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Post-2023 Kahramanmaraş Earthquake Assessment of Masonry Mosques and Minarets in Türkiye: Field Observations and Numerical Earthquake Analysis

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Abstract

Hatay (Ancient Antioch), one of Türkiye's most historically significant and seismically active provinces, experienced extensive damage during the 6 February 2023 Kahramanmaraş earthquake sequence (Mw = 7.7 and Mw = 7.6) and its aftershocks. Among the affected structures, masonry mosques and minarets suffered critical damage, revealing significant seismic vulnerabilities. This study provides a comprehensive evaluation of the seismic performance and structural vulnerabilities of masonry mosques and minarets in Hatay following the devastating 2023 Kahramanmaraş earthquake sequence. By integrating extensive field observations with advanced numerical analysis, the research documents widespread damage to both traditional kiosk-style and classical minarets, identifying critical factors such as poor local soil conditions, insufficient material strength, and lack of engineering services that contributed to structural collapses, including that of the historic Habibi Neccar Mosque. Through finite element analysis (FEA) using ABAQUS, the study compares different material configurations to assess nonlinear dynamic responses under representative seismic excitations, revealing that recorded ground motions in Hatay significantly exceeded current design-level spectra. The findings offer vital insights for the seismic assessment, retrofitting, and preservation of irreplaceable cultural and religious heritage structures in seismically active regions. This study addresses the enhancement of seismic resistance to historical structures not merely as a safety issue, but also as a social sustainability element that ensures the transmission of cultural heritage to future generations.

Keywords: masonry; earthquake; Kahramanmaraş; Hatay; Mosque; minarets

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1. Introduction

The preservation of historical and religious structures is a fundamental pillar of cultural sustainability, as these landmarks embody the identity and continuity of societies across generations. Protecting such architectural heritage from seismic hazards not only minimizes the environmental impact associated with post-disaster reconstruction and resource consumption but also ensures the socio-cultural resilience of urban environments. In this context, evaluating the structural integrity of masonry mosques and minarets in the aftermath of the 2023 Kahramanmaraş earthquakes is essential for developing sustainable conservation strategies that balance structural safety with the survival of historical legacies.

The earthquakes that occurred on 6 February 2023, at 04:17 and 13:24 local time, with epicenters in two different districts of Kahramanmaraş Province, Pazarcık and Elbistan, have been recorded as the largest disaster in Türkiye's history. The M_w = 7.7 and M_w = 7.6 magnitude earthquakes, occurring nine hours apart on the same day in the same region, marked the beginning of a series of large earthquakes, followed by M_w = 6.6, M_L = 5.7, M_w = 6.0, and M_w = 6.4 magnitude events. As a result of these earthquakes, over 50,000 people lost their lives across 11 provinces, more than 100,000 people were injured, and over 500,000 homes became uninhabitable. Following these events, which caused the highest human and material losses in the instrumental seismic activity period, widespread collapses, severe damage, and varying levels of structural damage were observed in various building systems. The successive nature of the earthquakes and the vast area affected set these events apart from other seismic occurrences. In addition to the immense human and material losses, secondary economic losses were also significant. This study evaluates the structural damage to mosques and minarets in the central and district areas of Hatay (Antioch), a city with deep historical roots dating back to the Hellenistic period, most affected by the earthquakes, based on field observations within the context of earthquake and civil engineering.

Mosques, which serve as places of worship for Muslims, are typically accompanied by minarets, tower-like structures constructed either attached or detached, used to call the faithful to prayer. During the devastating earthquakes that struck on 6 February 2023, numerous mosques and minarets within the affected region sustained varying degrees of damage, rendering many unusable. Given the rich historical background of the area, which has hosted numerous civilizations throughout history, a significant portion of these mosques and minarets are of considerable cultural and historical value. Consequently, the earthquakes not only caused substantial human and material losses but also inflicted severe destruction upon invaluable historical and cultural heritage sites. One of the most prominent examples of this devastation is the complete collapse of the Habibi Neccar Mosque in Hatay, originally constructed in 638 AD.

The impact of earthquakes on historical and cultural structures has been the subject of extensive scholarly research. These studies, often presented as case studies, provide critical insights for both practical applications and academic endeavors aimed at improving the seismic performance of such structures. Moreover, they offer valuable guidance regarding the methods and locations of necessary interventions for conservation and restoration efforts. For instance, Valente and Milani [1] developed three-dimensional finite element models of eight historical masonry towers located in northeastern Italy and evaluated their seismic vulnerability using simplified analytical approaches. Pouraminian and Didevar [2] used finite element modeling to assess the Gaskar brick minaret's response to wind and earthquake loads based on national codes. Majid Pouraminian's [3] study on the Gaskar brick minaret in northern Iran uses finite element modeling and probabilistic analysis to assess structural behavior under wind and seismic loads. The study by Laila Taoufiq et al. [4] analyzed the damage to reinforced concrete buildings from the 2023 Al Haouz earthquake,

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highlighting structural vulnerabilities and recommending improvements to Moroccan seismic regulations through international code comparisons. Similarly, Bilgin et al. [5] conducted a numerical modeling study on the St. Sotiri Basilica to assess its seismic performance. Işık et al. [6] performed structural analyses using numerical modeling to evaluate the seismic risk of a historical masonry minaret under various exceedance probabilities. In another study, Trešnjo et al. [7] explored the seismic behavior of a historical stone minaret in Bosnia and Herzegovina through numerical modeling informed by experimental data. Sunara [8] carried out modal and structural assessments of a historical clock tower located in Croatia. In the aftermath of the 6 February 2023, earthquakes centered in Kahramanmaraş, numerous studies have examined the damage sustained by mosques and minarets across the 11 affected provinces, both at the level of individual structures and within the context of different structural systems. Kocaman [9] investigated the damage observed in historical mosques and minarets in the earthquake-affected region, modeling the Adıyaman Grand Mosque using the finite element method to analyze damage mechanisms. Moreover, Erkek and Yetkin [10] conducted a detailed assessment of the seismic performance of a historical minaret following the Kahramanmaraş earthquakes. Işık et al. [11] examined the impact of the February 6 earthquakes on mosques and minarets in Adıyaman province. Onat et al. [12] conducted a damage and seismic performance evaluation for the Yusuf Ziya Paşa Mosque. Atmaca et al. [13] analyzed the damage observed in reinforced concrete (RC) and masonry minarets through field surveys in the earthquake zone and carried out numerical modeling for such minarets located in the Islahiye district. Kahya et al., in their study [14], combine field observations and nonlinear finite element analysis to investigate damage mechanisms in historical masonry buildings affected by the 2023 Kahramanmaraş earthquakes. Kocaman et al. [15] aimed to reveal the seismic effects through a finite element model of the Malatya Yeni Mosque, located in one of the most affected areas, Malatya. Avcil et al. [16] incorporated damage assessments of mosques and minarets with varying levels of destruction into their study, which focused on structural damage in different building systems in Kahramanmaraş province. Akar et al. [17] included mosque and minaret damage evaluations from the Gölbaşı district of Adıyaman province in their broader structural damage assessment. Nasery [18] used digital twin modeling to assess earthquake-induced damage in inaccessible areas of the Harran Grand Mosque minaret in Şanlıurfa. Ersoy [19] specifically examined Şeyh Ali Mosque and Habib-i Neccar Mosque in a study focused on the effects of earthquakes on historical structures. Soyluk and Demircan [20] analyzed the architectural impacts of earthquake damage on mosques and minarets. In their study, Cetin et al. [21] investigated the 2023 Kahramanmaraş earthquake in Adıyaman/Gölbaşı, highlighting the significant role of soil liquefaction and adverse site conditions in causing ground failures and structural damage. Yuzbasi [22] comprehensively addresses the structural damage assessment processes conducted following the 2023 Kahramanmaraş earthquakes, the lessons learned, and the challenges encountered. Köroğlu et al. [23] evaluate the structural damage resulting from the 2023 earthquakes in Türkiye, analyzing the performance of buildings in the affected regions. Furthermore, Peker et al. [24] conducted a comprehensive study on damage assessment, regional ground motion evaluation, and seismic performance analysis of a 14-story dual system building following the 2023 Kahramanmaraş earthquakes. Çetin and Ilgaç [25] examine the observed damage behavior of earthen dams during the 2023 Kahramanmaraş earthquakes. Donmez et al. [26] analyze the lessons learned from the 2023 Southeastern Türkiye earthquakes and evaluate the damaged reinforced concrete buildings using the Hassan Index. Gurbuz and Cengiz, A [27] provide a comprehensive assessment of the structural damage that occurred during the Kahramanmaraş earthquakes on 6 February 2023. Mertol et al. [28] examine the damage to reinforced concrete buildings following the 6 February 2023, Kahramanmaraş earthquakes, evaluating the compliance of the structures with seismic design regulations. Yuzbasi [29] utilized data from the February 6 Kahramanmaraş earthquake to investigate the effects of soft and weak story irregularities on structural behavior through advanced solid modeling and simulation analyses. Yılmaz et al. [30] conducted a field investigation on 27 historical masonry mosques and their minarets in Antakya after the 2023 Kahramanmaraş earthquakes to evaluate their seismic performance and document observed damage patterns. Atmaca et al. [31] investigated the seismic damage to the historical Habib-i Neccar Mosque in Antakya after the 2023 Kahramanmaraş earthquakes using field observations and nonlinear time history analysis. Dedeoglu et al. [32] examine geotechnical conditions, seismic data, and structural damage in Dogansehir, Malatya, highlighting how local geology and tectonics influenced the severe impact of the 2023 Kahramanmaraş earthquakes. These studies highlight the critical need for systematic assessment and preservation of culturally important structures, especially in earthquake-prone areas. By recording damage patterns and utilizing advanced analytical methods, this body of research plays a key role in shaping effective strategies to protect architectural heritage from future seismic risks.

Therefore, the primary objective of this study is to investigate the impact of the 6 February 2023, Kahramanmaraş (Türkiye) earthquakes on mosques and minarets located in Hatay Province and its districts, where the destruction was most severe. Based on field investigations, the observed damage to these structures has been examined within the civil and earthquake engineering framework, focusing on cause-and-effect relationships. Moreover, the study presents an extensive overview of the seismicity of Hatay Province and spectral accelerations recorded at various ground motion stations in Hatay during the Pazarcık earthquake. Also, the acceleration response spectrum as defined in the TBEC-2018 is provided. Last but not least, the structural analyses were conducted on a representative minaret model using the finite element method (FEM). In the numerical analyses, the effects of Kahramanmaraş earthquakes were evaluated for both masonry and concrete minaret models.

