground vibrations generated by the tram are perceived more distinctly by the structure, particularly in that column region, with the physical proximity of the relevant column to the tram line evaluated as the primary reason for this behavioral difference.

The effect of periodic external vibration sources on the structural behavior of historical structures is significant, as continuous or repetitive dynamic loading can contribute to material fatigue, accelerate micro-crack formation, and promote the propagation of existing cracks in the long term. Therefore, the magnitude of the recorded vibrations, as well as their repetition frequency and continuity, play a critical role in assessing structural damage. In conclusion, the accelerometer data confirm that the structure is significantly affected by environmental factors; specifically, tram induced vibrations cause localized increases in dynamic acceleration in specific columns. When this finding is evaluated in conjunction with the existing crack patterns of the structure, it is considered that environmental vibrations may contribute to the progression of damage; therefore, it is necessary to account for dynamic load sources in the immediate vicinity of the structure.

2.4 Material properties and non-destructive testing

Due to the monumental quality and historical value of the Karatay Sultan Selim Mosque, the application of destructive testing methods, such as core sampling, was not permitted to preserve the authenticity of the structure. Therefore, an integrated approach involving non-destructive testing (NDT) techniques performed on-site and mechanical tests conducted on similar material samples in the laboratory environment was adopted to characterize the physical and mechanical properties of the masonry units.

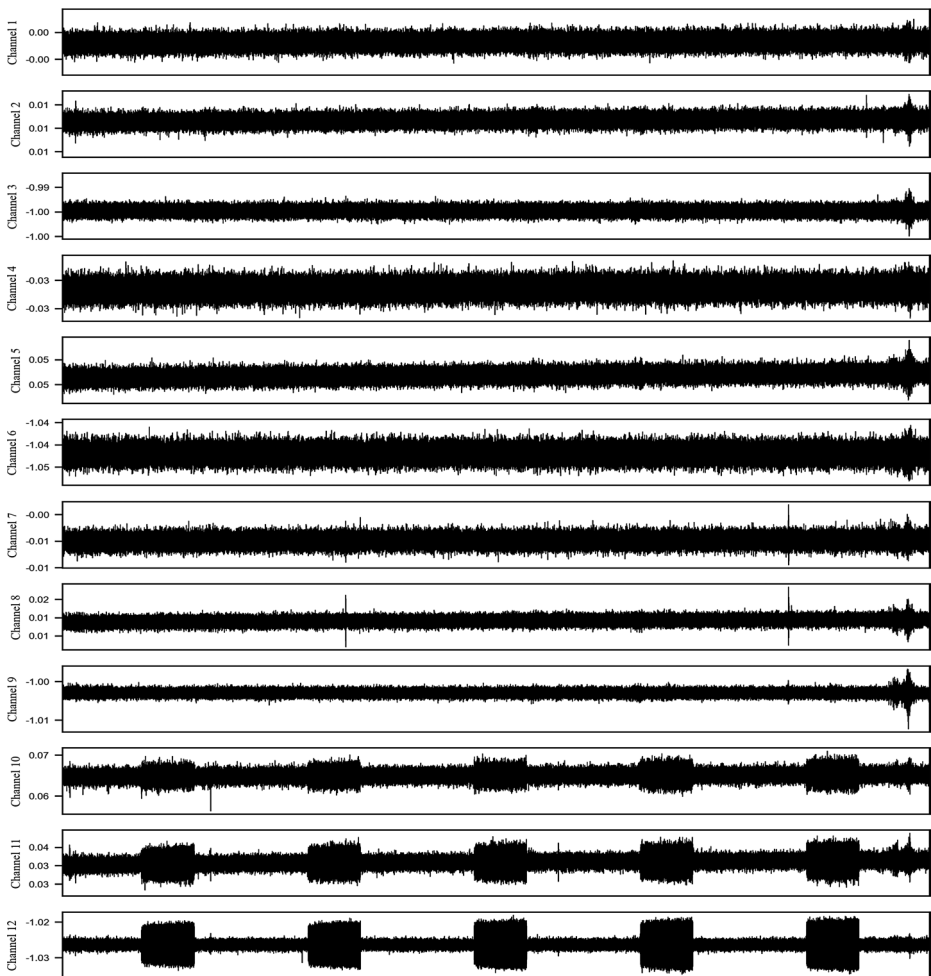


Fig. 5 Accelerogram

2.4.1 Ultrasonic pulse velocity tests

Ultrasonic Pulse Velocity (UPV) tests were conducted to assess the homogeneity of the masonry walls and to gather preliminary information on the material quality. A Pundit brand ultrasonic test device was used in the measurements. Due to the significant thickness of the load-bearing walls and the difficulty of accessing opposite surfaces in most sections, the indirect transmission (surface measurement) method was predominantly preferred over the direct transmission method.

Measurements were conducted at various points throughout the structure, with a particular focus on the main load-bearing piers. Transmitter and receiver probes were placed on the same surface at increasing distances to capture the wave propagation characteristics along the wall surface. Although the device can be used for estimated compressive strength (MPa), due to the uncertainties contained in indirect measurements made in histori-

cal masonry structures (internal voids, multi-layered wall sections, and mortar deterioration, etc.), these values were not used as direct input parameters in the numerical model. Instead, UPV results were evaluated as a qualitative tool to verify material consistency and to detect potential internal discontinuities. The UPV measurements approximately ranged between 3200 m/s and 3800 m/s, which showed parallel results with the laboratory measurements conducted on analogous stone samples.

2.4.2 Laboratory testing of analogous stone samples

Since it was not possible to take core samples directly from the mosque, natural stone blocks obtained from local quarries in the Konya region were used to represent the material used in the construction of the structure. These limestone samples, which possess the characteristic properties of the region, were standardized to geometric forms and subjected to uniaxial compressive strength tests in a laboratory environment.

As a result of the laboratory tests, the initial cracking was observed at 22 MPa in the specimen showing the lowest strength, while the ultimate compressive strengths reached values between 30 and 40 MPa. Adopting a conservative approach, these experimental findings provided the basis for the material density and limit strength parameters (f_c and f_t) used in the finite element model, with an approximately average unit volume weight of 2300 kg/m^3 . However, it is known that the global behavior of historical masonry structures is governed not only by the stone units but also by the mortar and the composite behavior of the wall as a whole. Therefore, the Modulus of Elasticity (E), which is the most critical parameter affecting dynamic behavior, was not fixed solely based on these component tests. The initial E values were updated and calibrated based on the global dynamic characteristics (natural frequencies) obtained by Operational Modal Analysis (OMA), as detailed in the following sections. It should be noted that the non-calibrated parameters such as density, compressive strength, and tensile strength, retain the uncertainty inherent to indirect estimation from analogous material tests. Although conservative values were adopted, the influence of this residual uncertainty on the nonlinear response predictions is acknowledged as a limitation of the present study.

2.5 Operational modal analysis

Considering the existing damage state and material uncertainties of the structure, the dynamic characteristics of the structure (natural frequencies, mode shapes, and damping ratios) were determined using the Operational Modal Analysis (OMA) method to ensure that the numerical model accurately reflects reality. OMA was preferred over forced vibration testing because applying controlled excitation to a monumental masonry structure of this scale is impractical and poses a risk to the historical fabric; furthermore, ambient excitation captures the dynamic response under actual operational conditions, which is more representative of the in-service state of the structure. The field measurements conducted in this context utilized custom-designed accelerometers and data acquisition units with high sensitivity to low-amplitude environmental vibrations, developed in-house by Tayfur (2025). While configuring the measurement setup, the historical nature of the structure and existing physical constraints played a significant role; sensor placement was performed on the four main load-bearing columns that dominate the global dynamic behavior of the structure,

rather than in risky access areas such as the dome and minaret. It is acknowledged that this restricted spatial coverage precludes a statistically robust MAC-based mode shape comparison; a denser sensor deployment encompassing the dome and minaret sections is identified as a priority for future monitoring campaigns.

