http://doi.org/1058225/sw.2023.2-78-88

OBSERVATIONS ON THE FAILURE MECHANISMS OF MASONRY STRUCTURES CAUSED BY THE KAHRAMANMARAS EARTHQUAKE ON FEBRUARY 6, 2023

Mercimek Omer- PhD., ass.pof. Deparment of Civil engineering, Ankara University, Turkey, omercimek@ankara.edu.tr
Erbash Yashar- PhD., research ass., Deparment of Civil engineering, Bartın University, Bartın
Salih Turker Mehmet- research ass., Deparment of Civil engineering, Ankara Yıldırım Beyazıt University, Turkey
Sercan Tuna Akkaya- research ass., Deparment of Civil engineering, Ankara Yıldırım Beyazıt University, Turkey
Ozgur Anil-PhD., prof., Deparment of Civil engineering, Gazi University, Turkey.
Kasimzade Azer– D.sc., Prof., Deparment of Mechanics, AzUAC, Baku, azer@omu.edu.tr

Abstract. In this study, the failure modes of masonry structures after the earthquake occured in Kahramanmaraş on February 6, 2023 were investigated by fieldwork. In this study, information was given about the building stock in the Turkey and the Middle East countries, and a literature including studies examining the general failure modes in masonry structures was presented. After presenting the ground acceleration data and earthquake parameters measured during the earthquake, damage distributions in historical masonry structures and masonry structures used as residences were examined. Failures were examined as out-of-plane, in-plane, and corner damages. In the examinations, it has been determined that the failure mechanisms are trigerred by unqualified wall-slab and wall-floor connections, insufficient axial load and material-strength, poor workmanship and lack of engineering service. In addition, how an earthquake resistant masonry structure could be build also discussed.

Keywords: masonry structure, out-of-plane, in-plane, corner failure, earthquake

Introduction. In Turkey, which hosts the second most active group of fault lines in the world, masonry building type is widely preferred especially in rural areas. Masonry structures, among other types of structures (reinforced concrete and steel), are the most difficult type of structure to determine their behavior under dynamic effects. Although there has been a decrease in the construction of new masonry structures in recent years, with the increase in migration from rural areas to cities in our country, it is predicted that the masonry building preference will continue in our country, at least considering the regional conditions and economic conditions in rural areas [1]. As a matter of fact, in order to make these new structures earthquake resistant, a new heading was opened for masonry building carrier systems under the influence of earthquakes in the 2019-Turkey Building Earthquake Code (2019 TBDY- Chapter-11) and very important steps were recorded for earthquake resistant masonry structure design. In addition, in order to increase the preferability of masonry buildings to a higher level, rather than being an alternative only for rural areas, considering new technological developments, masonry buildings with siege, reinforced and reinforced panel systems have been included in this new earthquake regulation, as well as traditional unreinforced masonry structures. All these important developments herald that masonry structures can be an alternative to other building types in our country, with new design criteria and technological developments, even under the influence of earthquakes. However, as expected, it cannot be said that special rules are applied for many masonry structures currently used, especially during the design and construction process, taking into account the earthquake effect. Another important issue is that many of our historical buildings are masonry structures. For this purpose, it is of great importance to determine the performance levels of existing masonry structures against earthquakes and to strengthen them quickly and economically, if necessary, either before the earthquake or in case of slight damage due to the earthquake. In the literature, it can be easily seen that most of the studies on earthquake resistant building design are on reinforced concrete and steel structure systems. This makes sense for many western countries because the usual building type in these countries is usually reinforced concrete and steel [2]. However, brick, adobe and stone masonry walls constitute the traditional building type in Turkey as well as in the Middle East and Eastern countries. Earthquakes cause collapse and loss of life in masonry buildings as well as reinforced concrete and steel structures. From this point of view, it is extremely important to understand the earthquake behavior of masonry buildings and to make such structures safe against earthquakes. During an earthquake, masonry structures can have different failure modes. A masonry wall that can carry and transfer vertical and horizontal forces without collapsing should have geometric and physical properties that allow a monolithic behavior [3]. It is thought that such a masonry wall could theoretically have two classes of failure modes, in-plane and out-of-plane, without any deterioration between brick and mortar [4-5]. Out-of-plane behavior includes tilting mechanisms, as shown in Figure 1, as well as belt-based mechanisms classified as horizontal and vertical bending mechanisms. In-plane mechanisms, on the other hand, are the mechanisms in which each wall works individually and consists of various crack patterns such as crushing, tensile, bending, diagonal shear and shear cracks, as seen in Fig. 2.

