

Article

Simplified FE-Based Post-Earthquake Vulnerability Assessment of a Partially Collapsed Historic Mosque

Rüya Kılıç Demircan 

Department of Construction Technology, Boyabat Vocational School, Sinop University, 57000 Sinop, Türkiye; ruyakilic86@gmail.com or rkdemircan@sinop.edu.tr

Abstract: On 6 February 2023, two major earthquakes struck southeastern Türkiye along the East Anatolian Fault, causing widespread structural damage, including the partial collapse of the historic Habibi Neccar Mosque in Antakya. This study presents a simulation-based approach to rapidly assess the seismic vulnerability of this partially damaged historic masonry structure. Due to the complexity and urgent condition of such heritage buildings, a simplified finite element (FE) modeling methodology is employed to evaluate structural behavior and support immediate stabilization decisions. Response spectrum analysis is applied to simulate and interpret stress distribution and deformation patterns in both undamaged and damaged states. The simulation results highlight significant tensile stress concentrations exceeding 0.2 MPa at dome–arch joints and vaults—primary indicators of localized failures. Additionally, the analysis reveals increased out-of-plane deformations and the influence of soil amplification in the remaining walls, both of which further compromise the structural integrity of the building. The findings demonstrate that simplified FE simulations can serve as practical and efficient tools for early seismic assessment of historic structures, contributing to rapid decision making, risk mitigation, and cultural heritage preservation in earthquake-prone areas.

Keywords: historic masonry structure; finite element modeling; post-earthquake assessment; structural simulation



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1. Introduction

On 6 February 2023, at 04:17 (01:17 GMT) and 13:24 (10:24 GMT), two large earthquakes shocked southern and southeastern Türkiye. The moment magnitudes (M_w) of these earthquakes were 7.7 M_w and 7.6 M_w , and occurred on the Eastern Anatolian Fault [1]. The epicenter of the first earthquake was the Pazarcık district of Kahramanmaraş province, and the depth was 8.6 km. A second earthquake occurred 9 h later in the Elbistan district of Kahramanmaraş province with a depth of 7 km. In addition to hundreds of aftershocks following the first two earthquakes, another large earthquake with a magnitude of 6.4 M_w and a depth of 22 km occurred in the Defne district of Hatay province on 20 February 2023 at 20:04 (17:04 GMT) [2,3]. Figure 1 marks the locations of these earthquakes.

These earthquakes were felt and effective in an expansive geography, including Lebanon, Cyprus, Iraq, Israel, Jordan, and Egypt, in addition to Türkiye and Syria, covering an area of approximately 350,000 km². In this wide region where more than 13 million people live in Türkiye, more than 50 thousand people lost their lives, and more than 100 thousand people were injured. Well over 40 thousand buildings were destroyed during the earthquakes, and 300 thousand buildings were found to be heavily damaged and in urgent need of demolition [3]. Many historical buildings, including Gaziantep Citadel,

Habib-i Neccar Mosque, Kahramanmaraş Great Mosque, Adıyaman Great Mosque, and the Latin Catholic Church in İskenderun, were severely damaged or destroyed. There are more than 8000 registered historical buildings and monuments in the area affected by the earthquake, some of which are on the UNESCO World Heritage List [4].

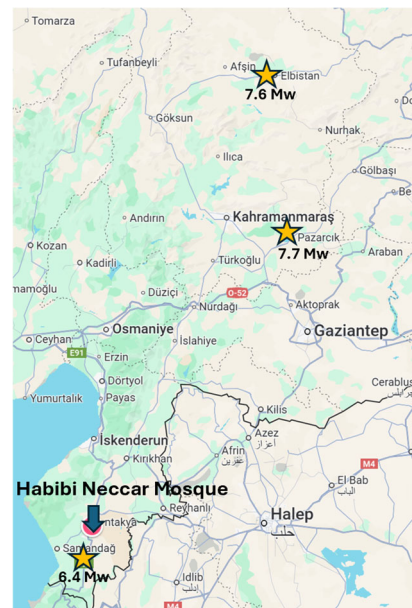


Figure 1. Epicenters of 6 February 2023, Kahramanmaraş-Pazarcık (Mw = 7.7), Kahramanmaraş-Elbistan (Mw = 7.6) and 10 February 2023 Defne-Hatay (Mw = 6.4) Earthquakes.

The Kahramanmaraş earthquakes have been extensively studied in the scientific community. Baltzopoulos et al. [5] analyzed ground motion around Gaziantep during the Mw 7.7 earthquake on 6 February 2023. Karataş et al. [6] proposed a systematic method for assessing post-earthquake damage at Antep Castle. Papazafeiropoulos and Plevris examined the effects of strong ground motions on building performance during the same event, while Binici et al. evaluated the performance of reinforced concrete (RC) buildings and provided recommendations for performance-based design [5–8]. In addition, repair and strengthening recommendations are given to eliminate the deformations that will occur in these structures [9,10]. Yurdakul et al. used 3D finite element modeling to assess the seismic performance of a 12th-century masonry minaret in Bayburt, identifying potential damage from tensile stresses caused by the Erzincan, Kocaeli-Düzce, and Van-Erciş earthquakes [11]. Kocaman analyzed the Molla Siyah Mosque using nonlinear dynamic analyses with ground motion records from the 1992 Erzincan, Cape Mendocino, and 1995 Kobe earthquakes, focusing on stress, displacement, and collapse mechanisms [12]. Schiavoni et al. studied the Church of Santa Maria Annunziata with advanced modeling techniques, including data from the February 2023 earthquakes in Türkiye, highlighting the role of material properties in seismic performance [9].

The seismic vulnerability of historical masonry structures in Türkiye and the Middle East has become a critical area of study. Kaya and Özkan [13] explored factors influencing the resilience of such structures in Türkiye, offering preservation and strengthening strategies. Aydın and Yılmaz [14] reviewed advances in failure analysis under seismic loads, evaluating modeling methods, while Toker and Alkan [15] analyzed post-earthquake damage in the Middle East, focusing on ground conditions, materials, and strengthening approaches. Recent studies emphasize developing effective seismic assessment methods that balance simplicity and accuracy to identify vulnerabilities and improve the resilience of historic structures, such as churches and mosques. These efforts aim to protect cultural

heritage by tailoring preservation strategies to the unique characteristics of masonry structures [13–17]. Also, Valente’s studies [18–20] indicate that slender bell towers in historical masonry churches suffer significant damage due to interactions with adjacent structures. While isolated towers develop initial cracks at the base, integrated towers experience cracking at connection points. These findings highlight the importance of considering structural interactions for accurate damage and collapse predictions [18–20].

Although the exterior masonry walls of many historic buildings appear as regular cut stone, their internal structure is often irregular and complex. Studies focusing on the structural behavior of such buildings under risk, modeling through simulations, and risk mitigation measures provide valuable guidance [21–23]. Gönen et al. highlighted how uncertainty in estimating the modulus of elasticity for masonry impacts numerical analysis results [24], as it is nearly impossible to define this property precisely in models [25–27]. Moreover, unlike reinforced concrete or steel, masonry materials lack true continuity due to inherent cracks, complicating accurate material definitions in structural modeling. Additionally, the heterogeneous nature of historical masonry materials, resulting from variations in stone types, mortar quality, and construction techniques, further complicates numerical modeling and seismic assessments. Research on heterogeneous material characterization and advanced modeling approaches plays a crucial role in improving the accuracy of structural analyses and developing more reliable assessment methods for historical buildings [28–35].

