Natural Hazards (2025) 121:873–909
https://doi.org/10.1007/s11069-024-06859-9

ORIGINAL PAPER

Evaluation of the seismic response of reinforced concrete buildings in the light of lessons learned from the February 6, 2023, Kahramanmaraş, Türkiye earthquake sequences

Burak Yön[1] · İbrahim Özgür Dedeoğlu[2] · Musa Yetkin[3] · Hakan Erkek[4] · Yusuf Calayır[5]

Received: 13 May 2024 / Accepted: 30 July 2024 / Published online: 7 August 2024
© The Author(s) 2024

Abstract
On 6 February 2023, two significant seismic events occurred in the southeastern region of Türkiye. The seismic activity, which was perceptible in numerous countries beyond Türkiye, resulted in a considerable number of fatalities. A considerable number of individuals lost their lives and were rendered homeless as a result of the disaster. Two of the most significant factors contributing to the occurrence of these tragedies are the magnitude of the earthquake and structural deficiencies. The present study is concerned with a detailed analysis of these two factors. This study initially considers the seismicity of the region where the earthquakes that occurred on 6 February 2023 took place, as well as the seismic characteristics of these earthquakes. Subsequently, the findings of the field studies conducted in Hatay, Adıyaman, Kahramanmaraş and Malatya, the cities where the earthquakes caused the most destruction, are presented. The objective of the field study is to ascertain the collapse patterns, structural damages and the factors influencing these damages in reinforced concrete structures in the region. The primary causes of damage to structures can be attributed to several factors, including the presence of a strong beam-weak column mechanism, the soft story-weak story mechanism, the pounding effect, the short column damage, the long cantilever and overhangs, the short beam damage, the buckling damage, the torsion effect, the quality of the materials, the insufficient transverse reinforcement, the compressive failure due to over-reinforcement, the corrosion effect, the damage to reinforced concrete shear walls, the infill wall damage, and the damage caused by the soil and foundation system. These causes have been evaluated and recommendations have been formulated to prevent structural damage.

Keywords 6 February 2023 earthquakes · Seismic characteristics · Seismicity of the region · Reinforced concrete buildings · Field study · Structural damage

Extended author information available on the last page of the article

1 Introduction

Natural disasters have been a great threat to societies in the past. The most devastating of these threats is earthquakes. Earthquakes occur naturally due to plate movements but also occur artificially. Earthquakes cause serious loss of life and property in regions with negative conditions such as weak soil conditions, weak building stock, and improper workmanship. The loss of life and property following earthquakes causes great losses in the country's economy and social trauma. States and societies need to be constantly prepared for this earthquake danger. These preparations are carried out in many ways. Some of these include preventing construction in areas with risky soil class and close to faults, or ensuring that construction is carried out by taking important precautions and strengthening or reconstructing risky building stock. In addition, the design and construction of new buildings are carried out by the current earthquake regulations.

After the earthquake, it was observed that many buildings survived the earthquake with good performance thanks to the designs made by the earthquake regulations. Therefore, it is very important to design structures appropriately. However, correct design is only possible by understanding what kind of damage the earthquake causes to the structures. Heavy experiences of the past contribute to the development of earthquake-resistant building designs and, accordingly, cause earthquake regulations to be constantly updated. Thus, codes for the design principles of more durable structures are determined.

Field studies after earthquakes provide valuable data in many aspects. Some of these are to determine and analyse the type/size of damage, to determine the intensity and distribution of damage, to assess regional and local structural risks, to provide planning and emergency planning for possible new earthquakes, to understand what type of retrofitting methods are needed in which types of buildings, to develop suggestions for the construction of new structures with high earthquake performance, and to develop new recommendations/updates for earthquake codes. Conducting a field study after earthquakes is like evaluating the results of a large experimental study carried out in an earthquake laboratory. It is a very difficult and costly process to learn the earthquake behaviour of real structures in a laboratory. However, for earthquakes occurring on the earth, determining and evaluating the performance of structures does not require researchers to do this difficulty and cost. Therefore, it is very valuable. The most important thing that researchers should do is to evaluate the earthquakes occurring in the earth laboratory with their knowledge and experience and to determine their effects on the performance of the structures. Many studies present the results of field studies carried out to determine the performance of structures after earthquakes and the solution proposals developed in light of these results. Here, some of the studies on a field study conducted by researchers will be mentioned.

Yön et al. (2013) conducted a field study after the earthquake that occurred in the Simav district of Kütahya on 19 May 2011 and evaluated the damage causes and collapse mechanisms of reinforced concrete and masonry buildings.

After the 23 October 2011 and 9 November 2011 Van (Türkiye) earthquakes, many researchers conducted field studies. Yön et al. (2015) identified the main reasons for heavy damages as low quality of structural materials, lack of engineering services, inappropriate design and construction with insufficient detailing of the structural elements. Bayraktar et al. (2013) found that 26% of the damaged building stock did not have a building license, 36% did not have a static project, 57% had an inadequate static project and the majority of the buildings (85%) did not have any soil report. Çelebi et al. (2013) stated that the earthquake spectra calculated with the records taken from the near-site station are well below the

design spectra given in the national code and that the damages in the structures are therefore caused by the designers not taking into account the design code or the constructers not constructing the structures as designed. Taşkın et al. (2013) stated that extensive liquefaction triggered lateral spread, landslide, and slope failures occur in non-residential areas and that one of the main reasons for heavy damages in Erciş was soil amplification. Yön et al. (2019) found that many infill and partition walls of reinforced concrete buildings were not designed according to engineering requirements. Ateş et al. (2013) found that aftershocks also caused progressive damage to the buildings within 17 days after the earthquakes.

After the 24 January 2020 Elazığ (Türkiye) earthquake, many researchers conducted field studies and obtained valuable findings. Atmaca et al. (2020) determined that a significant part of collapsed and damaged mosques and minarets did not receive adequate engineering services and/or were constructed without following national guidelines. Çağlar et al. (2023) and Sayın et al. (2021) stated that many structural insufficiencies and errors such as non-seismic reinforcement detailing, non-conforming earthquake-resistant construction techniques, poor quality of concrete, and poor workmanship in buildings cause damage. Dedeoğlu et al. (2022, 2023) identified the causes of damage to reinforced concrete structures and the types of damage in masonry buildings discussed the causes of these damages. They presented some retrofitting methods to improve the performance of masonry buildings with poor seismic performance against future earthquakes. Yetkin et al. (2020) identified the sections of damage to minarets in Elazığ province and assessed the causes of this damage. At the end of the study, they made some recommendations for the repair and strengthening of existing damaged minarets and the construction of new minarets. Doğangün et al. (2021) presented damage evaluation and identification for the damages observed in the earthquakes in the eastern region of Türkiye and suggested possible solutions.

After the 6 February 2023 earthquakes, one of the largest earthquakes of the twenty-first century, many researchers conducted field studies. Altunsu et al. (2024) encountered various problems in their research for reinforced concrete buildings and steel structures. Some of these problems are insufficient shear reinforcement, neglect of corrosion, utilizing low-quality concrete, insufficient development length in flexural reinforcement, and strong beam-weak column failure. Altunışık et al. (2023) emphasized the importance of complying with the regulations, conducting the performance evaluations and controls of the buildings according to the renewed earthquake regulations, and if necessary, repairing-strengthening works as a result of their field observations. Atmaca et al. (2023, 2024) presented a field investigation of engineering structures and found that many of the errors determined by professionals from previous earthquakes still exist today in the areas affected by earthquakes. Avcıl et al. (2024) observationally evaluated the effects of earthquakes on soil, reinforced concrete, masonry, prefabricated, and other structural systems. As a result of geotechnical and structural investigations conducted in various provinces, Demir et al. (2024) determined that reinforced concrete structures were damaged due to common reasons such as poor material quality, poor workmanship, unsuitability of reinforcement detailing, and inadequate earthquake-resistant construction techniques, and prefabricated concrete and masonry structures were damaged due to common reasons such as inadequate engineering service, poor materials, deficiencies during construction. Erkek and Yetkin (2023), and Coşgun (2023) investigated the performance of historical structures after the 6 February 2023 earthquakes. Hacıefendioğlu et al. (2024) focused on the identification of collapsed buildings through deep learning-based image segmentation models using satellite images from a region covering the eleven provinces in the south and southeast of Türkiye that were most affected by the Mw 7.7 Pazarcık (Kahramanmaraş) and Mw 7.6

Elbistan (Kahramanmaraş) earthquakes. Hussain et al. (2023), in their preliminary assessment for earthquakes, state that we can mitigate the risk of a future tragedy by addressing the issues of exposure, corruption, and poverty through strong governance mechanisms, and by ensuring universal access to good quality homes built to regulations that are tailored to the local seismic hazards. İnce (2024) stated that the earthquake codes were overlooked in the reinforcement details of reinforced concrete buildings in Adıyaman province and that the damages caused by the design errors made by the designers were very common. Işık et al. (2023; 2023) identified the collapse and failure mechanisms of existing unreinforced masonry buildings and 27 masonry and reinforced concrete mosques and minarets in rural Adıyaman province and the causes of structural damage. Işık (2023) determined the main causes of failure and collapse mechanisms of adobe structures and presented some suggestions for the prevention of structural damage in the adobe structures in the earthquake region. Kahya et al. (2024) pointed out the possible reasons for damage to masonry buildings and performed numerical simulations of a historical building in Hatay. At the end of the study, they presented some retrofitting proposals to assist the authorities in charge of the reconstruction and rehabilitation programs to better the interpretation and understanding of the seismic performance of masonry buildings. Kocaman (2023) determined that dome collapses and carrier wall damages in the historical mosques, and damages in the transition sections and spire parts of the minarets in the region, were concentrated. Mercimek (2023) and Onat (2024) presented the damage observed in masonry structures and made some suggestions for strengthening methods that can be used in masonry structures. Nemutlu et al. (2023) aimed to evaluate the actual losses by using the methodology used in the loss assessment study, which can predict losses due to earthquakes. Nemutlu et al. (2021), investigated structural damage conditions in reinforced concrete and masonry structures and expressed that they observed many structural deficiencies and mistakes such as non-ductile details, poor concrete quality, short columns, strong beams-weak columns mechanism, large and heavy overhangs, masonry building damages and inadequate reinforcement arrangements. Ozkula et al. (2023) conducted a general field study of residential structures, bridges, schools, hospitals, and places of worship, building foundations, earth dams, harbours, lifelines, ports, deep excavations, and retaining structures, and presented the damage they observed in these structures. Öztürk et al. (2023a) stated that the effects of design and application mistakes are quite high in the heavy destruction caused by earthquakes and that the earthquake code design criteria and requirements are insufficient in some regions. Öztürk et al. (2023b) investigated the damage types in various public-school buildings and discussed the causes of this damage. Öztürk et al. (2024) presented the results of their comprehensive assessments for various categories of structures, including liquid storage tanks, silos designed for the storage of grain-like materials, prefabricated reinforced concrete structures, and low-rise steel industrial buildings. Pujolet al. (2024) investigated 250 damaged reinforced concrete buildings, the majority of which were constructed in the last 10 years. Qu et al. (2023) presented the results of an assessment of the damage they observed in five base-isolated and seven fixed-base hospital buildings. Wang et al. (2023) stated that although a large number of buildings (in Hatay) were severely damaged to collapse, the majority of buildings in areas of extreme shaking were lightly or moderately damaged, which implies that well-designed and constructed buildings were able to survive and protect human lives even in over-design earthquakes. Vuran et al. (2024) presented a carefully selected set of examples comparing the pre-2000 and post-2000 building damages and collapses, and also made a detailed comparison of the code developments in Türkiye.

This paper presents the results of a comprehensive field study conducted by various researchers in the most affected provinces immediately after the 6 February 2023 earthquakes. Firstly, the tectonics of the region and the seismic characteristics of the 6 February 2023 earthquakes are introduced. Then, the damages observed in reinforced concrete structures during the field studies are presented and an assessment is made for these damages. At the end of the study, intervention strategies and retrofitting recommendations for existing damage are provided, as well as information on how to prevent similar damage in possible earthquakes.