Many experimental studies modeling the in-plane and out-of-plane behavior of masonry structures under the influence of earthquakes are available in the literature [6-10]. Apart from these failure mechanisms, the corner failure mechanism is the most important failure mechanism that will occur when a masonry structure is not constrained by other adjacent structures. Although this failure mechanism is frequently observed under the influence of earthquakes, there are only a few studies [11-13] in the literature. Casapulla et al. (2018) [14] conducted an analytical study and updated the macro model approach to include frictional resistances. The most basic experimental study in the literature was conducted by Casapulla and Maione in 2020 [15].

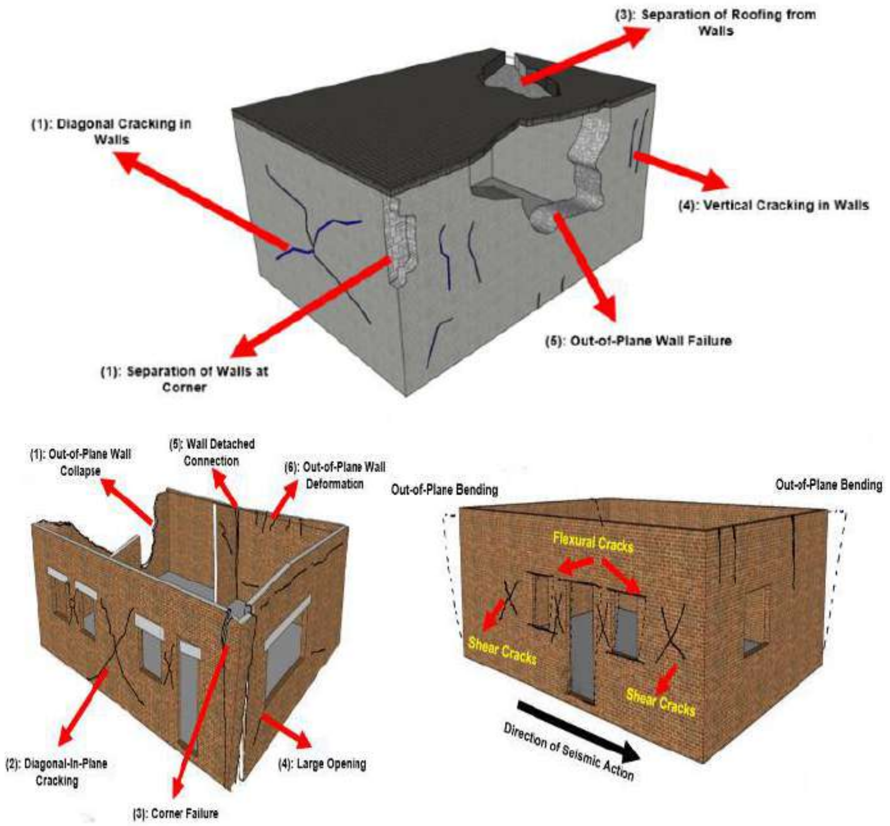


Figure 1. Common failure mechanism for masonry structures [6]

When the studies presented so far are examined, and as a result of on-site observations due to frequent earthquakes in our country, it is understood that masonry structures are frequently exposed to corner failure mechanisms under the influence of earthquakes.

Photographs of a study carried out after the Sivrice (Elazig) earthquake on February 9, 2007 are shown in Figure 2. As can be easily seen from the photographs, corner failure mechanisms are present in the masonry structures in the region.

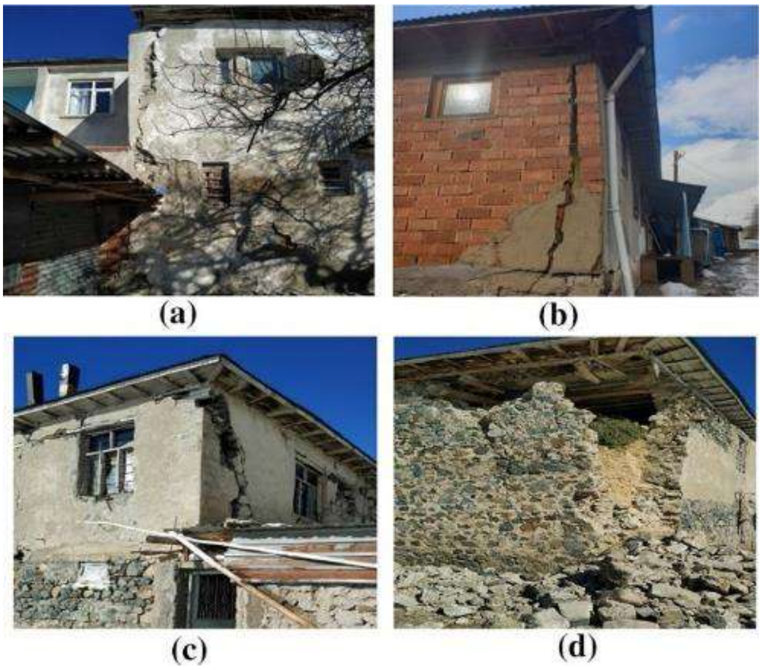


Figure 2. Corner failure mechanisms in masonry structures in the town of Sivrice [6]

On February 6, 2023, many masonry structures were damaged and destroyed in the Kahramanmaraş-centered earthquakes. Malatya is among the provinces affected by this earthquake and heavy damages were detected in the masonry structures. Within this study, the failure modes of the masonry structures in Malatya were investigated by fieldwork. During the examinations, the buildings were divided into two as historical and residential. Damages in the subject structures are considered as out-of-plane, in-plane and corner failure. Before these, Malatya-based acceleration records and parameters of the earthquake were evaluated.