This study follows a multi-staged methodology that bridges the gap between empirical field investigations and advanced computational modeling to provide a holistic assessment of masonry religious structures. While previous literature has often focused on generalized damage patterns, this research distinguishes itself by specifically analyzing the seismic response of traditional kiosk-style and classical minarets in Hatay, a region where recorded ground motions significantly surpassed current design standards. By utilizing high-fidelity finite element analysis in ABAQUS to compare diverse material configurations, the study addresses a critical knowledge gap in the nonlinear dynamic behavior of these unique architectural forms under extreme seismic loads. Furthermore, this work contributes to structural and cultural sustainability by providing evidence-based data necessary for resilient retrofitting, ensuring that historical identity is preserved with minimal resource waste and maximum structural longevity. Ultimately, these findings offer a vital framework for engineers and conservationists to protect heritage sites from future catastrophes, aligning structural safety with the principles of sustainable urban resilience.

Enhancing the seismic resilience of historical and religious structures is vital for ensuring social sustainability through the preservation of cultural heritage and for transmitting collective memory to future generations. This research, which examines the seismic performance of masonry mosques and minarets in Hatay, offers a cultural sustainability perspective that goes beyond structural safety, aiming to ensure the safe transmission of these works to future generations. Rehabilitating the existing historical fabric using modern engineering methods supports environmental sustainability and demonstrates a holistic approach to building resilient cities.

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2. East Anatolian Fault Zone and the 6 February 2023, Earthquakes

The East Anatolian Fault Zone (EAFZ) is one of the major tectonic structures in Türkiye and was the source of the 6 February 2023, Kahramanmaraş earthquakes. This fault zone has historically and instrumentally generated numerous earthquakes. Extending from the Yayladağı district in Hatay Province to the Karlıova district in Bingöl Province, the EAFZ intersects with the North Anatolian Fault Zone (NAFZ) at its eastern end. On 6 February 2023, the first earthquake occurred along the EAFZ at 04:17 local time, with a moment magnitude (Mw) of 7.7 and an epicenter near the Pazarcık district of Kahramanmaraş. Approximately nine hours later, a second independent earthquake struck the same fault zone at 13:24 local time, with a magnitude of Mw 7.6 and an epicenter located in Elbistan, also in Kahramanmaraş Province. Numerous aftershocks occurred between and after these two main events. Throughout the same day, several additional large-magnitude earthquakes with different epicenters further exacerbated structural losses in the affected region. The locations of all earthquakes with magnitudes equal to or greater than 5.0 ($M \geq 5$) that occurred on 6 February 2023, are presented on Türkiye's current seismic hazard map in Figure 1.

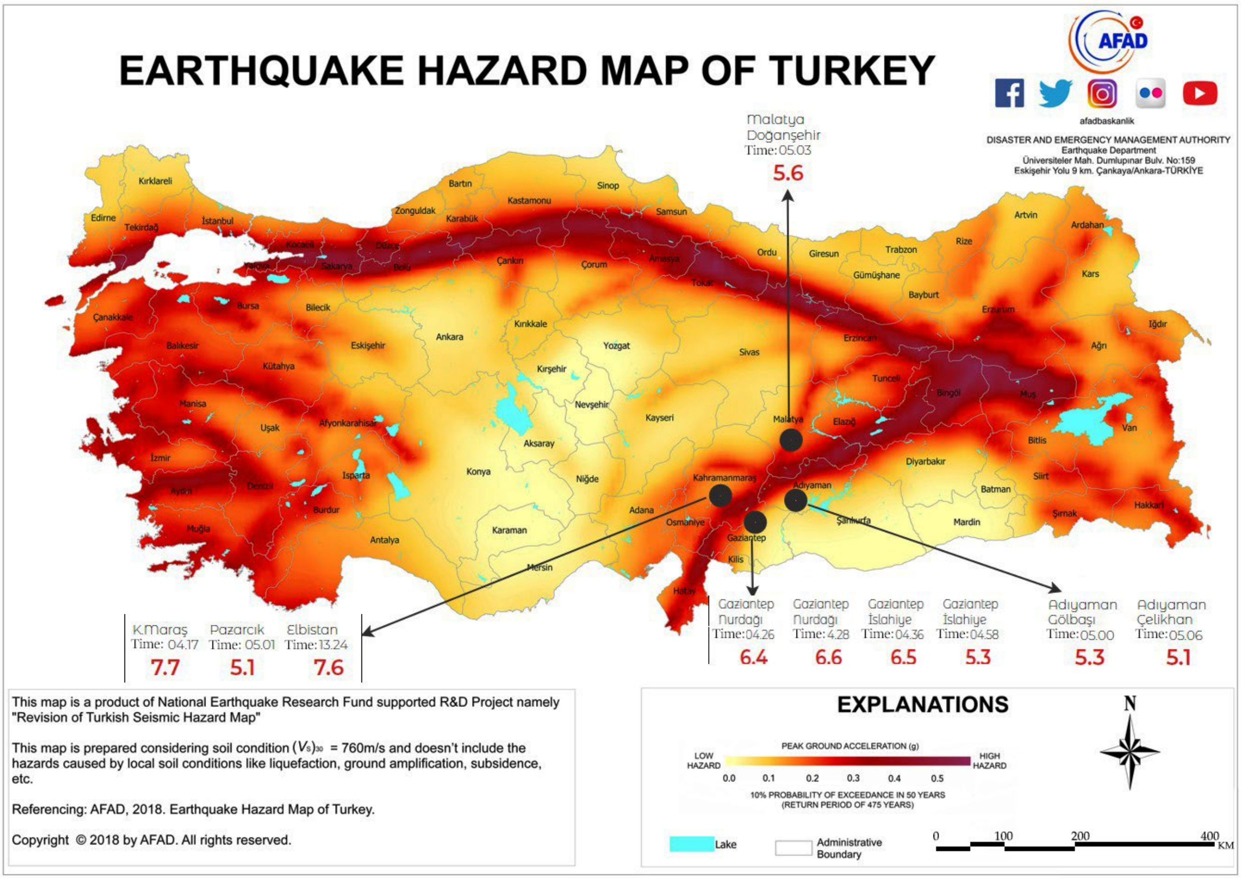

Figure 1. Major earthquakes ($M \geq 5$) that occurred in the region on 6 February 2023.

2.1. Seismotectonic Setting and Earthquake Impacts in the Hatay Region

In the Eastern Mediterranean region, plate movements occur along the left-lateral Amanos Fault, the Dead Sea Fault, and the Cyprus Arc, which lie at the boundaries of the Arabian/Anatolian, African/Arabian, and Anatolian/African plates. These structures' onshore extension is called the Cyprus-Hatay Transform Fault. In the Quaternary-aged Amik Basin near Hatay, more active faults converge to form a triple junction zone [33]. These active fault systems control the Quaternary seismicity observed in and around Hatay. The NNE-trending fault segment, approximately 145 km in length, is known as the Amanos Fault or Karasu Fault and is considered the southern continuation of the East Anatolian Fault Zone [33–35]. This fault system is situated along the western slopes of the Karasu Valley and the Amik Basin, which is approximately 30 km wide and filled with Plio-Quaternary sediments reaching thicknesses of up to 1000 m [36,37]. The Plio-Quaternary sediments and Quaternary volcanic unconformably overlie Miocene-aged formations (Figure 2).

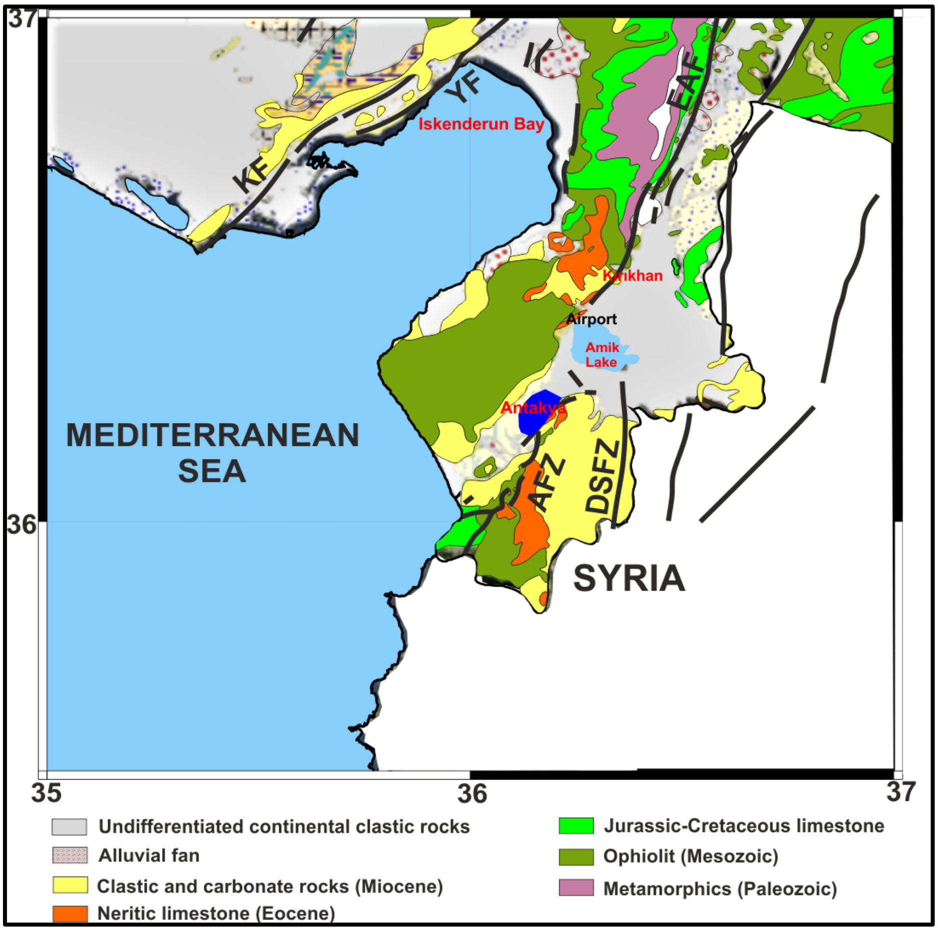

Figure 2. Regional geology map of the study area. The dark blue area shows the Antakya central settlement. EAF: East Anatolian Fault, AFZ: Amonos Fault Zone, DSFZ: Dead Sea Fault Zone, KF: Karasu Fault, YF: Yumurtalık Fault, adapted from [37].