2 Tectonics and seismicity of the region

Türkiye is in the Mediterranean earthquake zone, comprising the African, Arabian, Anatolian, and Eurasian plates. The colliding of African and Eurasian plates has caused complex deformations that can be seen in the form of both horizontal and vertical thrust faults. The North Anatolian Fault Zone (NAFZ), the East Anatolian Fault Zone (EAFZ), and the West Anatolian Stress Structure are the three main formations that govern seismic activity and hazards in Türkiye within this tectonic plate configuration (Fig. 1) (Bozkurt 2001). These formations have produced numerous earthquakes at their boundaries throughout history. Figure 2 illustrates the seismic activity that has occurred on these boundaries over the past century.

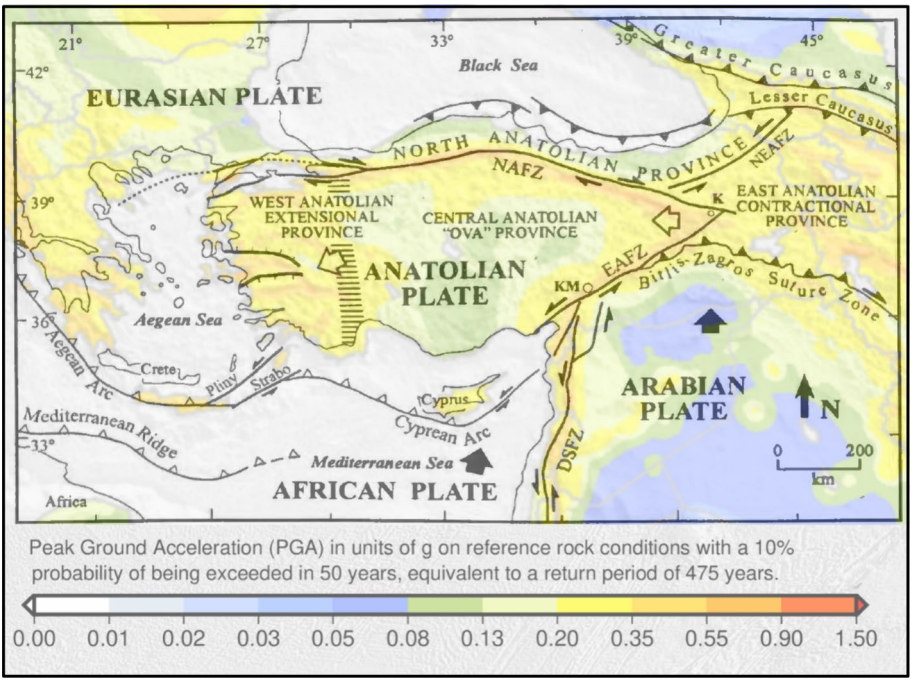


Fig. 1 Simplified tectonic map of Türkiye and Global Seismic Hazard Map (adapted from (Bozkurt 2001) and (Global Earthquake Model Foundation Accessed:13.03.2024))

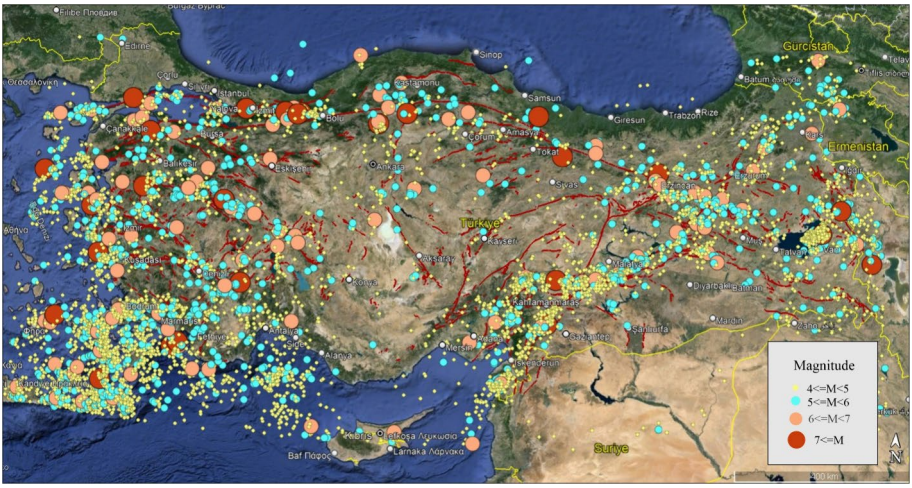


Fig. 2 Earthquakes in Anatolia, 1900–2023 (Active fault taken (Mineral Research and Exploration General Directorate 2019) and Earthquake data taken from (US Geological Survey, Earthquake Lists, Maps, and Statistics Accessed: 13.03.2024))

The EAFZ represents a left-lateral strike-slip fault zone, measuring approximately 30 km in width and 580 km in length, situated between the eastern Turkish Arabian and Anatolian plates (Kürçer 2023; Parlak et al. 2023). The EAFZ zone is located between Karlıova (Bingöl) in the northeast and Karataş (Adana), Samandağ (Hatay) in the southwest (Fig. 3). According to Duman and Emre (2013), the EAFZ is represented by a simple fault trace between Karlıova and Çelikhan and splits into two branches, the northern and southern branches, south of Çelikhan. On the southern branch, which is the main line of the EAFZ, seven segments, namely Karlıova, Ilıca, Palu, Pütürge, Erkenek, Pazarcık, and Amanos, were identified (Fig. 3). The Amanos Segment was ruptured during the 6 February 2023 Pazarcık (Kahramanmaraş) Earthquake (Mw = 7.7) (Kürçer 2023). The northern branch extending between Çelikhan and Karataş¸ districts and expressed by Sürgü, Çardak, Göksun, Savrun, Çokak, Toprakkale, Yumurtalık, Karataş, and Düziçi-Osmaniye segments is called the Sürgü-Misis fault system. It is approximately 380 km long (Fig. 3). On 6 February 2023 Elbistan (Kahramanmaraş) earthquake (Mw = 7.6) occurred on the Çardak fault (Parlak et al. 2023).

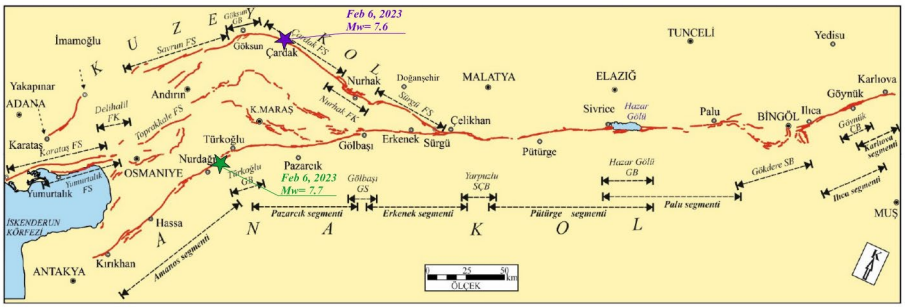


Fig. 3 Segments of EAFZ and Kahramanmaraş earthquakes (adapted from (Duman and Emre 2013))

3 Seismic characteristics of the earthquakes

The earthquakes that occurred on 6 February 2023 have been identified as the most tragic and distinctive seismic events of the past century. This assessment is based on several factors, including the geographic extent of the quakes, their magnitude, the absence of any consecutive earthquakes of this magnitude in recorded history, and the extensive damage they caused. The characteristics of these destructive earthquakes, as identified by various international organizations, are presented in Table 1. The magnitude of the first earthquake was 7.7–7.8, and the magnitude of the second earthquake was 7.5–7.6. The magnitudes of the earthquakes were found to be quite close to each other. Nevertheless, this proximity could not be attained due to the magnitude of the seismic event, which ranged between 5 and 20 kms in depth.

The seismic activity, which included a series of powerful earthquakes and their subsequent aftershocks, had a direct impact on 11 provinces in the southeastern region of Türkiye. These provinces include Adana, Gaziantep, Kilis, Osmaniye, Hatay, Kahramanmaraş, Adıyaman, Malatya, Elazığ, Diyarbakır, and Şanlıurfa. It is estimated that approximately 15 million people reside in these affected areas (Fig. 4). A considerable number of lives were lost, and there was extensive structural damage. Furthermore, the severe earthquakes and their aftershocks resulted in the irreparable loss of infrastructure and natural resources.

The time histories of the acceleration record components recorded in the horizontal and vertical directions at station 4614 (Pazarcık) for the Pazarcık (Kahramanmaraş) earthquake and at station 4612 (Göksun) for the Elbistan (Kahramanmaraş) earthquake are presented in Fig. 5. The velocity and displacement records derived from the aforementioned acceleration records are presented in Figs. 6 and 7.

In the case of the Pazarcık (Kahramanmaraş) earthquake, the maximum values recorded for acceleration, velocity, and displacement in the horizontal direction were 2.006 g, 81.95 cm/s, and 23.23 cm, respectively. The aforementioned values were recorded as 0.6406 g, 170.78 cm/s, and 23.23 cm for the Elbistan (Kahramanmaraş) earthquake. Conversely, the maximum acceleration in the vertical direction was calculated as 1.379 g, the maximum velocity as 32.87 cm/s, and the maximum displacement as 17.32 cm. The aforementioned values were measured as 0.439 g, 55.95 cm/s, and 35.73 cm for the second earthquake. It is noteworthy that the maximum vertical acceleration of the initial

Table 1 The characteristics of earthquakes according to various institutions

Stations	First earthquake				Second earthquake			
	Magnitude (M_w)	Depth (km)	Longitudinal	Latitude	Magnitude (M_w)	Depth (km)	Longitudinal	Latitude
DEMA	7.7	8.6	37.06	37.24	7.6	7.0	38.09	37.24
KOERI	7.7	5	37.12	37.11	7.6	5.5	37.21	38.07
USGS	7.8	10	37.02	37.22	7.5	15.0	37.21	38.02
GFZ	7.7	10	37.05	37.23	7.6	15	37.23	38.11
EMSC	7.8	20	37.08	37.17	7.5	10	37.24	38.11

KOERI, Kandilli Observatory and Earthquake Research Institute; DEMA, Turkish Ministry of Interior Disaster and Emergency Management Agency; USGS, United States Geological Survey; EMSC, European-Mediterranean Seismological Centre; GFZ, German Research Centre for Geosciences

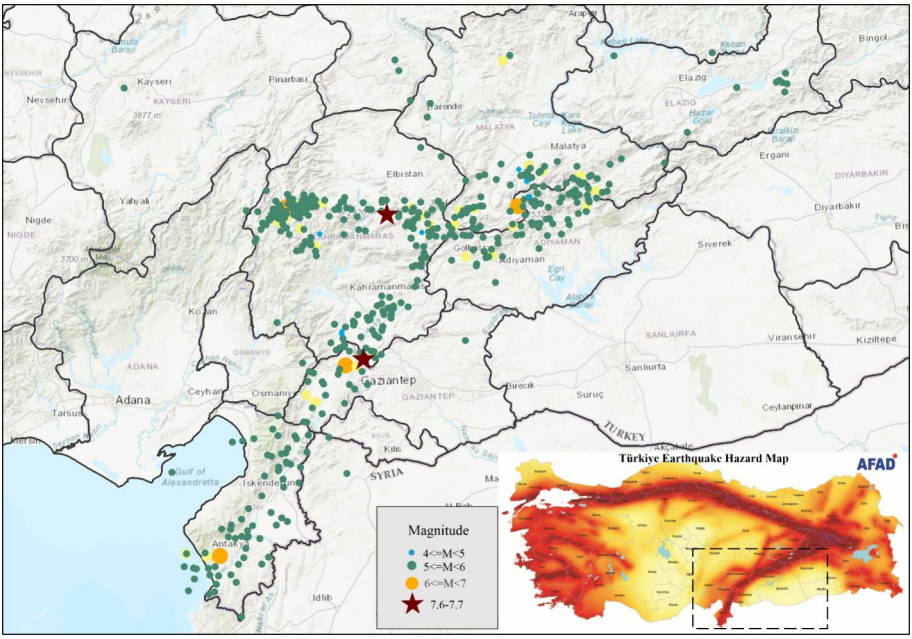


Fig. 4 6 February 2023 earthquakes epicentres and their aftershocks (Earthquake data taken from (DEMA, Accessed: 13.03.2024) and seismic hazard map (Disaster and Emergency Management Authority 2018)

