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RESEARCH ARTICLE

# On the earthquake-related damages of civil engineering structures within the areas impacted by Kahramanmaraş earthquakes

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## Abstract

Two major earthquakes occurred on the Eastern Anatolian Fault Line (EAF) on February 6, 2023, with an interval of nine hours. These earthquakes, measuring Mw 7.7 and Mw 7.6, were centered in the districts of Pazarcık and Elbistan in the province of Kahramanmaraş. They directly affected 11 provinces (Kahramanmaraş, Hatay, Adıyaman, Osmaniye, Gaziantep, Şanlıurfa, Malatya, Diyarbakır, Adana, Kilis, and Elazığ) in the Eastern and Southeastern Anatolia, caused significant loss of life and property. This study aims to present the field investigation and performance evaluation of engineering structures in the mentioned cities. The types of damages occurring in the reinforced concrete (RC) and masonry buildings, historical and industrial structures, bridges, and mosques were given in detail. According to the data of the Ministry of Treasury and Finance of Türkiye, it has been reported that the cost of these earthquakes is approximately 103.6 billion dollars, which corresponds to nine percent of Türkiye's national income expectation for 2023 and causes damage and losses of approximately six times more than the 1999 Marmara earthquake. In the areas affected by earthquakes, many of the errors determined by professionals from previous earthquakes still exist today.

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## 1. Introduction

Türkiye is located at the intersection of the Eurasian, African, and Arabian plate borders. Most earthquakes in Türkiye are caused by the movement of these plates. These plates' borders have generated active fault lines in Türkiye, including the North Anatolian Fault (NAF), East Anatolian Fault (EAF), and West Anatolian Fault (WAF), and a considerable number of earthquakes have occurred near these active fault lines. These faults have ruptured frequently throughout the 30 years before the present, resulting in approximately thirty large earthquakes. According to reports, around twenty of these earthquakes have moment magnitudes greater than Mw = 6.0. Many structures were demolished or severely damaged as a result of these earthquakes, and there was a massive loss of life as well as massive economic damage [1].

During earthquakes, the performance of engineering buildings exposed to seismic impacts can be assessed more accurately than through analytical studies or laboratory experiments. After earthquakes, it becomes possible to easily examine various aspects, such as the behavior of different types of structures, damage patterns on structural components, collapse mechanisms, and soil responses, among other factors. As a result, the earthquake-related damages must be thoroughly analyzed and interpreted. Past earthquake experiences serve as significant guides in minimizing the loss of life and property in future seismic eventsCountries have changed and/or modified their earthquake codes in recent decades, thanks to scientific advances in earthquake engineering and data collected following earthquakes. Similarly, between 1923 and 2018, the earthquake codes in Türkiye underwent several changes and/or modifications.

Many papers in the literature investigate the structural damage caused by past earthquakes in various locations of Türkiye to enhance our understanding of the seismic behavior of modern structures. Bruneau and Saatcioğlu [2] and Sucuoğlu and Erberik [3] evaluated the performance of unreinforced masonry buildings during the Erzincan earthquake of 1992. They noted that non-ductile buildings, such as unreinforced masonry structures, were severely damaged or collapsed as a result of the earthquake. After the earthquake that struck Adana-Ceyhan on June 27, 1998, Adalier and Aydingun [4] investigated the damage to RC structures. They pointed out that poor building quality and design practices were responsible for a sizable portion of the damage. They further stated that the lack of consideration of local soil conditions triggered these damages. Doğangün [5] and Kaplan et al. [6] evaluated the performance of RC structures during the Bingöl earthquake on May 2003 and examined the shortcomings that caused the damages. After the earthquakes that occurred in Adana-Ceyhan on June 27, 1998, and İzmit on August 17, 1999, Çağatay [7] studied the damaged RC structures and it has been observed that the majority of building collapses or damages after these earthquakes were caused by inadequate concrete quality. Arslan and Korkmaz [8] investigated the seismic performance of existing RC structures between 1992 and 2004. They noted that inadequate structural carrying systems and poor material quality were the primary causes of collapses and damages. İlki and Celep [9] underlined that lessons learned from previous severe earthquakes in Türkiye helped to improve material and construction quality, structural design methods, and seismic regulations. Ateş et al. [10] studied the structural behavior of RC, masonry, and adobe structures in the impacted region near Van, Türkiye, following two severe earthquakes (the Erciş earthquake on October 23, 2011, and the Edremit earthquake on November 9, 2011). Atmaca et al. [1] investigated the performance of masonry and reinforced concrete buildings in Türkiye following major earthquakes between 1992 and 2020. The damage in masonry and reinforced concrete buildings were detailed at the end of the research, and also the evolution of earthquake codes through time was presented. The damage and collapses of RC buildings, masonry structures, mosques, and minarets after the Elazığ-Sivrice earthquake presented by Demir et al. [11], Günaydın et al. [12] and Atmaca et al. [13]. The damages and collapses on the structures resulted on by the Aegean Sea Earthquake and Tsunami on October 30, 2020 were studied by Altunışık et al. [14]. The types and causes of damage to the buildings were thoroughly examined, considering the requirements of the current Turkish Building Earthquake Design Code (TBEC-2018) [15] as well as earlier Turkish Earthquake Codes.