Hatay, once the largest city of ancient Mesopotamia, has been repeatedly devastated by earthquakes throughout its history. The most significant historical events include the earthquakes of 13 August 1822 (Ms~7.5, I = X) and 3 April 1872 (Ms~7.2, I = IX), both of which caused extensive destruction in the Antakya district and its surroundings, resulting in the loss of more than 20,000 lives [38,39]. Records from both historical and instrumental periods reveal that the region has been affected by destructive earthquakes for approximately the past 2000 years [40–44]. Figure 3 illustrates the spatial distribution of earthquakes with magnitudes greater than 3 that have occurred in the instrumental period. An analysis of the focal depths of earthquakes in Antakya and its vicinity shows that these events are generally shallow and align along a northeast–southwest trending corridor.

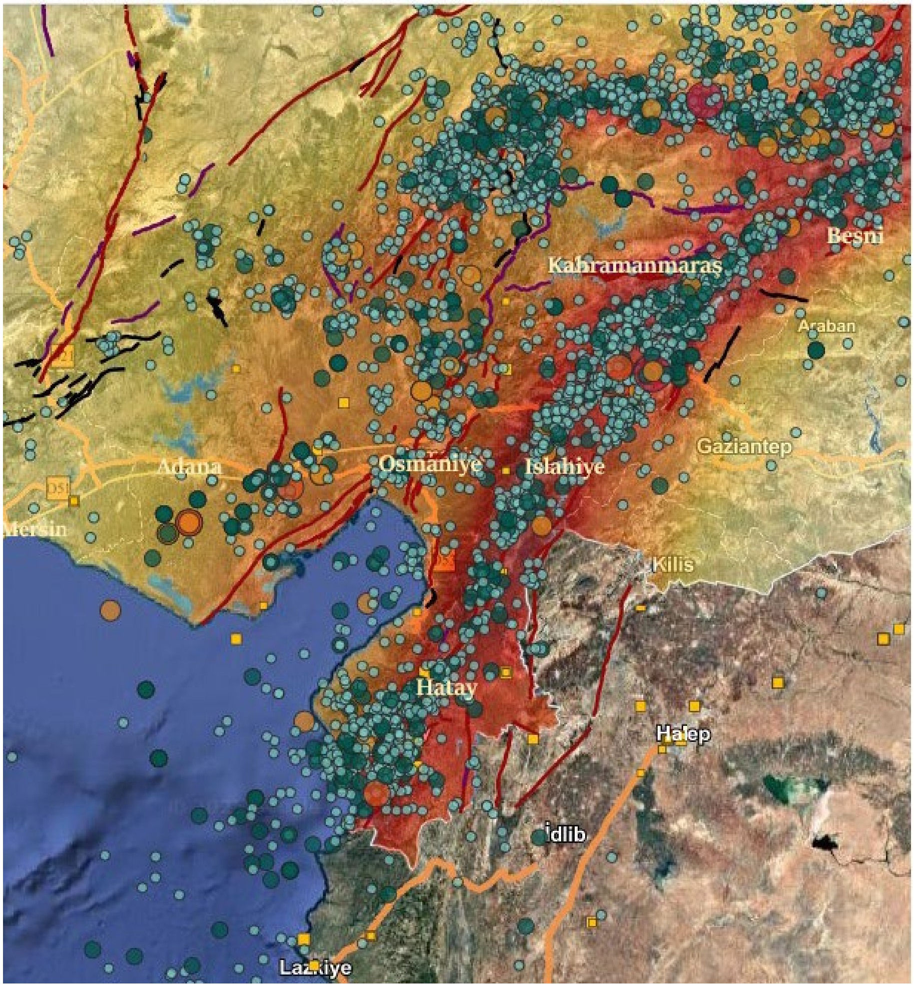

Figure 3. Epicentral distribution of earthquakes with magnitudes greater than 3.0 (M > 3.0) in Hatay and its surrounding region.

Before the 6 February 2023, Kahramanmaraş earthquakes, the most significant recent seismic events affecting Hatay occurred on 22 January 1997. These included a mainshock with a magnitude of 5.5 (Mb) and subsequent aftershocks of magnitudes 5.2 and 5.3. Despite their moderate intensity, with a maximum observed intensity of Io = VI–VII, these earthquakes still caused damage to some buildings. However, the 6 February 2023, Kahramanmaraş-centered earthquakes (Mw 7.7 and 7.6) caused the most extensive damage in Hatay among the eleven affected provinces. Over 24,000 lives were lost in Hatay alone, accounting for nearly half of the total fatalities. Additionally, more than 14,000 buildings collapsed, and nearly 100,000 were rendered uninhabitable. On 20 February 2023, another earthquake with a magnitude of 6.4 struck the Defne district, followed by two additional events with magnitudes of 5.8 and 5.2, respectively, all of which resulted in further casualties and property loss. Historically, settlements in Hatay were primarily located along the western foothills of the Amanos Mountains, which rise to elevations of up to 2200 m. However, modern urban development has shifted toward the alluvial plains of the Asi River. Seismic microzonation studies conducted at different times have characterized the local seismic response of Antakya city center and its surrounding areas. These studies revealed significantly high ground amplification factors, indicating a high level of seismic vulnerability, particularly across the Amik Plain [22,35,37,45]. The presence of such ground conditions contributed to the occurrence of extremely high ground accelerations during the 6 February 2023, earthquakes in Hatay.

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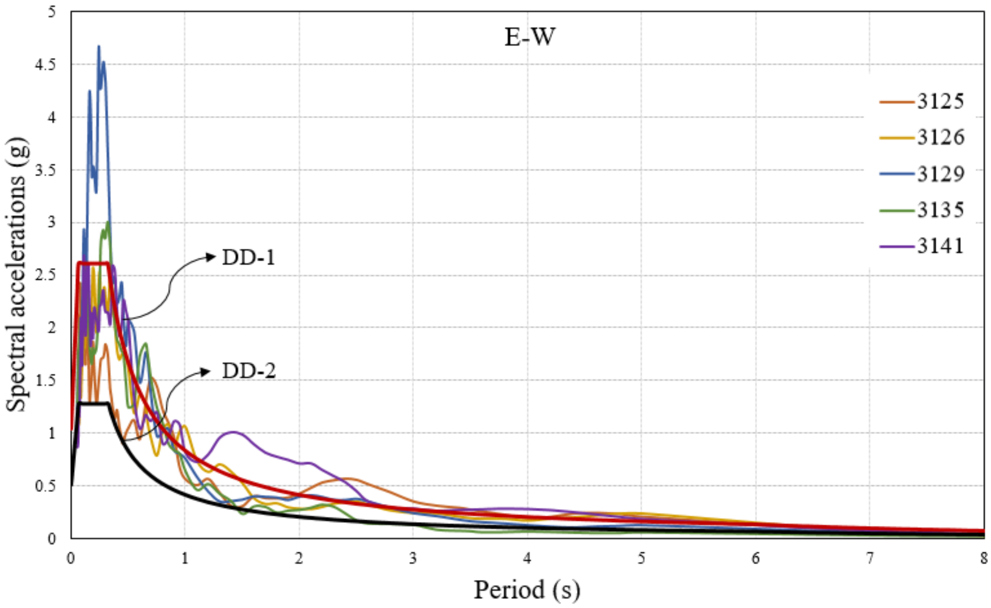
2.2. Recorded Ground Motions and Design Spectra in Hatay During the Pazarcık Earthquake

Figure 4 present the spectral accelerations recorded in the East–West (E-W) and North–South (N-S) directions at various ground motion stations in Hatay during the Pazarcık earthquake. In addition, the acceleration response spectrum corresponding to the design-level earthquake (DD-2) and the maximum considered earthquake (DD-1), as defined in the Turkish Building Earthquake Code 2018 [46] for a site class ZC are also provided. Damping ratio of 5% was adopted, in accordance with widely accepted assumptions for masonry and reinforced concrete structures. The recorded accelerations at all five stations in Hatay exceeded the DD-2 design-level spectrum in both the E-W and N-S directions. Furthermore, the ground motions recorded at stations 3129, 3135, and 3141 also surpassed the DD-1 maximum considered earthquake level. In addition, the spectral accelerations reached values on the order of around 5 g at very short periods, reflecting the exceptionally high seismic demand imposed by the Pazarcık earthquake.



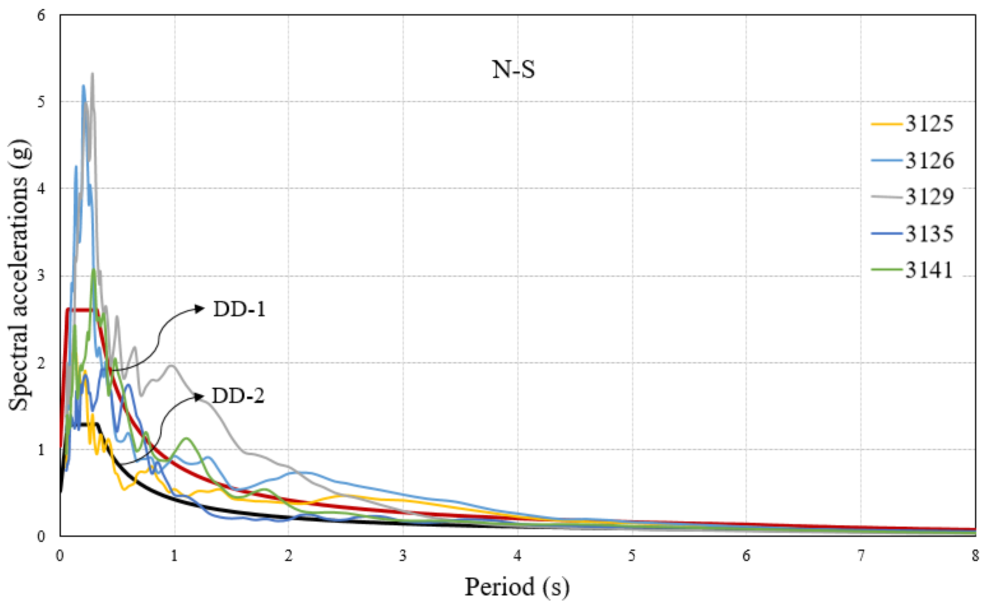


Figure 4. Measured spectral accelerations and design spectra in the province of Hatay in both the E-W and N-S directions.