Traditional engineering assessments for historical masonry structures, especially those that are partially damaged, often require highly detailed finite element models with complex material definitions and computationally intensive nonlinear analyses. However, such sophisticated methods are not always practical for urgent post-earthquake evaluations, where rapid and effective stabilization decisions are needed. In this context, the originality of this study lies not in proposing a new analysis method, but in adapting an established approach within a simplified FE framework tailored for the emergency evaluation of partially collapsed historical structures. This methodology bridges the gap between detailed nonlinear models and rapid post-disaster needs, providing a practical and interdisciplinary decision-making tool. In this study, a simplified FE modeling approach is adopted to provide an efficient and accessible structural assessment. This method focuses on identifying critical stress concentrations and deformation patterns in both the undamaged and damaged states of the structure, ensuring timely intervention and stabilization efforts. This study examines the primary advantages and limitations of the simplified modeling methodology, contrasting it with conventional finite element methods to determine its suitable application range for post-earthquake emergency assessment.

Moreover, post-earthquake assessments of historical structures involve not only engineers but also experts from various disciplines, including architects, art historians, and restorers. Since these professionals may not always interpret structural results purely from an engineering perspective, a simplified and rapid evaluation method facilitates interdisciplinary decision making and improves coordination in emergency response efforts. By balancing computational efficiency with practical applicability, this approach offers a valuable tool for the preliminary evaluation of seismic damage in cultural heritage structures.

This research addresses the specific problems posed by partially collapsed historic structures, unlike previous studies that mostly focus on intact historical buildings or general seismic assessments. The proposed analytical approach links extensive, resource-intensive evaluations with the urgent need for stabilization measures in post-disaster contexts. This method enables efficient and swift evaluations of seismic hazards in cultural heritage sites by prioritizing computational efficiency and practical applicability.

This study uses the Antakya Habibi Neccar Mosque as a case study to demonstrate the need for prompt evaluation and fortification of partially collapsed historical edifices after seismic occurrences. The main objective is to create a computationally efficient structural analysis method to assist in emergency stabilization and conservation planning for masonry structures damaged by earthquakes. This study introduces a simpler FE modeling strategy that supports rapid and dependable structural evaluations, in contrast to conventional methods that require comprehensive nonlinear analysis and in situ testing. Response spectrum analysis is employed to run numerical simulations for both the intact and compromised states of the mosque. The results indicate that tensile stress concentrations above 0.2 MPa at dome–arch joints, vaults, and piers led to localized collapses, which were amplified by soil-strengthening effects. The results confirm that an efficient analytical method can provide significant preliminary insight into the seismic vulnerability of heritage structures. This study’s innovation resides in its amalgamation of swift numerical modeling and post-earthquake heritage conservation, creating a framework that connects computational efficiency with practical applications. This methodology facilitates the establishment of standardized techniques for the protection of vulnerable cultural heritage edifices in seismically active areas, informing subsequent retrofitting and conservation initiatives.

2. Case Study and Methodology: A Simplified Structural Analysis Approach for Urgent Assessments

2.1. Case Study: The Mosque and Its History

The Habibi Neccar Mosque, located in Antakya, was built in 636 and is the first mosque built within the borders of present-day Türkiye. Madrasah rooms surround the mosque, with the Habibi Neccar Tomb situated 4 m below the northeast corner. The fountain in the mosque garden is a work of the 19th century [36]. The mosque was partially destroyed and heavily damaged during the 7.7 Mw earthquake centered in Kahramanmaraş.

The Habibi Neccar Mosque was located on an ancient street that has existed since the foundation of Antakya, connecting the two ends of the city on a southwest–northeast axis. The structure has a rectangular plan with approximate dimensions of 30 m in width and 20 m in depth, including the last congregation area. The overall height of the building is approximately 13.5 m, and it reaches up to 25 m at the apex of the central dome. Based on visual inspection and reference to similar Ottoman-era structures, the wall thickness ranges between 0.9 and 1.2 m, and the vault thickness was assumed to be 0.35 m during modeling. As seen in Figure 2, the mosque, which is easily recognizable due to its larger mass compared to the other buildings around it and its location on the street, has the appearance of a complex consisting of madrasah rooms and a fountain. These parts are located around a trapezoidal courtyard and are bounded by the road to the east and south while connecting with neighboring parcels and roads in other directions [37]. The entrance to the mosque is through the crown door with a round arch with an inscription as well as a relief and pointed arch. As seen in Figure 3, the mosque has large, pointed arches on both sides and an interlaced vault. The circular main dome of the Habibi Neccar Mosque is supported by four large, pointed arches and pendants. There are 12 windows in the part forming the pulley of the main dome [38,39]. Figure 4 shows the dome, vaults, pendentives, arches, and walls in the schematic plan describing the general structural form of the mosque.



Figure 2. General view of Habibi Neccar Mosque before it was partially collapsed. This figure has been adapted from “Türkiye Kültür Portalı-Hatay Habibi Neccar Camisi” [40].

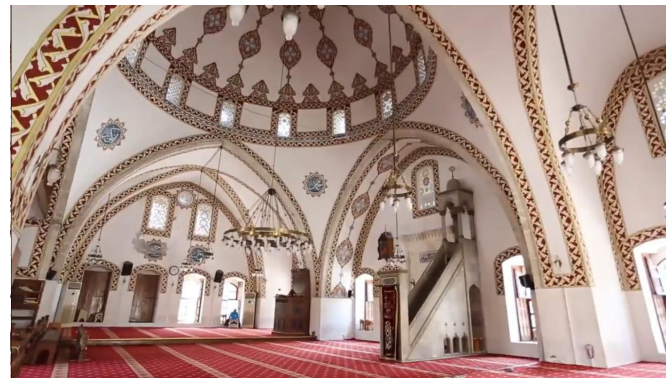


Figure 3. Interior view of the mosque before it was partially collapsed. This figure has been adapted from “Türkiye Kültür Portalı-Hatay Habibi Neccar Camisi” [40].

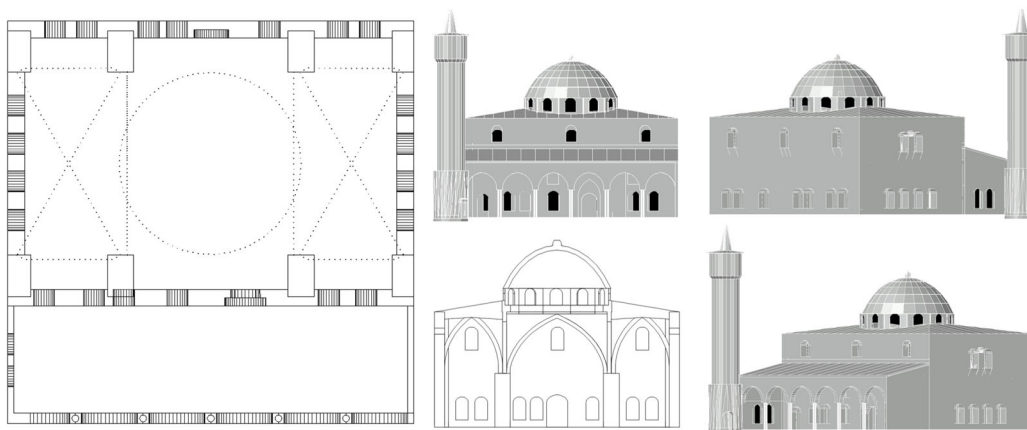


Figure 4. Schematic plan and general views of the mosque.