Ertürk et al. [16] and Aykanat et al. [17] investigated the reasons of the structural damage to the buildings after the earthquake that occurred in Gölyaka (Düzce) on November 23, 2022. Altunışık et al. [18] conducted field investigations in the affected areas and prepared a report. In their comprehensive earthquake report, they examined the seismic characteristics of the earthquakes and analyzed the engineering structures in the affected provinces. They also determined the factors responsible for causing damage to the structures.

On February 6, 2023, two devastating earthquakes occurred at a nine-hour interval on the Eastern Anatolian Fault Line (EAF). The Mw 7.7 and Mw 7.6 earthquakes were located in the districts of Pazarcık and Elbistan in the province of Kahramanmaraş. These earthquakes had a direct impact on 11 provinces (Kahramanmaraş, Hatay, Adıyaman, Osmaniye, Gaziantep, Şanlıurfa, Malatya, Diyarbakır, Adana, Kilis and Elazığ) in Eastern and Southeastern Anatolia, resulting in substantial loss of life and property. Lessons learned from past earthquake damage will be critical in minimizing potential future earthquake damages in these structures, so this study aims to present field investigation and performance evaluations of engineering structures in 11 different cities in that region after the earthquakes. The study provides detailed information about the types of damages observed in reinforced concrete and masonry structures, including historical buildings, industrial facilities, bridges, mosques, and so on. Furthermore, this study also examines the geotechnical and seismological evaluation of these unfortunate earthquakes.

## 2. Seismological aspects

According to the Disaster and Emergency Management Presidency of the Ministry of Interior (AFAD), two subsequent earthquakes having magnitudes of Mw 7.7 and Mw 7.6 with epicenters in Pazarcık (Kahramanmaraş) and Elbistan (Kahramanmaraş) that occurred on 6 February 2023 at 04:17 and 13:24 local time. The earthquakes were shallow-focused. The first earthquake occurred at a depth of 8.6 km, while the second earthquake occurred at a depth of 7.0 km. These earthquakes, which were felt in a large part of Türkiye, caused destruction, loss of life, and economic losses. These earthquakes, which were especially effective in the southeast region of Türkiye, caused great destruction in 11 provinces (Kahramanmaraş, Hatay, Adıyaman, Osmaniye, Gaziantep, Şanlıurfa, Malatya, Diyarbakır, Adana, Kilis and Elazığ). The closest settlement to the epicenter of the first earthquake was Pazarcık/Akdemir (2.72 km), and the closest settlement to the epicenter of the second earthquake was Elbistan/Gümüşdöven (1.70 km). Pazarcık (Kahramanmaraş) and Elbistan (Kahramanmaraş) earthquakes and aftershock activity (AFAD, 2023) [19] are given in Fig. 1.

Ground motions of the main and aftershocks in the Kahramanmaraş earthquakes were recorded at many stations operated by AFAD. According to the database of AFAD on March 6, 2023, the highest ground acceleration of the Kahramanmaraş-Pazarcık earthquake was recorded at the station coded 4614 and this value was 2.005g in the East-West component of the record. In the vertical, the highest acceleration was measured as 1.379g at the station coded 4614. The highest acceleration of the Kahramanmaraş-Elbistan earthquake was recorded at the station coded 4612 within the borders of the Göksun district of Kahramanmaraş province, which was obtained as 0.561g in the North-South component of the record. In the vertical, the highest acceleration was measured as 0.405g from the same station. Information about the stations where the highest accelerations of earthquakes were recorded is given in Table 1. The acceleration time, Arias intensities, and response spectra from some of stations 4614 and 4612 are presented in Fig. 2 and 3, respectively.