3. The Mosque and Minaret Structures Under Investigation

The 6 February 2023, earthquakes were strongly felt across a large portion of Türkiye and caused severe destruction across various structural systems in 11 provinces. In addition to widespread building collapses, the earthquakes also inflicted varying levels of damage on numerous structures considered part of the historical and cultural heritage, particularly in provinces such as Kahramanmaraş (the epicentral region), Hatay, Adıyaman, Adana, Malatya, Elazığ, Şanlıurfa, Kilis, Diyarbakır, Osmaniye, and Gaziantep. The most extensive structural destruction occurred in Hatay province and its districts. Contributing factors such as poor local ground conditions and structurally deficient characteristics further exacerbated the scale of devastation. Aerial imagery of Hatay city center clearly illustrates the extent of the destruction. The damage observed along the banks of the Asi River, both before and after the earthquake, is depicted in Figure 5.

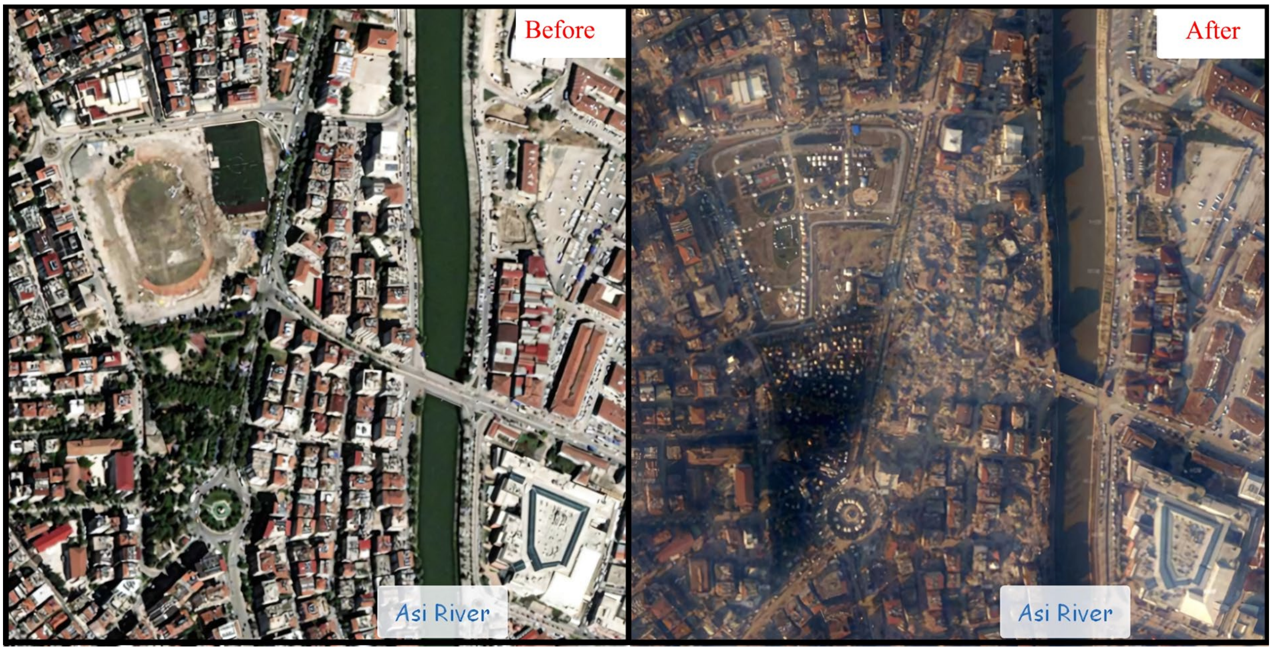


Figure 5. Structural damage observed along the banks of the Asi River, adapted from [47].

Mosques are the most significant places of gathering for worship in the Islamic faith. Minarets, tall, slender structures typically built of stone or brick, are used to call the faithful to prayer through the recitation of the adhan. These structures often feature a spiral staircase inside and may include one or more balconies (şerefe). Minarets can be constructed either adjacent to or detached from the mosque. Within the borders of Hatay Province, kiosk-type minarets can be found in some mosques, resembling those in certain regions of Anatolia. These structures, now considered immovable cultural heritage assets due to their age, are referred to by Eyice [48] as "minbar minarets." This type of minaret is typically built on the courtyard wall of the mosque and is sometimes located above the courtyard entrance. Accessed via an external staircase, these minarets feature a wooden kiosk-like balcony that serves the function of a şerefe, with a roof covered by a metal element and topped with an end ornament (alem) (Figure 6a). Another variation in kiosk-style minaret, also built using traditional construction techniques, is commonly found in mosques. These are typically positioned either adjacent to the mosque or directly above the entrance to the courtyard. The height of the minaret varies depending on the size of the mosque. Above the balcony is a wooden upper part of the body structure, capped with a conical spire and an end ornament (Figure 6b). This type of minaret is single-balconied and built using load-bearing masonry. In addition to these two registered cultural heritage types, a third commonly constructed type also exists (Figure 6c). These minarets, either masonry or reinforced concrete, incorporate classical minaret elements and may have more than one balcony. When constructed in masonry, stone and pumice are typically used as materials.

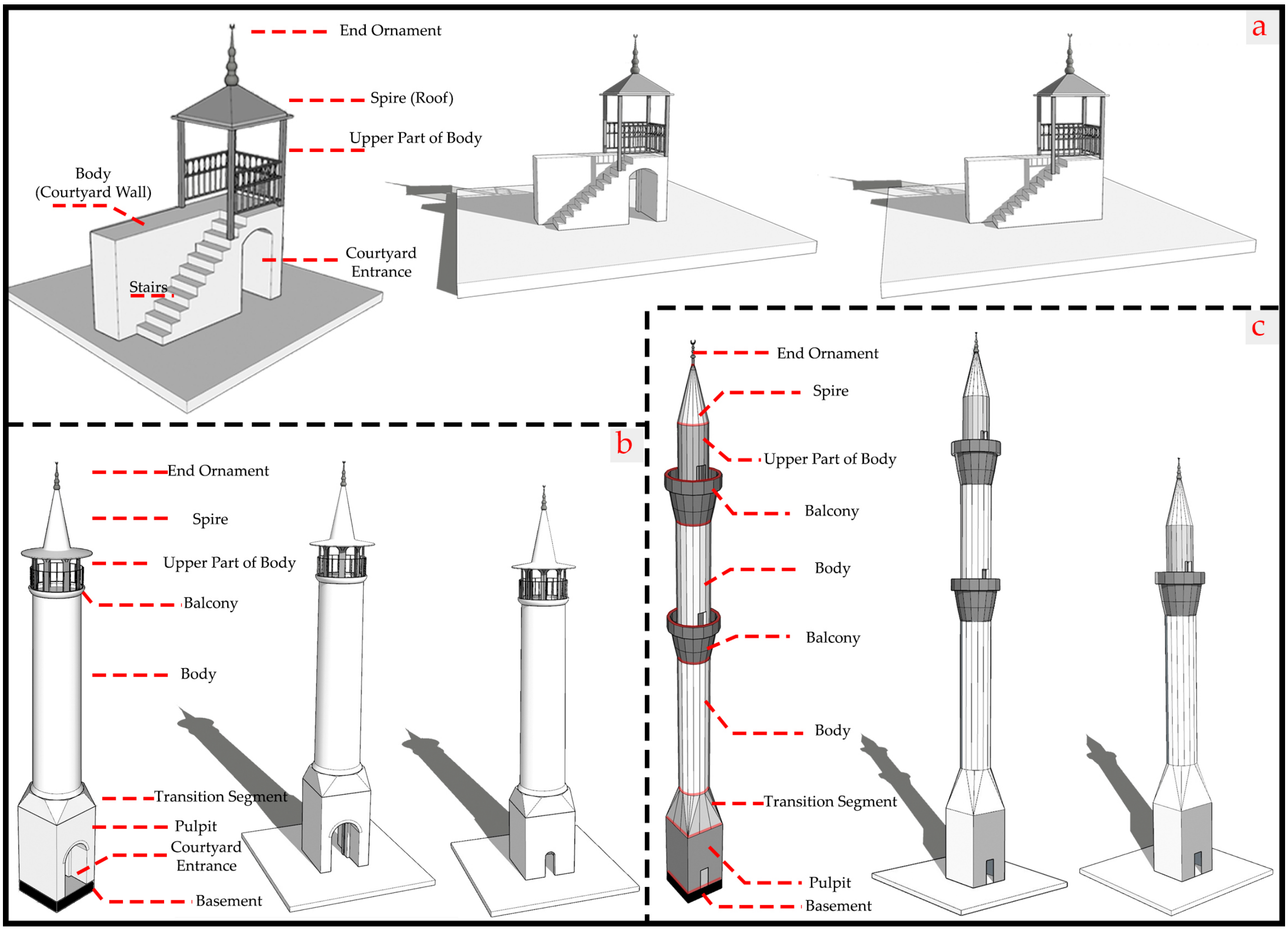


Figure 6. Common Types of Minarets Found in Hatay Province: (**a**) Kiosk-style minaret constructed on the courtyard wall, (**b**) Kiosk-style minaret, (**c**) Classical minaret.