During the data acquisition process, a sampling frequency of 250 Hz was selected to maximize signal resolution and prevent potential aliasing problems. The recording duration of approximately 30 minutes determined for the measurement set allowed for the recording of both stationary environmental effects, such as wind and micro-tremors, and transient high-amplitude vibrations created by the tram line passing in the immediate vicinity of the structure. After the obtained raw acceleration data were improved with basic signal processing techniques, they were analyzed using the Stochastic Subspace Identification (SSI) method, and in light of the data taken from the four main columns, the first five natural vibration modes of the structure and their damping ratios were successfully decomposed and made ready for numerical model calibration.

The sensor placement plan for the experimental study and the sensor mounting details applied in the field are presented in Fig. 6. As can be seen from the schematic representation, the accelerometer units (S1–S4) were deployed on the four main elephant feet, which play a crucial role in the dynamic behavior of the structure and transfer the dome loads to the ground. Triaxial data were recorded at each measurement station. The X and Y channels, specified in the scheme, were configured to characterize the translation and torsion movements of the structure in the horizontal plane. In contrast, the Z channels were used to characterize the vertical vibration components. In this setup, where synchronized data was collected from a total of 12 channels, the mounting of the sensor boxes was carried out with special fixing methods that would not cause any physical damage to the historical stone surfaces (without drilling or using permanent chemicals).

The stabilization diagram obtained from data processed using the Stochastic Subspace Identification (SSI-PC) algorithm, along with the singular value lines of the system, is presented in Fig. 7. When the diagram is evaluated, the massive mass and high lateral rigidity of the structure, when combined with the damping effects created by the soil conditions,

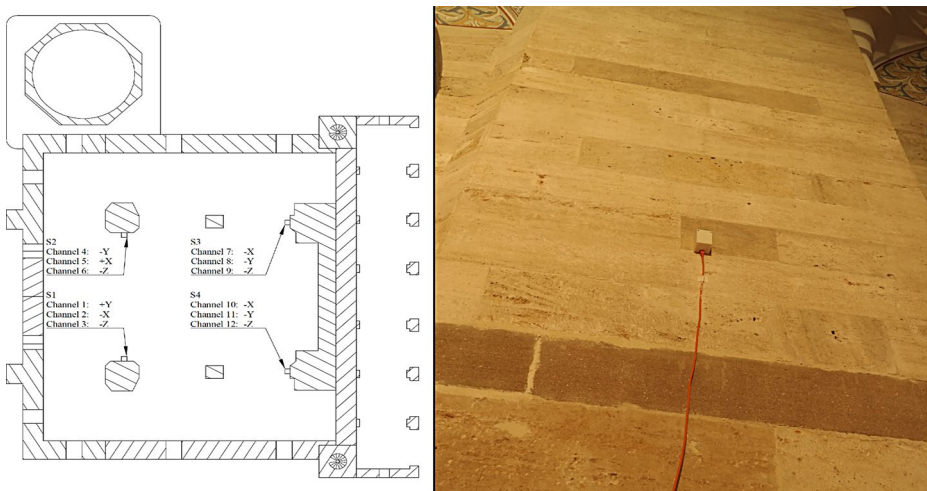


Fig. 6 Sensor placement

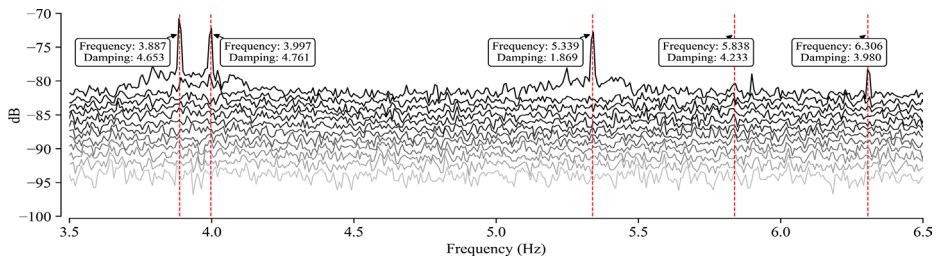


Fig. 7 SSI-PC stabilization diagram

caused a certain amount of flattening in the amplitudes of the spectral peaks and the modes to approach the noise level, as expected. However, thanks to the noise separation capability of the applied SSI method, five dominant modes were identified within the 3.5 Hz to 6.5 Hz frequency band, despite the challenging signal-to-noise ratio. In this identification process, in order to confirm the physical reality of the experimentally decomposed potential modes and their compatibility with structural behavior, the theoretical mode shapes and frequency values obtained from preliminary numerical analysis were used as a reference verification tool.

The fact that the first two modes, appearing at frequencies of 3.887 Hz and 3.997 Hz, are close to each other (closely spaced modes) is a characteristic behavior that also aligns with the numerical model predictions and originates from the geometric symmetry of the structure. As detailed in the visual, the damping ratios associated with the detected modes range from 1.869% to 4.761%. These values are associated with the soil-structure interaction and the energy absorption mechanism of existing damages, and provide a verified dataset for creating the damping matrix of the updated model.

3 Numerical model and optimized model updating

In this section, the processes of creating the finite element model used in the seismic performance assessment of the Karatay Sultan Selim Mosque, defining the material properties, and calibrating the model with experimental data are described in detail. The complex geometry and material uncertainties of historical structures require a precise modeling and verification process. Within the scope of this study, an advanced numerical modeling approach that also considers the existing damage state of the structure has been adopted.

3.1 Numerical model

The three-dimensional finite element model of the structure was created using ANSYS software. To accurately represent the various geometric components of the mosque, including the dome, pendentive, arch, and wall, 10-node SOLID187 higher-order elements with three translational degrees of freedom at each node were employed. This element type was preferred due to its compatibility in modeling curved boundaries and its capability to capture high stress gradients. The quality of the created mesh structure is of critical importance for the reliability of the analysis results. The meshing is shown in Fig. 8. The model consists of approximately 174,631 elements and 288,609 nodes in total.

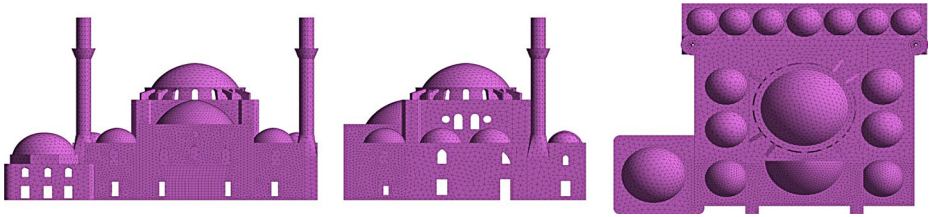


Fig. 8 Meshing of the structure

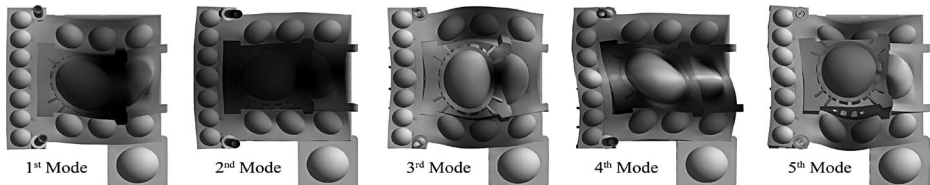


Fig. 9 First five modal shapes (minaret-related modes are excluded)

The first five free vibration modes of the structure were obtained from modal analysis. The first and second modes exhibit horizontal translational behavior in mutually perpendicular principal axes (X and Y directions), with natural frequencies of 3.887 Hz and 3.997 Hz, respectively. The close proximity of these frequencies indicates a well-balanced mass and stiffness distribution, suggesting that the center of rigidity largely coincides with the center of mass. The third mode is characterized by vertical and out-of-plane movements of the structural elements, particularly the dome and wall surfaces. The fourth mode exhibits a more complex deformation pattern involving anti-symmetrical bending and shear mechanisms. The fifth mode represents torsional behavior, characterized by rotational movement of the structure around the vertical axis. The appearance of the torsional mode at a higher frequency, after the fundamental translational modes, reveals that the structure exhibits translation-dominant behavior, which is expected for this kind of structures. The mode shapes belonging to the first five modes are presented in Fig. 9.