6 FEBRUARY 2023 KAHRAMANMARAŞ EARTQUAKES. All of the information given in this section has been obtained from the website of the Republic of Turkey Ministry of Internal Affairs, Disaster and Emergency Management Presidency (AFAD).

The Eastern Anatolian Fault System (EAFS) forms a NE-SW left lateral strike-slip transform boundary with an average width of 30 km and a length of 580 km between the northward moving Arabian Plate and the westward moving Anatolian Block. [17-24]. It meets the westward movement of the Anatolian block together with the EAFS and the North Anatolian Fault System (NAFS), which is one of the most active and active fault systems in Turkey and forms the border between the Anatolian and Arabian Plates. EAFS starts from Karlıova junction point (Kargapazarı) in the northeast and extends as a single zone to the west of Çelikhan. The southern branch of the fault, which splits into two branches here, continues from the north of Gölbaşı Basin and Pazarcık to the Türkoğlu junction in the southwest. The fault jumping to the right in the south of Türkoğlu continues by limiting the Sağlık, Kocagöl and Amik plains from the west and ends by scattering in the south of Kırıkhan. In this part of the EAFS, the Sakçagöz and Narlı parts of the Dead Sea Fault Zone delimit the dent basin, which includes the Sağlık and Narlı plains, from the east. The Narlı part extends from the North of Pazarcık to the EAFS for 30-40 km in the NNE direction. The northern branch, which separates to the west of Çelikhan, conforms to the morphology of the Southeast Taurus Mountain Belt and forms a convex bend to the north. This branch consists of the Sürgü Fault, Çardak Fault and the Savrun, Çokak and Toprakkale faults turning SW from Göksun (Fig.3).

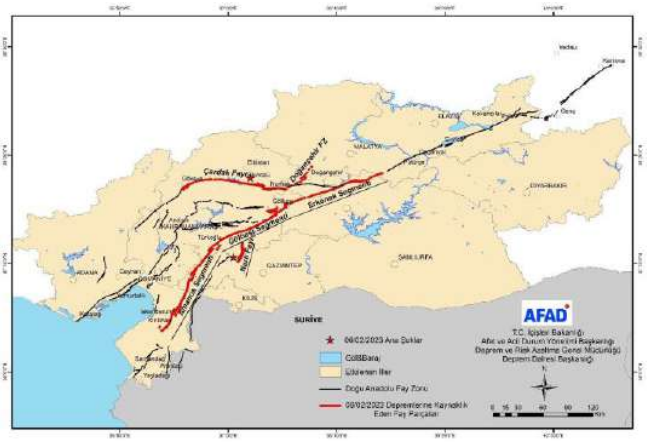


Figure 3. Map showing the fault parts of the Eastern Anatolian Fault System [6]

The Eastern Anatolian Fault System, which was the source of many major earthquakes in the historical period until the early 1900s, had a seismically active period especially in the 19th century. It created a series of earthquakes that started with the 1789 Palu earthquake, continued with the 1822, 1866, 1872, 1874, 1875, and 1893 earthquakes, and finally ended with the 1905 Malatya earthquake at the beginning of the last century. Although it seems to have entered a relatively quiet period after this earthquake, the 22 May 1971 Bingol (Ms=6.8) 5 May 1986 (Ms=5.8) and 6 May 1986 (Ms=5.6) Doğanşehir earthquakes are earthquakes by EAFS. These earthquakes are the average earthquakes produced by this fault in the last century.

A total of 13 earthquakes (Ms > 5.0) occurred that damaged the EAFS even in this period, when EAFS, which did not produce more than 7 earthquakes in the 20th century and almost forgot itself, was calmer in terms of producing large earthquakes compared to the 19th century. However, none of these were greater than Ms=6.8. The epicentral distributions of these earthquakes tend to concentrate at the boundaries of the segments.

On EAFS, which entered a more active period in the 2000s, respectively; 01.05.2003 Bingol (Mw 6.3), 14.03.2005 Karlıova Bingöl (Mw 5.8), 21.02.2007 Doğanyol Malatya (Mw 5.7), 08.03.2010 Kovancilar Elazig (Mw 6.1), 24.01.2020 Sivrice Elazig (Mw 6.8), 14.06 .2020 Karlıova Bingöl (Mw 5.7) damaging earthquakes have occurred.