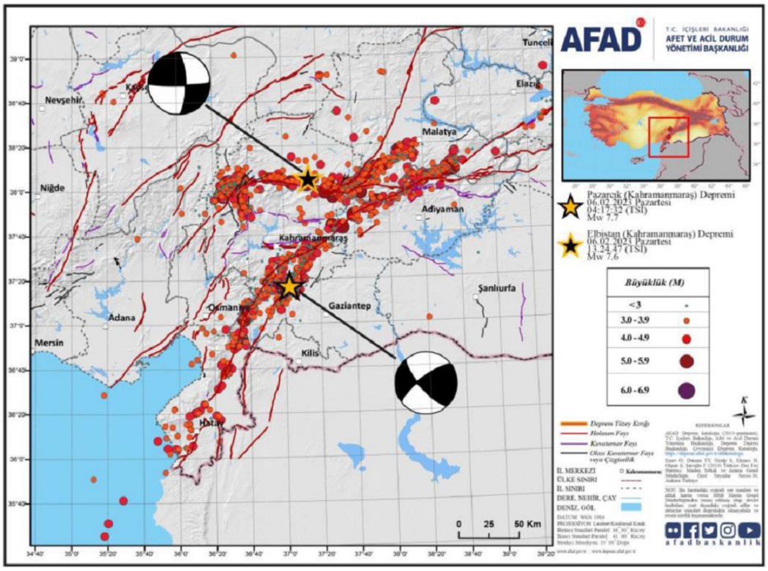



Fig. 1. The earthquakes and aftershock activity [19]

Table 1. Ground motion stations and recorded PGA values for earthquakes

| Kahramanmaraş-Pazarcık Earthquake Mw 7.7 | | | | | | | |
|---|---|---|---|---|---|---|---|
| Station Code | City | District | Latitude | Longitude | Acceleration (g) | | |
| | | | | | E-W | N-S | Vertical |
| 4614 | Kahramanmaraş | Pazarcık | 37.4851 | 37.2978 | 2.005 | 1.987 | 1.379 |
| **Kahramanmaraş-Elbistan Earthquake Mw 7.6** | | | | | | | |
| Station Code | City | District | Latitude | Longitude | Acceleration (g) | | |
| | | | | | E-W | N-S | Vertical |
| 4612 | Kahramanmaraş | Göksun | 38.0240 | 36.4819 | 0.497 | 0.561 | 0.405 |

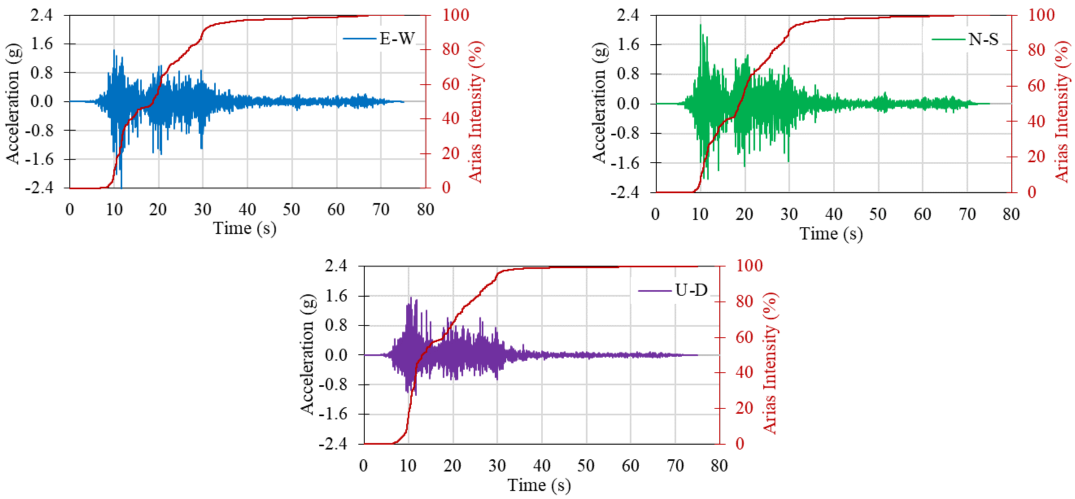



Fig. 2. Pazarcik Earthquake (Mw = 7.7), Station 4614 (Kahramanmaras/Pazarcik), Acceleration vs Arias Intensity and Response Spectra (ξ = 5%, Vs,30 = 541 m/s)