One of the most unique aspects of the model is the modeling technique used to represent the cracks present in the structure, as detected through visual inspections. The cracks were modeled using contact elements that simulate physical separation and interaction between surfaces, rather than element deletion or reduction of material properties (smeared crack) methods. Contact element pairs were defined between the crack surfaces. This approach enables the crack surfaces to transfer load under compression, open under tension, and exhibit frictional behavior during sliding. The friction coefficient was accepted as 0.6, taking into account similar studies, as suggested by Scozzese et al. (2019), in the literature and the roughness of the stone surfaces.

In the ANSYS environment, the contact interaction was implemented using CONTA174 and TARGE170 element pairs, which are specifically designed for surface-to-surface contact in three-dimensional solid mechanics problems. The Augmented Lagrangian formulation was adopted for normal contact behavior, providing more accurate penetration control compared to the pure penalty method. A critical clarification is warranted regarding the scope of this modeling approach: the contact elements are applied exclusively to represent

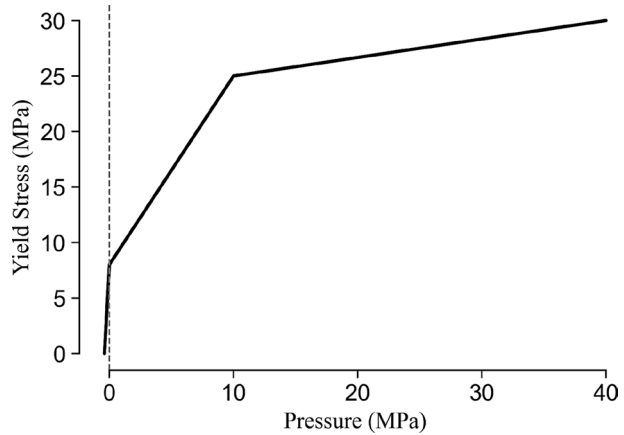
the mechanical interaction of pre-existing crack surfaces identified through visual inspection; they do not model crack propagation or the initiation of new cracks. The geometry of these interfaces is therefore fixed throughout the analysis, and the contact formulation governs the relative motion between the two opposing surfaces. Under compressive loading, the surfaces transfer normal stress through the contact stiffness; under tension, a gap opens as the contact status transitions from closed to open. This formulation accurately reproduces the “breathing” mechanism characteristic of pre-damaged masonry under cyclic seismic loading, wherein crack surfaces alternately separate and re-engage, dissipating seismic energy through friction (Stavroulaki et al. 2018).

Regarding the structural boundary conditions of the numerical model, fixed supports were applied at the foundation level of all load-bearing elements, constraining all translational and rotational degrees of freedom at the base. Soil-structure interaction (SSI) effects were not explicitly incorporated into the model. This decision was motivated by two primary considerations: the present study focuses on the global seismic assessment of the superstructure, and the detail level of the finite element model was calibrated accordingly; and sufficient in-situ geotechnical data (including shear wave velocity profiles and soil stiffness measurements) were not available to reliably parameterize a soil impedance or spring-dashpot SSI model. It is acknowledged that a partial fixity condition at the settled wall sections would in principle represent a more physically consistent boundary assumption; however, in the absence of experimentally validated soil stiffness parameters, introducing partial fixity would add unquantifiable uncertainty to the model rather than improving its fidelity. The adopted fixed boundary condition is therefore retained as a conservative assumption that is consistent with current practice in the finite element assessment of historical masonry structures where geotechnical data are limited. This limitation is identified as a scope for future investigation involving dedicated geotechnical site characterization.

3.2 Material properties

The Drucker-Prager (DP) yield criterion was preferred to simulate the nonlinear behavior of historical masonry structures. The DP criterion is widely used to model the behavior of brittle materials such as concrete and rock under compression. In this study, the “Drucker-Prager Strength Piecewise” material model (Korkmaz et al. 2018) was employed to more realistically reflect the pressure dependent behavior of the material under multi axial stress conditions (Fig. 10). This model facilitates the tracking of plastic deformations that occur, especially under seismic loads.

It is important to clarify the distinction between the classical Drucker-Prager criterion and the “Drucker-Prager Strength Piecewise” formulation employed here, as this distinction directly addresses the capacity of the model to capture local compressive failure (crushing). In the piecewise formulation, the yield surface is not defined by a single fixed apex but by a user-specified tabular relationship between yield stress and accumulated equivalent plastic strain. This curve has three clearly identifiable regions: an explicit yield point at the onset of inelastic response, a hardening branch rising to the peak compressive strength, and a post-peak softening branch beyond it. Yield and peak are therefore not conflated; yielding marks the elastic-to-plastic transition, whereas the peak corresponds to the ultimate compressive capacity. Localized crushing initiates as the stress state approaches the peak and develops along the softening branch, where load-carrying capacity decreases while plastic

Fig. 10 Drucker-Prager Strength Piecewise

strain accumulates. The Drucker-Prager cone governs the pressure-dependent shape of the yield surface in multiaxial stress space, ensuring that confinement effects are accounted for, while the piecewise hardening/softening law controls the evolution of the yield surface with plastic deformation. This formulation is therefore capable of tracking localized compressive failure at confined zones such as arch haunches, column bases, and dome-wall junctions under seismic loading. Parameter ranges consistent with prior numerical studies on analogous stone-masonry materials (Korkmaz et al. 2018; Cakir 2022; Venghiac et al. 2023) were adopted, and the Modulus of Elasticity, which is the parameter most sensitive to global dynamic response, was subsequently calibrated through OMA-based model updating, providing global dynamic validation of the elastic regime. It is openly acknowledged, as a limitation of the present study, that a direct experimental validation of the post-peak softening branch on specimens extracted from this specific structure was beyond the scope of the project; the adopted parameters were instead bounded conservatively within ranges reported for analogous historic stone masonry.

In determining material parameters, the laboratory test results presented in Sect. 2 (unit volume weight: 2300 kg/m^3 , uniaxial compressive strength) were adopted as a conservative reference for the initial parameter set, rather than as direct inputs. However, due to the heterogeneous structure of historical masonry walls and the effect of mortar, it is insufficient to determine parameters affecting global rigidity, such as the Modulus of Elasticity (E), solely by sample tests. Therefore, different material groups were defined for various structural elements, such as minarets, exterior walls, main columns, and the dome, and the Modulus of Elasticity of these groups was defined as variables to be updated according to OMA results. In Table 1, the material properties before and after optimization are summarized. The fact that the modulus of elasticity of the “Library” section, which draws attention in the table, is relatively low compared to other elements, was interpreted as the global mode shapes of the main structure not being affected by this part of the structure. An examination of the mode shapes illustrated in Fig. 9 further confirms this situation.

3.3 Model updating with Particle Swarm optimization

To ensure that the finite element model accurately represents the real dynamic behavior of the structure, the model parameters were updated based on the experimental OMA results.