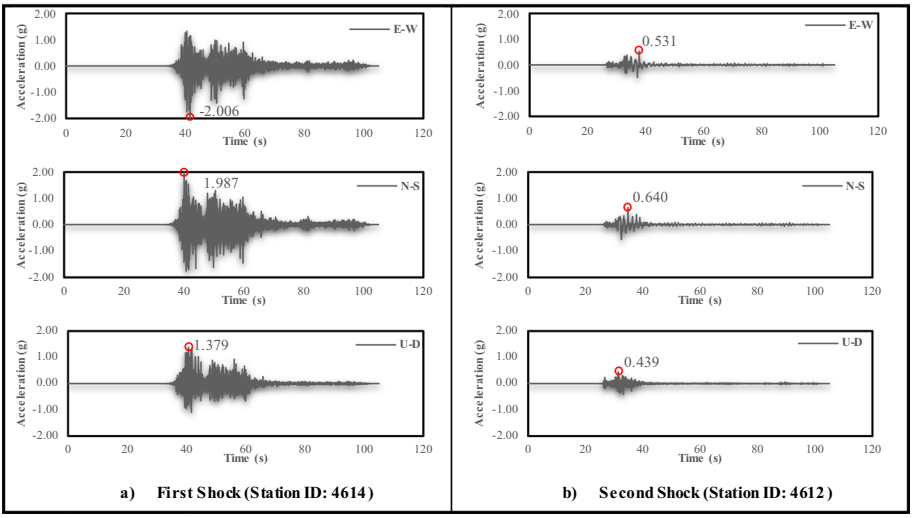


Fig. 5 Acceleration records of the Kahramanmaraş earthquakes (Disaster and Emergency Management Authority 2023)

seismic event exceeded the acceleration of gravity by 37.9%. The aforementioned magnitudes indicate that the earthquakes were effective in both the horizontal and vertical planes. A comparison of the two earthquakes, whose moment magnitudes are similar,

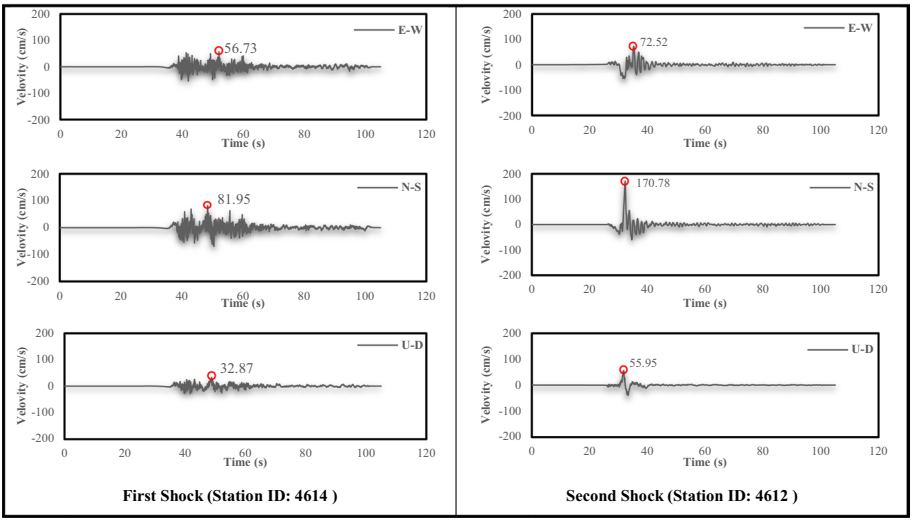


Fig. 6 Velocity records of the Kahramanmaraş earthquakes (Disaster and Emergency Management Authority 2023)

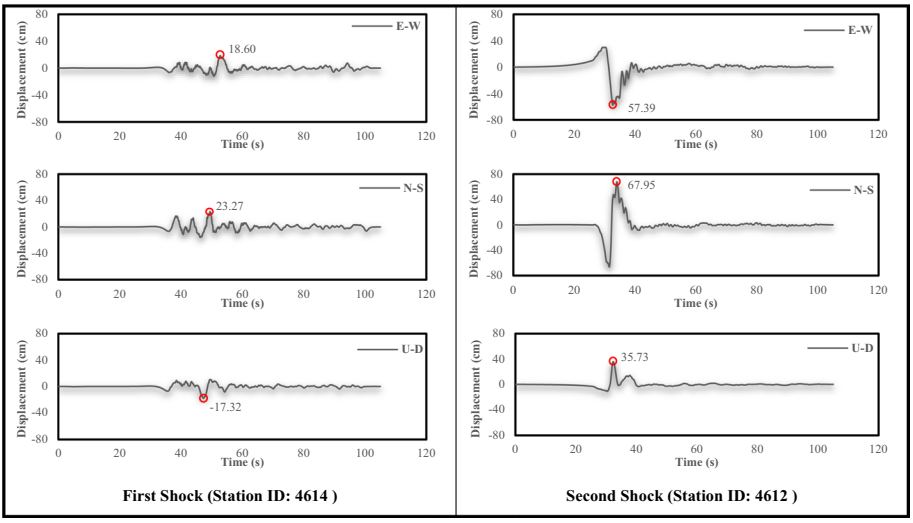


Fig. 7 Displacement records of the Kahramanmaraş earthquakes (Disaster and Emergency Management Authority 2023)

reveals that the acceleration values of the Pazarcık earthquake are significantly greater than those of the Elbistan earthquake. Nevertheless, it is not possible to conclude that a comparable situation pertains to velocities and displacements. The velocity and displacement values of the Elbistan earthquake are greater than those of the Pazarcık earthquake. There were earthquake acceleration recording stations in many regions of Türkiye that captured the Kahramanmaraş earthquakes. The acceleration values of the first and second shock, measured at some earthquake recording stations located in some of the primarily

affected provinces, are given in Tables 2 and 3, respectively. The acceleration records of the Pazarcık (Kahramanmaraş) earthquake, as documented in the central region of Kahramanmaraş, the Nurdağı and Islahiye districts of Gaziantep province, the Adıyaman provincial centre, and Hatay province in general, indicate that the maximum acceleration values measured in both the horizontal and vertical directions are notably elevated. Similarly, it is observed that the maximum acceleration values measured in the horizontal and vertical directions are notably high in the acceleration records recorded in the Nurhak and Göksun districts of Kahramanmaraş and the Akçadağ district of Malatya province for the Elbistan (Kahramanmaraş) earthquake. It is seen that the maximum acceleration values recorded in the horizontal direction at these stations exceed the maximum acceleration values determined for that region in the 1996 (Ministry of Public Works and Settlement 1996) and 2018 (TBEC 2018) Türkiye earthquake maps (for an earthquake with a probability of exceedance of 10% in 50 years, recurrence period 475 years). A comparison of the two earthquake maps, evaluated together according to the maximum acceleration values, reveals that the most recent map is safer than the previous one in terms of earthquake hazard. Nevertheless, it is irrefutable that the recorded maximum acceleration values exceed the values indicated in the two maps. Furthermore, seismic activity is also highly effective in the vertical direction.

In the design of structures, earthquake forces are typically calculated using the acceleration design spectra outlined in the relevant codes, with consideration given to the period of the structure and the soil characteristics of the region in question. It is therefore important to evaluate the acceleration spectra obtained from the acceleration records of earthquakes. Figures 8, 9, 10, and 11 illustrate the acceleration response spectra of the Pazarcık (Kahramanmaraş) earthquake, while Figs. 12 and 13 depict the acceleration response spectra of the Elbistan earthquake. These figures have been obtained from the acceleration records recorded in various provinces, and they are presented alongside the design acceleration spectra determined in the last two codes for that region.

The response spectra ordinates obtained from the horizontal and vertical acceleration records recorded at station 4614 (Pazarcık), which is close to the epicentre of the Pazarcık (Kahramanmaraş) earthquake, exceed the acceleration spectrum ordinates provided for DD1 (severe earthquake) in TBEC-2018 (2018), particularly within the short-period region. The graphs demonstrate the considerable acceleration and response of the earthquake. Nevertheless, the response spectra of the acceleration records recorded at Nar (Narlı), 4616 (Türkoğlu), and 4621 (Merkez/Kahramanmaraş) stations of the earthquake generally approached the design spectrum, and in some periods, exceeded it.

Upon examination of the acceleration response spectra of the acceleration records obtained from earthquake monitoring stations situated within Gaziantep province, where the Pazarcık earthquake had a notable impact and resulted in extensive structural damage, it was observed that the acceleration responses of the earthquake recorded at the 2712 (Nurdağı) and 2718 (Islahiye) district stations typically align with or exceed the design acceleration spectrum specified for this region in the TEC-2007 (2007) guidelines. Upon evaluation according to the TBEC-2018 design spectrum, the acceleration responses of the earthquake in question were found to align with the design spectrum.

An examination of the acceleration response spectra of the acceleration records made at some earthquake recording stations in Hatay province, where the Pazarcık earthquake had a significant impact and caused considerable damage to buildings, reveals that the acceleration responses of the earthquake recorded at Hassa and Kırıkhan stations are typically at or above the design acceleration spectrum specified for this region in TBEC-2018. Conversely, the response spectra from the acceleration records in the İskenderun and Defne

Table 2 Evaluation of the Pazarcık (Kahramanmaraş) earthquake, together with the acceleration values measured at some stations in the priority provinces and the seismic values specified in the last two earthquake codes, Disaster and Emergency Management Authority (DEMA, 2023)

	Station	Province	District	Longitude (°)	Latitude (°)	R_{jb}	R_{rup}	R_{epi}	TEC-2007 Seismic Zone	TEC-2007 PGA (g)	TBEC-2018 PGA (g) %10	Measured peak ground acceleration PGA (g)			TEC-2007	TBEC-2018
												N-S	E-W	U-D	$PGA_{Earthquake}/PGA_{(TEC\ 2007)}$	$PGA_{Earthquake}/PGA_{(DD2)}$
First Shock	Nar	Kahramanmaraş	Narlı	37.1574	37.3919	0.00	7.47	15.35	1	0.4	0.448	0.692	0.638	0.229	1.730	1.545
	4616	Kahramanmaraş	Türkoğlu	36.8384	37.3755	4.03	22.42	20.54	1	0.4	0.462	0.622	0.437	0.395	1.555	1.346
	2712	Gaziantep	Nurdağı	36.7328	37.184	2.74	11.58	29.79	1	0.4	0.496	0.567	0.604	0.320	1.510	1.218
	4614	Kahramanmaraş	Pazarcık	37.2978	37.4851	0.00	8.25	31.42	1	0.4	0.470	1.987	2.006	1.379	5.015	4.268
	4621	Kahramanmaraş	Dulkadiroğlu	36.9291	37.5935	28.49	36.32	35.42	1	0.4	0.361	0.376	0.229	0.678	0.940	1.042
	2718	Gaziantep	İslahiye	36.6266	37.0078	0.00	2.10	48.30	1	0.4	0.533	0.667	0.643	0.604	1.668	1.251
	3144	Hatay	Hassa	36.4857	36.757	12.36	12.36	77.04	1	0.4	0.603	0.615	0.789	0.481	1.973	1.308
	3142	Hatay	Kırıkhan	36.3661	36.498	38.09	38.09	106.49	1	0.4	0.517	0.665	0.754	0.466	1.885	1.458
	4408	Malatya	Doğanşehir	37.8873	38.0962	43.66	48.34	116.59	1	0.4	0.466	0.102	0.139	0.100	0.348	0.298
	0201	Adıyaman	Merkez	38.2674	37.7612	45.76	48.06	120.12	2	0.3	0.245	0.383	0.282	0.206	1.277	1.563
	3141	Hatay	Antakya	36.2197	36.3726	54.20	54.20	125.42	1	0.4	0.443	1.011	0.852	0.681	2.528	2.282
	3129	Hatay	Defne	36.1343	36.1912	75.71	75.71	146.39	1	0.4	0.452	1.378	1.222	0.731	3.445	3.049
	8002	Osmaniye	Bahçe	36.562	37.1916	12.59	21.04	43.91	1	0.4	0.391	0.247	0.207	0.343	0.618	0.632

Table 3 Evaluation of the Elbistan (Kahramanmaraş) earthquake, together with the acceleration values measured at some stations in the priority provinces and the seismic values specified in the last two earthquake codes, Disaster and Emergency Management Authority (DEMA, 2023)

