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Domino Collapse in Urban Settings: A 19th Century Mosque Collapsed During the 2023 Kahramanmaraş Earthquake Sequence

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Abstract. The seismic vulnerability of historical masonry structures has been extensively studied, with efforts primarily focused on assessing their earthquake resistance. However, such studies often consider these structures in isolation, disregarding their urban context. In densely built environments, the collapse of adjacent buildings during an earthquake can have a devastating impact on nearby heritage structures, even if they are inherently capable of withstanding seismic loads. On February 6, 2023, two major earthquakes, with magnitudes of Mw 7.7 and Mw 7.6, occurred nine hours apart, affecting the southeastern region of Türkiye. Post-earthquake site investigations revealed that the collapse of the historical Adıyaman Grand Mosque was likely triggered by the failure of a substandard reinforced concrete building in close proximity. This paper aims to investigate the failure mechanism of the Adıyaman Grand Mosque in a broader context. Preliminary study highlights the importance of conducting an extended analysis for heritage structures in urban environments, for reasons such as: (i) the complex interactions between buildings in densely populated areas during earthquakes, (ii) the detrimental effect of the failure of a nearby building on heritage structures, and (iii) the development of more effective mitigation strategies to protect and preserve heritage structures in such environments.

Keywords: Domino collapse · Architectural heritage · 2023 Kahramanmaraş Earthquake Sequence · Historical mosque · Urban setting

1 Introduction

Structures of interest are often analysed under the assumption that they exist as isolated entities. However, when assessing historical buildings in urban settings, a comprehensive diagnosis must also account for their surrounding context. In Türkiye, rapid urbanisation has often led to unplanned or irregular development, and it is common to find heritage structures in close proximity to multi-story buildings, as shown in Fig. 1. These

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spatial constraints can significantly influence the structural integrity and safety of historical buildings, as interactions with adjacent structures may promote damage during an earthquake.

The February 6, 2023, Kahramanmaraş earthquake sequence provided clear evidence of the influence of urbanisation on the seismic vulnerability of historical structures. Işık et. al (2023) [1] documented a list of religious structures in Adıyaman, nine of which are stone masonry structures, that were severely damaged. Based on the field observations, the failure mechanisms are categorised in three primary groups: (i) local damage on minarets, (ii) damage to the mosques caused by minaret collapse, and (iii) damage to the neighbouring buildings due to minaret failure [1].



(a) (b)

Fig. 1. Examples for architectural heritage in urban settings in Adıyaman, (a) The Grand Mosque [2], (b) Çarşı Mosque [3].

While Işık et al. (2023) [1] categorised the failure mechanisms observed during the aforementioned seismic event, this study highlights a critical but previously overlooked factor: the collapse of adjacent multi-story substandard buildings as a contributing cause of severe damage to historical structures. This highlights the importance of assessing heritage buildings within their broader urban context, rather than in isolation. International heritage conservation principles [4–6] emphasise that the protection of historical buildings or sites extends beyond their boundaries to their urban setting, which contributes to their significance and structural integrity. This setting includes surrounding buildings, spatial organisation, and visual relationships, all of which can influence a structure's vulnerability to external forces, including seismic activity. Unregulated urban development poses a risk to heritage buildings, particularly when adjacent or nearby buildings are not designed or maintained to withstand earthquakes.

This issue is particularly pressing in Türkiye, where a substantial portion of reinforced concrete (RC) buildings constructed before 2000 are presumed to be substandard due to several factors emphasised by Kazaz et al. (2024) [7]. Lack of quality control in construction materials, design and inspection, as well as inadequacies in seismic design and construction codes, are some of the critical issues causing extensive substandard construction before 2000. Without proper structural assessment and potential interactions with nearby heritage buildings, these neighbouring structures could impose unintentional hazards during earthquakes, triggering cascading failures and amplifying

damage. Therefore, integrating urban context into seismic risk assessments is essential for developing more effective mitigation strategies that ensure the long-term protection of historical buildings in seismic-prone areas.