Table 1 Material properties of the numerical model

	Density (kg/m^3)	Young's Modulus (MPa)	Poisson	f_t (MPa)	Fracture Energy (Jm^2)
Minarets	2300	2175	0.18	0.5	100
Exterior Walls	2300	2756	0.18	0.5	100
Main Columns	2300	2369	0.18	0.5	100
Dome	2300	819	0.18	0.5	100
Library	2300	400	0.18	0.5	100

For this purpose, the Particle Swarm Optimization (PSO) algorithm (Kennedy and Eberhart 1995), a robust meta-heuristic method, was employed. PSO is an algorithm inspired by the social behaviors of bird flocks or fish schools, which does not require derivatives and has high performance in finding the global optimum. It has been demonstrated that PSO is an effective algorithm that provides successful results in engineering problems (Hasançebi et al. 2009). Compared to traditional trial-and-error methods, PSO can optimize a large number of parameters simultaneously and eliminates human error. Beyond this, PSO was specifically preferred over gradient-based optimization methods because the ANSYS parametric environment does not provide analytical gradient information, and the non-convex nature of the multi-variable search space necessitates a global search strategy to avoid entrapment in local minima. The principal limitation of PSO is that convergence to the global optimum is not mathematically guaranteed.

The objective function of the optimization problem is established on minimizing the difference between the natural frequencies obtained from the numerical model (f_{num}) and the experimentally measured frequencies (f_{exp}):

$$\text{minimize } f(x) = \sum_{i=0}^{n-1} \left(\frac{2 \cdot \Delta_i (n-i)}{n^2 + n} \right) + \sqrt{\frac{\sum_{i=0}^{n-1} (\Delta_i - \bar{\Delta})^2}{n}} \quad (1)$$

Here, Δ_i expresses the frequency difference for the i -th mode. The weighting terms in the equation were added to ensure that low-frequency modes (modes that affect the global behavior of the structure more) are more dominant in the optimization process.

The optimization process was carried out by integrating IronPython and ANSYS software. In each iteration of the algorithm, PSO proposes new Modulus of Elasticity (E) values for each material group as particle positions. These values are transferred to the ANSYS model as input to perform modal analysis. The resulting first five natural frequencies are then returned to the algorithm, where the objective function is calculated and the velocities and positions of the particles are updated. This loop continues until the error rate falls below a specified tolerance or the maximum number of iterations is reached. The pseudo-code of the algorithm is presented in Algorithm 1.

Algorithm 1 Pseudo-Code of PSO Implementation

```

1: function RUNFEA( $\mathbf{x}$ ) ▷  $\mathbf{x} \in \mathbb{Z}^5$ 
2:   Update the five bodies with materials indexed by  $\mathbf{x}$ 
3:   Solve the finite–element model
4:   return first–five natural frequencies  $\mathbf{f}$  ▷  $|\mathbf{f}| = 5$ 
5: end function
6: function FITNESS( $\mathbf{x}$ )
7:    $\mathbf{f} \leftarrow \text{RUNFEA}(\mathbf{x})$ 
8:    $\mathbf{a} \leftarrow [3.887, 3.997, 5.339, 5.838, 6.306]$  ▷ Target frequencies
9:    $n \leftarrow 5$ 
10:  for  $i = 0$  to  $n - 1$  do ▷ Frequency differences
11:     $\Delta_i \leftarrow |a_i - f_i|$ 
12:  end for
13:   $\bar{\Delta} \leftarrow \frac{1}{n} \sum_{i=0}^{n-1} \Delta_i$  ▷ Mean difference
14:   $S \leftarrow \sum_{i=0}^{n-1} \frac{2(n-i)}{n^2+n} \Delta_i$  ▷ Weighted sum favoring low-frequency modes
15:   $\sigma \leftarrow \sqrt{\frac{1}{n} \sum_{i=0}^{n-1} (\Delta_i - \bar{\Delta})^2}$  ▷ Std. deviation
16:  return  $S + \sigma$  ▷ Objective value, consistent with Eq. (1)
17: end function
18: function PSO( $I, N, \ell, u, w, c_1, c_2$ )
19:   Initialise positions  $P_i \sim \mathcal{U}([\ell, u])$ , velocities  $V_i \leftarrow 0$ 
20:   for  $i = 1$  to  $N$  do
21:      $pbest_i \leftarrow P_i$ ;  $fbest_i \leftarrow \text{FITNESS}(P_i)$ 
22:   end for
23:    $(gbest, f_g) \leftarrow \min_i fbest_i$ 
24:   for  $t = 1$  to  $I$  do
25:     for  $i = 1$  to  $N$  do
26:       for  $d = 1$  to  $5$  do
27:          $r_1, r_2 \sim \mathcal{U}(0, 1)$ 
28:          $V_{i,d} \leftarrow wV_{i,d} + c_1r_1(pbest_{i,d} - P_{i,d}) + c_2r_2(gbest_d - P_{i,d})$ 
29:          $P_{i,d} \leftarrow \text{clip}(\text{round}(P_{i,d} + V_{i,d}), \ell, u)$ 
30:       end for
31:        $f \leftarrow \text{FITNESS}(P_i)$ 
32:       if  $f < fbest_i$  then
33:          $pbest_i \leftarrow P_i$ ;  $fbest_i \leftarrow f$ 
34:         if  $f < f_g$  then
35:            $gbest \leftarrow P_i$ ;  $f_g \leftarrow f$ 
36:         end if
37:       end if
38:     end for
39:   end for
40:   return  $gbest$ 
41: end function

```

The objective function was deliberately based exclusively on natural frequencies, rather than incorporating mode shape correlation indicators such as the Modal Assurance Criterion (MAC). This choice is justified by two considerations specific to the present study. First, the sensor network was restricted to the four main load-bearing columns, imposing a funda-

mental limitation on the spatial resolution of mode shape identification: with only four measurement locations across a geometrically complex three-dimensional structure, the MAC matrix computed from these data would not be statistically representative of the full mode shape vectors. Second, and equally important from a structural standpoint, the pre-existing settlement cracks have introduced a degree of asymmetry and local stiffness irregularity into the actual structure that the homogenized continuum model cannot fully replicate by design. The actual mode shapes of the damaged structure consequently deviate from the idealized predictions of the FE model in ways that reflect the physical state of the structure rather than modeling inaccuracies. Incorporating MAC into the objective function under these conditions would penalize the model for accurately representing the undamaged portions of the structure, potentially biasing the calibration toward a physically incorrect solution. The qualitative agreement between numerically predicted and experimentally identified mode shapes (both exhibiting translational dominance in the first two modes, a vertical component in the third mode, and progressive torsional behavior in the higher modes) was assessed and confirmed to be satisfactory. Future studies employing a denser sensor network would benefit from a multi-objective calibration strategy that incorporates both frequency errors and MAC values, or from a Bayesian inference framework that fully characterizes parameter uncertainty (Monchetti et al. 2022, 2024, 2026; Ponsi et al. 2022).

While surrogate modeling and metamodeling are recognized as powerful strategies in the literature (Ponsi et al. 2022; Salachoris et al. 2024) to alleviate computational costs, this study adopted a direct FEA–PSO loop. Given the inherent efficiency of linear modal analyses, this direct approach was preferred to maintain maximum fidelity and eliminate the approximation errors typically associated with response surface models.

As a result of the optimization, the frequencies of the numerical model largely matched the experimental results (Table 2). In particular, the error in the frequencies of the first two modes (translational modes) was reduced to below 3%. The convergence graph shown in Fig. 11 indicates that the algorithm achieved the optimal solution after approximately 500 iterations. The updated model represents the existing stiffness distribution and damage state of the structure (especially in regions assigned a low modulus of elasticity) more accurately. This situation is of vital importance for the reliability of seismic analyses.

In Fig. 12, the variation of the optimization process in the parameter space is visualized. These graphs show how the algorithm scans the search space and converges to the global optimum. Consequently, the PSO-supported model updating procedure successfully simulated the complex dynamic behavior of the historical structure in the numerical environment.

Table 2 Frequency comparison of experimental and numerical model

Mode	Initial Numerical		Updated Numerical		OMA		
	Freq. (Hz)	Mod Shape	Freq. (Hz)	Mod Shape	Freq. (Hz)	Damping	Mod Shape
1	3.61	X	3.986	X	3.887	4.653	X
2	3.62	Y	4.130	Y	3.997	4.761	Y
3	4.808	Z	5.447	Z	5.339	1.869	Z
4	4.844	Tors.	5.648	Tors.	5.838	4.233	Tors.
5	5.229	Tors.	6.016	Tors.	6.306	3.98	Tors.