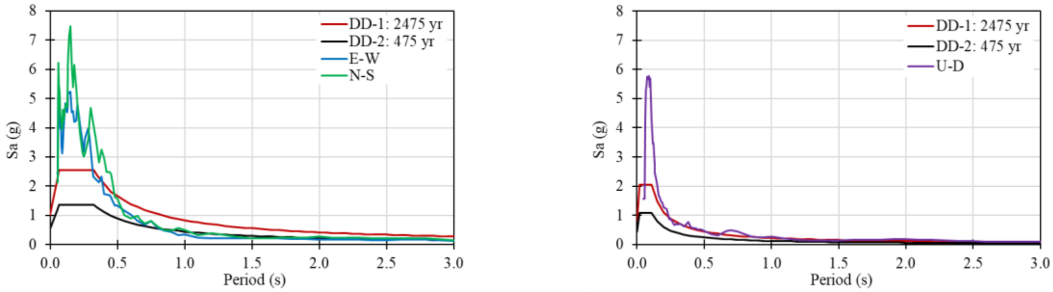



Fig. 2. Continued

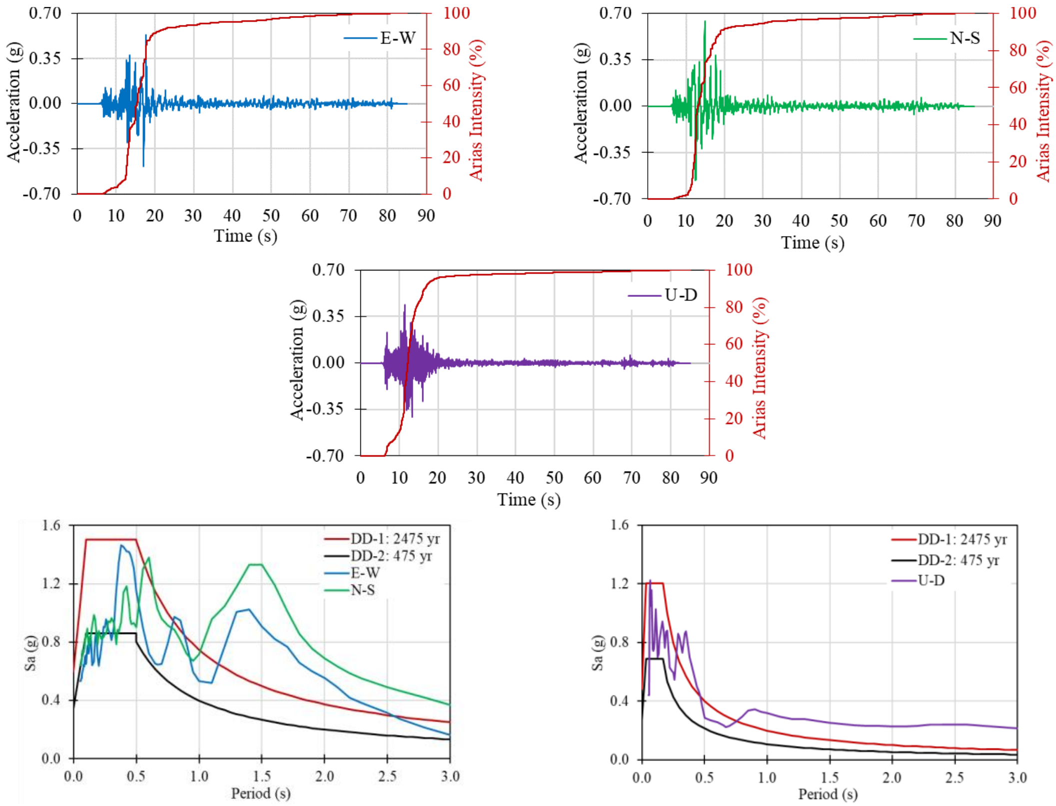



Fig. 3. Elbistan Earthquake (Mw = 7.6), Station 4612 (Kahramanmaraş/Göksun), Acceleration vs Arias Intensity, Response Spectra (ξ = 5%, Vs,30 = 246 m/s)

## 3. Soil damages

When factors such as soil conditions, lithology, thickness, and groundwater level are evaluated with ground motion, they can directly affect structural damages. Studies conducted after earthquakes have demonstrated the significance of soil characteristics in the design and construction of superstructures. In the field investigations after the Kahramanmaraş earthquakes, it was observed that the surface fractures displaced the roads and these displacements reached the dimensions that could change the land boundaries in some places. According to AFAD records lateral displacements were measured 1.4-3.0 m for the earthquake that occurred in Pazarcık and 1.8-6.0 m for the earthquake that occurred in Elbistan [18].