Damage Observations

Masonry walls are brittle and anisotropic, with high compressive strength but significantly lower tensile strength, making them particularly vulnerable to horizontal seismic forces [41]. Built using masonry stone elements, the Habibi Neccar Mosque is part of a larger complex that includes two mausoleums, madrasah sections, and a fountain. As seen in Figures 5 and 6, the complex does not follow a strict linear alignment, which may have influenced the structural response during the earthquake.



Figure 5. Habibi Neccar Mosque street lines. The figure has been adapted from “Hatay Governorship-Anadolu’nun ilk camisi” website [42].

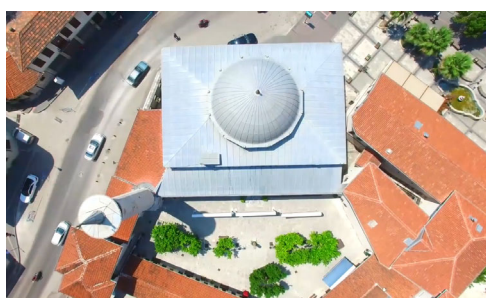


Figure 6. Top view of Habibi Neccar Mosque. The figure has been adapted from “Hatay Governorship-Anadolu’nun ilk camisi” website [42].

The mosque sustained severe damage during two large earthquakes (Mw 7.7 and Mw 7.6) on 6 February 2023, causing partial collapse of the structure and complete collapse of the minaret (Figures 7 and 8). The minaret, located southwest of the mosque, collapsed onto the adjacent buildings, affecting the walls of the complex. However, the surrounding complex walls and the fountain remained undamaged, indicating that the damage intensity was more severe for the primary load-bearing elements of the mosque.



Figure 7. Complete collapse of the minaret and dome of the Habibi Neccar Mosque after the earthquake of Mw 7.7. The debris also affected the adjacent buildings on the southwest side. The figure has been adapted from the “DHA” website [43].

Shear cracks in the south and east walls caused by window openings can be seen in Figures 9 and 10, indicating the effects of lateral seismic forces. Figure 9 illustrates the formation of shear cracks along the southern and eastern walls, especially near the apertures. The cracks indicate the lateral seismic forces exerted on the unreinforced masonry walls during the earthquake. Figure 10 illustrates diagonal shear cracking on the southern wall of the mosque, especially in the vicinity of the window area. This damage indicates a common failure mode resulting from horizontal seismic forces impacting unreinforced masonry. The west wall of the mosque (Figure 11) collapsed completely, while the north

and east arches supporting the dome survived. The damage pattern suggests a significant compromise in the mosque's structural integrity, with localized damage accumulating in the most vulnerable areas.



Figure 8. Collapse of the west wall and partial roof failure of the Habibi Neccar Mosque, with debris indicating the fall of the minaret onto adjacent structural elements. The figure has been adapted from the “DHA” website [43].



Figure 9. Aerial view of the Habibi Neccar Mosque showing visible shear cracks along the south walls. This figure has been adapted from the “DHA and istockphoto” website [43,44].

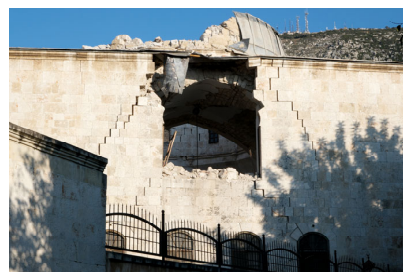


Figure 10. Diagonal shear cracks observed on the south wall of the mosque, extending through the masonry units and aligned with the window openings. This figure has been adapted from the “DHA and istockphoto” website [43,44].



Figure 11. Interior view showing the collapse of the mosque's west wall, while the north and east arches that support the dome remain standing. This figure has been adapted from the “DHA” website [43].

A detailed assessment of these damage patterns emphasizes the role of out-of-plane deformations, weak connections between structural elements, and the effects of ground shaking amplification. The progressive collapse seen in Figures 7–11 was likely caused by a mix of horizontal seismic forces, uneven mass distribution, and wall bonds that were already weak. These findings are consistent with damage patterns seen in other historic masonry structures subjected to strong seismic events [25,30]. In addition to visual damage indicators, quantitative results such as tensile stress concentrations (0.15–0.20 MPa), complete collapse of the west wall and eastern vault, and shear cracks aligned with lateral force concentrations near window openings were identified and discussed in the Results section.

2.2. Methodology: Structural Assessment of the Damaged Building and the Formation of the Numerical Model

The simplified numerical modeling approach used in this study provides a practical and efficient method for assessing the structural integrity of partially collapsed historical masonry buildings, such as the Habibi Neccar Mosque, following the 6 February 2023, earthquakes. This method addresses the unique challenges of historical masonry structures, including complex geometry and material properties, while producing reliable results to guide emergency interventions. Compared to more detailed modeling techniques incorporating nonlinear analyses and advanced material characterization, this approach offers an effective alternative for rapid structural assessments. The sequence of steps followed in the structural evaluation process is summarized in Figure 12 to enhance clarity and reproducibility. The validity of this simplified approach was supported by comparing the FE model results of the undamaged structure with the actual damage patterns observed in the field after the earthquake.

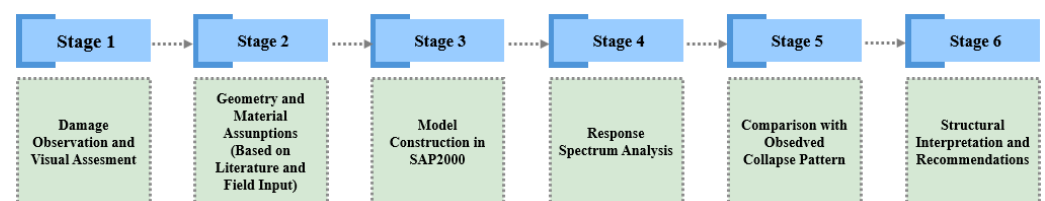


Figure 12. Flowchart of the simplified post-earthquake structural assessment approach.

Interventions to improve the earthquake performance of the building or to reduce the risk of damage require both a managerial and a technical approach. Technical strategies include interventions such as restoration of possible damages and defects in the structural system, increasing the strength and stiffness of the structure, examining the lateral displacement capacity, increasing the energy consumption capacity, or reducing the seismic susceptibility. The main criterion for intervention decisions is to limit the damages to the structural elements in terms of structural safety [45,46]. On the other hand, whether the intervention can be carried out while the structure is in use, whether it is divided into phases, and whether the use of the structure is limited or changed according to the risk level are the main elements of the managerial strategy.

Research-based diagnosis enables the organization of measures and indicators necessary for restoration and seismic retrofitting. Further research is needed to carefully analyze the unusual damage mechanisms observed in many historic buildings after the disaster and especially to correctly interpret the damage caused by previous structural retrofitting interventions. Furthermore, damage assessment and seismic vulnerability research allows a preparatory analysis for the design of temporary interventions and planning of the implementation method [47]. Systematic observation of emergency temporary interventions after previous disasters provides information on whether the methods chosen and the solutions

considered appropriate sometimes contradict the safety measures taken on site. Due to their unusual characteristics, it is sometimes not possible to use conventional engineering solutions for emergency fortification of historic buildings. Therefore, specific and systematic research activities are required to optimize safety precaution techniques for damaged historic buildings by means of fast and simplified numerical calculation methods [47–49].