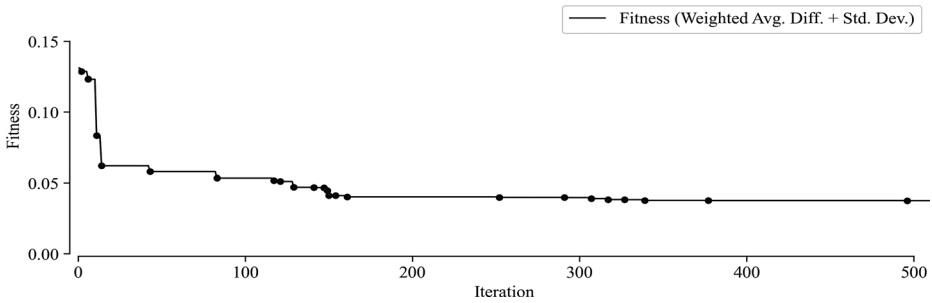


Fig. 11 Convergence results

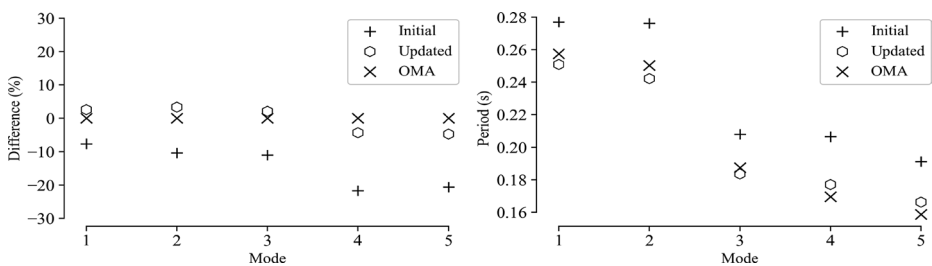


Fig. 12 Optimization results

4 Site-specific ground motion selection

To evaluate the seismic performance of the structure using nonlinear time-domain analyses, real earthquake records suitable for the site conditions must be selected and scaled. Nonlinear time-history analysis was preferred over nonlinear static (pushover) analysis because the three-dimensional geometry, pre-existing contact interfaces, and multi-directional seismic loading cannot be adequately represented through a monotonic static procedure; in particular, the cyclic opening-closing behavior of the crack surfaces and frictional energy dissipation require a transient dynamic formulation. The limitation of this approach is the higher computational cost and sensitivity to ground motion selection. In this study, based on the Turkish Building Earthquake Code (TBEC 2018) (Disaster and Emergency Management Authority 2018) and probabilistic seismic hazard characterizations, a site-specific seismic hazard analysis was performed for the location of the structure in the Konya city center. Using Disaster And Emergency Management Presidency (AFAD) Earthquake Hazard Map data, a design spectrum was created for the EL-2 (Earthquake Level, “DD-2”) earthquake level with a 10% probability of exceedance in 50 years (a return period of approximately 475 years). Soil conditions were classified as ZD (medium dense sand, gravel, or very stiff clay layers), based on a conservative assumption.

In accordance with TBEC 2018, at least 11 earthquake records must be selected for use in analyses to be performed in the time domain. The following criteria were observed in the selection of these records: (i) The moment magnitude (M_w) and fault mechanism of the records should be compatible with the seismic sources in the region, (ii) The soil conditions (V_{s30}) of the records should show similarity with the project site, (iii) The scaled average

spectrum of the selected records should not be less than 90% of the design spectrum in the 0.2T to 1.5T period range. In line with these criteria, 11 real acceleration records were selected from the PEER (Pacific Earthquake Engineering Research Center PEER 2008) and AFAD (AFAD 2020) databases. The selected earthquake set was diversified to include both near-fault and far-fault effects (Evangelista et al. 2017; Jayalakshmi et al. 2021). The properties of selected ground motions are presented in Table 3.

The acceleration spectra for the selected earthquake records, along with a comparison of the geometric mean of these records with the target design spectrum, are presented in Fig. 13a. As can be seen from the graph, the average of the scaled records exhibits a high agreement with the target spectrum in the relevant period band. In addition, the time-acceleration graphs of the 11 ground motion records used in the analyses are provided in detail in the subgraphs in Fig. 13b to 13l. These records were applied to the model simultaneously in both horizontal directions (X and Y) to test the structure's behavior under earthquake loads with different frequency contents and energy levels.

5 Results and discussions

The global and local response parameters obtained from the time domain analyses performed under the selected 11 site-specific ground motions are presented in Fig. 14. The figure matrix summarizes, for each ground motion (Fig. 14a–k) respectively, the hysteresis curves showing the Base Shear - Top Displacement relationship of the structure in X and Y

Table 3 Properties of selected ground motions

ID	Source	Event	Year	Station	Comp.	Mag.	Mech.	VS30	Rjb	Rrup	Sf
#01	PEER	Imperial Valley-06	1979	Compuertas	X	6.53	S. Slip	259.86	13.52	15.30	1.09
#02	PEER	Kobe, Japan	1995	Sakai	X	6.90	S. Slip	256	28.08	28.08	1.09
#03	PEER	Joshua Tree, CA	1992	Thousand Palms Post Office	X	6.10	S. Slip	333.89	17.15	17.86	1.09
#04	PEER	Coyote Lake	1979	Gilroy Array #2	X	5.74	S. Slip	270.84	8.47	9.02	1.09
#05	PEER	Joshua Tree, CA	1992	Thousand Palms Post Office	Y	6.10	S. Slip	333.89	17.15	17.86	1.09
#06	PEER	Imperial Valley-07	1979	El Centro Array #5	Y	5.01	S. Slip	205.63	8.56	11.23	1.09
#07	PEER	Managua, Nicaragua-02	1972	Managua, ESSO	X	5.20	S. Slip	288.77	4.33	4.98	1.09
#08	PEER	Parkfield	1966	Cholame - Shandon Array #8	Y	6.19	S. Slip	256.82	12.90	12.90	1.09
#09	PEER	Northern Calif-05	1967	Ferndale City Hall	X	5.60	S. Slip	219.31	27.36	28.73	1.09
#10	PEER	Coyote Lake	1979	Gilroy Array #3	X	5.74	S. Slip	349.85	6.75	7.42	1.09
#11	PEER	Imperial Valley-06	1979	Aeropuerto Mexicali	Y	6.53	S. Slip	259.86	0.00	0.34	1.09