2 Kahramanmaraş Earthquake Sequence and Damage Distribution

The February 6, 2023, Kahramanmaraş earthquake sequence included two major earthquakes, Mw 7.7 and Mw 7.6, occurring within a nine-hour interval in the Pazarcık and Elbistan districts, respectively (Table 1 and Fig. 2). Both earthquakes originated at shallow depths of 8.6 km for Mw 7.7 and 7.0 km for the Mw 7.6 event and generated strong ground motions, including high peak ground acceleration (PGA), velocity (PGV), and displacement (PGD). The sequence resulted in over 500 km of surface rupture, primarily along the East Anatolian Fault (EAF) with approximately 345 km attributed to the Mw 7.7 Pazarcık event, and around 175 km observed along the Çardak Fault, a splay of the EAF, during the Mw 7.6 Elbistan event. Following the mainshocks, nearly 1300 aftershocks were recorded across southeastern Türkiye between the initial mainshock at 04:17 local time on 6 February and 16:00 on 9 February 2023. These aftershocks range in magnitude and depth, and their spatial distribution closely followed the rupture zones, with notable clustering along the Narlı Segment (Mw 7.7) and the Çardak Fault (Mw 7.6) [8].

The Earthquakes had a devastating impact across 11 Provinces, covering a region of more than 100.000 km^2. The official authorities confirmed over 50.000 casualties and more than 115.000 people injured, marking the disaster as one of the most catastrophic in the country's recent history [8].

Table 1. Seismic characteristics of the Kahramanmaraş earthquake sequence [8]

	Pazarcık (Kahramanmaraş)	Elbistan (Kahramanmaraş)
Date	06/02/2023, 04:17 (local time)	06/02/2023, 13:24 (local time)
Location	Pazarcık	Elbistan
Latitude (°N)	37.288	38.089
Longitude (°E)	37.043	37.239
Depth (km)	8.6	7.0
Mw	7.7	7.6

Figure 3 illustrates the distribution of historical structures by damage state across the earthquake-affected districts, based on systematic field surveys. The majority of reported damage ranges from light to severe, with a significant concentration of structural collapses observed in urban centres such as Antakya, Kahramanmaraş, and Adıyaman. These findings underscore the spatial variability in vulnerability and highlight the critical

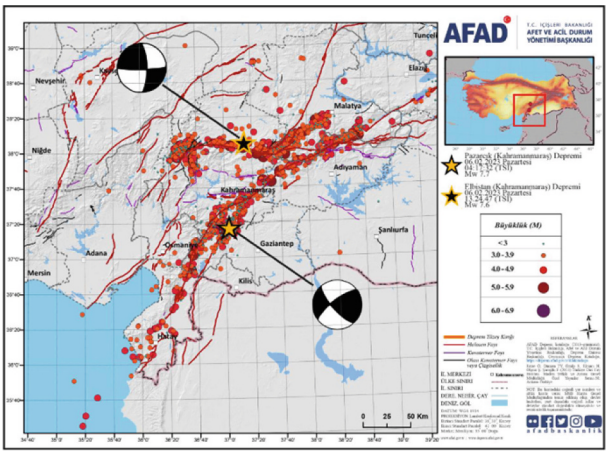


Fig. 2. February 6, 2023, Pazarcık (Mw 7.7) and Elbistan (Mw 7.6) earthquakes and aftershock activity [8]

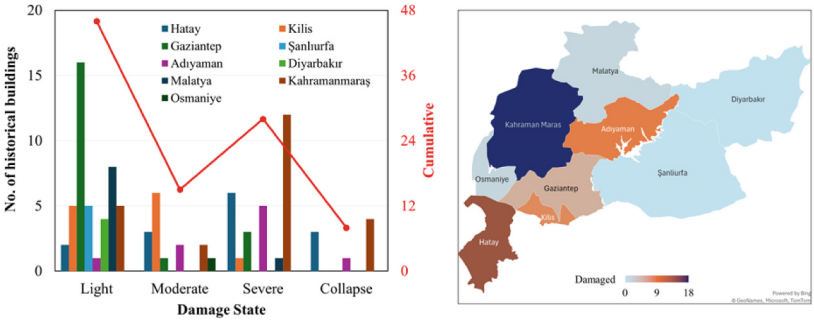


Fig. 3. Number of historical structures reported from field observation and their damage state distribution within the affected districts, adapted from [9]

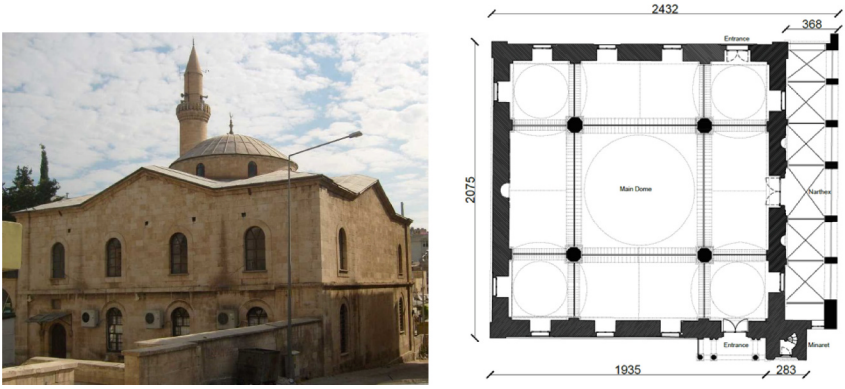
influence of local construction typologies, urban density, and proximity to the epicentral zones in determining the extent of seismic damage to heritage assets.