According to the report released by the provincial mufti's office, the public institution responsible for mosques in Hatay, 299 out of 1107 mosques in the province were destroyed (categorized as either severely damaged or completely collapsed) following the earthquake. Additionally, 85 mosques sustained moderate damage, while 723 remained operational with either minor or no damage. Out of the 1003 minarets reported before the earthquake, 633 were recorded as destroyed [49]. The high rate of destruction among minarets may be attributed to the need for demolition and reconstruction of any structurally compromised minaret, regardless of the severity of damage, to eliminate potential safety hazards. Figure 7 presents a comparative visual representation of several mosques included in the report, showing their conditions before and after the earthquake.

The earthquake caused significant damage to several mosques and minarets, which are of great cultural and architectural importance. Among these, the Habibi Neccar Mosque is a prominent example of a culturally and architecturally significant structure that sustained severe damage during the earthquake. Habib-i Neccar mosque, originally a structure from the Roman period and later used as a church during the Crusader era, was restored and converted into a mosque by the Mamluk Sultan Baybars. Recognized as one of the symbolic landmarks of the city, the Habib-i Neccar Mosque and its minaret have sustained damage from various earthquakes and have undergone multiple restorations over time [51].

Since the Mamluk period, the structure has functioned as a mosque. Adjacent to it lies an underground burial site, which is believed to contain the head of Habib Neccar, a Figure known for his efforts in spreading Christianity, while his body is said to rest on Mount Silpius. This association has led to the mountain being named Mount Habib-i Neccar. Situated on Kurtuluş Street, the building is known to have served as a temple during the Roman era and was later converted into a church [52]. The mosque suffered severe damage during the earthquake on 6 February 2023. The main dome collapsed, the minaret was destroyed, the portico of the last congregation area was demolished, and the madrasa section sustained heavy damage as shown in Figure 8.

Figure 7. Pre-earthquake and post-earthquake images of some mosques and minarets: (**a**) Miraç Mosque, (**b**) Mehmet İpek Mosque, (**c**) Çökek Mosque, adapted from [49,50].

In addition to the Habibi Neccar Mosque, many other masonry and reinforced concrete mosques and minarets were damaged during the earthquake. These damages reveal the seismic vulnerability of both traditional and modern structures. The examined structures were assessed for their seismic performance following the Earthquake Risk Management Guide for Historical Buildings (TYDRYK-2017) [53], issued by the General Directorate of Foundations in Türkiye. Figure 9 presents the performance levels specified in this guide. The specific damages to these mosques and minarets in Hatay are presented in Figure 10.

In mosques built using masonry construction, varying degrees of damage occurred due to insufficient interlocking between load-bearing walls and the effects of low material properties. Examples of damage to the load-bearing masonry walls are illustrated in Figure 11.

Additionally, damage to the keystone was observed in load-bearing walls constructed in an arch style. An example of this damage, which occurred in the Debruz Mosque, is illustrated in Figure 12.

The Kürt Fakih Mosque, which exhibited soft-story mechanisms due to differences in rigidity between the floors, was at a performance level just before collapse. It is shown in Figure 13.

Similarly, shear cracks have occurred in the infill walls of structures built as reinforced concrete (RC). Additionally, due to insufficient reinforced concrete, total collapses have occurred in the slabs and minarets constructed of RC. These examples of damage are shown in Figure 14.

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Figure 8. Habibi Neccar Mosque (**a**,**b**) front view, (**c**,**d**) entrance (**e**,**f**) courtyard (photos by Google Street View and by authors).

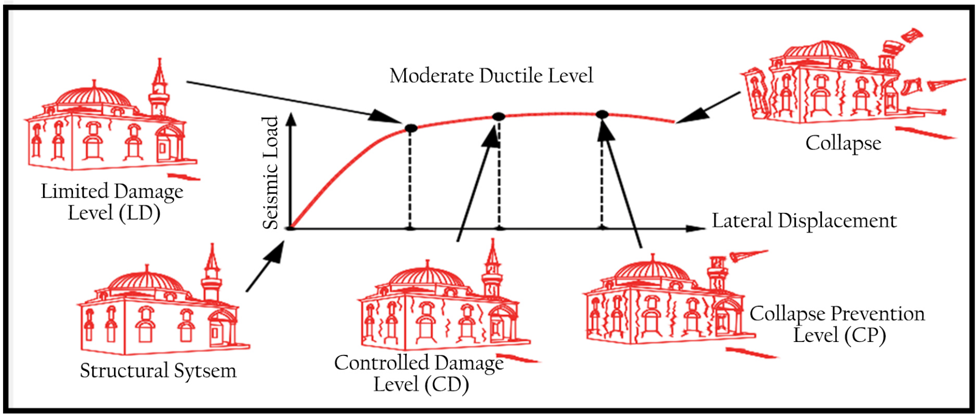

Figure 9. Performance levels specified in TYDRYK-2017.

Minarets are generally constructed by local craftsmen without any engineering services. As a result, their tall and slender design, coupled with the use of materials with low strength, directly impacted the level of damage in both the minarets and mosques. In terms of faulty design, damage occurred in the minarets due to an inadequate connection in the transition from the square to the circular form.

As a result of field investigations, schematic representations of the damage have been created to facilitate a clearer and more comprehensive understanding of the damage in the mosque and minaret. These are presented in Figure 15.

Şeyh Ali Mosque
The domes of the mosque have completely collapsed, and the minaret has collapsed starting from the transition segment.
/ Collapse

Abdulgazi Mosque
The minaret has completely collapsed starting from the transition segment, while the mosque has sustained severe damage.
/ Collapse

Sofular Mosque
The minaret has completely collapsed, starting from the transition section, while the mosque has sustained severe damage.
/ Collapse

Devecioğlu Bekir Mosque
The end ornament of the minaret has collapsed, and out-of-plane displacement has occurred in the stones of the balcony section.
/ CP

Kürtfakih Mosque
The minaret has collapsed at the midpoint of the pulpit section, while the mosque has sustained severe damage.
/ Collapse

Yeni Mosque
The portion of the minaret above the body section collapsed onto the mosque, contributing to its destruction.
/ Collapse

Mahremiye Mosque
The minaret collapsed starting from the balcony (şerefe) section, while the mosque has completely collapsed.
/ Collapse

Meydan Mosque
The minaret has collapsed from the transition segment, while the mosque has sustained severe damage.
/ Collapse

İhsaniye Mosque
The mosque and the minaret have completely collapsed.
/ Collapse

Zülfikar Mosque
A structural crack has formed between the kiosk-type minaret section and the courtyard wall, while the mosque has sustained severe damage.
/ CP

Ahmediye Mosque
The minaret has collapsed at the transition segment, and the mosque's load-bearing walls have sustained severe damage.
/ Collapse

Semerciler Mosque
The kiosk-type minaret section has toppled starting from the wooden upper part of the body, and hairline cracks are present in the courtyard gate located beneath it.
/ CP

Figure 10. *Cont.*

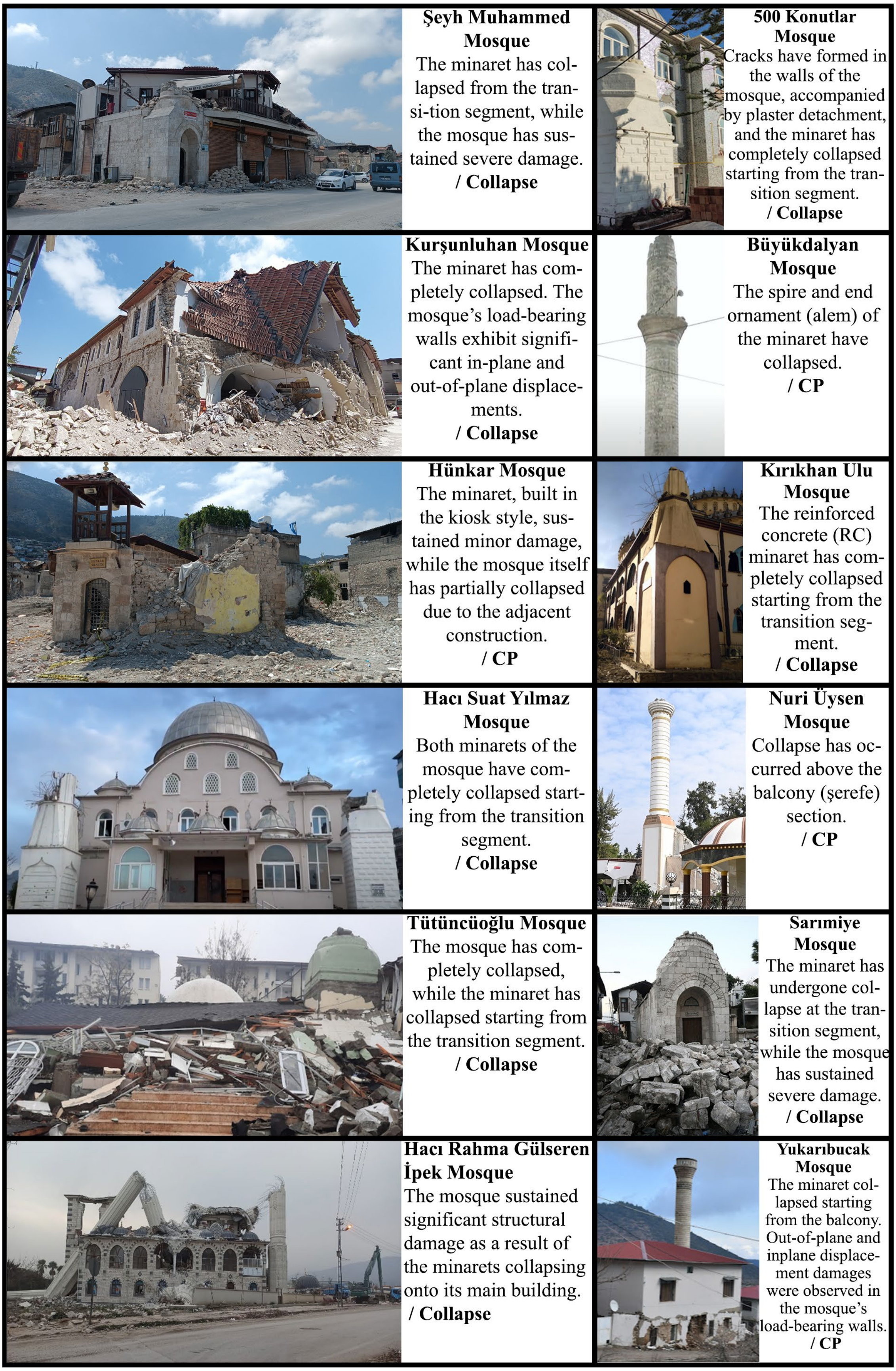

Figure 10. *Cont.*

Figure 10. Earthquake-Induced Damages to Masonry and Reinforced Concrete Mosques and Minarets in Hatay (photos by the authors).