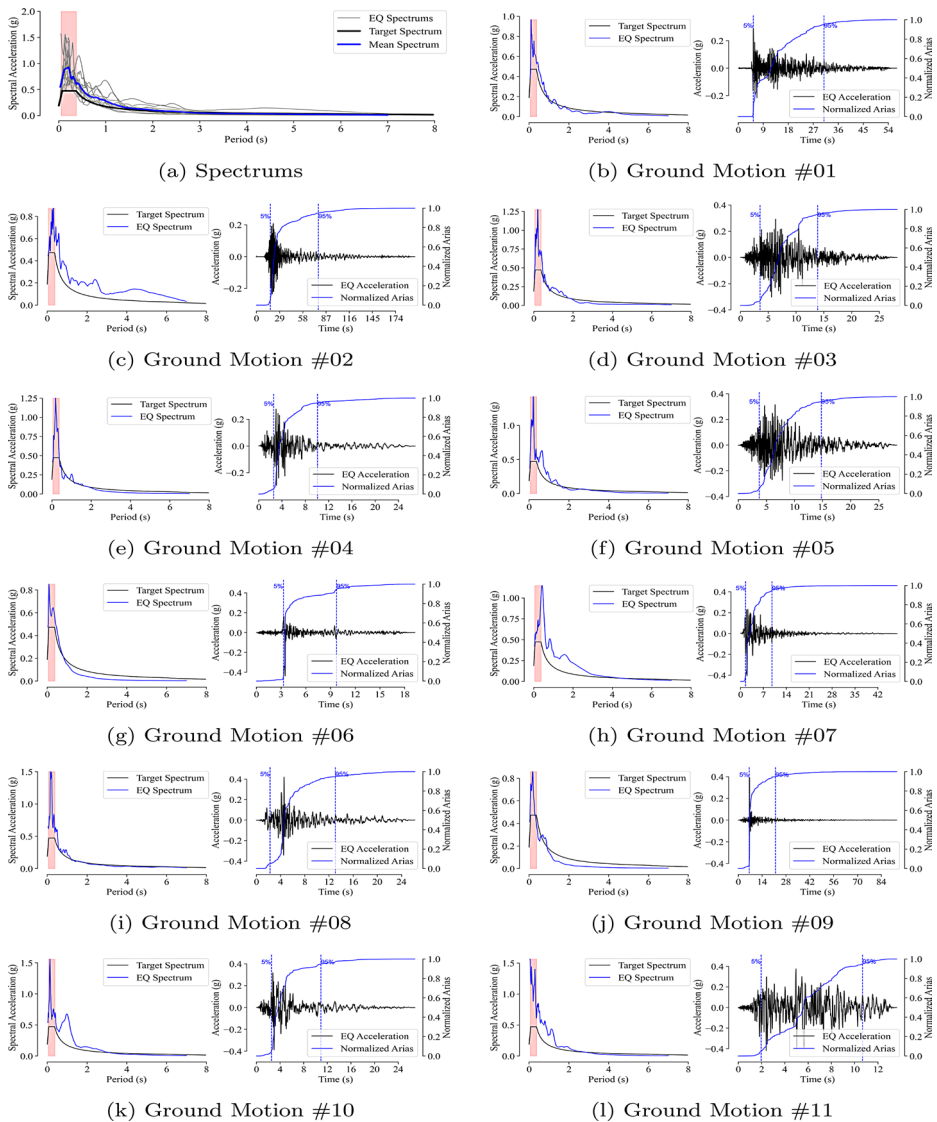


Fig. 13 Selected ground motion properties

directions, the variation of maximum principal strains in critical sections with time, and the course of frictional stresses at the existing crack surfaces defined in the model.

Upon examining the obtained hysteresis loops, it is evident that the structure exhibits distinct nonlinear behavior under all ground motions. Especially in the graphs belonging to ground motions #06, #09, and #10 (Fig. 14f-j), the behavior termed as “pinching”, which is a characteristic feature of masonry structures, is clearly monitored. This behavior indicates that the opening and closing of existing cracks and shear interlocking mechanisms become active during seismic loading, resulting in cyclic degradation of the structure’s stiffness.

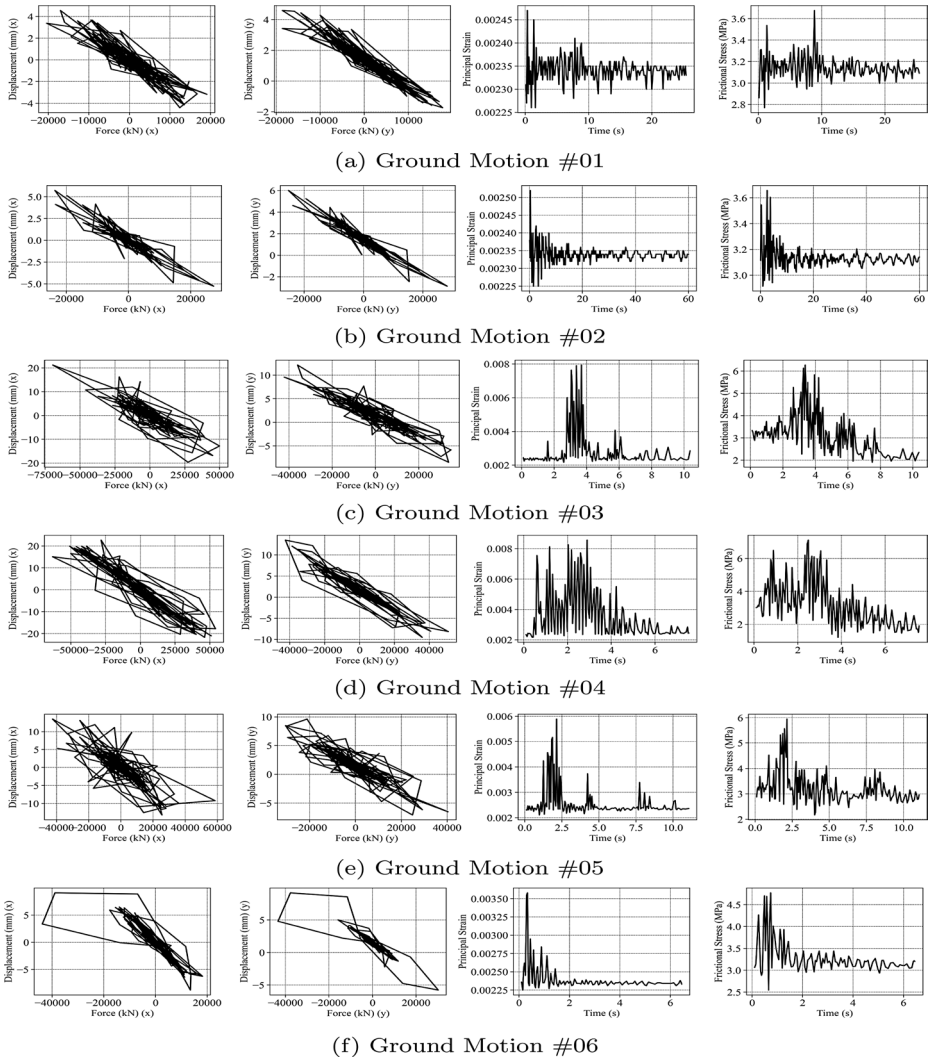
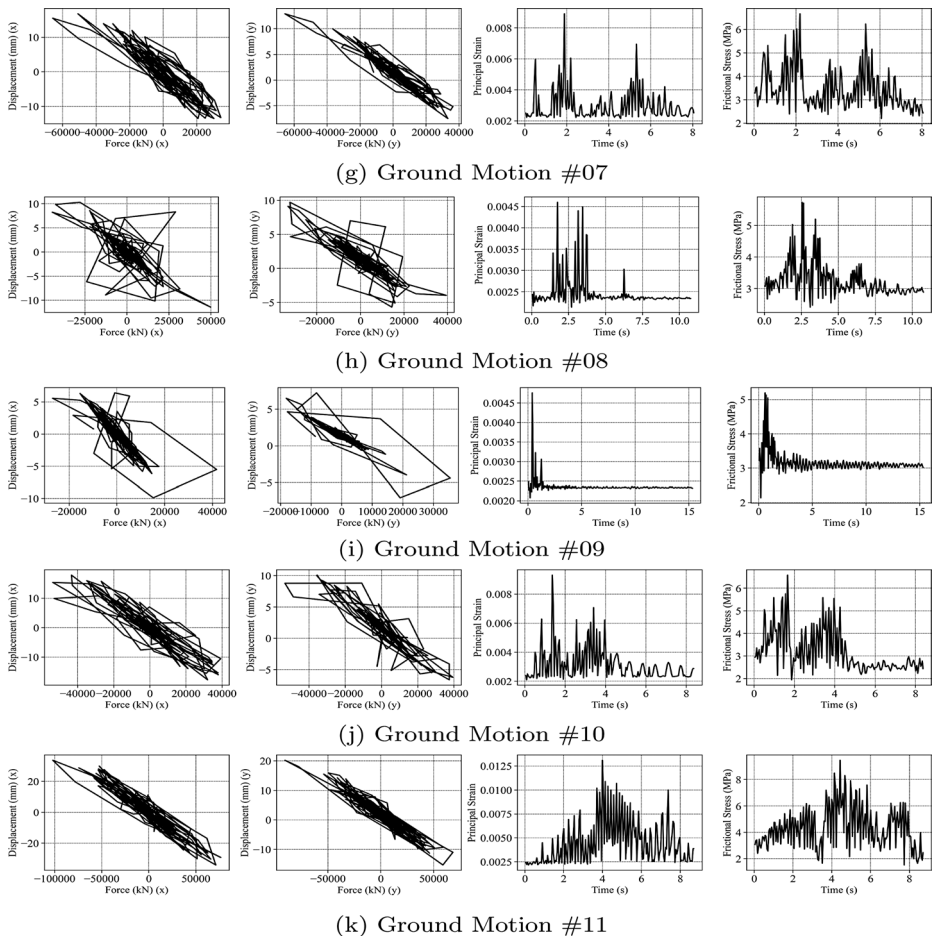