	Station	Province	District	Longitude (°)	Latitude (°)	R_{jb}	R_{rup}	R_{epi}	TEC-2007 Seismic Zone	TEC-2007 PGA (g)	TBEC-2018 PGA (g)	Measured peak ground acceleration PGA (g)			TEC-2007	TBEC-2018
											%10	N-S	E-W	U-D	$PGA_{Earthquake}/PGA_{(TEC\ 2007)}$	$PGA_{Earthquake}/PGA_{(DD2)}$
Second shock	4631	Kahramanmaraş	Nurhak	37.4277	37.9663	11.60	19.69	21.43	2	0.3	0.408	0.324	0.400	0.559	1.333	0.980
	4611	Kahramanmaraş	Çağlayancerit	37.2843	37.7472	0.00	6.85	38.21	1	0.4	0.376	0.196	0.136	0.073	0.490	0.521
	4612	Kahramanmaraş	Göksun	36.4819	38.0234	62.18	62.18	66.68	3	0.3	0.296	0.640	0.531	0.439	2.133	2.162
	0213	Adıyaman	Tut	37.9296	37.7967	55.16	61.35	68.73	1	0.4	0.440	0.123	0.129	0.072	0.323	0.293
	4406	Malatya	Akçadağ	37.9738	38.3439	60.69	66.64	70.17	2	0.3	0.395	0.454	0.390	0.290	1.513	1.149
	5807	Sivas	Gürün	37.2475	38.7269	4.52	8.65	70.94	4	0.1	0.219	0.095	0.075	0.056	0.950	0.434
	3802	Kayseri	Sarız	36.5036	38.4781	58.12	58.12	77.41	4	0.1	0.165	0.197	0.222	0.122	2.220	1.345
	2703	Gaziantep	Şahinbey	37.35	37.058	48.50	49.49	115.06	3	0.2	0.175	0.095	0.064	0.028	0.475	0.543
	8002	Osmaniye	Bahçe	36.562	37.1916	66.70	33.24	116.24	1	0.4	0.391	0.067	0.046	0.029	0.168	0.171
	0127	Adana	Tufanbeyli	35.9204	37.8162	112.56	112.56	119.52	4	0.1	0.169	0.175	0.085	84.76	1.750	1.036
	3143	Hatay	Hassa	36.5571	36.8489	92.14	88.36	150.45	1	0.4	0.603	0.043	0.040	0.023	0.108	0.071

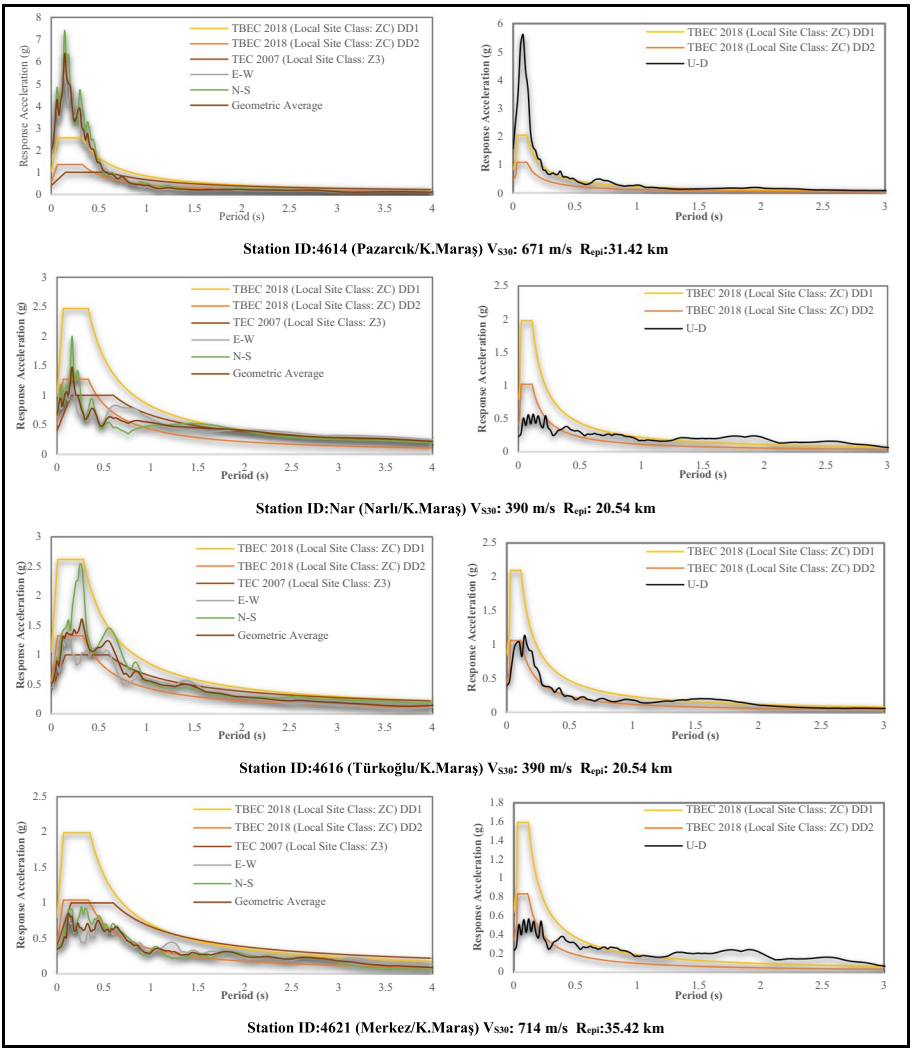


Fig. 8 Response spectra of the Pazarcık earthquake obtained from acceleration records recorded at earthquake acceleration recording stations in the Kahramanmaraş province and design spectra given for the station area in the last two earthquake codes (Damping ratio 5%) (adapted from Disaster and Emergency Management Authority (2023)

districts of Hatay province were found to exceed the spectra prescribed for DD1 (severe earthquake) and DD2 (design earthquake) in TBEC-2018 and TEC-2007 for this region. The acceleration ordinates exhibited approximately twofold values. It is evident from the graphs of the two station records that the vertical response of the earthquake may also be an important factor.

When the acceleration response spectra of the acceleration record components recorded in Adıyaman, another region affected by the Pazarcık earthquake, were analysed, it was found that they exceeded (TBEC-2018) and approached (TEC-2007) the

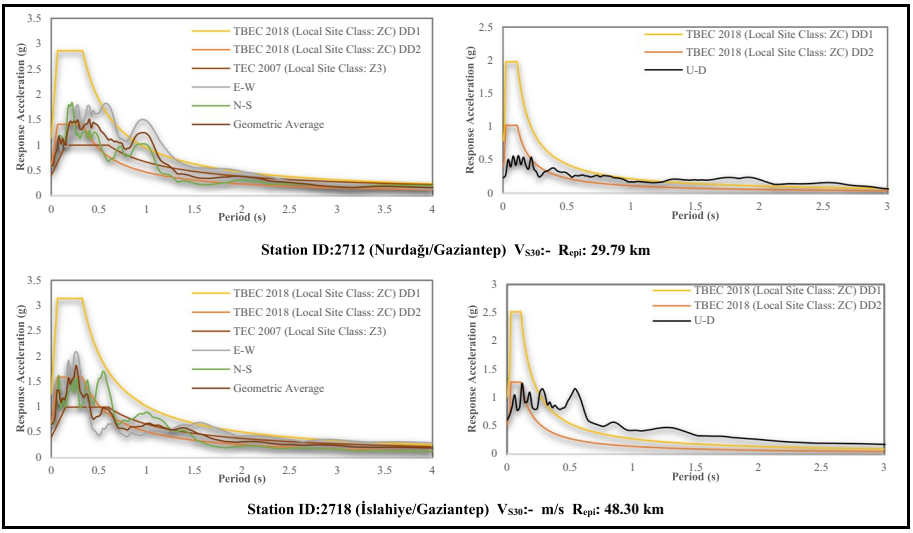


Fig. 9 Response spectra of the Pazarcık earthquake obtained from acceleration records recorded at earthquake acceleration recording stations in the Nurhak and Islahiye districts of Gaziantep province and design spectra given for the station area in the last two earthquake codes (Damping ratio 5%) (adapted from Disaster and Emergency Management Authority (2023)

ordinates of the design acceleration spectra given in the last two earthquake codes, especially in short periods.

When the acceleration response spectra obtained from the acceleration record of the Elbistan earthquake recorded at station 4612 (Göksun) are considered, it is observed that the acceleration responses of the earthquake are close to the ordinates of TBEC-2018 and TEC-2007 design spectra in short periods but exceed the spectra in medium and long periods. It even exceeded the coordinates of the TBEC-2018 DD1 acceleration spectrum in some period regions. When the responses of the acceleration records recorded at station 4631 (Nurhak), located near the epicentre are evaluated, they are generally parallel to the ordinates of the TBEC-2018 and TEC-2007 design acceleration spectra in medium and long periods.

Upon analysis of the acceleration response spectra of the acceleration record components recorded in the Akçadağ, another region affected by the Elbistan (Kahramanmaraş) earthquake, it was determined that they exceeded the coordinates of the design acceleration spectra outlined in the most recent two codes during short periods.

4 Field studies

This section presents the findings of the field studies carried out to determine the structural damage in reinforced concrete buildings in the cities of Hatay, Adıyaman, Kahramanmaraş, and Malatya. These damages are analysed under different subheadings with solutions proposed.

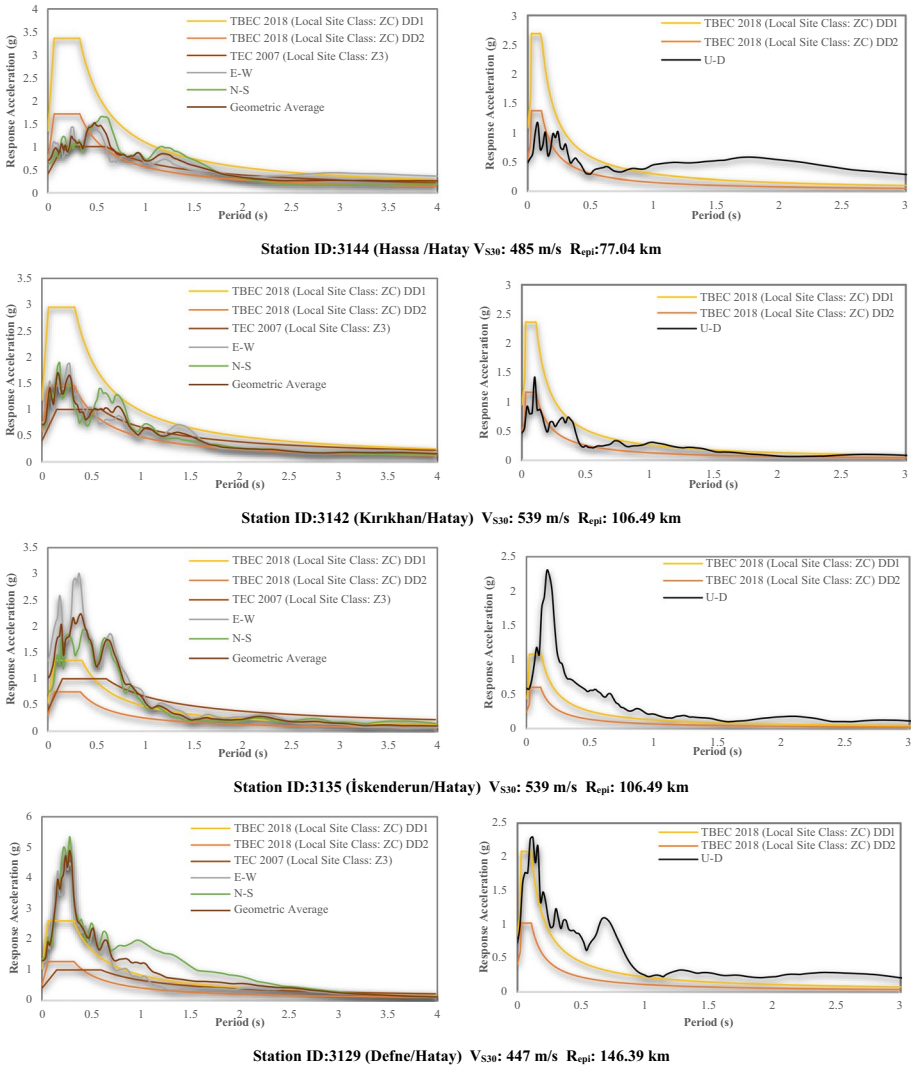
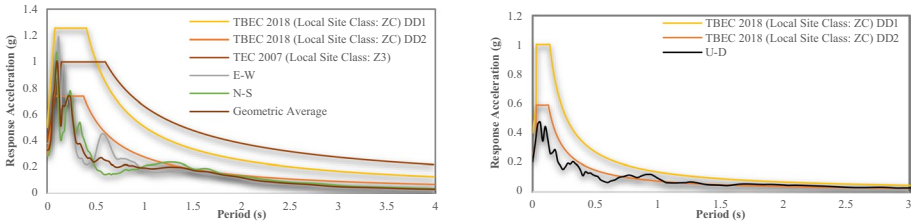