Figure 11. Load-Bearing masonry walls damages: (**a**) Inadequate Interlayer Bonding, (**b**) Closer View of Inadequate Interlayer Bonding, (**c**) Out-of-Plane Displacement, (**d**) In-Plane Wall Damage.

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Figure 12. Keystone damage in Debruz Mosque.

Figure 13. Prevention of collapse performance level due to soft-story (Kürt Fakih Mosque).

Figure 14. Various types of damage in the RC mosque and minaret structures (**a**) shear cracks in the infill walls; (**b**) slab collapse; (**c**) minaret collapse.

Figure 15. Schematic representations of observed structural damages: (**a**) Bekir Devecioğlu: Mosque damage to the conical roof and balcony, (**b**) Mahremiye: damage above the balcony and upper part of the body section, (**c**) Meydan: damage to the body and above, (**d**) Kürtfakih: pulpit damage or total collapse, (**e**) Sheikh Ali: collapse of the minaret and damage to the mosque dome, (**f**) Zülfikar Köşk: separation between the minaret base and courtyard wall, (**g**) Mahremiye: voids and cracks between voussoirs (yemerler), (**h**) Debruz: damage and cracks in the keystone, (**i**) Sheikh Ali: damage to the dome and arches, adapted from [50–52,54].

4. Numerical Analysis of Material Effects on Minaret Structural Behavior

In this section of the study, numerical analyses were conducted to examine the effects of commonly used masonry and concrete materials in minaret construction. The dimensions of the minaret, its cross-sections, the FE model, and the meshed model in the ABAQUS software (Version 6.14) are presented in Figure 15. Both geometric and material nonlinear behaviors were taken into consideration. The model adopted a macro-modeling strategy widely applied to historic masonry towers and minarets. This approach enables an efficient and sufficiently reliable evaluation of global seismic response [55–59]. All geometric and structural properties of the minaret were kept constant, with the only variable being the choice of construction material. The modeling and structural analyses were carried out using the ABAQUS software package [60]. In the selection of material parameters, the national guideline TYDRYK-2017 [53], the Earthquake Risk Management Guide for Historic Buildings, was used. To account for material nonlinearity, the Concrete Damaged Plasticity model available in ABAQUS was adopted. This model has been successfully applied in the modeling and analysis of various masonry structures [61–63]. The sample minaret, with a total height of 27.4 m, was modeled using quadratic tetrahedral elements of type C3D10, comprising a total of 35,558 nodes and 21,073 elements.

Table 1 presents the geometric and modeling properties of the reference minaret used in the numerical analyses. The structure was modeled based on the characteristic proportions and morphological features of ancient-period minarets. All geometric dimensions and structural parameters were kept constant throughout the analyses, while only the construction material was varied.

Table 1. Geometric and modeling properties of the reference minaret.

Parameter	Description/Specification
Total Height	27.40 m (from base level 0.00 m to apex of conical spire +27.40 m)
Software Used	ABAQUS (Finite Element Analysis)
Element Type	Quadratic tetrahedral (C3D10)
Number of Nodes/Elements	35,558 nodes; 21,073 elements
Base Segment (0.00–7.00 m)	Square cross-section: 3.44 m × 3.44 m (constant)
Transition Segment (7.00–8.50 m)	Gradual transformation from square to circular section
Main Shaft (8.50–20.80 m)	Circular cross-section; radius = 1.55 m
Balcony Segment (20.80–21.78 m)	Gradual widening to radius = 1.95 m (Şerefe)
Inner Cylindrical Void	Radius = 1.14 m, extends from +21.78 m to +25.40 m (staircase core)
Conical Spire (25.40–27.40 m)	Tapered conical top section
Geometric Reference	Based on morphological characteristics of Ottoman-period minarets
Figure Reference	Figure 15—Elevation, cross-sections (A–A, B–B, C–C), and FE mesh

The reference minaret has a total height of 27.4 m, beginning at the base level (0.00 m) and terminating at the apex of the conical spire (+27.40 m). The geometry of the structure was precisely defined based on traditional morphological characteristics observed in Ottoman-period minarets. The base segment, from 0.00 m to +7.00 m, consists of a square cross-section measuring 344 cm × 344 cm and remains constant in this range. Between +7.00 m and +8.50 m, the cross-section transitions smoothly, tapering into a circular form.

At elevation +8.50 m, the circular shaft begins with a radius of 1.55 m and continues uniformly up to +20.80 m. This segment represents the main cylindrical body of the minaret. From +20.80 m to +21.78 m, the cross-section gradually widens to form the balcony (şerefe), reaching a maximum outer radius of 1.95 m, as illustrated in Section A–A. Internally, a concentric cylindrical void with a radius of 1.14 m is maintained above the balcony, extending from +21.78 m to +25.40 m, accommodating the helical staircase core.

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The final segment is a conical spire extending from +25.40 m to +27.40 m, completing the upper architectural profile of the structure. Cross-sectional views and transitions between segments are detailed in Sections A–A, B–B, and C–C in Figure 16, capturing the minaret's morphological and functional complexity.

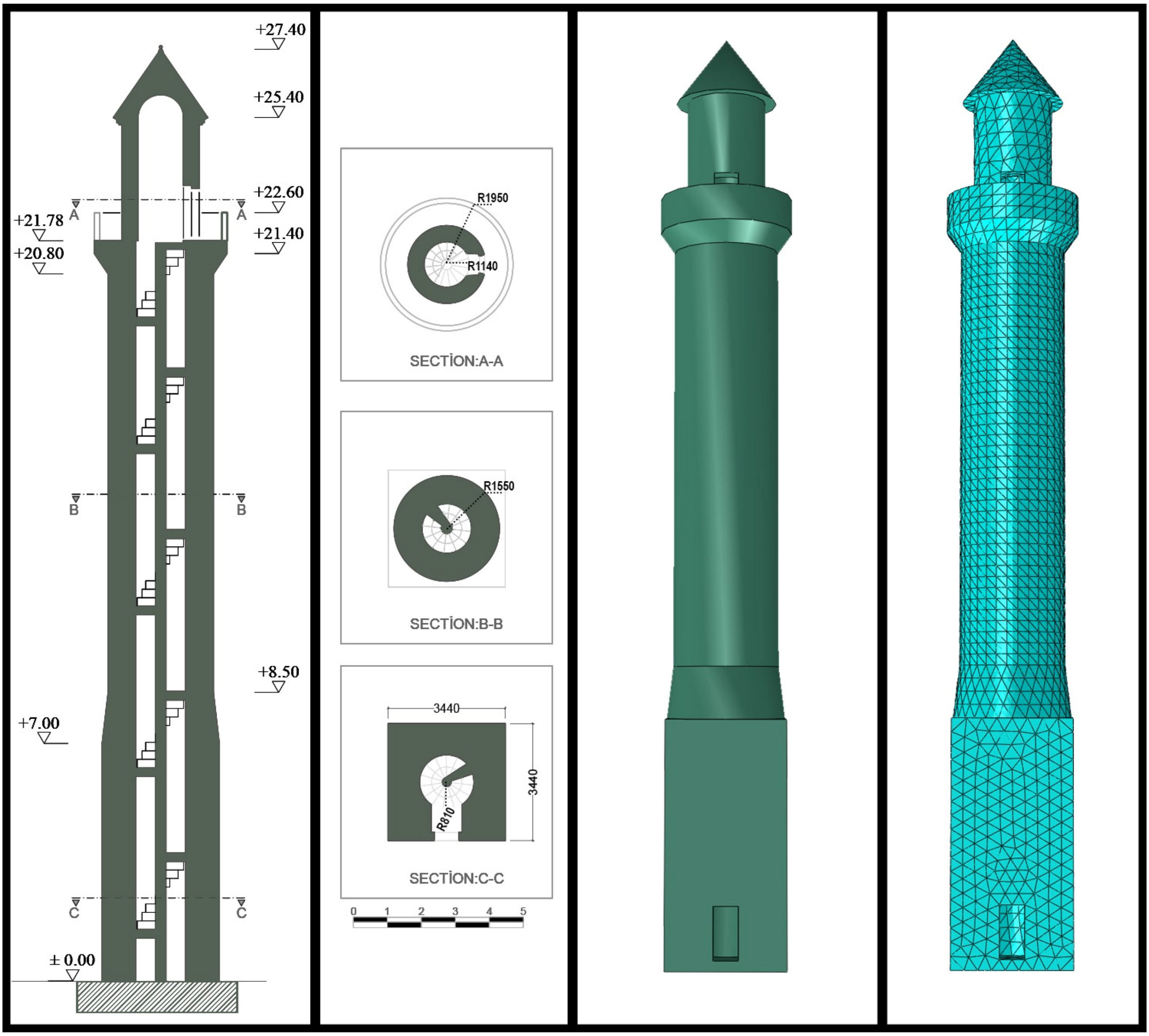

Figure 16. Dimensions, cross-section, and FE model of the minaret.

Figure 15 presents the detailed geometric configuration of the minaret, showing the elevation-based segmentation, cross-sectional views at critical heights, and the three-dimensional finite element mesh developed for structural simulation.

The mechanical properties of the cut-stone masonry and reinforced concrete materials used in the numerical analysis are summarized in Table 2. These parameters include Young's modulus, Poisson's ratio, and unit weight, which were adopted from representative experimental and standard-based sources to ensure realistic and consistent modelling conditions. Additionally, to provide a broader comparative perspective, typical values for other commonly used construction materials, such as brick masonry and unreinforced concrete, are also presented. This inclusion enables potential benchmarking for future studies and enhances the interpretability of the results (Table 2).

Table 2. Mechanical properties of the materials considered in the analysis and comparative reference values [64–66].