Fig. 14 Results of the analysis

The width of the area enclosed by the loops points out that the structure damps a significant amount of seismic energy through plastic deformations and friction.

One of the most unique findings of the analyses is the “Frictional Stress” time history graphs presented in the fourth column. The stress fluctuations in these graphs prove that the existing damage regions (settlement cracks) defined with contact elements in the model do not remain passive during the earthquake; on the contrary, they “work” with friction and sliding mechanisms. The fact that stress values show sudden drops or approach lower values at certain moments confirms that the crack surfaces momentarily separate from each other (gap opening), and then continue to transfer load by contacting again. This cyclic gap-opening and re-closure of the crack surfaces is consistent with the “breathing” mechanism

**Figure 14** (continued)

described in the literature for cracked masonry and composite-strengthened masonry elements subjected to dynamic excitation (Hamed and Rabinovitch 2008; Lengyel and Németh 2018); while it does not threaten the global stability of the structure, it reveals that existing damages contribute to the energy absorption capacity under seismic loads. The sudden jumps in the principal strain graphs (3rd column) correspond to the time intervals during which the tensile stresses in the structure exceed the material strength, triggering new micro crack formations at the moments when the peak ground acceleration (PGA) acts.

Graphs showing the global damage distribution of the structure and the mechanical behavior of the existing crack interfaces at the most critical moment (peak ground acceleration) of the time domain analyses are presented in Figs. 15, 16 and 17.

When the total strain distributions given in Fig. 15 are examined, it is observed that plastic deformations and damage concentrations accumulate in regions where the stiffness change is most significant, as expected. Especially the connection points of the dome skirt and pendentives, arch support regions, and corners of window openings stand out as critical

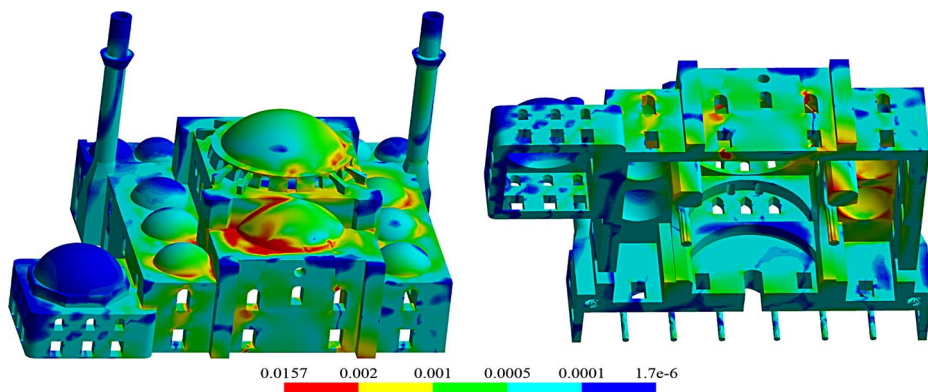


Fig. 15 Total strain

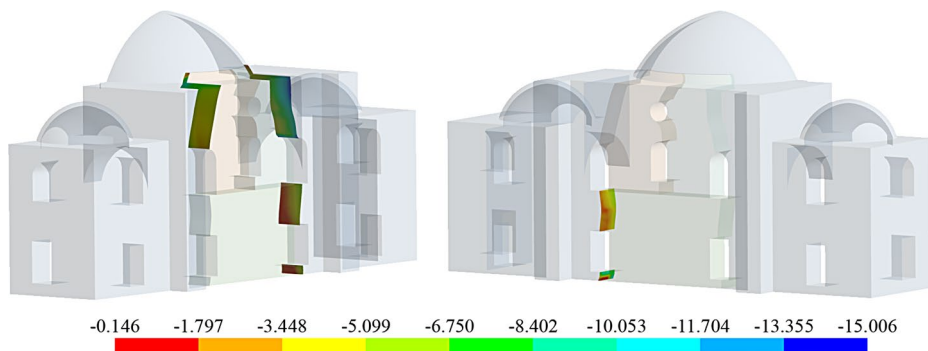


Fig. 16 Contact surface gap status (mm)

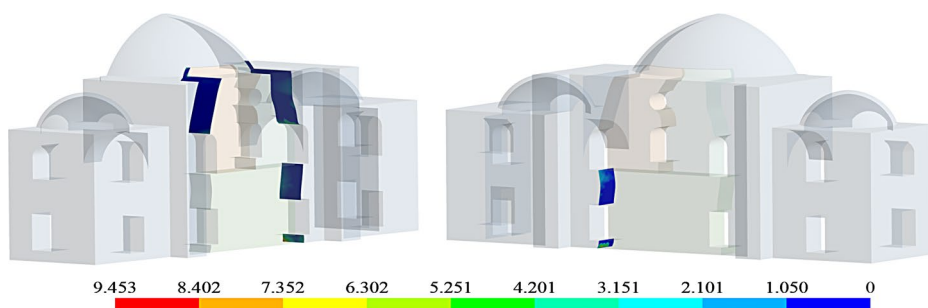


Fig. 17 Contact frictional stress (MPa)

sections where stress concentrations are experienced most intensely. In addition, significant deformation demands occurred in the body and balcony transition regions of the minarets, which have a high slenderness ratio. This distribution shows that the structure develops a damage mechanism suitable for “masonry structure mechanics” under seismic loads.

The results of the “contact element” approach, which constitutes the study’s originality, are detailed in Figs. 16 and 17. The “Contact Surface Gap Status” map in Fig. 16 proves that the existing settlement cracks defined in the model do not remain static during the seismic shaking, but on the contrary, are exposed to relative displacements in the order of millimeters (reaching up to 15 mm in places). The separation of crack surfaces (gap opening) indicates that the structure moves by dividing into rigid blocks, and these openings serve as a “fuse” in damping seismic energy.

In parallel with this, the “Frictional Stress” distribution presented in Fig. 17 reveals the mechanical interaction between the crack surfaces. The frictional stresses occurring along the crack, reaching levels of 9 MPa, confirm that the wall blocks undergo a sliding movement relative to each other. Through this friction, a significant amount of energy is absorbed and converted into heat. This situation, which is the physical equivalent of the “pinching” behavior observed in hysteresis curves, reveals that existing damage works as a mechanism that contributes to ductility up to a certain level, rather than causing the collapse of the structure.

As demonstrated in the accelerometer measurements, the tramway crossing causes significant amplitude amplification in the one column. This dynamic response is highly likely to trigger microcracks, which are extremely difficult to observe visually or using traditional inspection methods. The vibrations caused by the tram may activate resonance modes in the column, leading to amplitude growths that could affect serviceability limits. The correlation between tram passage times and amplitude peaks suggests that continuous monitoring of this column is essential for long-term structural health assessment, which has proven to be a highly effective data-driven approach for ensuring the sustainable preservation of heritage masonry structures (Standoli et al. 2026). Future studies should investigate the cumulative effects of these tram induced vibrations on the progression of existing settlement cracks through finite element modeling that includes experimental data of the soil that structure settled on.