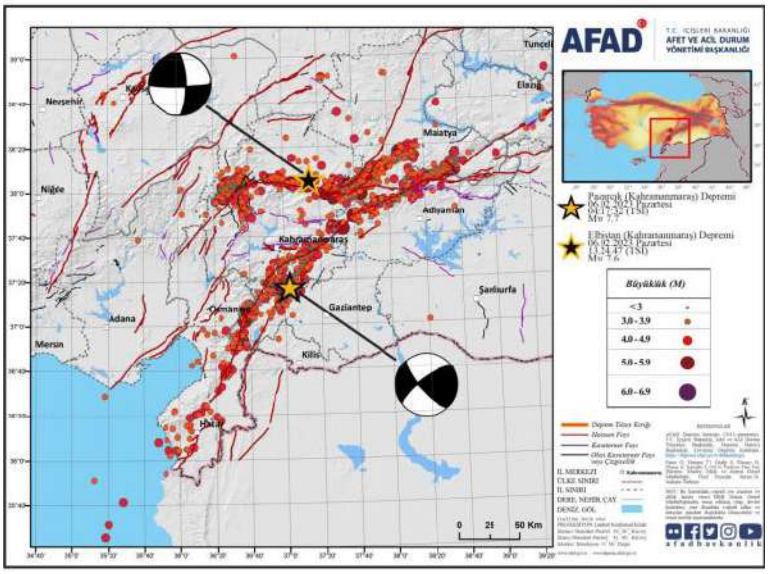


Figure 4. Map showing aftershocks activity of 06.02.2023 earthquakes [7]

On EAFS, on 06.02.2023, at 04:17 Turkey time, Pazarcık (Kahramanmaraş) Mw 7.7 and Elbistan (Kahramanmaraş) Mw 7.6 earthquakes occurred. Oludeniz Fault with a line that includes parts of the Eastern Anatolian Fault System between Çelikhan Pötürge in the northeast of the epicenter earthquake (65 km between

Çelikhan-Gölbaşı), Gölbaşı (90 km between Gölbaşı-Türkoğlu), Amanos (110 km between Türkoğlu-Kırıkhan). He broke the Pomegranate Piece at the North end of the System; The second Elbistan eccentric earthquake was thought to be related to the Çardak Fault and the Doğanşehir Fault Zone (Figure 4).

INVESTIGATION OF RECORDS FROM EARTHQUAKE STATIONS IN MALATYA WITHIN THE SCOPE OF TURKEY BUILDING EARTHQUAKE REGULATIONS. As of January 2019, a total of 1056 earthquake observation stations, 299 of which are velocity and 757 accelerometers, are operated within the body of AFAD Earthquake Deparment.

Although some stations did not work after the Mw 7.7 earthquake, which is one of the 6 February 2023 earthquakes, data were recorded in many stations in our country during the Mw 7.7 and 7.6 earthquakes. Pictures of the nearest accelerometers recording both earthquakes are given in Figure-5 and Figure-6.

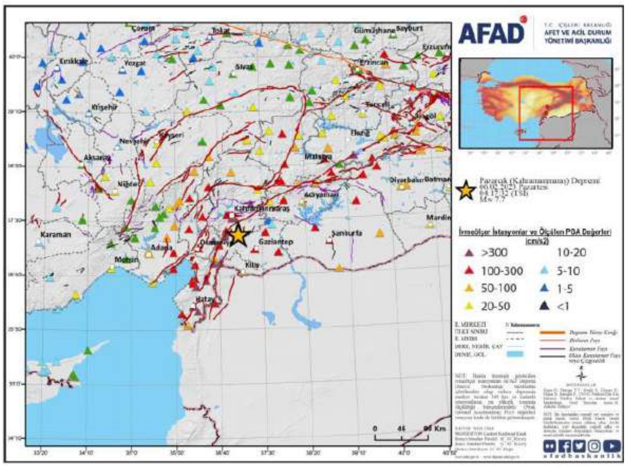


Figure 5. Distribution of nearest accelerometer stations recording the Mw 7.7 earthquake [7]

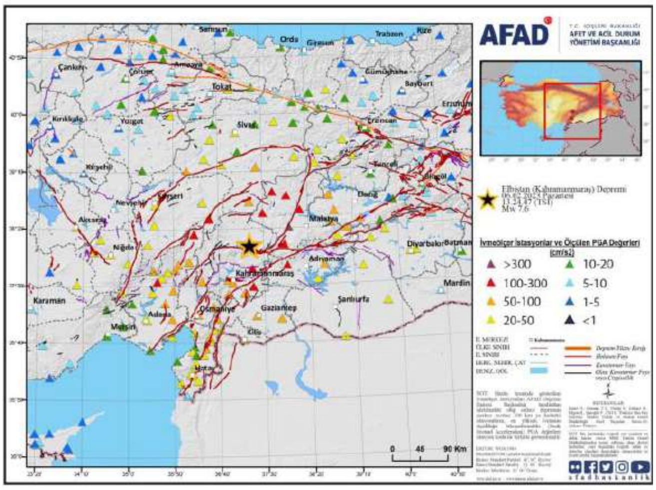


Figure 6. Distribution of nearest accelerometer stations recording the Mw 7.6 earthquake [8]