Material Type	Elasticity Modulus (E) (MPa)	Unit Volume Weight (t/m^3)	Poisson's Ratio (υ)	Remarks
Cut-Stone Masonry	4000	3.06	0.20	Used in analysis
C25 Concrete	30,000	2.50	0.20	Used in analysis
Brick Masonry	3000–5000	1.90	0.18	Comparative
Unreinforced Concrete (Low-Strength)	15,000–20,000	2.30	0.20	Comparative

Modal analysis was conducted to determine the mode shapes, natural frequencies, and free vibration periods of the structure. Through this analysis, the dynamic characteristics of the minaret were identified. Figure 17 presents the first five mode shapes of a sample minaret constructed with Cut Stone and C25 Concrete, with a total height of 27.40 m. Due to the square cross-section of the minaret, the mode shapes and corresponding frequencies in the X and Y directions are nearly identical. Initially, the modal analysis results were validated by comparing the computed natural frequencies with values reported in the literature [67]. The frequency and period values for the first five modes of both cut stone and concrete materials are presented in Table 3.

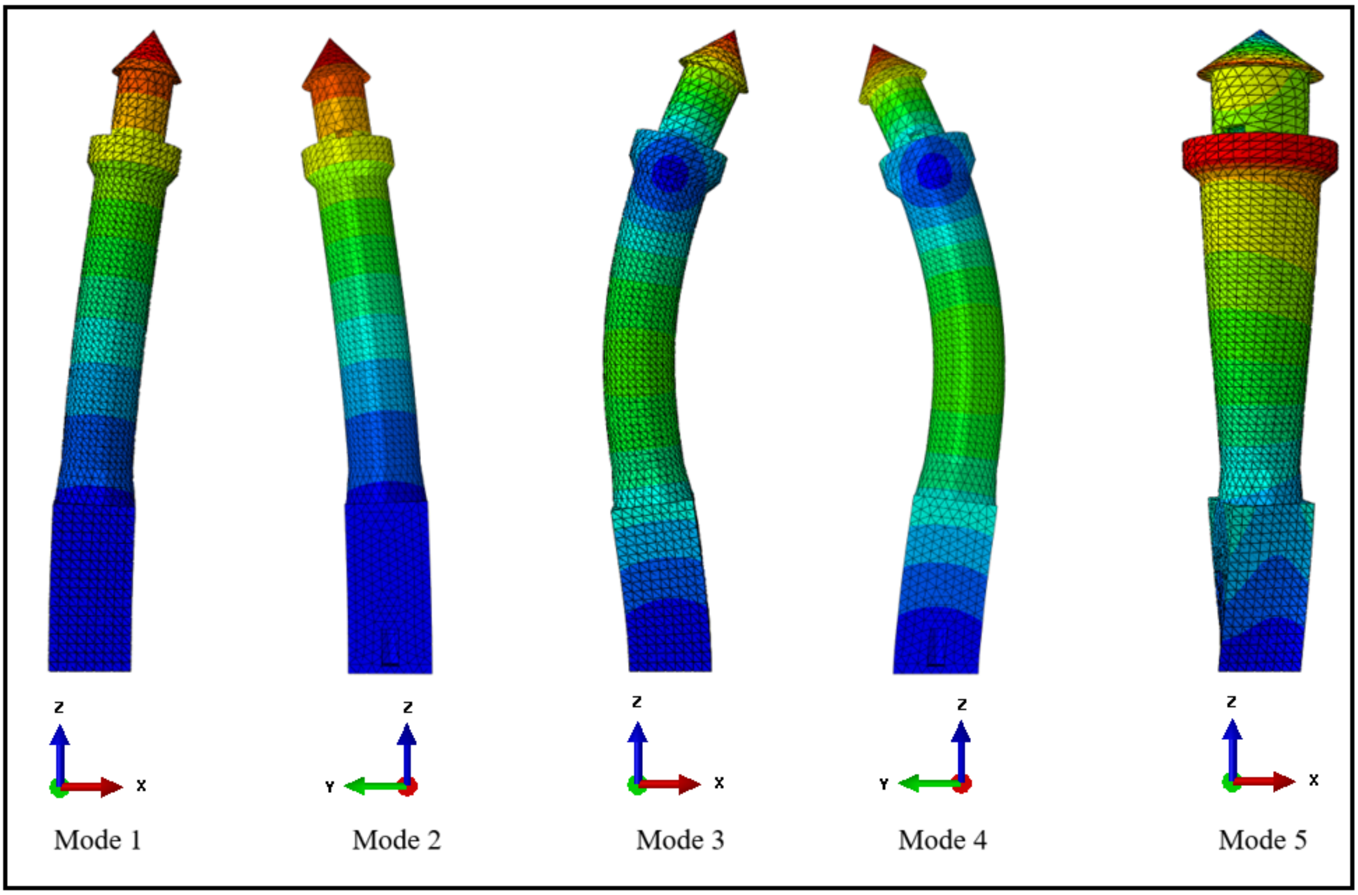

Figure 17. First five mode shapes showing dominant lateral bending behaviour.

Table 3. Modal analysis of the minaret model.

Mode Number	Frequency (Hz)		Periods (Second)	
	Cut Stone	C25 Concrete	Cut Stone	C25 Concrete
1	1.172	3.552	0.853	0.282
2	1.184	3.586	0.845	0.279
3	5.503	16.673	0.182	0.060
4	5.545	16.800	0.180	0.060
5	8.631	26.150	0.116	0.038

The modal analysis revealed significant discrepancies between the natural frequencies of the minaret depending on the construction material. As shown in Table 3, the first five natural frequencies for the C25 concrete model were consistently and substantially higher than those for the cut-stone model.

For instance, the fundamental frequency of the cut-stone minaret was found to be 1.172 Hz (corresponding to a period of 0.853 s), while the same mode in the concrete model exhibited a frequency of 3.552 Hz (0.282 s). This trend was preserved across all modes, indicating a stiffer dynamic behavior in the concrete alternative. This divergence is attributed to two primary factors:

(1) The higher elastic modulus of reinforced concrete compared to traditional masonry;
(2) The homogeneous and monolithic structural continuity offered by concrete, in contrast to the discontinuous and jointed nature of stone masonry construction.

Dynamic analyses were conducted using recorded ground-motion data from the Kahramanmaraş (Elbistan) Earthquake, specifically acceleration records from Station 4612 in the East–West (E-W) and North–South (N-S) directions. A total duration of 105 s was considered. Figure 18 presents the acceleration time histories of the 4612 ground motion record along with the corresponding normalized Arias intensity curves. The acceleration records indicate the strong ground motion is primarily concentrated between approximately 30 and 45 s. The rapid increase observed in the normalized Arias intensity curves within this time interval demonstrates that a significant portion of the seismic energy was released during this period, highlighting the record's effective duration and energy content.

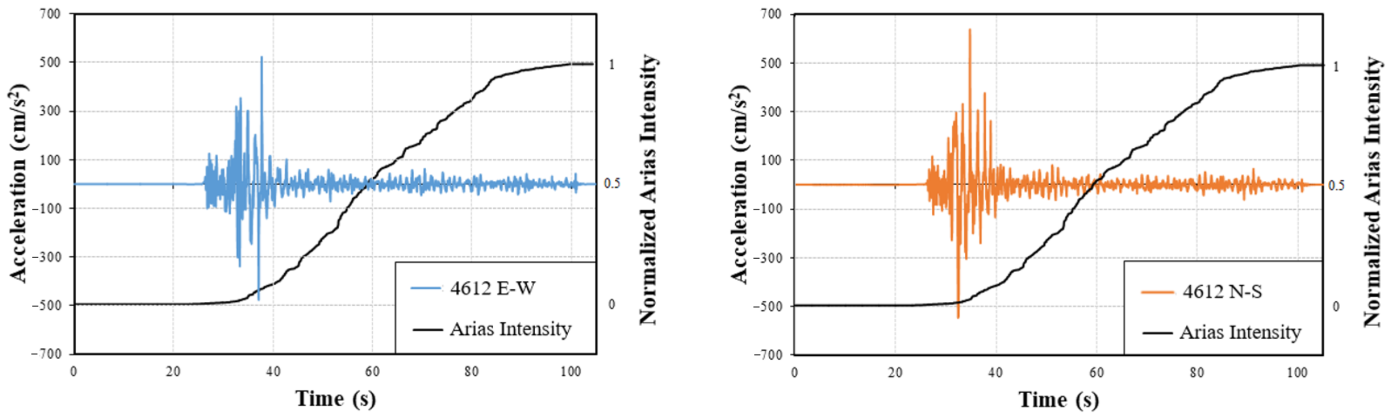

Figure 18. Recorded ground accelerations along with the Arias intensity at station number 4612 in Kahramanmaraş.

Based on the time history analysis performed using the applied acceleration records, it was determined that the minaret constructed with cut stone masonry reached a maximum lateral displacement of 306.43 mm at the 37th second, while the minaret constructed with C25 concrete reached a maximum lateral displacement of 55.59 mm at the 35th second, as shown in Figure 19.

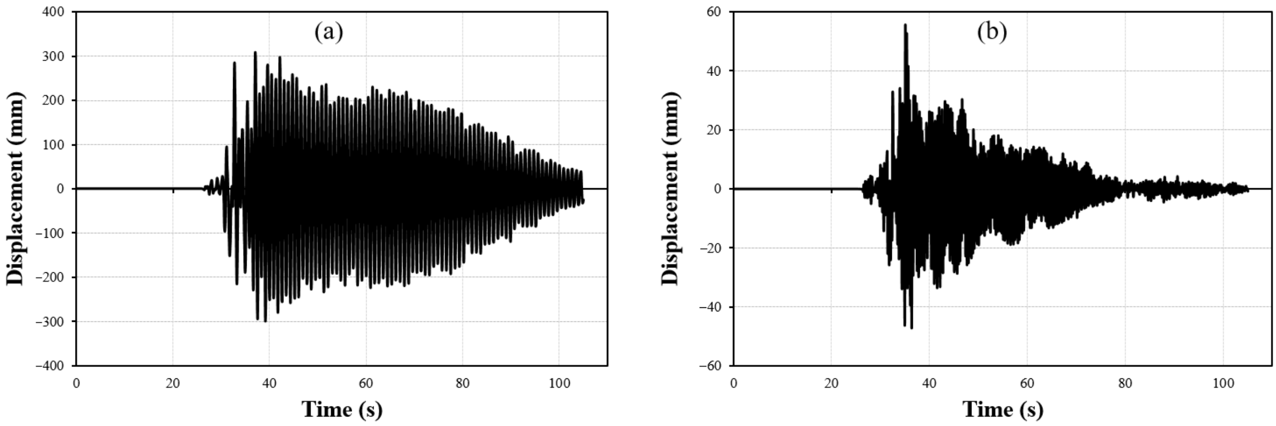

Figure 19. Lateral displacement at the top of the minaret based on its materials: (**a**) cut-stone, (**b**) C25 concrete.