Although the settlement cracks demonstrate an energy dissipating effect during seismic analysis, any prospective structural failure would most probably initiate in the vicinity of these pre damaged regions. Settlement cracks, resulting from differential foundation movements, act as hysteretic dampers by dissipating seismic energy through crack opening and friction. The hysteresis curves confirm that the cracks serve as energy dissipators through gap opening and frictional sliding mechanisms. However, these same zones become critical weak points under cyclic loading, where stress concentrations amplify local strains, potentially initiating failure modes such as shear banding at high strain levels. This duality highlights the importance of monitoring these regions and considering targeted interventions to prevent progressive damage accumulation while preserving the inherent energy dissipation capacity of the structure.

The utilization of contact elements to model existing cracks represents a key methodological contribution of this study. Unlike smeared crack approaches, the contact element formulation captures the discrete nature of crack opening and sliding, enabling realistic simulation of frictional energy dissipation. The crack surfaces exhibited relative displacements reaching up to 15 mm and frictional stresses up to 9 MPa during seismic loading. Their inclusion is critical for realistic load transfer, preventing overestimation of stiffness and underprediction of localized failures. This explicit crack modeling approach provides

a more accurate representation of the structure's actual behavior compared to conventional continuum based damage models, reducing analysis discrepancies significantly.

The damage distribution observed in the analyses concentrates in critical structural regions, including the connection points of the dome skirt and pendentives, arch support regions, and corners of window openings. These locations, consistent with the visual inspection findings presented in Sect. 2, represent zones where stress concentrations are most severe. The structural regions exhibiting damage act as weak links that could amplify second order effects under extreme loading conditions. The coincidence of analytically predicted damage patterns with observed crack locations validates the modeling approach and confirms that these regions require priority attention in any future intervention planning.

The minarets, as slender vertical elements with high aspect ratios, exhibited significant deformation demands at their base and balcony transition regions. While these elements were included in the global modal analysis and their behavior was captured in the mode shapes, the high slenderness ratios of minarets make them prone to out-of-plane buckling and torsional vibrations under dynamic loads. A detailed assessment of minaret specific vulnerabilities such as local buckling and out-of-plane bending requires separate focused investigations that prioritize these secondary appendages, as they may amplify local demands if overlooked in detailed modal analyses.

The ground motion selection methodology, following TBEC 2018 provisions, effectively captured a range of frequency contents and energy levels to comprehensively evaluate the structure's seismic response. The 11 selected records, spanning various magnitude levels and fault distances, provided diverse loading scenarios that revealed consistent patterns in the structural response through conditional spectrum matching. This approach ensures that records replicate site-specific hazard levels, capturing peak spectral accelerations and velocities that excite multiple modes from fundamental shear to higher flexural and torsional responses. The agreement between the scaled record spectra and the design target spectrum confirms the appropriateness of the selected ground motion set for site-specific seismic assessment, mitigating uncertainties in fragility assessments.

The dual mechanical role of pre-existing settlement cracks revealed by the analyses warrants a broader discussion of its implications for structural conservation practice. The frictional sliding and gap-opening mechanisms documented through the contact element results contribute positively to seismic performance by dissipating energy that would otherwise be transmitted as elastic strain to the surrounding undamaged masonry. This phenomenon is analogous in function to the role of controlled expansion joints or seismic isolation interfaces in modern structures, albeit with a different design intent. The implication is that not all pre-existing damage in historic masonry structures should be treated as a uniformly detrimental condition; certain crack configurations, particularly those with sufficiently rough interfaces and adequate confinement, may function as natural hysteretic dampers that enhance the structure's effective ductility under moderate seismic loading. On the other hand, the analyses simultaneously reveal that the same crack surfaces represent preferential zones for stress concentration and potential failure initiation under stronger or longer-duration ground motions. The accumulated principal strains observed at crack tips and adjacent masonry regions confirm that, beyond the current loading level, these zones could evolve from energy-dissipating interfaces into propagating failure planes. This duality underscores the inadequacy of assessment approaches that either neglect pre-existing damage entirely—thereby overestimating residual capacity—or treat it solely as a stiffness-

reducing defect without accounting for its frictional energy dissipation capacity. From a conservation strategy perspective, these findings suggest that targeted micro-invasive interventions—such as compatible grout injection at the most critical stress concentration zones to arrest potential propagation—may be preferable to wholesale crack consolidation, which would eliminate the frictional interface and the associated energy dissipation mechanism. The decision between intervention and monitoring should therefore be informed by site-specific evaluations of the type presented here, rather than by generic damage classification criteria (Valente and Milani 2019; Korswagen et al. 2022; Krentowski et al. 2023).

6 Conclusions

This study presents a comprehensive seismic performance assessment of a 500-year-old historic mosque exhibiting significant settlement cracks through an integrated framework encompassing Operational Modal Analysis (OMA), Particle Swarm Optimization (PSO) based finite element model updating, and contact element nonlinear analysis. The main findings and contributions of this study are summarized as follows:

- The Operational Modal Analysis results provided critical insights beyond modal identification. The accelerometer recordings revealed that one of the main columns experiences periodic amplitude increases correlated with tram passages on the adjacent line. This cyclic excitation represents a persistent fatigue source that may contribute to microcrack formation and the progression of existing cracks over time. The correlation between tram schedules and vibration amplitudes confirms the necessity of considering operational environmental factors in the assessment of historic structures located in urban settings.
- The Particle Swarm Optimization algorithm demonstrated high efficacy in model calibration, minimizing material uncertainties and reducing frequency discrepancies between numerical simulations and experimental data. The optimization converged after approximately 500 iterations, achieving frequency errors below 5% for all five modes. The updated material properties, particularly the varying elastic moduli assigned to different structural components, provide a realistic representation of the current stiffness distribution that accounts for material degradation and damage effects.
- The contact element approach adopted for modeling existing settlement cracks revealed important insights into the seismic behavior of pre damaged masonry structures. The analyses demonstrated that crack surfaces experience gap openings up to 15 mm and frictional stresses up to 9 MPa during seismic loading. This “breathing” mechanism, characterized by cyclic opening and closing of cracks, serves as an energy dissipation mechanism while also indicating the need for careful monitoring of crack propagation under repeated loading.
- The nonlinear analyses revealed that damage concentrates in predictable regions, including dome-wall connections, pendentive transitions, and window opening corners. These findings are consistent with the crack patterns observed during visual inspection and validate the modeling methodology. The structure maintains global stability under the design level earthquake; however, the existing cracks may serve as initiation points for more severe damage under stronger ground motions.

- Future intervention planning should prioritize monitoring of the identified critical regions and consider appropriate strengthening measures compatible with the historical character of the structure. Additionally, measures to reduce tram induced vibrations, such as track isolation or vibration barriers, may help mitigate the long-term fatigue effects on the adjacent column.

While each monument necessitates a unique diagnostic approach, this study provides a transferable framework for automated model updating and explicit damage modeling. It serves as a concise methodological reference for the evidence-based seismic assessment and conservation of historic masonry structures.

Acknowledgements The authors acknowledge the contributions of Directorate General of Foundations, Konya Regional Directorate to this study.

Author contributions All authors contributed to the study conception and design. Bilal Tayfur: Conceptualization, Formal analysis, Software, Visualization, Writing – original draft; Osman Tunca: Data curation, Formal analysis, Investigation, Validation; Musa Artar: Validation, Visualization, Writing – review & editing; Serdar Carbas: Project administration, Supervision, Validation, Writing – review & editing

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK). The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Data availability Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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