In Malatya, which is one of the provinces most affected by the Mw 7.7 and 7.6 earthquakes, data were recorded at many stations during these earthquakes. The stations closest to Malatya Center are given in Fig.7.

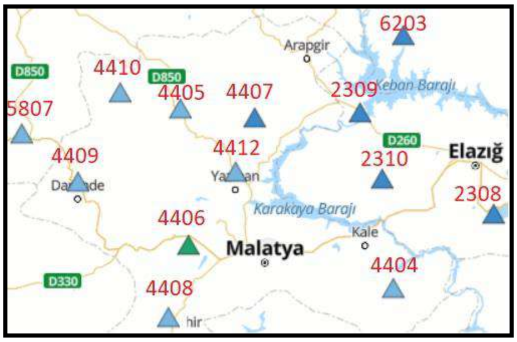
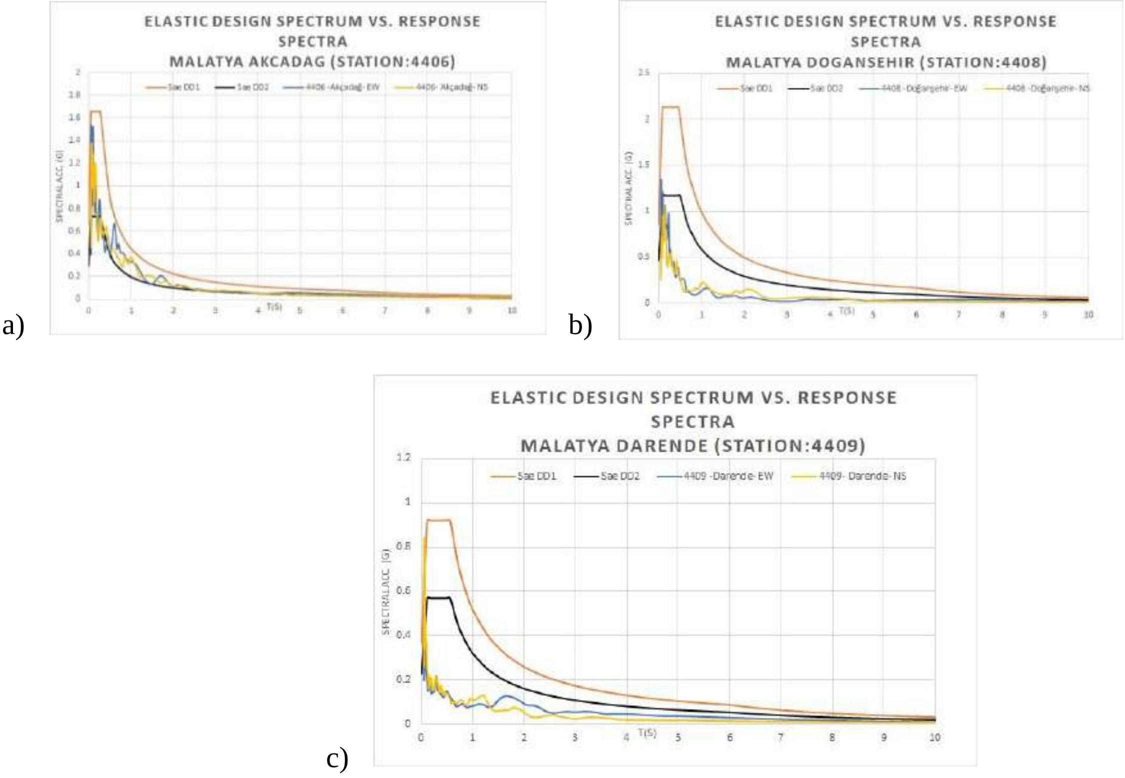


Figure 7. Distribution of accelerometer stations closest to Malatya Center [9]

The reaction spectra created according to the acceleration values received from the stations closest to the center of Malatya, the coordinates of the stations and the graphs created according to the ground are given in Fig.8. As can be seen from these graphs, the reaction spectrum of the earthquake is more than DD2 at most moments and has reached DD1 level at some moments. This is one of the reasons why the destruction of earthquakes is so great.



a)

b)

c)

Figure 8. Comparison of the response spectrum and design spectra based on the acceleration values obtained from a) 4406, b) 4408 and c) 4409 stations [10]

INVESTIGATION OF FAILURE MODES IN HISTORICAL AND PUBLIC BUILDINGS. In this section, damage modes in Taşhoran Culture and Art Center, Ulu Mosque, Sütlü Minare Mosque, Malatya Governor's Office, Yeni Mosque are examined.