After the Kahramanmaraş earthquakes, typical damages due to soil liquefaction were observed widely in Gölbaşı in Adıyaman and İskenderun in Hatay. Sand cones formed in Adıyaman and İskenderun as a result of soil liquefaction are given in Fig. 4. When the soil problems occurring in these districts are examined on site, it has been determined that the common defect in Gölbaşı is not liquefaction, but the loss of bearing capacity. In terms of the formation of this district, the lake sedimentation symbolizes the dominance of soft clays in the region. Soft clays tend to soften rather than liquefy under dynamic effects. As a result, it is understood that the dominance of the situation that causes the excessive deformation of these buildings in Gölbaşı is not in liquefaction, but in the loss of bearing capacity of soft clays under dynamic loads. Uniformly seated, differentially seated, and overturned buildings occurring in Gölbaşı buildings are seen in Fig. 5.

Another ground-based damage type experienced after the 6 February 2023 earthquakes is mass movements. Mass movements are defined as processes of erosion, transport, and accumulation of material that occur on both gentle and steep slopes mainly owing to gravitational forces. The mass movements occurred in Hatay and the rock falls on the Gaziantep İslâhiye Kökçü road are shown in Fig. 6.

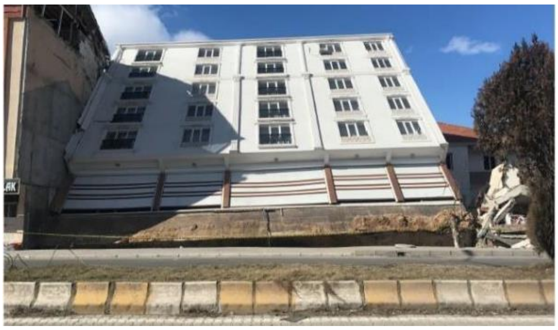
Adıyaman - Gölbaşı

Hatay - İskenderun

Fig. 4. Sand cones formed in Adıyaman and İskenderun as a result of soil liquefaction

Uniform settlement

Non-ıniform settlement



Overturn

Fig. 5. Sand cones formed in Adıyaman and İskenderun as a result of soil liquefaction

Mass movement in Hatay

Rockfall in Gaziantep

Fig. 6. Mass movement and rock fall

## 4. Damages observed in reinforced concrete buildings

After the Kahramanmaraş earthquakes, structural and non-structural damages have occurred in many reinforced concrete (RC) buildings in the provinces of Kahramanmaraş, Hatay, Adıyaman, Adana, Osmaniye, Kilis, Malatya, Şanlıurfa, Diyarbakır, Gaziantep, and Elazığ. As a result of the field investigations, the damages that occur in RC buildings are evaluated under two headings: errors made during the design and construction stages.

### 4.1. The main errors made during the design stages

Kahramanmaraş earthquakes showed that many RC buildings were damaged or collapsed because of errors made during design stages such as (i) short column, (ii) column-beam connection failures, (iii) existence of short and unconfined lap splices, (iv) inadequate safe distance, (v) insufficient transverse reinforcement, (vi) damages caused by hollow flooring application, (vii) structural irregularities, (viii) strong beam-weak column (ix) soft and weak story, (x) incorrect end hook angle, (xi) improper selection of the structural system.

One of the most crucial tasks is the selection of structural systems. The use of a regular and symmetrical structural system guarantees that applied lateral and vertical loads are transmitted to the ground as quickly as possible. Symmetry in the plan, on the other hand, will guarantee that the stiffness and mass center of the structure approach each other as much as possible, decreasing the torsion moments that will occur in the building during the earthquake.

The spaces left for lighting and ventilation in the infill walls of the buildings or the half walls made in the ground and basement floors play an important role in the formation of short columns. Since the short columns formed have high rigidity and low ductility, they are damaged by shear fracture if necessary precautions are not taken under horizontal displacements. Structural damages due to short column formation were determined in field observations (Fig. 7). Column-beam connection points of RC structures are exposed to great forces under the effect of earthquakes. Excessive stresses in these regions cause structural damage. As a result of the field observations made in the earthquake zone, the damages in the column-beam regions were observed (Fig. 8). If the overlapping length of the reinforcements is insufficient, the seismic performance of RC buildings is adversely affected. To avoid such problems, it is necessary to comply with the conditions in the codes. Details of damage due to insufficient overlap length observed are given in Fig. 9.