Fig. 10 Response spectra of the Pazarcık earthquake obtained from acceleration records recorded at earthquake acceleration recording stations in the Hatay province and design spectra given for the station area in the last two earthquake codes (Damping ratio 5%) (adapted from Disaster and Emergency Management Authority (2023)

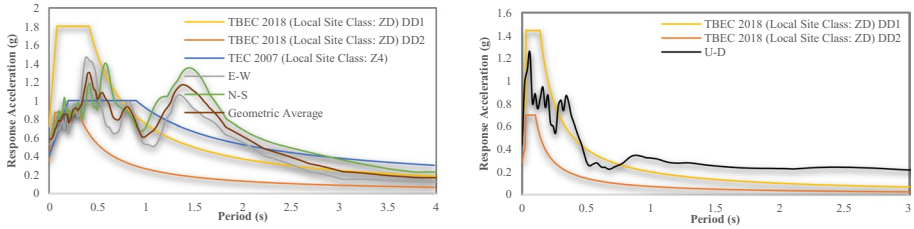
4.1 Strong beam-weak column

In order to satisfy architectural requirements, designs are created by reducing the dimensions of columns and reinforced concrete shear walls within the buildings. This was done to prevent the columns or shear walls from protruding into the rooms. However, due to the preference for wider spaces in modern construction, long spans are often crossed with deep beams. In the event of an earthquake, these structures begin to behave elastically, carrying loads initially. However, as the load increases, the structure undergoes a brittle fracture and

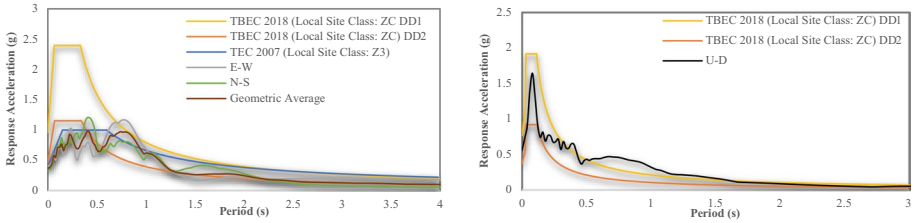


Station ID:0201 (Merkez /Adıyaman V_{S30}: 485 m/s R_{epi}:120.12 km

Fig. 11 Response spectra of the Pazarcık earthquake obtained from acceleration records recorded at the earthquake acceleration recording station in Adıyaman province and design spectra given for the station area in the last two earthquake codes (Damping ratio 5%) (adapted from Disaster and Emergency Management Authority (2018)

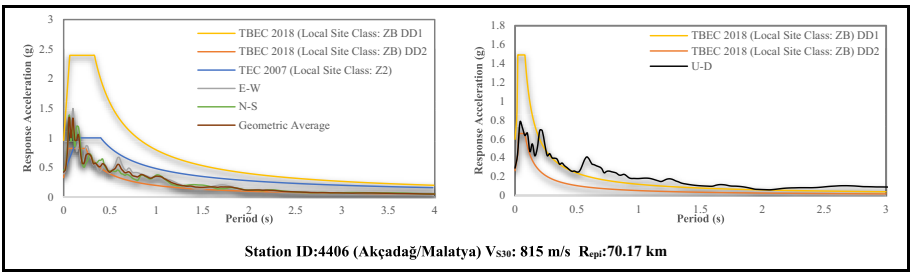


Station ID:4612 (Göksun/K.Maraş) V_{S30}: 246 m/s R_{epi}:66.68 km



Station ID:4631 (Nurhak/K.Maraş) V_{S30}: 543 m/s R_{epi}:21.43 km

Fig. 12 Response spectra of the Elbistan earthquake obtained from acceleration records recorded at the earthquake acceleration recording stations in Göksun and Nurhak districts of the Kahramanmaraş province and design spectra given for the station area in the last two earthquake codes (Damping ratio 5%) (adapted from Disaster and Emergency Management Authority (2018)



Station ID:4406 (Akçadağ/Malatya) V_{S30}: 815 m/s R_{epi}:70.17 km

Fig. 13 Response spectra of the Elbistan earthquake obtained from acceleration records recorded at the earthquake acceleration recording stations in Akçadağ district of Malatya province and the design spectra given for the station area in the last two earthquake codes (Damping ratio 5%) (adapted from Disaster and Emergency Management Authority (2018)

collapses, failing to demonstrate any inelastic behaviour. Axial load represents a significant factor influencing ductility. The axial load on beams is significantly less than that on columns. Consequently, it is more straightforward to guarantee ductility in beams than in columns. It is therefore recommended that columns be constructed with greater strength than beams and that plastic joints be formed in beams rather than columns. By the TEC-2007 and TBEC-2018, the bearing capacity of columns joining at a node must be a minimum of 20% greater than the bearing strength of beams joining at the same node. However, it was observed that this design was not implemented in earthquake-prone zones, resulting in the collapse of numerous structures. Figure 14 illustrates the phenomenon of a strong beam-weak column in earthquake areas.

4.2 Soft story-weak story mechanism

The soft-story mechanism is a type of brittle failure that often occurs after earthquakes. In these buildings, where the ground floor is designed as a commercial space, the height of this floor is higher than the other floors. In addition, the use of insufficient reinforced concrete shear walls or thick columns on this floor to ensure that the front façade of the commercial space remains open, and the lack of infill walls, are other factors that reduce the stiffness of this floor. Due to this incorrect design, the stiffness of this floor is quite low compared to other floors. In the serviceability limit state assumed for the slab and beam in the design, cracks may occur in the relevant elements. However, the low-stiffness vertical members on this floor may collapse without cracking in the same limit state. A second

36.56831, 36.15665 (Hatay)

36.41218, 35.89168 (Hatay)

36.57064, 36.15823 (Hatay)

36.42404, 35.90599 (Hatay)

Fig. 14 Strong beam-weak column mechanism in the earthquake area

error in the design of these structures is the consideration of peak displacements. It would be more accurate to consider the drift of the floors relative to each other rather than the peak displacement in the design. Figure 15 illustrates the soft-story mechanism in earthquake areas.

Another type of damage observed in seismic regions is that of a weak floor mechanism. This type of damage, which causes brittle fracture, is primarily caused by the abrupt reduction in the size of columns and reinforced concrete shear walls between floors, or the removal of these structural elements. However, the omission or subsequent removal of infill walls to create large spaces between floors represents another significant cause of damage. Such errors result in a reduction in the effective shear areas of the structural members on the floor in question. Consequently, the floor, which has been weakened by the earthquake, enters a state of collapse. Figure 16 illustrates the mechanism of weak-story failure in seismic zones.

4.3 Pounding effect

In order to make more efficient use of the limited urban space available in city centres in Türkiye, multi-story buildings are constructed without allowing sufficient space between them. Since the floor heights of these buildings are different when they are constructed, the floor of one building may coincide with the column of another building. These buildings with different periods are subject to collision because they oscillate differently during

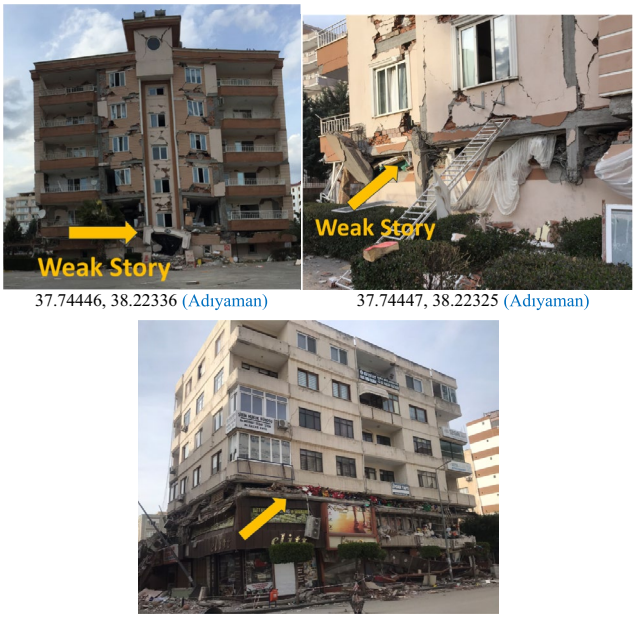
36.41953, 35.90215 (Hatay)

36.58911, 36.17352 (Hatay)

36.55670, 36.08996 (Hatay)

36.58506, 36.16724 (Hatay)

Fig. 15 Soft-story mechanism in earthquake areas



37.74446, 38.22336 (Adıyaman) 37.74447, 38.22325 (Adıyaman)

36.59322, 36.17098 (Hatay)

Fig. 16 Weak-story failure mechanism in the earthquake areas

the earthquake. Due to this pounding effect, buildings with weak rigidity can be severely damaged or go into collapse mode. TBEC-2018 (2018) offers two approaches to the minimum amount of space that should be left between adjacent buildings to prevent a collision, and the amount of space is determined according to the unfavourable one of these two approaches. In the first approach, the minimum size of gaps should be 30 mm up to 6 m in height, and from thereon, a minimum of 10 mm should be added for each 3 m height increment. In the second approach, the amount of gap is determined depending on the α parameter. If the floor slabs of neighbouring buildings are at the same level on all floors, $\alpha = 0.25(R/I)$ should be taken, and if the floors of neighbouring buildings are at different levels, $\alpha = 0.50(R/I)$ should be taken for the whole building. In these equations, the factor of the structural behavior and building important coefficient is shown by R and I, respectively. During the field study, it was observed that there was insufficient space between the buildings, which resulted in significant damage to the structures (Fig. 17).

4.4 Short column damage

Short columns that are not taken into account by engineers during the design process are an important mistake that causes severe damage to structures affected by earthquakes. However, short columns can also be constructed later by users while the building is in service. Strip windows made for lighting purposes, especially in buildings such as schools, hospitals, dormitories, or basements of buildings, cause this damage. Earthquake force affects columns in proportion to their lateral stiffness. If it is remembered that the lateral stiffness of a column with two ends fixed is $k = 12EI/h^3$, the shear force on the column is inversely proportional to the third power of the column length. Accordingly, an undesigned column

36.56671, 36.15519 (Hatay) 36.57043, 36.15792 (Hatay)

37.75129, 38.24375 (Adıyaman) 36.56671, 36.15450 (Hatay)

Fig. 17 Pounding effect

may be seriously damaged in an earthquake. Turkish earthquake code requires a separate condition for the shear force to be used in transverse reinforcement calculation for situations where the formation of short columns is not prevented. According to this,

$$V_e = \frac{M_a + M_{ü}}{l_n} \leq \left\{ \begin{array}{c} V_r \\ 0.85 A_w \sqrt{f_{ck}} \end{array} \right\}$$

where M_a and $M_{ü}$ are the end moments obtained by multiplying the bearing capacity moment at the lower and upper ends of the short column by the coefficient of 1.4 l_n is the length of the short column, V_r is the shear strength of the column cross-section, A_w is the effective body area of the column cross-section, and f_{ck} is the characteristic compressive strength of the concrete. During the field study, no special stirrup details were found to meet the earthquake shear force of short columns. For this reason, these structures were severely damaged (Fig. 18).