Following the 6 February 2023 earthquakes, an emergency structural analysis was carried out to determine the structural performance of the damaged Habibi Neccar Mosque during possible aftershocks. Since there were no drawings documenting the structural details of the building, and fieldwork opportunities were limited due to emergency conditions, new and accurate measurements could not be made. At this point, the importance and necessity of a facilitated numerical calculation method emerged once again.

Two numerical models were developed to represent the mosque before and after the earthquakes, ensuring accurate definition of stiffness and material properties. Special attention was given to the structural identification process, as experience plays a key role in modeling historical buildings. For instance, while the actual thickness of the main dome was accurately defined, the filling material on vaults and pendentives was considered only as additional weight. Such details are crucial, as digital documentation methods may sometimes overlook them, leading to discrepancies in stiffness and material representation. The pre-damage analysis results were validated by comparing the stress distribution with the observed damage patterns, a widely accepted methodology in structural assessment studies. To confirm the results, the calculated stress and deformation patterns were compared with actual damage assessments post-earthquake, including the collapse of the eastern vault and the failure zones at the dome–arch connections. In the damaged-state model, visual observations were used to define the collapse pattern, ensuring a realistic representation of the structural failure mechanisms.

Seismic Data for Station Selection, Numerical Model and Analysis of Historical Mosque

Figure 13 below shows the location of Station 3131 in relation to the Habibi Neccar Mosque. Due to its proximity to the mosque and similar ground conditions and regional seismic activity, Station 3131 is a good reference point for seismic data. This area is designated as a high seismic activity zone in the Turkish Seismic Hazard Map (AFAD). Alluvial soil layers, which are known to amplify seismic waves, are present in both locations [13]. The effects of ground amplification are compounded by relatively high groundwater levels. Station 3131 was selected for the seismic investigation of this study due to its similar soil characteristics and proximity to the mosque [50].

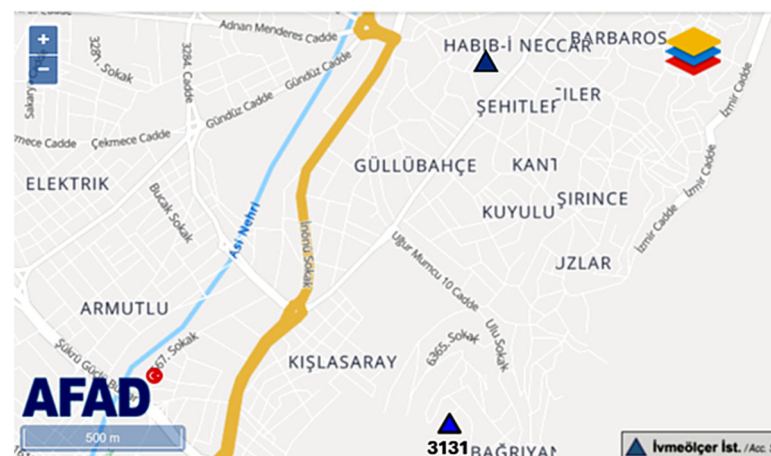


Figure 13. Location of the Habibi Neccar Mosque and the AFAD strong motion station 3131.

This study performs 3D linear analyses using the FE method to observe the dynamic properties of the Habibi Neccar Mosque. The behavior of masonry is characterized by using shell elements that can have their stiffness modified by constitutive assumptions about the elastic behavior of the material. Shell elements were chosen over brick elements in the FE model of the Habibi Neccar Mosque due to their efficiency in modeling thin-walled masonry structures, such as vaults, domes, and arches. This approach ensures accurate in-plane and out-of-plane deformation analysis while keeping computational costs manageable. Shell elements are widely used in historical masonry studies, providing reliable seismic response assessments without excessive computational complexity. A typical FE modeling scheme is used based on the concepts of homogenized material.

Creating a numerical model to study the seismic behavior of historic masonry structures requires a difficult process due to the complexity of the geometrical configuration of the structure and material properties that are nonlinearly inelastic and cannot be fully defined by laboratory tests [51]. The prerequisite for acquiring reliable analysis results is to create a refined mesh. However, due to the large number of parameters and degrees of freedom involved in the definition of the numerical model, the refined mesh cannot be properly applied to complex structural systems. However, the linear elastic static and dynamic analysis of such structures with simplified numerical models provides considerable information about the overall behavior and the interaction between the basic elements of the structure [52].

To develop the structural analysis models, SAP 2000 v14 software has been used by combining several element types depending on the structural members of the mosque. Four-noded quadrilateral or three-noded triangular shell elements were selected for meshing domes, vaults, pendentives, arches, and walls. The FE mesh for the first model, which describes the undamaged state of the mosque, consists of 7632 shell elements and 7512 nodes, while the second model, which describes the partially collapsed state, consists of 5786 shell elements and 5885 nodes (Figures 14 and 15).

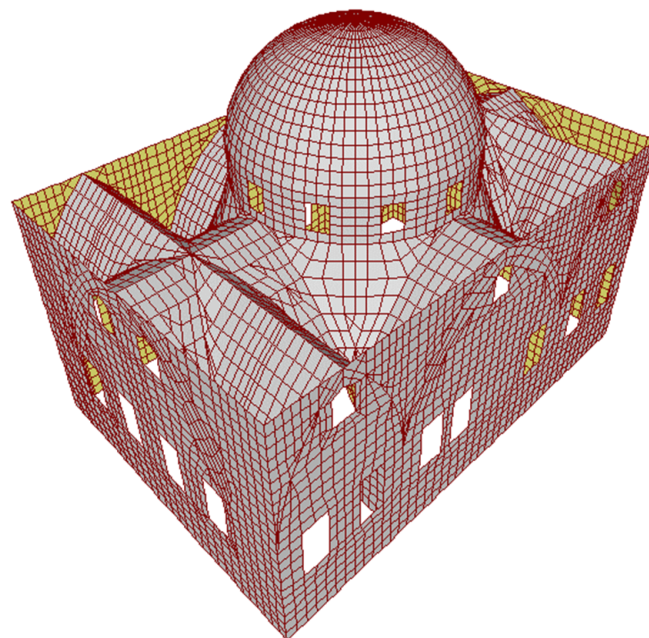


Figure 14. Numerical model for non-collapsed case.

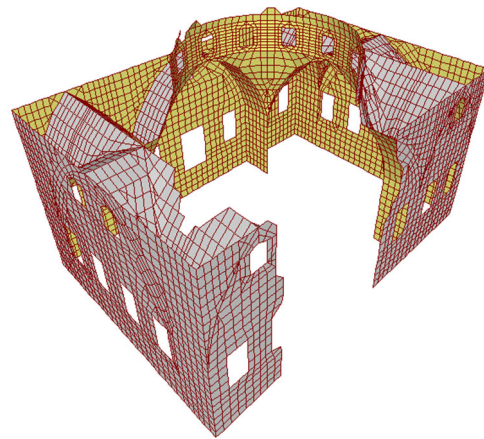


Figure 15. Numerical model for collapsed case.