While high seismic vulnerability is widely accepted for historical masonry structures, certain features observed on RC buildings, particularly those that are substandard, could potentially harm the heritage assets in an urban context. Field investigations conducted in Adıyaman following the 2023 Kahramanmaraş earthquakes revealed numerous systemic deficiencies in the design and construction of reinforced concrete (RC) buildings, many of which were constructed before 2000. The vulnerability of pre-2000 RC buildings can be associated with the outdated seismic codes, poor material quality, limited regulations in construction and inspection, and socio-economic pressures that prioritised rapid urban development over structural resilience.

3 Case Study: The Adıyaman Grand Mosque

The Adıyaman Grand Mosque, situated in the city centre's historic marketplace, is believed to have originally been constructed between 1506 and 1515 during the governance of the Dulkadiroğulları period. However, the structure was entirely rebuilt in 1863, taking on its pre-earthquake form. It represents a typical example of 19th-century Ottoman Mosque architecture in an eclectic style, blending Empire and Rococo elements. Constructed by finely cut stone, the mosque features a square prayer hall crowned by a large central dome with four smaller domes at each corner, supported by barrel vaults in between. Entry was provided through three doors, north, east, and west, while the minaret, thought to be original from the Dulkadiroğulları period, rises beside the eastern entrance (Fig. 4). The structure used to preserve many of its original architectural features and decorative details [10].

Among the affected historical structures, the Adıyaman Grand Mosque, which was a historical and cultural landmark of the city (Fig. 4), suffered severe structural damage, including the total collapse of its minaret and substantial failure of the main structural system during the earthquake. The epicentral distances were approximately 120.8 km from the Mw 7.7 Pazarcık earthquake and 98.2 km from the Mw 7.6 Elbistan earthquake.



(a) (b)

Fig. 4. The Adıyaman Grand Mosque, (a) before February 6, 2023, Kahramanmaraş Earthquake Sequence [11] and (b) structural plan in mm.

3.1 Societal Impact

The Adıyaman Grand Mosque, emblematic of Ottoman-era architectural heritage, embodies the region's religious and historical identity. As a symbol of continuity across centuries of religious and local tradition, its destruction due to an earthquake signifies not only the loss of the structure but also the disruption of a historical narrative embedded in the built environment. The mosque functioned as more than a place of worship, such as a socio-cultural hub where communal practices, religious ceremonies, and educational activities were regularly held. As a central spiritual and communal space, the

mosque's collapse disrupted local religious life. In many societies, historical structures like mosques are integral to both daily life and collective memory. Reconstruction efforts must go beyond structural considerations to include the preservation of cultural and symbolic meaning. Restoration techniques must follow compatible materials and methods to ensure the authenticity of the structure. The mosque's failure reflects broader vulnerabilities in historical urban environments. This study highlights the need for integrated planning, culturally sensitive retrofitting, and seismic policy reform to safeguard heritage structures in future seismic events. The failure of the Adıyaman Grand Mosque also points to systematic vulnerabilities in preserving heritage sites within seismically active urban settings. Risk mitigation for historic structures should incorporate the urban setting and/or planning through a multidisciplinary approach. This includes the assessment of surrounding building stock, particularly to evaluate their compliance with current seismic codes, as interactions with substandard or poorly maintained structures in close proximity can escalate damage to heritage sites during seismic events.

3.2 Previous Interventions

A series of structural interventions based on the observed damage was executed before the 2023 earthquake sequence. The assessment identified two parallel forged iron ties embedded in the masonry leaf along the building's perimeter. These embedded ties were anchored by U-shaped iron frames and carved into the masonry, as illustrated in Fig. 5, played a critical role in resisting lateral forces and in helping to provide the structural integrity. However, several embedded ties had ruptured at their joints, as shown in Fig. 6a, exceeding their tensile capacity. The intervention involved reinforcing the fractured embedded ties by attaching steel plates over the joint to restore continuity in tensile strength.