Fig. 7. Structural damage from short column formation

Fig. 8. Column-beam connection failures

Fig. 9. Existence of short and unconfined lap splices

Adjacent structuring is frequently encountered in Türkiye. However, if there is not enough space between these structures, horizontal movements of buildings can have destructive effects on each other (Fig. 10). The transverse reinforcements used in RC structural elements have main functions such as preventing buckling of the longitudinal reinforcements, increasing the ductility of the core concrete, increasing the compressive strength of the core concrete and meeting the shear forces. As a result of the field observations made in the earthquake zone, it was observed that the requirements given in the codes were not taken into account in the selection and placement of the transverse reinforcements, and the damages that occurred due to this reason are given in Fig. 11. A floor system consisting of evenly spaced shallow beams and a thin plate is called rib flooring. In rib flooring systems, a hollow floor system is obtained by filling the gaps between shallow beams with non-bearing building materials. They are preferred due to the reduction in mold and plaster workmanship, and the architectural advantages that allow economical and fast production. This type of flooring creates problems in terms of beam-column connection performance (Fig 12). In TBEC-2018, situations that cause irregularity in buildings are defined under two headings as irregularities in the plan and the vertical direction. Irregularities in the plan are classified as torsional irregularity (A1), slab discontinuities (A2), and projections in plan (A3), while the weak story (B1), soft story (B2) and discontinuity of the vertical elements of the carrier system (B3) are classified as vertical irregularities. The weak story damages observed in field investigation are shown in Fig.13


Fig. 10. Inadequate safe distance

Fig. 11. Insufficient transverse reinforcement

Fig. 12. Damages caused by hollow flooring application

Fig. 13. Soft story damages

## 4.2. The main errors made during the construction stages

Field observations demonstrate that errors made during the construction stage of RC buildings can cause different levels of damage. These errors are poor concrete quality, unribbed reinforcing bar and corrosion, and workmanship defects (incorrect placing of reinforcement bar, incorrect end hook angle and length, and weak gable walls)

One of the biggest factors causing damage and destruction to structures in past earthquakes in Türkiye is the low concrete quality (Fig. 14). For this reason, it is seen that the quality of concrete is gradually increasing in the codes that came into force in the following years. In TBEC-2018, which is currently in force, the minimum characteristic strength of the concrete was determined as 25 MPa. For RC, to show the expected behavior, adherence must be formed between the concrete and the reinforcements that make it up. In particular, to increase adherence ribbed reinforcements are produced. The combination of non-ribbed reinforcement and poor quality concrete causes weaker adhesion formation and adversely affects the behavior of RC (Fig. 15). Incorrect placing of reinforcement bar, incorrect end hook angle and length, and weak gable walls can be defined as workmanship defects. The damages caused by workmanship defects are given in Fig. 16.

## 5. Damages observed in masonry buildings

The masonry construction technique is a construction method that is frequently used in different parts of theworld and dates back centuries. Masonry buildings constitute a substantial part of the building stock in Türkiye. This ratio increases from the city to the countryside. In masonry buildings, almost all walls are load-bearing elements. Earthquake forces create in-plane and out-of-plane effects on these walls. In-plane (Figure 17) and out-of-plane (Figure 18) damage and/or collapse mechanisms occur on the walls due to these effects.

Fig. 14. Poor concrete quality

Fig. 15. Unribbed reinforcing bar and corrosion

The incorrect placing of the reinforcement bar    Incorrect end hook angle and length

Fig. 16. The workmanship defects

Fig. 17. In-plane damages on masonry buildings

Fig. 18. Out-plane damages on masonry buildings

## 6. Damages observed in industrial structures

Industrial buildings in the earthquake zone generally consist of prefabricated reinforced concrete systems, a small number of steel carrier systems, and small industrial structures consisting of classical reinforced concrete frame systems. In the field observation, it is seen that the majority of reinforced concrete prefabricated factories have structural damage, and a lower rate of damage occurs in a small number of steel-constructed industrial structures. Steel structures can be damaged in earthquakes due to application and design errors and not receiving adequate engineering services (Fig. 19). In prefabricated industrial structures, load transfer cannot be completed in the system because the columns on the roof are not connected with sufficient rigid elements. They are connected with articulated purlins and a rigid diaphragm is not formed. Roof beams are placed perpendicular to the long direction in industrial buildings and are supported by pin connections to the columns. Similarly, purlin beams are articulated to the roof beams with very weak pins. For these reasons, damages occurred to the roof and purlin beams (Fig. 20).