In linear elastic numerical models, brick and stone masonry have been considered as linear isotropic materials with their properties shown in Table 1 [51,52]. The information given in Table 1 was obtained from the literature. These data were obtained by destructive test methods. The stone masonry pillars supporting the main arches, with cross-sectional dimensions of about $4\text{ m} \times 2\text{ m}$, were selected as massive in the models. However, these pillars surrounded by masonry stone were considered with a reduced modulus of elasticity in both analysis cases, due to infilled rubble material. Material properties were defined based on literature sources and destructive test data from comparable historical masonry buildings. The modulus of elasticity, unit weight, and unit mass values for the brick domes, stone walls, and piers are detailed in Table 1. These values reflect an isotropic material assumption to maintain computational efficiency while retaining consistency with historical material behavior.

Table 1. Material properties of the finite element model.

Element Type	Modulus of Elasticity E (kN/m ²)	Unit Weight (kN/m ³)
Brick dome and the pendants (with mortar)	1,200,000 (1200 MPa)	24
Stone walls (with mortar)	450,000 (450 MPa)	24
Pillars (with inner filled materials)	200,000 (200 MPa)	34

The properties of the building materials were selected from data obtained from previous studies in the international literature [51,52]. The masonry was considered an isotropic material to simplify the analysis while maintaining computational efficiency, a common approach in large-scale historical structure modeling. The modulus of elasticity and unit weight values were determined by considering the masonry units and mortar as a single material.

Three different loads, namely gravity and earthquake loads, were applied to numerical models. In both analyses, calculations were made according to the damaged state of the building before and after the earthquake. The seismic effects provided by the Turkish Earthquake Code [53] were applied as two different load groups in the direction of the two main axes of the mosque perpendicular to each other (EQx: longitudinal, east–west direction) and (EQy: transversal, north–south direction).

Two load combinations, $G + EQ_x$ (earthquake load in the X direction and vertical load) and $G + EQ_y$ (earthquake load in the Y direction and vertical load), have been defined to assist in the evaluation of the results. This study conducted bi-directional seismic analyses to consider the combined impacts of ground motion in both the longitudinal (X) and transverse (Y) directions. The earthquake impacts were implemented separately in each direction as $G + EQ_x$ (east–west) and $G + EQ_y$ (north–south) load combinations, in line with seismic code guidelines. This method provides a more accurate evaluation of the mosque's dynamic reaction, considering the simultaneous impact of seismic pressures in orthogonal directions. In the response spectrum analysis, spectral calculation was performed for the first 30 modes. Some of the material properties considered in the finite element analysis of the Habibi Neccar Mosque are summarized in Table 1.

The spectrum curve used in the analysis of the Habibi Neccar Mosque is given in Figure 16. 3131 E-W is the spectral acceleration in the east–west direction, 3131 N-S is the spectral acceleration in the north–south direction, and 3131 U is the acceleration in the vertical direction. The earthquake acceleration causes the highest displacement in the horizontal direction, as shown by the dotted lines representing the east–west and north–south directions. In comparison, 3131 U, which corresponds to the vertical acceleration, has a lower magnitude in the figure. The spectrum curve was determined according to the values recommended for Antakya in the Turkish Building Earthquake Code. Figure 16 shows the differences between the design response spectra (DD1/DD2) and the measured response spectra (3131 E-W/3131 N-S). The DD1/DD2 spectra, derived from the Turkish Seismic Code [53], provide a simplified illustration of seismic demand, whereas the recorded spectra reflect the actual ground motion characteristics at Station 3131. The differences among these spectra highlight the impact of local soil conditions, site effects, and topography elements, which may result in the amplification or attenuation of seismic waves. The differences highlight the necessity of integrating site-specific seismic data in structural evaluations of historical masonry buildings. For example, while the design spectrum (DD-2) used for Antakya assumes a peak ground acceleration (PGA) of 1.11 g, the actual recorded PGA at Station 3131 was significantly lower, around 0.37 g. Additionally, the recorded spectral accelerations in both horizontal directions show sharper peaks at different periods compared to the smoother code-based curve. The evidence suggests that local soil conditions and topography caused site-specific amplification, which should be considered when evaluating seismic demand on the structure. In the dynamic analysis performed according to the condition of the building before the damage, the elastic spectrum was determined by considering the soft soil type (type ZE) containing loose sand and clay layer properties and the DD-2 earthquake ground motion level 2 (DD-2) category in the latest Turkish Earthquake Code. DD-2 earthquake ground motion is characterized by infrequent earthquake ground motion with a 10% probability of exceeding the spectral magnitudes in 50 years and a corresponding recurrence period of 475 years. This earthquake ground motion is also called standard design earthquake ground motion. Accordingly, for Antakya, the spectral acceleration coefficient (PGA) is taken as 1.11, which is equivalent to 111% of the gravitational acceleration.

In the 6 February 2023 earthquakes, the ground accelerations measured at five different stations around Antakya, whose locations are marked in Figure 17, vary between 123% g and 37% g, as shown in Table 2. In this case, it is not possible to include the PGA value at the location of the mosque in the calculations in a precise way. In fact, this is a very complex criterion, and it varies according to the ground conditions and the actual geometry and stiffness of the structure. Therefore, it is considered that the calculations made according to the DD-2 earthquake ground motion, which is recommended as the “standard design

ground motion” in the Turkish Earthquake Specification for the purpose of emergency stabilization of the mosque after the disaster, are extremely consistent.

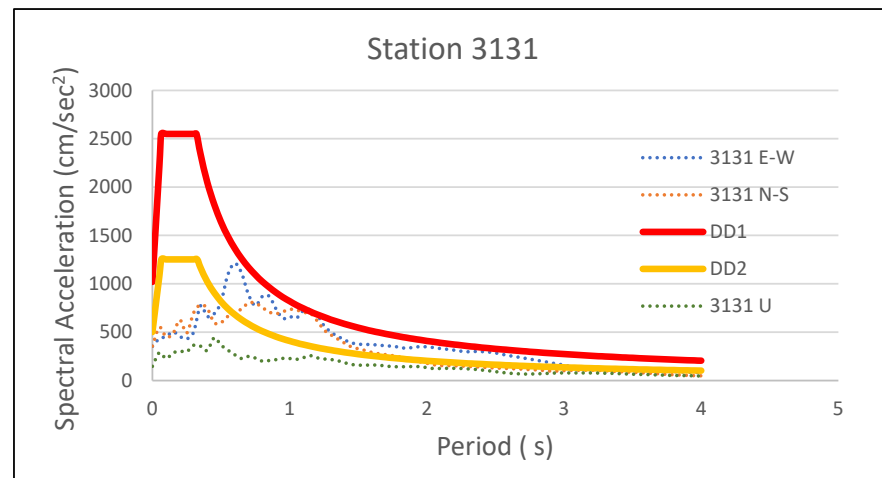


Figure 16. Response spectrum data of Station 3131.

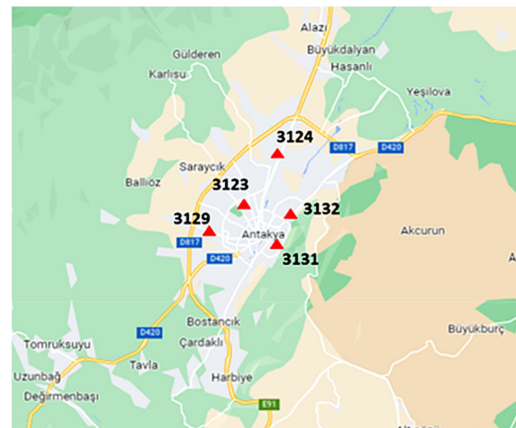


Figure 17. Location of the stations.