4.5 Long cantilever and overhangs

Buildings with long cantilever balconies and heavy closed overhangs are greatly affected by the vertical acceleration of the earthquake. With the vertical movement of the earthquake, large moments occur in the built-in support of the console. Long consoles that are not detailed according to this effect go into collapse mode. In closed cantilevered

37.58374, 36.91191 (Kahramanmaraş) 37.18159, 36.74473 (Gaziantep) 37.75854, 38.27105 (Adıyaman)

Fig. 18 Short column damages

structures, external infill walls may be damaged in-plane or out-of-plane as a result of vertical movement. Considering the effect of the vertical component of the earthquake in the design of structures and representing this effect with the vertical elastic design spectrum has become possible with TBEC-2018 (2018). Unfortunately, before this date, buildings were designed only for the horizontal earthquake effect, without taking into account its vertical component effect. Despite this, serious damage was observed in buildings with cantilever balconies and closed exits that are new or under construction in the earthquake region (Fig. 19). TBEC-2018 has made it mandatory to use the vertical elastic design spectrum in the design of the structures given below (2018):

a) Buildings containing beams with horizontal projection of spans of 20 m or more,
b) Buildings containing consoles with the horizontal projection of openings of 5 m or more,
c) Buildings containing columns resting on beams,
d) Buildings whose columns are inclined relative to the vertical.

However, the authors recommend that vertical acceleration should be taken into account in all building designs.

4.6 Short beam damage

It may be necessary to create openings in reinforced concrete shear walls for reasons such as doors, windows, etc. Consequently, hollow shear wall systems are formed. While a shear wall without openings shows bending behaviour, due to the openings opened in the wall, this behaviour exhibits shear behaviour depending on the opening ratio. In hollow shear wall systems, column stiffnesses will be considerably higher than beam stiffnesses. Since hollow shear elements are very rigid under earthquake forces, they do not create double curvature. Double curvature deformation occurs in the beams. Thus, the tie beams are under the influence of both bending and shearing. This causes serious damage to the short beams. This type of damage has been observed in the region affected by the earthquake. Figure 20 illustrates the damage sustained by the short beam damages. Reinforcement detailing of these beams should not be done as in classical beam design. Special

36.22422, 36.16269 (Hatay) 36.57101, 36.15614 (Hatay)

36.20623, 36.15794 (Hatay) 37.75193, 38.24453 (Adıyaman)

Fig. 19 Long Cantilever and Overhang damages

38.20082, 37.19937 (Kahramanmaraş) 37.75129, 38.24375 (Kahramanmaraş)

Fig. 20 Short beam damages

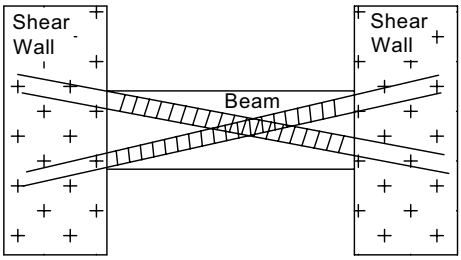
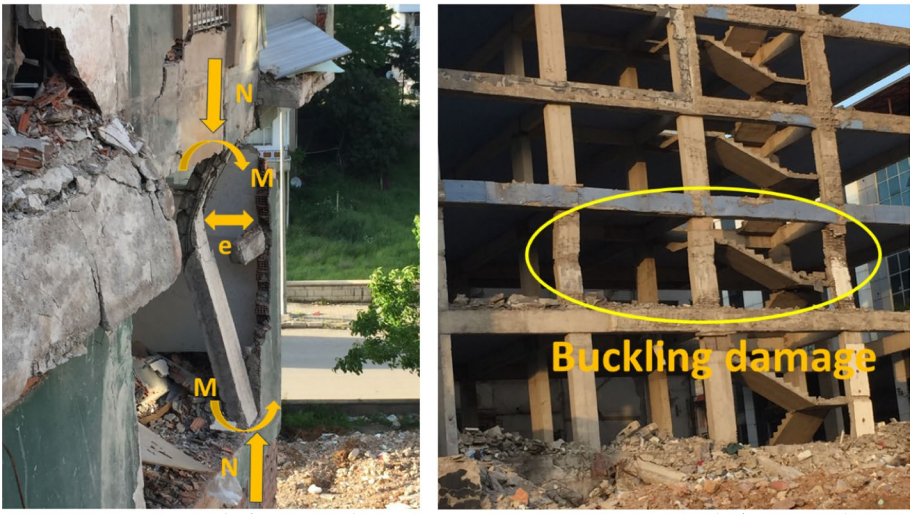


Fig. 21 Special detailing of the short beams



37.58337, 36.90658 (Kahramanmaraş) 37.57439, 36.93467 (Kahramanmaraş)

Fig. 22 Buckling damage

reinforcement detailing be employed to prevent damage to these beams. Figure 21 illustrates the specific reinforcement detailing of the tie beams.

4.7 Buckling damage

The buckling of reinforced concrete columns is influenced by many factors. The aforementioned factors include the dimensions of the column cross-section, the length of the column, the support conditions at both ends of the column, the single and double curvature of the column in systems where slip is prevented, and the quality and wrapping effect of the material. The behaviour of thick columns and slender columns is quite different from each other. In thick columns, fracture occurs in the form of buckling of reinforcement and crushing of concrete, while in slender columns, it occurs in the form of stability fracture (buckling along the column). In slender columns, vertical load also becomes important due to increased lateral translation due to horizontal forces, and the columns break under the effect of second-order moments. In observations made in earthquake regions, columns subjected to buckling damage were found. These damages are presented in Fig. 22. When this figure is examined, it is seen that in addition to the Moment (M), the column is subjected to

an additional second-order moment of the normal force $(N) \times e$. As a result of this effect, the columns were severely damaged.

4.8 Torsion effect

Torsion represents a significant source of stress on buildings during seismic events. As reinforced concrete walls are not placed in a regular pattern, the centre of mass and the centre of rigidity of the structure move away from each other. The centre of stiffness displaces the area in which the reinforced concrete walls are concentrated. Depending on the distance between the two centres, additional torsional moments occur in the structure. These moments, which are not taken into account in cross-section calculations, force the columns to rotate and cause brittle fractures. During the examination carried out in the earthquake area, the structures damaged due to torsion are noteworthy. Figure 23 shows the damage caused by the torsion effect. To be protected from additional torsional moments in buildings, great attention should be paid to the placement of reinforced concrete walls and columns. These elements should be placed considering their rigidity. However, the positions of columns and shear walls should not be changed randomly during the construction phase of the building. Changes that will increase or decrease the rigidity of columns and walls should be avoided.

4.9 Material quality

One of the most fundamental factors that determine the earthquake performance of reinforced concrete structures is material quality. In Türkiye, it became mandatory to use concrete prepared in concrete batching plants and to use ribbed steel with 420 MPa yield

(Kahramanmaraş) (Kahramanmaraş) (Kahramanmaraş)

Fig. 23 Torsion damage

strength instead of smooth surface reinforcement with 220 MPa yield strength in buildings constructed after the 1999 Kocaeli earthquake. However, while the minimum concrete compressive strength was stated to be 20 MPa in the TEC-2007, the earthquake code renewed in TBEC-2018 required the minimum concrete compressive strength to be 25 MPa. Observations made in the earthquake area showed that the concrete strength of most of the heavily damaged old buildings was between 6–10 MPa and their reinforcements had flat surfaces. Due to this feature of the reinforcement used, it was determined that there was no adherence between the reinforcement and the concrete, and the reinforcement was stripped from the concrete (Fig. 24). It has been observed that the concrete strength in new buildings is relatively higher than in old buildings, but remains below the concrete strength specified in the codes. It was determined that the placement of the concrete was not particularly taken into consideration and there were gaps in the concrete (Fig. 25). It has been determined that there are segregations in structural elements caused by concrete pouring. As a result of our observations, it was concluded that the supervision in newly constructed buildings is still inadequate, additional water is used to settle the concrete between the reinforcement, the concrete is placed without using a vibrator, and no curing process after concrete pouring.

4.10 Insufficient transverse reinforcement

Transverse reinforcement fulfils some crucial functions, including enhancing the strength of the concrete by exerting lateral pressure, conferring ductility upon the structural element, preventing the buckling of longitudinal reinforcement, and satisfying the shear forces induced by seismic activity (TBEC 2018). Despite the crucial role of transverse reinforcement in structural integrity, non-compliance with established guidelines persists, even in newly constructed

37.93041, 37.94855 (Malatya) 37.93041, 37.94855 (Malatya)

Fig. 24 Material quality of old buildings

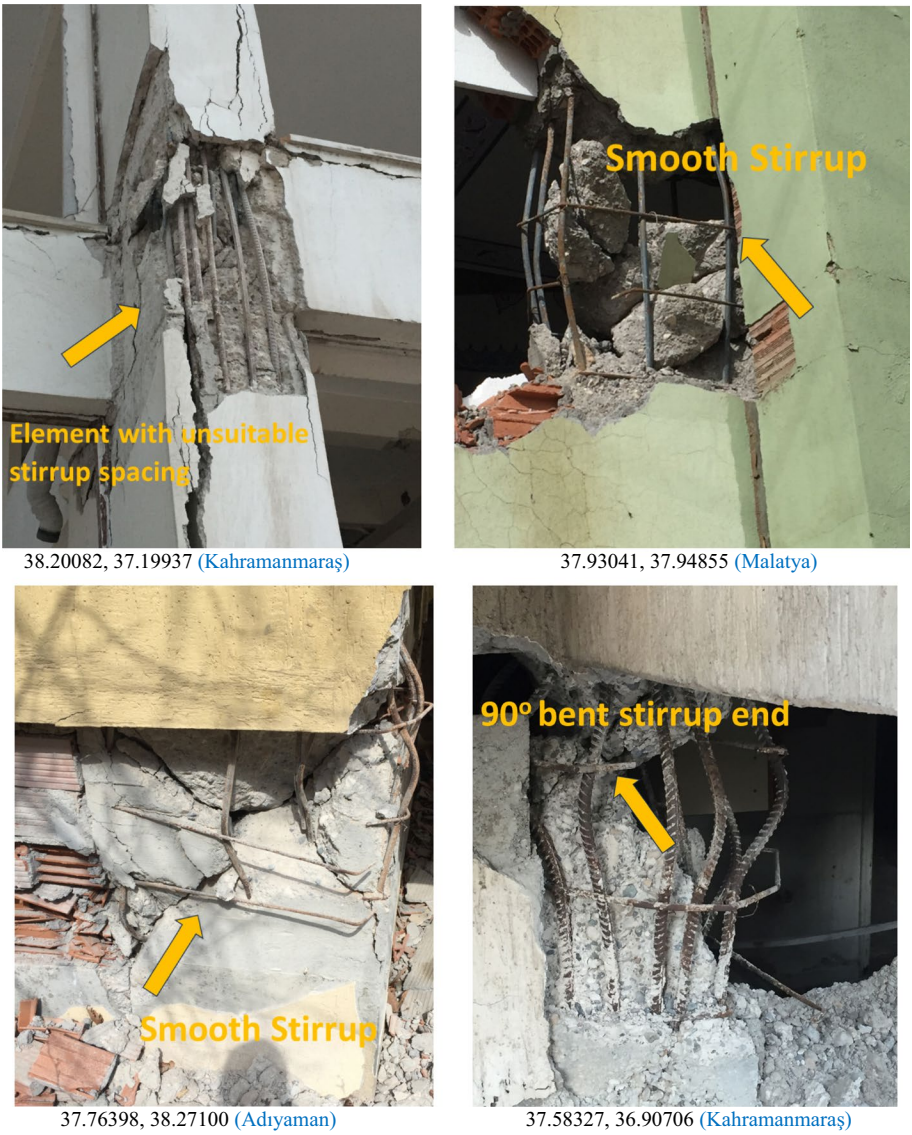
37.58327, 36.90706 (Kahramanmaraş) 36.58392, 36.17273 (Hatay)

Fig. 25 Material quality of new buildings

buildings. This can be attributed to various factors, including inadequate inspection procedures, design errors, and negligence on the part of construction workers. In the field studies carried out in the earthquake zone, it was observed that plastic joints occurred and appropriate stirrup tightening was not made in the column end areas that required special detailing. In addition, as a result of using flat-surface transverse reinforcement and not bending the ends of the stirrups, serious shear damage occurred in the structural elements. In field studies, it was determined that the stirrup spacing, which was expected to be between 5–10 cm in the column end regions, was between 20–40 cm. Additionally, it was observed that in large columns, a single stirrup was made surrounding the reinforcement. For this reason, the longitudinal reinforcements were buckled and serious shear damage occurred in the core concrete. Turkish Earthquake Codes (1997 (TEC 1997, Onat 2022), 2007, and 2018) require that special seismic cross ties and hooks should be bent 135° in all seismic zones. Figure 26 illustrates the structural elements that failed due to inadequate transverse reinforcement, improper hooks, and smooth bars.