## 7. Damages observed in bridges

Bridges and viaducts are indispensable elements for transportation systems. Bridges play an important role, especially in areas such as providing transportation to the areas where destruction took place after earthquakes, the transmission of aid elements, and the evacuation of people. Commonly encountered damages in earthquakes can be listed under three headings as ground-foundation damages (Fig. 21), infrastructure damages, and joint and support damages (Fig. 22).

Fig. 19. The damages on steel industrial structures

Fig. 20. The damages on steel industrial structures

Fig. 21. Ground-foundation damages

Fig. 22. The joint and support damages

## 8. Damages observed in historical bridges

As a result of the investigations carried out in the region, no structural damage was detected in some masonry bridges, some of them were slightly damaged, while others were severely damaged. Devil (Memluk) Bridge located in Kahta District of Adıyaman separation and fractures were observed in the arch stones of the bridge. In the examination carried out in Hatay, it was determined that some of the spandrel walls of the bridge had completely collapsed and some had obvious cracks (Fig. 24).

## 9. Damages observed in mosques and minarets

Many mosques have been built with different materials, construction techniques, and architectural styles throughout history. The carrier system of many mosques consists of similar elements. The main basic structural elements of the carrier system in mosques are listed as domes, arches, vaults, pillars, and columns. It has been observed that in the mosques built with reinforced concrete and masonry technique, damages are similar to those mentioned in building-type structures in the above sections. The damages observed on RC and masonry mosques are shown in Fig. 25 and Fig. 26, respectively. Most of the mosques in Türkiye have minarets and there is no regulation in force regarding the design of these structures. This situation causes these structures to be built without technical requirements and restrictions, and to be damaged or even completely collapsed under dynamic loads such as wind and earthquake. The demolition of minarets causes damage to mosques and nearby structures and even loss of life. The damages observed on RC and masonry minarets are shown in Fig. 27 and Fig. 28, respectively.

Fig. 23. Damages observed on Devil (Memluk) Bridge

Fig. 24. Observed collapsed and cracks of the spandrel wall

Fig. 25. Observed damages on reinforced concrete mosques

## 10. Conclusion

On February 6, 2023, two major earthquakes occurred on the Eastern Anatolian Fault Line (EAF). The Mw 7.7 and Mw 7.6 earthquakes were located in the districts of Pazarcık and Elbistan in the province of Kahramanmaraş. These earthquakes directly damaged 11 provinces in Eastern and Southeastern Anatolia (Kahramanmaraş, Hatay, Adyaman, Osmaniye, Gaziantep, Şanlurfa, Malatya, Diyarbakır, Adana, Kilis, and Elazığ), causing substantial loss of life and property. The goal of this study is to give field investigation results and performance evaluations of engineering structures in the 11 different cities affected by earthquakes. The results obtained within the scope of the study are given below:

- It is seen that buildings constructed before a specific period (2000s), in particular, are not resistant to earthquakes.
- It is revealed that the building damage types and formation mechanisms detected after the devastating earthquakes that have occurred in Türkiye since 1992 are almost the same.
- The main causes of damage in reinforced concrete buildings are (i) inadequate concrete quality, (ii) use of non-ribbed (flat) reinforcement, (iii) construction on unsuitable soil, (iv) design of the carrier system as hollow slab, (v) using of heavy cantilever, and (vi) stores/shops with higher story heights on the lower floors of the buildings.

- The main causes of damage in masonry buildings have been identified as (i) insufficient material properties of binders and masonry units, (ii) weak bearing walls due to lack of beam and lintel, and (iii) inappropriate connection details.
- Damages developed and progressed due to poor workmanship and a lack of application details in reinforced concrete and masonry constructions.
- It is determined that proper restoration works have not been carried out on our historical structures.

Fig. 26. Observed damages on masonry mosques

Fig. 27. Observed damages on reinforced concrete minarets

Fig. 27. Continued

Fig. 28. Observed damages on reinforced masonry minarets

## Conflict of interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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## Data availability statement

No new data were created or analyzed in this study.

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