Table 2. The (PGA) ground accelerations measured at five different stations around Antakya.

Station No.	Location	PGA %g
3123	36.214° N 36.160° E	66.73
3124	36.239° N 36.172° E	65.04
3129	36.191° N 36.134° E	137.86
3131	36.191° N 36.163° E	37.19
3132	36.207° N 36.172° E	52.51

3. Results and Discussions: Assessment Method Based on Simplified Linear Dynamic Analysis

Numerical analyses were performed for the pre- and post-earthquake damage states of the Habibi Neccar Mosque to comprehensively assess its structural behavior and response to seismic forces. The pre-earthquake investigation established a benchmark for understanding the initial structural capacity of the mosque and identifying inherent risks. The post-earthquake investigation facilitated an assessment of how the partial collapse and damage affected the seismic performance of the structure. This dual approach is essential

to guide both emergency stabilization efforts and long-term retrofit initiatives to ensure the effective preservation of the mosque as a cultural heritage site.

The periods and mode shapes obtained from the analyses of the mosque before and after the damage are presented in Figures 18 and 19, respectively. Tables 3 and 4 present the periods and mass participation ratios of the principal vibration modes in the transverse, longitudinal, and vertical directions for the non-collapsed and collapsed cases, respectively. As previously stated, the spectral calculation was conducted for the initial 30 modes included in the response spectrum. As can be seen in Table 2, 85% mass participation is achieved after Mode 22, which indicates that the number of modes selected for these analyses is sufficient. The modal analysis results show that only the first five modes contribute significantly to the dynamic response of the structure and capture the primary deformation patterns. The higher modes, including those up to and beyond mode 22, exhibited negligible involvement in the overall structural behavior. These mode shapes indicate that the structure exhibited significant torsional flexibility after the collapse, particularly due to the loss of stiffness in the northern and eastern walls. The shift from 0.56 s to 0.67 s in the first mode period confirms the increased deformability and reduced global stiffness of the structure. Additionally, the high out-of-plane deformations in the south and east walls observed in the first and second modes suggest a loss of diaphragm action and structural continuity in those regions. This is one of the objectives of the simplified calculation method. Analyses conducted with extensive finite element models encompassing a vast number of points necessitate high-performance computing hardware, resulting in prolonged analysis times. Due to the intricate geometry of historical masonry structures, inadequate integration of the finite element mesh may introduce unanticipated errors in matrix formulations and solutions.

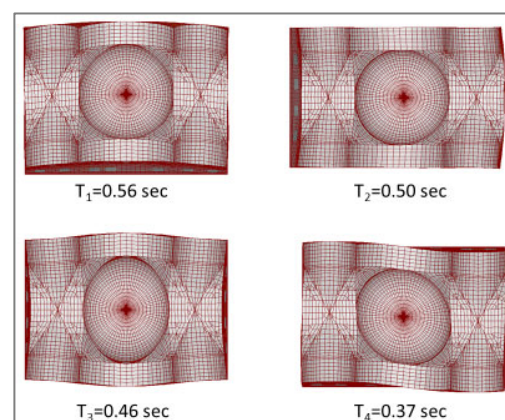


Figure 18. Periods and mode shapes of the 3D model for non-collapsed case.

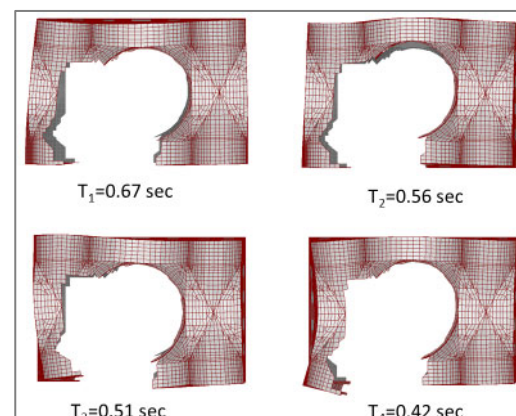


Figure 19. Periods and mode shapes of the 3D model for collapsed case.

Table 3. Periods and modal participating mass ratios for non-collapsed case (ΣM_{eff} : cumulative effective modal mass participation ratio).

Mode Number	Period (s)	ΣM_{eff} % in X-Longitudinal Direction	ΣM_{eff} % in Y-Transversal Direction
1	0.56	0	75.05
2	0.50	78.05	75.05
3	0.46	78.05	75.05
4	0.36	78.07	75.06
22	0.16	84.12	83.13
23	0.15	84.14	83.13
24	0.15	84.38	83.13
25	0.14	84.38	83.20

Table 4. Periods and modal participating mass ratios for collapsed case (ΣM_{eff} : cumulative effective modal mass participation ratio).

Mode Number	Period (s)	ΣM_{eff} % in X-Longitudinal Direction	ΣM_{eff} % in Y-Transversal Direction
1	0.67	6.25	15.89
2	0.56	44.92	32.05
3	0.51	68.97	37.59
4	0.42	69.36	69.79
27	0.13	83.16	83.83
28	0.13	83.25	84.01
29	0.13	83.31	84.04
30	0.12	83.38	84.18

As illustrated in Figure 18, the first mode of the undamaged building exhibits translational motion in the transverse direction, wherein the primary structural weakness is observed, accompanied by a notable out-of-plane deformation of the wall elements. The second mode shape illustrates a translation in the longitudinal direction, where the main body is observed to be robust. The third mode shape illustrates torsional deformations, thereby confirming the balanced distribution between the transverse and longitudinal structural elements of the mosque. The subsequent two mode shapes (not depicted herein) correspond to the second torsional mode (fourth mode) and the third torsional mode (fifth mode), respectively. Subsequently, the subsequent mode shapes are constituted by a combination of the transverse vibration mode and the torsional mode. The distribution of the mode shapes demonstrates that the perimeter walls, which exhibit low transversal and torsional stiffness, undergo significant out-of-plane deformations despite the presence of robust structural elements surrounding the building.

As stated in the previous paragraphs, the northern walls, main dome, eastern and northern main arches, and the largest part of the eastern vault were collapsed in the 6 February Türkiye earthquakes, thus giving the structure the appearance of a crescent with its open part facing north. As shown in Figure 19, in the first mode, the south walls experienced a considerable amount, or significant, out-of-plane deformation, while the east walls and more than half of the collapsed east vaults were translated outwards. In the second mode, the deformations at these locations have progressed similarly, but in the opposite direction. Considering that the modal shapes in modal analysis give important indications about the structural behavior of the building, this simplified analysis approach

also critically guides urgent structural measures. The third and fourth modal shapes show the torsional deformations depending on the configuration of the transverse and longitudinal structural elements of the significantly collapsed mosque.

The periods listed comparatively in Tables 2 and 3 show important results for the simplified analyses performed for both cases (before and after demolition). The reason why the periods calculated in the analyses performed for the demolished state of the mosque are 10% higher is the regularization and weakening of the structural system. For instance, the first mode period increased from 0.56 s to 0.67 s after the collapse, indicating a reduction in global stiffness. Additionally, modal mass participation in the primary modes shifted significantly. In the undamaged model, over 75% of mass participated in the first two modes, whereas in the damaged case, this distribution was more scattered and delayed. These shifts point to a loss of regularity and a more flexible response due to partial structural degradation. Structural analyses performed for similar historical buildings in the scientific literature indicate that the mode shapes and periods depend on the exact material definition and the correct discretization of the geometry of the building. In this framework, in the context of emergency disaster management, it is essential to use experience-based data, visual observations, and statistics from official regulations in simplified structural analyses.