Substantial cracks exceeding 1 cm in width were observed in the vaults, arches, and masonry walls, particularly above openings and in zones where the embedded ties had been damaged (Fig. 6b). These cracks were addressed using hydraulic lime-based injection, followed by external stabilisation using metal clamps, such as metal stitches. This is later proved to be effective, as post-earthquake inspections revealed no aggregation of cracks on the remaining West wall (Fig. 7).

Differential settlement was identified along the western wall, resulting in deep vertical cracking extending to the foundation, as shown in Fig. 6c. Foundation widening and peripheral drainage were recommended to reduce further differential settlement. Multiple steel tie rods were either broken or showed signs of yielding (Fig. 6d). These were replaced or retrofitted based on their condition.

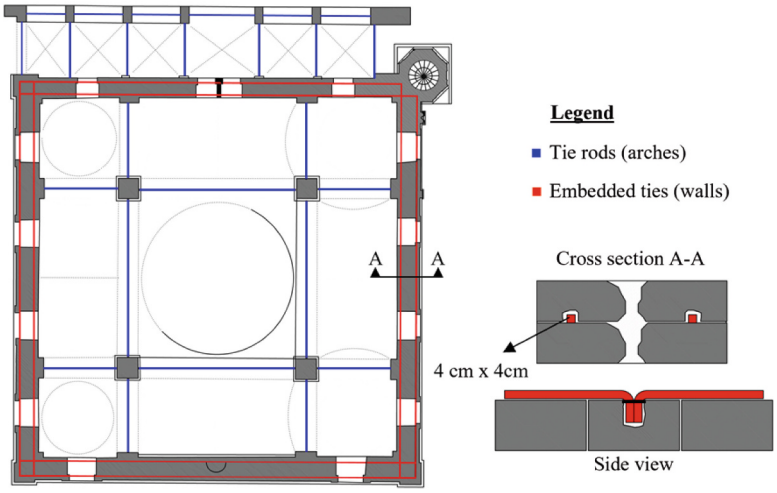


Fig. 5. Configuration of the embedded ties along the perimeter of the structure and tie rods connected at the arch spans

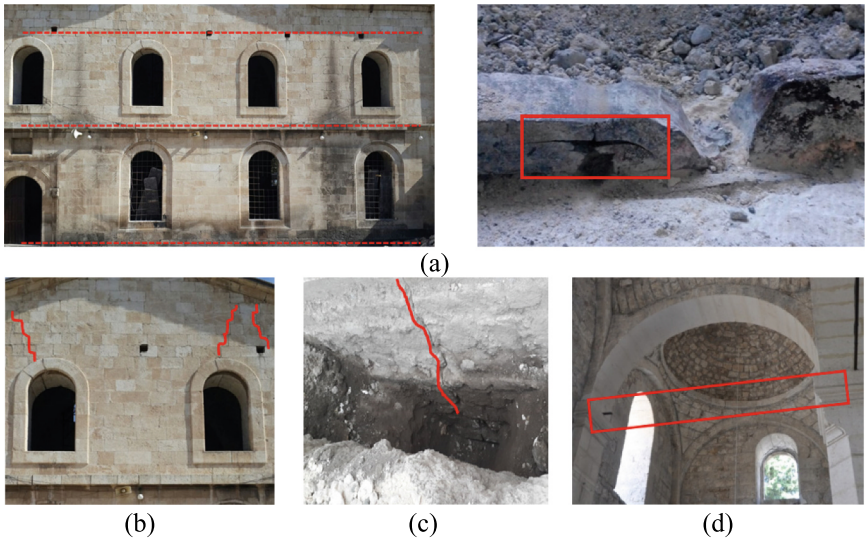


Fig. 6. Reported damage prior to the latest interventions, (a) ties embedded to stone walls and joint rupture of the embedded ties, (b) previously repointed diagonal cracks on the west façade, (c) vertical crack at the foundation due to non-uniform settlement, (d) broken steel tie rods

3.3 Failure Mechanism

The present study examines the case of the Adıyaman Grand Mosque, where the collapse of a nearby reinforced concrete (RC) building appears to have significantly contributed to the mosque's failure, as observed in Fig. 7. As shown in Fig. 1a, the distance between the collapsed RC building and the south wall of the mosque is approximately 6.7 m. The

visible debris from the adjacent multi-story building within the mosque's plot strongly suggests that additional lateral forces, debris impact, or direct structural collisions may have contributed to the failure of the mosque, beyond the effects of ground shaking alone.