Tashhoran Culture and Art Center. Damages in this structure are shown in Figure 9. A rather large arch-shaped frontal window on the entrance door has fallen to the ground. Although this is not the damage to the carrier system, considering the weight of the glass and the floor it falls on, it is seen that the connection quality of such elements is very important. In addition to this, some diagonal shear damages occurred, the largest of which was at the junction of the stone blocks forming the wall on the right front. These shear damages occurred at the mortar interface. There was no crushing or out-of-use in the carrier units.

Figure 9. Damage distrubition of Taşhoran Culture and Art Center [10]

Ulu Cami. Damages detected in the historical Ulu Mosque are shown in Figure 10. No damage that could cause collapse has been detected in the minaret, which was previously reinforced with carbon fiber textile. Local capillary mortar cracks were observed in some areas. A nearby historical minaret, which was built at the same time, was heavily damaged because no reinforcement was applied. Deep vertical cracks formed in the middle part of the minaret were detected. At the ends of these deep cracks, failure of the joint mortars due to rotation and peeling of the bricks were observed.

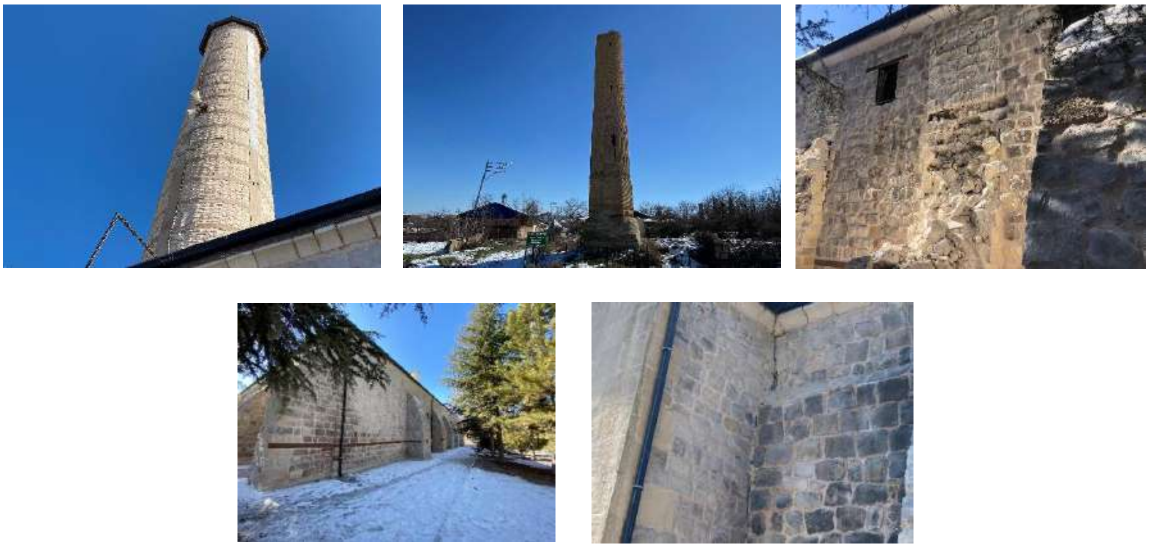


Figure 10. Damage distrubition of Ulu Cami [10]

In addition to these, collapses occurred in the regular masonry system buttresses, which were built in order to prevent possible out-of-plane collapses on the walls. There was no serious damage to all buttresses. However, while some of them had adherence losses at the junction with the main wall and local failures in the masonry overflows (left), some of them were completely destroyed. The absence of any curvature in the plane of the anchor rods driven into the main wall indicates that these rods did not hold the buttress wall sufficiently during the earthquake.

Sutlu Minare Cami. In the structure shown in Figure 11, the shear cracks starting from the minaret floor on the left progressed diagonally, causing deterioration in the wall of the arch in the middle. In addition, as examples of vertical and horizontal discontinuities, it has been severely damaged due to the irregularity of the blocks in the building and the position of the arch in the middle. In addition, the corner failure mechanism, which occurs as a result of out-of-plane behaviors, was observed.

Figure 11. Damage distribution of Sütlü Minare Cami [10]

Malatya Governor's Office. In Figure 12, the damage distribution of Malatya Governorship Building after the earthquake is given. The first image shows the typical shear damage of masonry structures, especially on the ground floors. In the wall spaces between the windows, X-shaped diagonal shear cracks formed as a result of the impulse-tensile effect. Thanks to the vertical and horizontal alignment of the gaps on the frontal and the siege beams, the cracks formed here proceeded in a controlled manner and did not result in any collapse on this frontal.