In seismic vulnerability assessments of historical masonry structures, comparing calculated stresses with accepted limit values is a key parameter. Due to uncertainties in material modeling and stress limits, direct validation remains challenging. However, by matching the stress patterns from the undamaged model with the actual way the structure collapsed, we can obtain a better estimate of the material's maximum stress limits, especially in emergency assessments after an earthquake.

Figures 20 and 21 illustrate the stress distribution under the applied design earthquake spectrum and the G + EQX and G + EQY load combinations. The results indicate that tensile stresses between 0.15 MPa and 0.20 MPa are concentrated at the dome–arch junctions and vaults, which are known as critical weak points in masonry structures. In the undamaged state, tensile stresses near the dome–arch joints reached around 0.20 MPa. In contrast, compressive stresses in the piers were over 2.5 MPa but still within safe limits. For the damaged condition, out-of-plane displacements at the upper part of the south wall reached nearly 8 mm under G + EQY loading. This suggests that the remaining wall segments are highly vulnerable, especially during possible aftershocks. These results are consistent with the observed damage and help explain the collapse pattern.

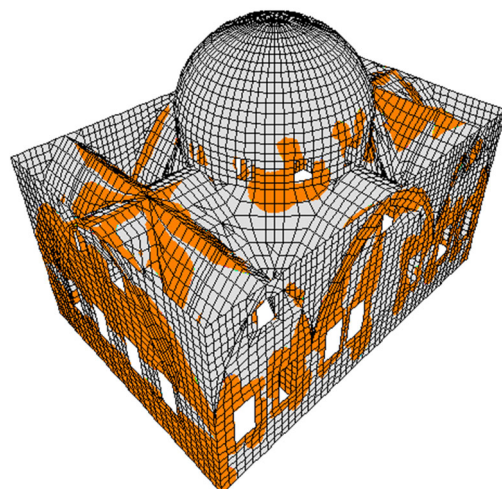


Figure 20. Regions where 0.2 MPa limiting tensile stresses are exceeded due to G + EQX loading (east–west direction) in non-collapsed case.

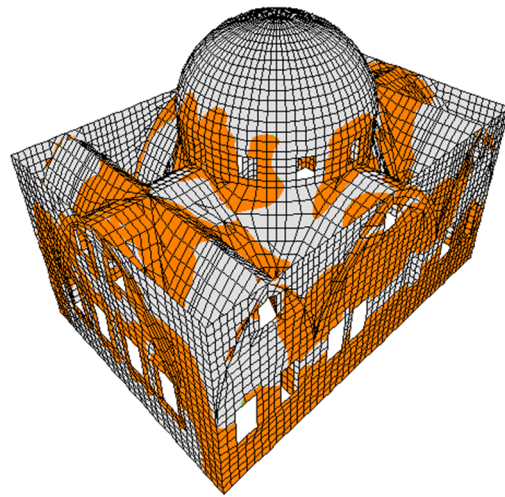


Figure 21. Regions where 0.2 MPa limiting tensile stresses are exceeded due to G + EQY loading (north–south) in non-collapsed cases.

The collapse of the mosque was not caused by isolated tensile failures alone, but rather by the progressive formation of a collapse mechanism, as cracks propagated and connected over time. While the eastern vault, which experienced tensile stresses of approximately 0.2 MPa, collapsed during the February 6 earthquakes, the western vault, subjected to similar stresses, remained intact, raising questions about additional influencing factors.

In addition to tensile stresses, compressive stress distributions were examined, particularly in piers and lower wall sections, to assess potential crushing failures. However, since masonry is significantly weaker in tension than in compression, the collapse was primarily driven by tensile failure. The observed damage pattern suggests that a limit state was exceeded when multiple tensile cracks merged, leading to a loss of structural stability.

Despite uncertainties in numerical modeling assumptions and seismic load estimations, the calculated tensile stress values (0.15–0.20 MPa) are consistent with widely accepted limits for historical masonry structures and generally align with the observed collapse pattern of the mosque. Previous research has identified comparable tensile strength values for unreinforced masonry. Asteris et al. [25], for example, reported that tensile capacities typically range from 0.1 to 0.3 MPa, influenced by the material properties and workmanship quality. Lourenço and Mele et al. have similarly noted that due to the inherently brittle and irregular nature of historical masonry, tensile failure generally initiates at stress levels below 0.3 MPa [25,30,51]. The tensile stresses obtained in the present study fall within this established range, reinforcing the plausibility of the numerical findings and corresponding damage patterns observed in the mosque.

In contrast to laboratory studies, the tensile stress capacity of masonry used in the construction of historic buildings is a hitherto unverified unknown for existing structures. Many ruined heritage structures have survived for hundreds of years, although unquestionably subjected to pure tensile stress. Therefore, it is not a correct approach to define the collapse sequence based only on tensile stresses. Initial cracks due to tensile stresses during an earthquake change the structural integrity of the building, and enormous compressive stresses may occur at unexpected locations. The usual limit for compressive stress in stone and brick masonry is between 2 MPa and 7 MPa, so the stress patterns shown in Figures 22 and 23 help us understand how the building might collapse. Considering that the undamaged building has had a certain regime of strength capacity for centuries based on its original architectural and structural configuration, major assumptions have been made when interpreting the results of this simplified analysis due to the complex properties of the masonry material. In this context, since the proposed simplified analysis

method is for the emergency consolidation of historical buildings damaged by disasters, the stress distribution obtained in the analyses for the partially collapsed state of the mosque in Figures 24 and 25 will guide consolidation planning.

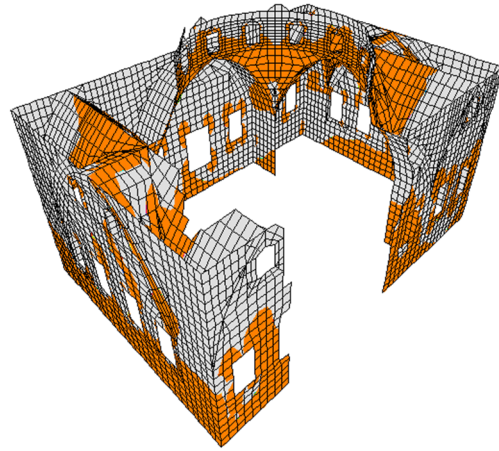


Figure 22. Regions where 0.2 MPa limiting tensile stresses are exceeded due to G + EQX loading (east–west direction) in collapsed case.

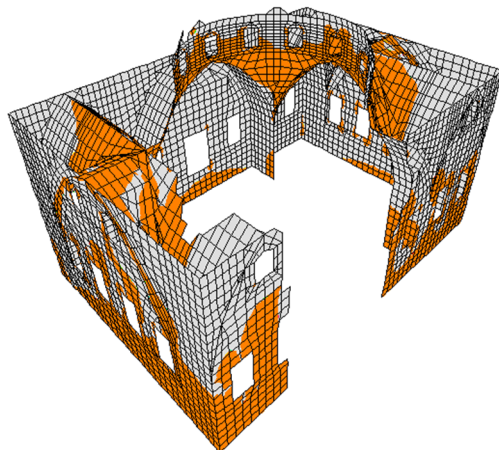


Figure 23. Regions where 0.2 MPa limiting tensile stresses are exceeded due to G + EQY loading (north–south) in collapsed case.