A key indication of this interaction is that the building collapsed in a way that its columns were lying horizontally and oriented towards the mosque, suggesting the structure collapsed onto the historical mosque. To verify this interaction mechanism, the static plan of the RC building was examined, with particular attention to the arrangement of its vertical structural elements. It was observed that the columns, which had rectangular cross-sections, were predominantly aligned in one direction, making the structure particularly vulnerable to lateral forces toward the mosque during a seismic event. This leads to a critical research question: Would the Adıyaman Grand Mosque have remained structurally stable during the earthquake if the neighbouring building had not collapsed onto it?



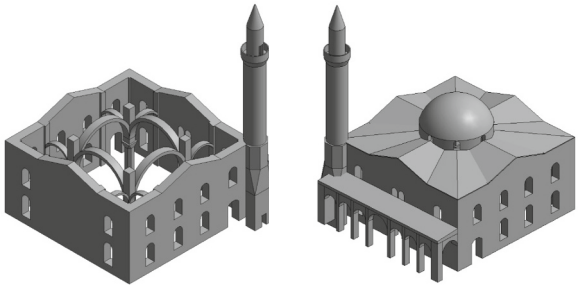
Fig. 7. Aerial view of the Adıyaman Grand Mosque (coordinates: 37°45′34.4"N 38°16′39.0"E) captured from a drone on 15 February 2023.

4 Future Work

While the seismic vulnerabilities of historical masonry structures are well-documented, the influence of neighbouring structures on their dynamic behaviour remains limited. In densely built urban settings, heritage buildings often share proximity with mid- and

high-rise constructions, yet current assessment frameworks typically treat these structures in isolation [12–17]. Existing studies mainly focus on the pounding effect where adjacent buildings collide due to out-of-phase vibrations, amplifying localised stress concentrations and progressive failure sequences [18–20].

To address this gap, future work will follow a computational investigation using the finite element method to analyse the seismic response of the Adıyaman Grand Mosque (Fig. 8). A three-dimensional model of the mosque has been developed, and nonlinear dynamic analyses will be performed under two distinct scenarios: (i) the mosque subjected to the ground motion only, and (ii) the mosque subjected to both seismic loading and the impact forces from a collapsing nearby multi-story RC building. This comparative analysis aims to answer the research question. By considering these interactions, a comprehensive approach that accounts for the broader urban context in seismic risk assessment for heritage buildings will be addressed. This research will not only contribute to the understanding of the specific failure mechanisms in this case but also will provide insights that could be applied to similar situations worldwide.



(a) (b)

Fig. 8. The 3d geometry of the Adıyaman Grand Mosque, (a) South-East, (b) North-West façade.

5 Final Remarks and Suggestions

The case of the Adıyaman Grand Mosque underscores the significant risks that historical structures face in densely built urban environments, particularly during large-scale seismic events. While intrinsic vulnerabilities in unreinforced masonry are well recognised, the added complexity of proximity to mid- and high-rise buildings introduces additional hazards, such as seismic pounding, impact loading, and progressive collapse from adjacent failures. This case highlights the urgent need to reframe seismic risk assessments for heritage buildings within an urban context. Heritage structures are rarely isolated; their behaviour during earthquakes is shaped not only by their own condition but also by the dynamic interaction with surrounding buildings. The collapse of adjacent reinforced concrete buildings, for example, can generate unforeseen loads that exceed the capacity of fragile historic masonry, accelerating or initiating failure.

Urban planning and seismic policy must therefore shift toward an integrated approach that treats heritage buildings as part of a broader, interconnected system. This includes (i) mapping the vulnerability of surrounding structures to anticipate potential interaction effects, (ii) establishing buffer zones or structural separation where possible,

(iii) incorporating seismic assessment of structures in close proximity to critical heritage assets, and (iv) ensuring that urban densification policies do not unintentionally increase seismic risk for heritage buildings. The lessons from Adıyaman contribute to a growing body of evidence that safeguarding historical structures requires not only conservation-focused strategies but also proactive urban risk management. In seismically active regions, the resilience of heritage buildings must be considered within the urban setting.