Figure 12. Damage distribution of Malatya Governor's Office [10]

As can be seen from the second image in Figure 12, diagonal shear cracks were formed in the wall part between the windows on the left and middle part of the building. In addition, linear connection cracks have formed between the masonry wall and the vertical and horizontal beams. On the right side of the building, the horizontal bending effect disrupted the vertical stability of the wall, while the vertical bending effect caused out-of-plane rotation damage in the middle part of the wall. The cracks produced by this rotational damage were combined along the wall cross-section with X-shaped diagonal shear cracks formed as a result of in-plane behavior. As a result, collapse occurred as a result of the articulation in the middle region of the wall.

From the third image in Figure 12, it was determined that typical shear cracks were formed in the wall part between the windows on the left and right of the building. The horizontal and vertical distribution of the windows and the presence of horizontal and vertical beams prevented the progression of these cracks throughout the building.

As shown in the fourth image in Figure 12, it has been determined that there are serious cracks and failures on the walls in the interior of the building. First of all, serious cracks were seen extending from the door openings to the upper floor. Quite wide and deep shear cracks developed on the left. Corner failure mechanism of the two walls and out-of-plane collapse of the right wall drew attention in the middle region. The main reason for these collapses can be i) the lack of horizontal beam application despite the rather large wall height, ii) the irregularity of the partitions such as rooms, corridors or doorways in the plan, iii) the discontinuity of the masonry walls in the interior of the building.

In the fifth image, plaster cracks, which can be considered as slightly damaged, are shown. Very thin capillary, non-progressed cracks were observed in the masonry wall opposite. In the last image, the heavy shear damage at the junction of the vertical and horizontal beams is shown. Stirrups were opened, longitudinal reinforcements yielded.

Damage distribution of masonry structures. In this section, firstly, images related to in-plane, ou-of-plane and corner failure were shared. While the in-plane damage distributions are shown in Figure 13, the images related to the out-of-plane and corner mechanisms are shown in Fig.14. In addition, examples of tie beam application preventing the failure of the entire building are shown in Fig. 15.

Figure 13. In-plane damages in masonry structures in Malatya [10]

Figure 14. Failures caused by out-of-plane movement in masonry structures in Malatya [10]

Figure 15. Examples of limiting damage in buildings using tie beams [10]

Conclusion. In the Kahramanmaraş-centered earthquake of February 6, 2023, the structures in Malatya were affected and some of them were severely damaged. One week after the earthquake, a field study was carried out in Malatya and the masonry structures were examined in detail. After the field study, the causes of damage distribution in masonry structures in Malatya can be listed as follows;

- Heavy buildings attracting large seismic forces,
- Very low tensile strength, especially in weak mortars,
- Low shear strength, especially in weak mortars,
- Brittle behavior in compression as well as in tension,
- Poor connection between walls,
- Stress concentration in window and door corners,
- General asymmetry in the plan and facade of the building,
- Asymmetry caused by the imbalance in the size and location of the openings in the walls,
- Defects in construction (substandard use of materials, unfilled joints between bricks, improper connection between walls)

References

1. N. Bayülke, “Yığma yapılar,” TMMBO İnşaat Mühendisleri Odası Ankara Şubesi, 2018.
2. R. Kanit, M. Erdal, N. S. I. Ş. Ik, and G. S. E. R. İ. Mer, “Düzlem Dışı Yüklenen Yığma Yapıların Deneysel Davranışı,” 2005.
3. D. F. D’Ayala, and S. Paganoni, “Assessment and analysis of damage in L’Aquila historic city centre after 6th April 2009,” Bulletin of Earthquake Engineering, vol. 9, no. 1, pp. 81-104, 2011.
4. N. Augenti, and F. Parisi, “Learning from construction failures due to the 2009 L’Aquila, Italy, earthquake,” Journal of Performance of Constructed Facilities, vol. 24, no. 6, pp. 536-555, 2010.
5. S. Lagomarsino, “Seismic assessment of rocking masonry structures,” Bulletin of earthquake engineering, vol. 13 no. 1, pp. 97-128, 2015.
6. B. H. Pandey and K. Meguro, “Simulation of brick masonry wall behavior under in-plane lateral loading using applied element method,” 13th World Conf. Earthq. Eng. Vancouver, BC, Canada, August, no. 1664, pp. 1–6, 2004.
7. M. Mistler, A. Anthoine, and C. Butenweg, “In-plane and out-of-plane homogenisation of masonry,” Comput. Struct., vol. 85, no. 17–18, pp. 1321–1330, 2007.
8. T. T. Bui, A. Limam, V. Sarhosis, and M. Hjiaj, “Discrete element modelling of the in-plane and out-of-plane behaviour of dry-joint masonry wall constructions,” Eng. Struct., vol. 136, pp. 277–294, 2017.
9. A. Anthoine, “Derivation of the in-plane elastic characteristics of masonry through homogenization theory,” Int. J. Solids Struct., vol. 32, no. 2, pp. 137–163, 1995.