The most striking result from the time-history analysis is the dramatic difference in lateral displacement at the top of the minaret (Figure 18). The cut-stone minaret experienced a maximum lateral displacement of 306.43 mm at 37 s, compared to just 55.59 mm for the C25 concrete model at 35 s. This six-fold difference in displacement highlights the vulnerability of traditional masonry structures, particularly those with high slenderness ratios, to seismic excitation.

The relationship between the displacement-based dynamic analysis results and the observed damage distribution has been revised within the framework of the performance criteria defined in the Türkiye Earthquake Risk Management Guide for Historic Buildings (TERMFHB-2017). According to the guideline, seismic performance is defined based on three fundamental objectives: (i) no damage to structural and non-structural elements under low-intensity earthquakes (Damage Limitation performance level), (ii) limited and repairable damage under moderate-intensity earthquakes (Controlled Damage performance level), and (iii) controlled damage with limited permanent structural damage under severe earthquakes (Prevention of Collapse performance level). For the Damage Limitation performance level, the earthquake-induced drift ratio should not exceed 0.3% (82.2 mm). For the Controlled Damage level, the drift ratio should remain below 0.7% (191.8 mm), and for the Prevention of Collapse performance level, it should not exceed 1% (274 mm). These displacement limits were calculated considering the total height of the minaret, which is 27.4 m. Within this scope, the maximum displacement demands obtained from the dynamic analyses were compared with the limit values defined for the corresponding performance levels. It is observed that the cut-stone minaret exceeds the PC performance level limits, whereas the concrete minaret satisfies the Damage Limitation performance level criteria.

This outcome can be directly correlated to the material damping and energy dissipation characteristics of the two models [68,69]. While concrete exhibits some ductility and capacity for damage redistribution under nonlinear conditions, masonry, by contrast, behaves in a more brittle fashion, accumulating displacement rapidly once cracking initiates.

Furthermore, the modal period elongation in the stone model contributes to greater resonance under long-period earthquake components, which are characteristic of large-magnitude events like the Kahramanmaraş earthquake. The combination of lower stiffness, higher mass participation in the fundamental mode, and insufficient damping capacity renders the stone minaret particularly susceptible to large-amplitude swaying.

Based on the findings, the following key conclusions can be drawn:

- Material stiffness significantly influences dynamic characteristics. The use of reinforced concrete more than tripled the natural frequencies of the minaret, thereby reducing susceptibility to low-frequency seismic components.

- Displacement demand on the masonry minaret was critically high, with over 300 mm of peak lateral displacement recorded under the applied ground motions. This level of displacement would likely result in structural instability or collapse in real scenarios.
- Modal analysis confirms that both systems primarily respond through global bending modes, suggesting that strengthening strategies, if applied, should focus on enhancing flexural stiffness and base confinement.
- Reinforced concrete construction offers significantly improved dynamic performance, reducing lateral drift and potentially extending the functional lifespan of such tall slender structures in seismically active regions.
- While the historical authenticity and cultural value of stone minarets are indisputable, retrofit measures or internal strengthening using modern materials may be essential to ensure seismic resilience without compromising visual integrity.

Future studies should aim to incorporate damage modeling, base–soil interaction, and probabilistic seismic demand to further refine the risk assessment for masonry-based religious heritage structures.

5. Seismic Strengthening and Restoration Recommendations for Mosque Minarets

In Hatay, a province with a high density of cultural heritage assets, the rubble of immovable cultural properties serves as a critical form of documentation for the reconstruction process. Therefore, the removal of this debris must be carefully managed. In this context, 21 days after the earthquake, the Ministry established the Hatay Disaster Zone Excavation Directorate to conduct archaeological studies of the debris.

- ➢ One of the often-overlooked aspects in the restoration of historic mosque minarets is the strengthening of foundations. The foundations of minarets, whether damaged or undamaged by earthquakes, should be exposed and assessed, and those requiring reinforcement should be structurally strengthened.
- ➢ In the restoration projects of monumental structures located in earthquake-prone regions, geotechnical investigations must be mandatory. The seismic behavior of the structure should be analyzed using three-dimensional (3D) models, and recommendations should be developed based on these analyses.
- ➢ For the complete reconstruction of mosques that have been entirely destroyed, reconstruction projects based on accurate documentation and records must be prepared. During the reconstruction process, reusable original structural materials of the mosque should be incorporated. Decorative elements such as stone, wood, and metal must be preserved and reused whenever possible.
- ➢ Before the preparation of restoration projects, a thorough geotechnical study should be conducted, and necessary foundation reinforcement should be carried out accordingly.
- ➢ Metal ties and dovetail joints should be employed in the construction of walls and minarets to enhance structural integrity.
- ➢ In strengthening efforts, tensioning systems should be considered between arches.
- ➢ For cracks that have formed in vaults, Fiber-Reinforced Polymer (FRP), such as Fibranet, may be applied as a reinforcement method.
- ➢ Minarets that exhibit cracking in the body but do not pose an immediate risk of collapse should be preserved using confinement techniques, such as steel banding, instead of complete reconstruction.
- ➢ In many historic mosque minarets, staircases do not continue beyond the balcony, resulting in increased vulnerability to lateral forces in the upper part of the body and spire sections. Structural solutions should be developed to interconnect the horizontal

stone courses in these areas, for example, using wooden or metal lintels or internal vertical metal confinement rings.
- ➢ In newly constructed mosque minarets, the use of stone cladding over reinforced concrete should not be permitted, as it may compromise structural integrity.
- ➢ The balcony access doors located in the upper part of the body section create voids that reduce structural resistance to horizontal and vertical loads. Additionally, since door frames are typically made of wood, they do not act integrally with the surrounding masonry. To ensure continuity and increase resistance to applied loads, a metal cage or frame should be installed around the door area.
- ➢ Adequate staggering should be applied in the overlapping of stones in new minaret construction to ensure proper load transfer and stability.
- ➢ Strengthening strategies using carbon fiber should be developed for the internal surfaces of minarets to improve seismic resilience.
- ➢ The ones that pose significant seismic hazards and are beyond the possibility of effective retrofitting may be systematically deconstructed in a controlled manner in terms of safety.

Intervention processes should be carried out more carefully in structures that qualify as cultural heritage assets. In international conservation circles, the principles concerning this issue are clearly defined. Interventions are recommended only when necessary, and the extent of the intervention should be kept to a minimum. Conservation practices are expected not to hinder future interventions and should be reversible. Another important consideration in practice is that decorative elements and ornamental features that form part of the structure should not be concealed or covered [70,71].

6. Conclusions

On 6 February 2023, Türkiye experienced devastating human and material losses due to the earthquakes centered in Kahramanmaraş. These earthquakes have gone down in history as causing the highest casualties and damage within the country's instrumental seismic period. The destructive effects of the earthquakes were observed across various structural systems, including mosques and minarets.

This study evaluates the damage at different levels observed in mosques and minarets located in Hatay province and its districts, which suffered the highest levels of casualties and destruction. Based on visual inspections and observational damage assessments conducted on the examined mosques and minarets, the following conclusions were drawn:

- ➢ In minarets, section changes occur at the transition zones, leading to discontinuities in the cross-section, which contribute significantly to structural damage.
- ➢ In structures constructed using masonry techniques, the tensile and shear strengths of the materials used are generally low, which directly influences the extent of damage.
- ➢ For masonry minarets, the application of metal ties and dowels should be carefully considered to improve structural integrity.
- ➢ Particular sensitivity must be shown to preserve the authenticity of historical minarets and mosques during restoration efforts.
- ➢ In newly constructed masonry minarets, the use of high-strength binding mortars is recommended to prevent certain types of earthquake-induced damage and enhance seismic resilience.
- ➢ In the masonry walls of mosques, inadequate interlocking between layers has resulted in separation between layers and out-of-plane displacements, leading to significant damage.
- ➢ In minarets constructed adjacent to the mosque (attached layout), the collapse of the minaret onto the mosque has caused varying levels of damage to the mosque structure

and dome. Future minarets should be encouraged to follow a detached construction layout to mitigate such risks.

➢ In kiosk-style minarets, the connection details between the timber framework and stone structure need to be properly designed and reinforced. For those constructed over courtyard walls, horizontal elements should be used to prevent damage resulting from sectional differences between the courtyard wall and the minaret base.

Beyond the documentation of observed damage, this study bridges a critical gap by correlating empirical field data with quantitative numerical simulations under extreme seismic conditions. The 2023 Kahramanmaraş earthquakes provided a unique 'natural laboratory' where recorded spectral accelerations in Hatay significantly bypassed the TBEC-2018 design spectra. By modeling these specific loading conditions in a finite element environment, our analysis identifies the precise transition points from elastic behavior to structural failure in masonry minarets. This differentiation between 'kiosk-type' and 'classical' minaret responses under site-specific ground motions provides a more nuanced understanding than generalized masonry failure theories. Consequently, the findings presented here move beyond qualitative observation, offering a data-driven foundation for developing targeted retrofitting strategies for high-risk heritage zones.

The findings of this study reveal that analyzing the seismic resistance of historical masonry structures using scientific methods is not only a technical requirement but also an integral part of a holistic sustainability strategy. The damage mechanisms documented at the Hatay scale and the finite element analyses performed confirm the importance of preserving cultural heritage in terms of social sustainability (preserving social identity) and economic sustainability (extending the lifespan of existing structures and avoiding large-scale reconstruction costs). Consequently, adopting engineering solutions sensitive to local material properties and dynamic soil conditions will ensure the resilience of the historical fabric against seismic risks, allowing the architectural heritage of the past to be safely passed on to future generations in accordance with sustainable preservation principles.

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