References

1. Işık, E., et al.: Kahramanmaraş earthquakes. Eng. Fail. Anal. **2023**, 151 (2023). https://doi.org/10.1016/j.engfailanal.2023.107345
2. Camileri, D., Ulu Camii, A.: https://dunyacamileri.blogspot.com/2018/03/ulu-cami-adyaman.html (2018) Accessed 2 Apr 2025
3. TRT Haber. Adıyaman'ın tarihi camileri eski ihtişamına kavuşacak (2020). https://www.trthaber.com/haber/turkiye/adiyamanin-tarihi-camileri-eski-ihtisamina-kavusacak-502620.html Accessed 2 April 2025
4. UNESCO/ICCROM/ICOMOS/IUCN. Guidance and Toolkit for Impact Assessments in a World Heritage Context (2022)
5. ICOMOS. International Charter for the conservation and restoration of monuments and sites (The Venice Charter 1964). International Congress of Architects and Technicians of Historic Monuments pp. 1–4 (1964)
6. ICOMOS. ICOMOS Turkey Architectural Heritage Conservation Charter (2013)
7. Kazaz, İ, Avşar, Ö., Dilsiz, A.: Importance of building inspection on the seismic response of a severely damaged RC structure during the February 6, 2023 Kahramanmaraş earthquake sequence. Eng. Fail. Anal. **162**, 108410 (2024)
8. AFAD. 06 Şubat 2023 Pazarcık-Elbistan Kahramanmaraş (Mw: 7.7–Mw: 7.6) Depremleri Raporu. Disaster and Emergency Management Authority, vol. 2, Ankara, Türkiye (2023)
9. Alidost, E., Özdemir, T.Z., Al Ragabi, H.Ş.: Kahramanmaraş Depreminin Türkiye'deki Tarihi Kültürel Mirasa Verdiği Zararlar hakkında. **2023** (2023)
10. Bilgin Altınöz, A.G., Neriman, Ş.G.: Adıyaman taşınmaz kültür varlıkları envanteri. Ortadoğu Teknik Üniversitesi Mimarlık Fakültesi (2018)
11. Kültür ve Turizm Bakanlığı, T.C.: Cami ve Kiliseler 2025. https://adiyaman.ktb.gov.tr/TR-165846/cami-ve-kiliseler.html Accessed 2 Apr 2025
12. Aşıkoğlu, A., Avşar, Ö., Lourenço, P.B., Silva, L.C.: Effectiveness of seismic retrofitting of a historical masonry structure: Kütahya Kurşunlu Mosque, Turkey. Bull. Earthq. Eng. **17**, 3365–3395 (2019). https://doi.org/10.1007/s10518-019-00603-6
13. Silva, L.C., Mendes, N., Lourenço, P.B., Ingham, J.: Seismic structural assessment of the Christchurch catholic basilica. New Zealand. Struct. **15**, 115–130 (2018). https://doi.org/10.1016/j.istruc.2018.06.004
14. Scacco, J., Bianchini, N., Mendes, N., Cullimore, C., Jain, L.: Seismic assessment of the church of Carmo Convent. Congresso de Métodos Numéricos em Engenharia (2019)
15. Ramírez, R., Mendes, N., Lourenço, P.B.: Diagnosis and seismic behavior evaluation of the Church of São Miguel de Refojos (Portugal). Buildings **9**, 138 (2019). https://doi.org/10.3390/buildings9060138
16. Kocaman, İ., Mercimek, Ö., Gürbüz, M., Erbaş, Y., Anıl, Ö.: The effect of Kahramanmaraş earthquakes on historical Malatya Yeni Mosque. Eng. Fail Anal. **161** (2024). https://doi.org/10.1016/j.engfailanal.2024.108310

17. Kocaman, İ.: The effect of the Kahramanmaraş earthquakes (Mw 7.7 and Mw 7.6) on historical masonry mosques and minarets. Eng. Fail Anal. **149** (2023). https://doi.org/10.1016/j.engfailanal.2023.107225
18. Tomić, I., Penna, A., Dejong, M.J.: Shake table testing of a half-scale stone masonry building. Bull. Earthq. Eng. (2022); Under subm
19. Tomić, I., Penna, A., Dejong, M.J., Butenweg, C., Correia, A., Candeias, P.X., et al.: Shake-table testing of a stone masonry building aggregate: overview of blind prediction study. Bull. Earthq. Eng. (2024)
20. Battaglia, L., Ferreira, T.M., Lourenço, P.B.: Seismic fragility assessment of masonry building aggregates: a case study in the old city centre of Seixal, Portugal. Earthq. Eng. Struct. Dyn. 1–20 (2020). https://doi.org/10.1002/eqe.3405