10. D. Addessi and E. Sacco, “Enriched plane state formulation for nonlinear homogenization of in-plane masonry wall,” Meccanica, vol. 51, no. 11, pp. 2891–2907, 2016.
11. S. Nayak, and S. C. Dutta, “Failure of masonry structures in earthquake: A few simple cost effective techniques as possible solutions,” Engineering Structures, vol. 106, pp. 53-67, 2016.
12. C. Casapulla, and E. Speranza, “Definition of collapse mechanisms and seismic vulnerability of historic masonry buildings,” Earthquake Spectra, vol. 19 no. 3, pp. 479-509, 2003.
13. E. Speranza, “An integrated method for the assessment of the seismic vulnerability of historic buildings. Ph.D. Thesis”, University of Bath (UK), 2003.
14. C. Casapulla, A. Maione, L. U. Argiento, and E. Speranza, “Corner failure in masonry buildings: An updated macro-modeling approach with frictional resistances,” European Journal of Mechanics-A/Solids, vol. 70, pp. 213-225, 2018.
15. C. Casapulla, and A. Maione “Experimental and Analytical Investigation on the Corner Failure in Masonry Buildings: Interaction between Rocking-Sliding and Horizontal Flexure,” International Journal of Architectural Heritage, vol. 14 no. 2, pp. 208-220, 2020.
16. El-Maissi, A. M., Kassem, M. M., Tan, C. G., Fikri, R., & Nazri, F. M. (2022). Damage index seismic assessment methodologies of URM buildings: a state-of-the-art review. Engineering Journal, 26(1), 39-53.
17. Aksoy, E., İnceöz, M., Koçyiğit, A., 2007. Lake Hazar Basin: a Negative Flower Structure on the East Anatolian Fault System (EAFS), SE Turkey. Turkish Journal of Earth Sciences Vol.16, 2007, pp. 1-TÜBİTAK.
18. Arpat, E. ve Şaroğlu, F., 1972. Doğu Anadolu Fayı ile ilgili bazı gözlemler ve düşünceler. Maden Tetkik ve Arama Enstitüsü. Ankara ss:44-50
19. Jackson, J. and McKenzie, D. P., 1984. Active tectonics of the Alpine-Himalayan Belt between western Turkey and Pakistan. Geophysics J. R. Ast. Soc. 1984. 77, 185-264.
20. Lyberis, N. T., Yürür, T., Chorowicz, J., Kasapoğlu, E., Gündoğdu, N., 1992. The East Anatolian Fault: an oblique collisional belt. Tectonophysics 204, 1-15.
21. Nalbant, S. S., McCloskey, J., Steacy, S. and Barka, A. A., 2002. Stress accumulation and increased seismic risk in eastern Turkey. Earth and Planetary Science Letters 195 (2002) 291- 298. Elsevier P.
22. Şaroğlu, F., Emre, Ö. ve Kuşçu, i., 1992. The East Anatolian fault zone of Turkey. Annales Tectonicae, Special Issue-Supplement to volume VI, 99-125.
23. Şengör, A.M.C.,Görür, N., Şaroğlu, F., 1985. Strike-slip faulting and related basin formation in zones of tectonic escape; Turkey as a case study, in; Biddle K.T., Christie –Blick N.(Eds.), Strike-slip Faulting and Basin Formation, Soc. Econ.Paleontol. Mineral.Sp. Pub., 37,227-264.
24. Westaway, R., 2003. Kinematics of the Middle East and Eastern Mediterranean Updated. Turkish Journal of Earth Sciences. Vol.12, 2003, pp. 5-46. TÜBİTAK.

Məqaləyə istinad: Mercimek Ö., Erbaş Y., Salih T.M., Sercan T.A., Özgür A., Qasımzadə A. 6 Fevral 2023-cü il tarixdə Kahramanmaraşda baş vermiş zəlzələnin səbəb olduğu hörgü konstruksiyaların nasazlıq mexanizmləri ilə bağlı müşahidələr. Elmi Əsərlər/Scientific works, AzMİU, s. 78-88, N2, 2023
For citation: Mercimek O., Erbash Y., Salih T.M., Sercan T.A., Ozgur A., Kasımzade A. Observations on the failure mechanisms of masonry structures caused by the Kahramanmaras earthquake on february 6, 2023. Elmi Əsərlər/Scientific works, AzUAC, p. 78-88, N2, 2023

Məqalə INTERNATIONAL CONGRESS ON ADVANCED EARTHQUAKE RESISTANT STRUCTURES (AERS2023) adlı konfrans materialıdır.