4.11 Compressive failure due to over reinforcement

The Turkish Earthquake Codes impose minimum and maximum limitations on the use of reinforcement to ensure ductility in beam and column designs. The maximum limit is for the element to exhibit ductile fracture behaviour without undergoing compression failure. When the reinforcement ratio in the elements is higher than the balanced reinforcement, the concrete is crushed without the reinforcement flowing during the fracture. This situation causes compression fracture, which is a brittle fracture. In the field studies made after the earthquake, it was determined that the reinforcement did not flow in the elements where the reinforcement ratio was too high, whereas the core concrete was crushed and broken. Figure 27 illustrates the phenomenon of compression fracture.



38.20082, 37.19937 (Kahramanmaraş)

37.93041, 37.94855 (Malatya)

37.76398, 38.27100 (Adıyaman)

37.58327, 36.90706 (Kahramanmaraş)

Fig. 26 Inadequate transverse reinforcement, improper hooks, and smooth bars

4.12 Corrosion effect

Basements and ground floors of buildings are more affected by groundwater and rainwater. Especially the reinforcement of structural elements with poor external insulation and inadequate concrete cover are subject to corrosion for various reasons. As a result of corrosion, reinforcement loses its properties and begins to flake over time. This results in a loss of functionality for the reinforcement and a reduction in the bearing capacity of the structural elements. Many structural elements with corroded reinforcement were found in

36.42028, 35.89434 (Hatay) 37.18415, 36.73260 (Gaziantep)

Fig. 27 Compression failure in columns due to excessive reinforcement

the earthquake zone (Fig. 28). Maintenance and repair processes must be continued after the construction of reinforced concrete buildings to eliminate factors that cause damage, such as corrosion.

4.13 Reinforced concrete shear wall damages

Reinforced concrete shear elements provide significant horizontal rigidity to structures by restricting their horizontal displacements. For this reason, they are structural elements of great importance in earthquake-resistant building design. Shear walls are exposed to more bending moments and shear forces than columns. The effects caused by the earthquake

36.39399, 35.91097 (Hatay) 36.39520, 35.91149 (Hatay)

Fig. 28 Corroded reinforcement

force especially stress the end areas of the walls and the areas close to the foundation. For this reason, when detailing wall element reinforcement, attention should be paid to the end zones and critical height. Examinations carried out in the earthquake area showed that the damaged shear walls were exposed to large shear forces. It was determined that the shear wall end zone was not made in the damaged shear wall elements and there was no appropriate reinforcement detailing. it was also observed that the buildings with fewer shear walls than required were insufficient to resist the earthquake forces. Shear wall damages for these types of buildings are presented in Fig. 29.

4.14 Infill wall damages

While designing reinforced concrete structures, the contribution of infill walls to the earthquake performance of the structure is neglected. In reality, infill walls increase the lateral rigidity of structures in the direction of their planes. Infilled walls are exposed to shear forces in the direction of their planes, showing a behaviour similar to that of reinforced concrete shear walls. The thickness of the wall and the strength of the plaster used are important factors affecting the shear strength of the walls. In newly constructed buildings, wall thicknesses are thinned and only gypsum plaster is applied to the wall surface instead of cement mortar plaster. This application reduces the shear strength of the wall and causes large cracks to form. These cracks increase with the cyclic earthquake force and form *X*-shaped shear cracks. As the crack width increases, the wall loses its stability and partially or completely topples out of the plane. Figure 30 illustrates the in-plane damage observed in infill walls.

Infill wall damage may also manifest as out-of-plane wall damage. The exterior walls of some buildings in Türkiye are constructed with two layers to provide heat and sound insulation. In this application, which is done by placing insulation material between two walls, the outermost wall layer falls out of its plane due to the earthquake effect, due to the lack of connection elements between the walls and insufficient mortar. In addition, increasing space widths for architectural reasons leads to the construction of higher and wider walls. These weak walls, which have low thickness, do not have beams between

38.20124, 37.20012 (Kahramanmaraş) 36.22369, 36.16129(Hatay) 36.22122, 36.16308 (Hatay)

Fig. 29 Shear wall damages

37.74446, 38.22336 (Adıyaman) 37.76378, 38.27526 (Adıyaman) 37.49381, 37.30190 (Kahramanmaraş)

Fig. 30 In-plane damage to infill walls

the walls and are anchored to the frames only with mortar, easily toppling out of their planes. Figure 31 demonstrates the out-of-plane damages in infill walls.

4.15 Damages arose from soil and foundation system

In the examinations carried out in the earthquake area, it was observed that the soils of the earthquake-affected areas had a high probability of liquefaction and their bearing capacity was weak. It has been determined that the foundation systems of structures built on agricultural lands are generally not chosen to suit the ground. When Fig. 32a is examined, the building was exposed to a wholesale collapse due to the lack of a basement and the effect of liquefaction on the ground. Figure 32b illustrates that the foundation made in the form of individual footing does not have the appropriate depth and foundation size, thus rotation of the foundation occurred and caused severe damage at

Fig. 31 Out-of-plane damages to infill walls

Fig. 32 Damages arose from the Soil and Foundation system

the upper end of the column. Figure 32c shows a situation in which the foundation was not selected appropriately for the ground with insufficient bearing capacity, resulting in the building sinking into the ground.

5 Recommendations to prevent damages

The previous sections provide a detailed description of structural faults detected through observation in earthquake zones. In this part of the study, the detected structural damage types are presented and strategies to prevent them are suggested. This information is tabulated in Table 4.

Table 4 The causes of damage and the recommendations to be made to prevent these damages

Damage type	Recommendation/Solution
Strong beam-weak column	The bearing capacity of columns joining at a node be at least 20% greater than the bearing strength of beams joining at the same node
Soft story-weak story mechanism	It would be to consider the drift of the floors relative to each other rather than the peak displacement in the design. To increase the stiffness of this floor, reinforced concrete shear walls should be used or column sizes should be increased. In addition, applications such as mezzanine floors should be avoided
Pounding effect	The minimum space should be left between adjacent buildings according to the peak displacements obtained as a result of analyses given in the earthquake codes
Short column damage	Short columns should be avoided in buildings as much as possible. Where it is necessary to construct short columns, closely spaced stirrups should be used to increase the shear safety of these columns. The sides of the columns should be walled or crushable material should be placed
Long cantilever and overhangs	The vertical elastic design spectrum should be considered in the design of structures and cantilevers should be detailed in this effect
Short beam damages	Reinforcement detailing of these beams should not be done as in classical beam design. Special reinforcement detailing must be done to prevent damage to these beams
Buckling damage	The buckling effect should be considered in the design by the designer
Torsion effect	To protect against additional torsional moments in buildings, great care should be taken in the placement of reinforced concrete walls and columns
Material quality	Buildings must be constructed to the minimum concrete strength required by earthquake codes. Control should be ensured at every stage of the building's construction
Insufficient transverse reinforcement	Special seismic cross ties and hooks should be bent 135° in all seismic zones
Compressive failure due to over reinforcement	The limits on the use of reinforcement required by TBEC-2018 to ensure ductility in beam and column designs must be complied with
Corrosion effect	Maintenance and repair processes must continue after the construction
Reinforced concrete shear wall damages	Shear walls should be used as much as necessary; attention should be paid to the end zones and critical height when detailing the reinforcement of the shear wall element
Infill wall damages	The thickness of the walls should not be reduced, cement mortar plaster should be preferred on the surface of the walls, and connecting elements should be made between the walls built in two layers

Table 4 (continued)

Damage type	Recommendation/Solution
Damages arose from the soil and foundation system	On soils with a high probability of liquefaction, construction should not be carried out or the soil water should be removed, on soils with a low bearing capacity, the building should be constructed accordingly, a basement should be built, foundation depths and dimensions should be designed according to the bearing capacity of the soil

6 Conclusions and final remarks

On 6 February 2023, earthquakes of Mw = 7.7 and Mw = 7.6 on the Eastern Anatolia Fault zone killed more than 50 thousand people in 10 cities of Türkiye and caused billions of dollars of damage. The fact that these shocks, which occurred on the same day, were shallow earthquakes according to their depths and occurred on the same fault zone significantly affected the destruction caused by the earthquakes.

When the seismic characteristics of the earthquakes are analysed, the destructive effects of the earthquakes are seen. While the maximum acceleration value in the horizontal direction is 2.006 g for the first shock, this value is 0.641 g for the second shock. On the other hand, the maximum acceleration value in the vertical direction is 1.379 g for the first shock while the acceleration amplitude for the second shock is 0.439 g. These acceleration values show how strong the earthquakes were both horizontally and vertically. When the response acceleration spectra are compared with the design spectra used in the design process of the structures, it is determined that the values of the response spectra are above those of the design spectrum for the DD2 earthquake level given in TBEC-2018 in the short-medium-long period regions. It was even observed that the ordinates of the response spectra exceeded those of the design spectrum for DD1 earthquake level in some period regions. These destructive effects of the earthquake also revealed the weaknesses in the structures. In this study, the causes of damage to reinforced concrete buildings in the cities of Hatay, Adıyaman, Kahramanmaraş, and Malatya, which were the most affected cities by the earthquake, were analysed in detail.

Consequently, the destruction caused by the February 6, 2023 earthquake showed that no lessons were learned from past earthquakes. The damages experienced once again demonstrated that academic knowledge and experience are not reflected in practice. To prevent destruction and loss of life; Settlement selection should be made very carefully, and more training should be given to increase earthquake awareness among those working in the construction sector, from engineers to workers. Great importance should be given to the quality of materials and workmanship. Absolute control must be ensured by competent civil engineers in the construction of buildings and every stage of production must be followed meticulously.

Author contributions Burak Yön: Methodology, Writing- Reviewing and Editing. İbrahim Özgür Dedeoğlu: Field observation, Writing. Musa Yetkin: Field observation, Writing. Hakan Erkek: Field observation, Writing. Yusuf Calayır: Field observation, Editing.

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK). The authors received no support for their work. They did all the work with their means.

Declarations

Conflict of interest The authors have declared no conflict of interest.

Informed consent The authors declare that the information used in the article is entirely their own and that other information used in the study is referenced.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Altunışık AC, Arslan ME, Kahya V, Aslan B, Sezdirmez T, Dok G, Baltaci A (2023) Field observations and damage evaluation in reinforced concrete buildings after the February 6th, 2023 Kahramanmaraş-Türkiye earthquakes. J Earthq Tsunami 17:2350024

Altunsu E, Güneş O, Öztürk S, Sorosh S, Sarı A, Beeson ST (2024) Investigating the structural damage in Hatay province after Kahramanmaraş-Türkiye earthquake sequences. Eng Fail Anal 157:107857

Ates S, Kahya V, Yurdakul M, Adanur S (2013) Damages on reinforced concrete buildings due to consecutive earthquakes in Van. Soil Dyn Earthq Eng 53:109–118

Atmaca B, Demir S, Günaydin M, Altunişik AC, Hüsem M, Ateş Ş, Adanur S, Angin Z (2020) Field investigation on the performance of mosques and minarets during the Elazig-Sivrice earthquake. J Perform Constr Facil 34:04020120

Atmaca B, Arslan ME, Emiroglu M, Altunışık AC, Adanur S, Demir A, Akgül T (2023a) On the earthquake-related damages of civil engineering structures within the areas impacted by Kahramanmaraş earthquakes. J Struct Eng Appl Mech 6(2):98–116

Atmaca B, Ertürk Atmaca E, Roudane B, Güleş O, Demirkaya E, Aykanat B, Akgül T (2024) Field observations and numerical investigations on seismic damage assessment of RC and masonry minarets during the February 6th, 2023, Kahramanmaraş (Mw 7.7 Pazarcık and Mw 7.6 Elbistan) Earthquakes in Türkiye. Int J Archit Herit. https://doi.org/10.1080/15583058.2024.2337651

Avcil F, Işık E, İzol R, Büyüksaraç A, Arkan E, Arslan MH, Aksoylu C, Eyisüren O, Harirchian E (2023) Effects of the February 6 Kahramanmaraş earthquake on structures in Kahramanmaraş City. Nat Hazards 120:2953–2991

Bayraktar A, Altunişik AC, Pehlivan M (2013) Performance and damages of reinforced concrete buildings during the October 23 and November 9, 2011 Van, Turkey, earthquakes, Soil Dyn. Earthq Eng 53:49–72