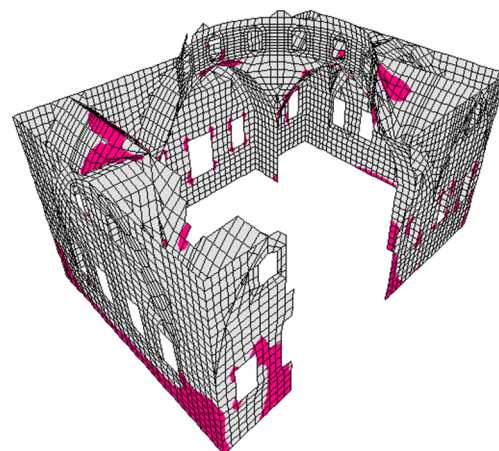


Figure 24. Regions of potential compressive failure identified in the collapsed state of the mosque under the G + EQX load combination (east–west direction). High compressive stress concentrations are observed along the lower wall segments and arch supports.

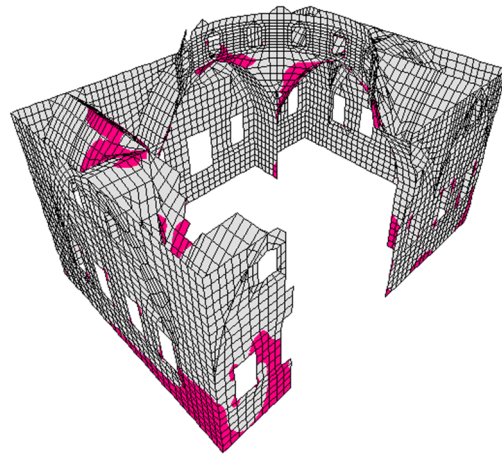


Figure 25. Regions of potential compressive failure identified in the collapsed state of the mosque under the $G + EQY$ load combination (north–south direction). Significant compressive zones appear near the dome base and the central structural elements (Results are compared with field observations showing collapse at the same locations, validating the FE simulation.).

The partial collapse of the mosque has severely altered its structural continuity. In its undamaged state, the structural form of the dome, vaults, and pendentives has been disrupted. With the collapse of the dome and vaults, the peripheral walls (peripheral walls–exterior walls) were left unsupported, making them much more vulnerable to a possible aftershock. Based on both field observations and simulation results, the most severely damaged parts of the structure include the eastern vault, the dome–arch connection zones, and the unsupported western wall. These areas showed high tensile stresses and displacements, and their structural role is critical in maintaining overall stability. Their failure directly contributed to the collapse pattern seen after the earthquake. These results are consistent with the observed damage and help explain the collapse pattern. These results confirm that the undamaged FE model accurately predicted the collapse zones, validating the model’s use for vulnerability assessment.

Ensuring the safety of the Habibi Neccar Mosque and its surroundings demands adherence to disaster and risk management principles, alongside a structural assessment of the damaged building in line with conservation and restoration practices for historic structures.

Figures 18–25 show the structural behavior of the mosque pre- and post-earthquake, emphasizing the impact of seismic forces on its integrity. The stress distribution prior to the earthquake was largely uniform, exhibiting regulated tensile and compressive stresses in key regions. The post-earthquake analysis reveals notable stress concentrations in specific regions where tensile stress surpasses the material’s capacity, leading to localized failures and partial collapses, especially in the dome and upper wall sections.

Figures 20 and 21 indicate that the highest tensile stress concentrations were observed at the dome–arch intersections, the east and west vaults, and the upper sections of the piers. These regions exhibit increased vulnerability because of geometric discontinuities, material problems, and the impact of seismic forces. Field observations indicate that the eastern vault collapsed because of tensile stresses surpassing 0.2 MPa, whereas the western vault remained intact despite experiencing comparable stress levels. This discrepancy suggests potential variations in material properties or localized damage mechanisms. The stress concentrations aligned with the observed cracks and partial displacements at the openings of the north and east walls.

The results suggest that the collapse was not due to isolated tensile failures but rather a progressive failure mechanism involving the propagation and interconnection of multiple cracks, which ultimately surpassed a limit state and compromised the mosque’s stability.

The findings offer a comprehensive insight into the impact of seismic forces on the structure, surpassing the information available from damage photographs alone.

The findings highlight the susceptibility of historical masonry structures to seismic forces and stress the necessity for focused restoration and retrofitting efforts. The identified critical zones in the post-earthquake context provide a basis for planning structural interventions aimed at restoring stability and improving future seismic performance. This analysis offers insights into damage mechanisms and establishes a framework for prioritizing retrofitting strategies in comparable historical structures.

4. Conclusions

Rapid post-earthquake assessment of historic masonry structures requires effective and reliable numerical modeling methods to aid in their prompt stabilization and long-term preservation and restoration planning. In this study, a simplified FE modeling approach is proposed to assess the structural integrity of the Habibi Neccar Mosque case study, which was severely damaged during the 6 February 2023 Kahramanmaraş earthquakes.

The results highlight several important aspects of the mosque's structural fragility:

- These findings not only support the accuracy of the simplified analysis but also offer theoretical insights into post-collapse behavior in historic masonry structures.
- Stress concentrations at the dome–arch joints and vaults exceeded material limits, contributing to local failures and partial collapse.
- Significant out-of-plane deformations were observed in the remaining walls, making them highly vulnerable to aftershocks and progressive damage.
- Ground amplification effects played a major role in increasing the seismic demand, further exacerbating the structural response and damage severity.

These results confirm that a simplified numerical modeling approach can provide rapid and valuable insights into the post-earthquake condition of historic structures. Such methods are essential for emergency decision making, ensuring timely stabilization measures and reducing the risk of further collapse.

In contrast to conventional finite element modeling techniques that require comprehensive geometric and material information, the simplified method introduced in this work provides expedited implementation, reduced processing demands, and adequate insights for emergency reactions. Nonetheless, it entails constraints, including linear material assumptions and a restricted ability to intricately simulate progressive failure causes. This trade-off renders it especially appropriate for preliminary evaluations, particularly when urgent structural assessments are required; however, time, data, or access to the structure is limited. For similar historic buildings with limited documentation and urgent stabilization needs, simplified FE-based modeling supported by measured ground motion data can offer valuable early-stage assessments. Such approaches are particularly useful in prioritizing structural interventions, identifying collapse-prone areas, and informing conservation strategies under seismic risk.

Future research should focus on the following aspects to improve the reliability and applicability of structural assessments for historic buildings:

- Creating and using nonlinear material modeling in a numerical setting: using detailed nonlinear analyses to show how damage builds up over time and how masonry units and mortar interact with each other.
- Improving damage assessment techniques: utilizing remote sensing, photogrammetry, and AI-based analysis to enhance the rapid evaluation of earthquake-damaged cultural heritage structures.
- Development of standardized emergency assessment protocols: establishing guidelines for the rapid assessment and stabilization of heritage sites in seismic zones.

By combining efficient computational methods with practical conservation strategies, these approaches can significantly enhance the earthquake resilience of historic buildings and ensure their preservation as vital cultural heritage assets.

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