Bozkurt E (2001) Neotectonics of Turkey—a synthesis. Geodin Acta 14:3–30

Caglar N, Vural I, Kirtel O, Saribiyik A, Sumer Y (2023) Structural damages observed in buildings after the January 24, 2020 Elazığ-Sivrice earthquake in Türkiye. Case Stud Constr Mater 18:e01886

Çelebi E, Aktas M, Çağlar N, Özocak A, Kutanis M, Mert N, Özcan Z (2013) October 23, 2011 Turkey/Van-Ercis earthquake: structural damages in the residential buildings. Nat Hazards 65:2287–2310

Cosgun SI (2023) Seismic evaluation of historical Pertev Pasha Mansion under February 6 Kahramanmaraş (Pazarcık) Earthquake (Mw 7.7). J Struct Eng Appl Mech 6(5):468–481

Dedeoğlu İÖ, Yetkin M, Calayır Y (2022) 24 January 2020 Sivrice-Elazığ earthquake: assessment of seismic characteristics of earthquake, earthquake territory and structural performance of reinforced concrete structures. Sak Univ J Sci 26:892–907

Dedeoğlu İÖ, Yetkin M, Calayır Y, Erkek H (2023) January 24, 2020 Sivrice-Elazığ (Türkiye) Earthquake: the seismic assessment of the earthquake territory, geotechnical findings and performance of masonry buildings, Iran. J Sci Technol Trans Civ Eng. https://doi.org/10.1007/s40996-023-01318-0

Turkish Ministry of Interior Disaster and Emergency Management Authority, DEMA, https://en.afad.gov.tr/

Demir A, Celebi E, Ozturk H, Ozcan Z, Ozocak A, Bol E, Sert S, Sahin FZ, Arslan E, Dere Yaman Z, Utkucu M, Mert N (2024) Destructive impact of successive high magnitude earthquakes occurred in Türkiye's Kahramanmaraş on February 6, 2023. Bull Earthq Eng. https://doi.org/10.1007/s10518-024-01865-5

Disaster and Emergency Management Authority, Türkiye Earthquake Hazard Maps Interactive Web Application (2018) https://tdth.afad.gov.tr/TDTH/main.xhtml

Disaster and Emergency Management Authority TADAS (2023) https://tadas.afad.gov.tr/. Accessed 28 Sep 2023

Doğangün A, Yön B, Onat O, Öncü ME, Sağıroğlu S (2021) Seismicity of East Anatolian of Turkey and failures of infill walls induced by major earthquakes. J Earthq Tsunami 15:2150017

Duman TY, Emre Ö (2013) The East Anatolian Fault: geometry, segmentation and jog characteristics. Geol Soc Lond Spec Publ 372:495–529

Erkek H, Yetkin M (2023) Assessment of the performance of a historic minaret during the Kahramanmaraş earthquakes (Mw 7.7 and Mw 7.6). Structures 58:105620

Global Earthquake Model Foundation https://www.globalquakemodel.org/

Hacıefendioğlu K, Başağa HB, Kahya V, Özgan K, Altunışık AC (2024) Automatic detection of collapsed buildings after the 6 February 2023 Türkiye earthquakes using post-disaster satellite images with deep learning-based semantic segmentation models. Buildings 14(3):582

Hussain E, Kalaycıoğlu S, Milliner CW, Çakir Z (2023) Preconditioning the 2023 Kahramanmaraş (Türkiye) earthquake disaster. Nat Rev Earth Environ 4(5):287–289

İnce O (2024) Structural damage assessment of reinforced concrete buildings in Adıyaman after Kahramanmaraş (Türkiye) Earthquakes on 6 February 2023. Eng Fail Anal 156:107799

Işık E (2023) Structural failures of adobe buildings during the February 2023 Kahramanmaraş (Türkiye) Earthquakes. Appl Sci 13:8937

Işık E, Avcil F, Büyüksaraç A, İzol R, Hakan Arslan M, Aksoylu C, Harirchian E, Eyisüren O, Arkan E, Şakir Güngür M, Günay M, Ulutaş H (2023a) Structural damages in masonry buildings in Adıyaman during the Kahramanmaraş (Turkiye) earthquakes (Mw 7.7 and Mw 7.6) on 06 February 2023. Eng Fail Anal 151:107405

Işık E, Avcil F, Arkan E, Büyüksaraç A, İzol R, Topalan M (2023b) Structural damage evaluation of mosques and minarets in Adıyaman due to the 06 February 2023 Kahramanmaraş earthquakes. Eng Fail Anal 151:107345

Kahya V, Genç AF, Sunca F, Roudane B, Altunişik AC, Yilmaz S, Akgül T (2024) Evaluation of earthquake-related damages on masonry structures due to the 6 February 2023 Kahramanmaraş-Türkiye earthquakes: a case study for Hatay Governorship Building. Eng Fail Anal 156:107855

Kocaman İ (2023) The effect of the Kahramanmaraş earthquakes (Mw 7.7 and Mw 7.6) on historical masonry mosques and minarets. Eng Fail Anal 149:107225

Kürçer A, Elmacı H, Özdemir E, Güven C, Güler T, Avcu İ, Olgun, Avcı HO, Aydoğan H, Yüce AA, Çetin FE, Ayrancı A, Akyol Z, Soykasap ÖA, Altuntaş G, Demirörs U, Karayazı O, Bayrak A, Özalp S (2023) 06 February 2023 Pazarcık (Kahramanmaraş) earthquake (Mw 7.8) field observations and evaluations, Mineral Research and Exploration General Directorate, vol 14138, pp 187, Ankara, Türkiye

Mercimek Ö (2023) Seismic failure modes of masonry structures exposed to Kahramanmaraş earthquakes (Mw 7.7 and 7.6) on February 6, 2023. Eng Fail Anal 151:107422

Mineral Research and Exploration General Directorate (2019) Annotated active fault map of Türkiye, scale 1:1.250.000, Special Broadcast Series, vol 30, pp 89–89

Ministry of Public Works and Settlement (1996) Republic of Turkey, Earthquake Zones Map of Türkiye

Nemutlu ÖF, Balun B, Sarı A (2021) Damage assessment of buildings after 24 January 2020 Elazığ-Sivrice earthquake. Earthq Struct 20(3):325–335

Nemutlu ÖF, Sarı A, Balun B (2023) Comparison of actual loss of life and structural damage in 06 February 2023 Kahramanmaraş earthquakes (Mw 7.7-Mw 7.6) with estimated values. Afyon Kocatep e Univ J Sci Eng 23(5):1222–1234 ((**in Turkish**))

Onat O, Yön B, Öncü ME, Varolgüneş S, Karaşin A, Cemalgil S (2022) Field reconnaissance and structural assessment of the October 30, 2020, Samos, Aegean Sea earthquake: an example of severe damage due to the basin effect. Nat Hazards 112(1):75–117

Onat O, Yön B, Uslu A, Öncü ME, Varolgüneş S, Karaşin IB, Gör M (2024) Seismic resistance and performance evaluation of masonry dwellings after the February 6, 2023, Kahramanmaras earthquake sequence in Turkiye. J Earthq Tsunami. https://doi.org/10.1142/S1793431124500131
Ozkula G, Dowell RK, Baser T, Lin JL, Numanoglu OA, Ilhan O, Olgun CG, Huang CW, Uludag TD (2023) Field reconnaissance and observations from the February 6, 2023, Turkey earthquake sequence. Nat Hazards 119:663–700
Ozturk M, Arslan MH, Korkmaz HH (2023a) Effect on RC buildings of 6 February 2023 Turkey earthquake doublets and new doctrines for seismic design. Eng Fail Anal 153:107521
Ozturk M, Arslan MH, Dogan G, Ecemis AS, Arslan HD (2023b) School buildings performance in 7.7 Mw and 7.6 Mw catastrophic earthquakes in southeast of Turkey. J. Build. Eng. 79:107810
Öztürk S, Altunsu E, Güneş O, Sarı A (2024) Investigation of industrial structure performances in the Hatay and Gaziantep provinces during the Türkiye earthquakes on February 6, 2023. Soil Dyn Earthq Eng 179:108569
Parlak O, Yavuzoğlu A, Bayrak A, Karayazı O, Olgun Ş(2023) 06 February 2023 Elbistan (Kahramanmaraş) earthquake (Mw 7.6) field observations and evaluations, Mineral Research and Exploration General Directorate vol 14139, p 99, Ankara, Türkiye
Pujol S, Bedirhanoglu I, Dönmez C, Dowgala JD, Eryilmaz-Yildirim M, Klaboe K, Koroglu FB, Lequesne RD, Ozturk B, Pledger L, Sonmez E (2024) Quantitative evaluation of the damage to RC buildings caused by the 2023 southeast Turkey earthquake sequence. Earthq Spectra 40:505–530
Qu Z, Wang F, Chen X, Wang X, Zhou Z (2023) Rapid report of seismic damage to hospitals in the 2023 Turkey earthquake sequences. Earthq Res Adv 3:100234
Sayın E, Yön B, Onat O, Gör M, Öncü ME, Tuğrul Tunç E, Bakır D, Karaton M, Calayır Y (2021) 24 January 2020 Sivrice-Elazığ, Turkey earthquake: geotechnical evaluation and performance of structures. Bull Earthq Eng 19:657–684
Taşkın B, Sezen A, Tuğsal ÜM, Erken A (2013) The aftermath of 2011 Van earthquakes: evaluation of strong motion, geotechnical and structural issues. Bull Earthq Eng 11:285–312
TBEC (2018) Türkiye Building Earthquake Code, Disaster and Emergency Management Presidency (in Turkish)
TEC (1997) Türkiye Earthquake Code, Ministry of Public Works and Settlement (in Turkish)
TEC (2007) Türkiye Earthquake Code, Ministry of Public Works and Housing, Disaster and Emergency Management Presidency (in Turkish)
US Geological Survey, Earthquake Lists, Maps, and Statistics. https://www.usgs.gov
Vuran E, Serhatoğlu C, Timurağaoğlu MÖ, Smyrou E, Bal İE, Livaoğlu R (2024) Damage observations of RC buildings from 2023 Kahramanmaraş earthquake sequence and discussion on the seismic code regulations. Bull Earthq Eng. https://doi.org/10.1007/s10518-023-01843-3
Wang T, Chen J, Zhou Y, Wang X, Lin X, Wang X, Shang Q (2023) Preliminary investigation of building damage in Hatay under February 6, 2023 Turkey earthquakes. Earthq Eng Eng Vib 22:853–866
Yetkin M, Dedeoğlu İÖ, Calayır Y (2021) Investigation and assessment of damages in the minarets existing at Elazig after 24 January 2020 Sivrice earthquake. Fırat Univ J Eng Sci 33:379–389 ((**in Turkish**))
Yön B, Sayın E, Köksal TS (2013) Seismic response of buildings during the May 19, 2011 Simav Turkey earthquake. Earthq Struct 5:343–357
Yön B, Sayın E, Calayır Y, Ulucan ZÇ, Karataş M, Şahin H, Alyamaç KE, Bildik AT (2015) Lessons learned from recent destructive Van Turkey earthquakes. Earthq Struct 9:431–453
Yön B, Onat O, Öncü ME (2019) Earthquake damage to nonstructural elements of reinforced concrete buildings during 2011 Van Seismic Sequence. J Perform Constr Facil 33:04019075

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Burak Yön[1] · İbrahim Özgür Dedeoğlu[2] · Musa Yetkin[3] · Hakan Erkek[4] · Yusuf Calayır[5]

✉ Burak Yön
burakyon@munzur.edu.tr

İbrahim Özgür Dedeoğlu
iozgur.dedeoglu@batman.edu.tr

Musa Yetkin
musayetkin@firat.edu.tr

Hakan Erkek
hakanerkek@osmaniye.edu.tr

Yusuf Calayır
yusuf.calayir@yalova.edu.tr

[1] Department of Civil Engineering, Munzur University, 62000 Tunceli, Turkey

[2] Department of Civil Engineering, Batman University, 72100 Batman, Turkey

[3] Department of Civil Engineering, Fırat University, 23119 Elazig, Turkey

[4] Department of Civil Engineering, Osmaniye Korkut Ata Üniversitesi, 23119 Osmaniye, Turkey

[5] Department of Civil Engineering, Yalova University, 77200 Yalova, Turkey