




Effects of the February 6, 2023, Kahramanmaraş earthquake on structures in Kahramanmaraş city

Fatih Avcil¹ · Ercan Işık¹ · Rabia İzol²  · Aydın Büyüksaraç³ · Enes Arkan⁴ · Musa Hakan Arslan⁵ · Ceyhun Aksoylu⁵ · Onur Eyisüren⁶ · Ehsan Harirchian⁷

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Abstract

Large-scale loss of life and property occurred in Kahramanmaraş and its districts, which are the city center where the epicenters of the earthquake couples that occurred on February 6, 2023, in Türkiye. Major damage has occurred in different structural systems due to the earthquake. In addition, fault traces that are the source of the earthquake were clearly observed on the ground surface. In this study, the effects of both earthquakes on soil, reinforced concrete, masonry, prefabricated, and other structural systems were evaluated observationally in Kahramanmaraş and its districts. Comparisons were made on the last two earthquake maps used in Türkiye for the locations of strong ground motion measuring devices in Kahramanmaraş. The masonry structures, which are common in rural areas in the epicenter, have been heavily damaged because they have not received engineering service. However, it is seen that the concrete buildings have insufficient strength and ductility. A similar situation is also present in industrial precast structures, and it has been observed that the damaged and collapsed in these structures are manufactured without complying with the type connection details given for prefabricated reinforced concrete structures in the codes. It has also been observed that the soil-structure interaction is the most determining parameter in the structure's performance in these earthquake couples. Especially in weak soils, the damage to the structures has been quite heavy. The field data obtained from the earthquakes showed that some of the conditions of the current earthquake code should be discussed again.

Keywords Kahramanmaraş · Earthquake couple · Damage · Seismic risk · Map · Surface faulting

1 Introduction

The February 6, 2023, Kahramanmaraş epicenter earthquake couple, which occurred on the Eastern Anatolian Fault Zone and related faults, one of the most important tectonic elements of Türkiye, has been recorded in history as the earthquakes that experienced the greatest loss of life and property in the country. After the great disaster, which directly affected 14% of the country's surface area, more than 50,000 lives were lost. The spread of

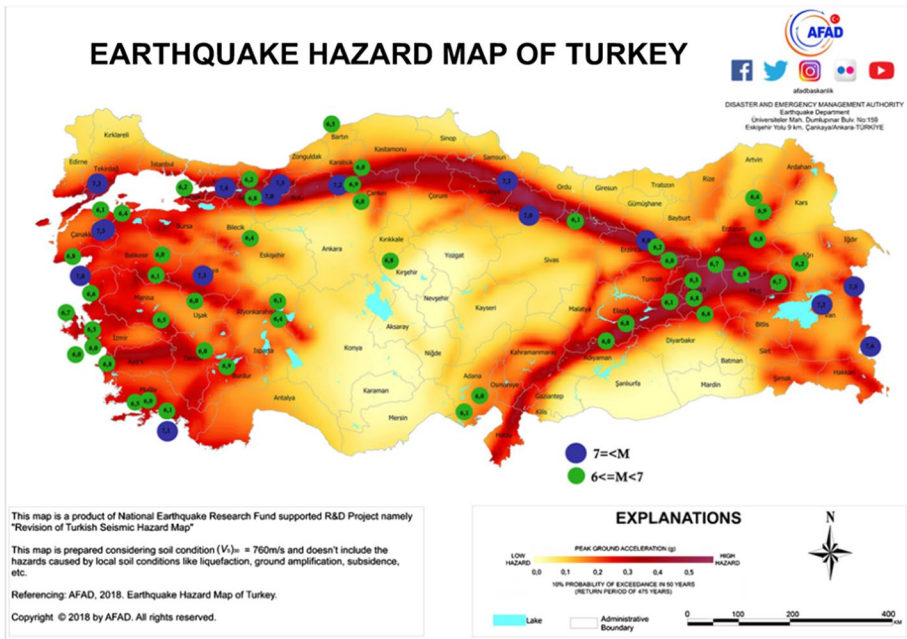


Fig. 1 Representation of $M \geq 6$ earthquakes that occurred in the instrumental period in Türkiye on the current earthquake hazard map

the earthquake zone over a large area and a couple of earthquakes ($M_w = 7.7$ and $M_w = 7.6$) that occurred at nine-hour intervals showed their devastating effect. With the second earthquake ($M_w = 7.6$) that occurred in Ekinözü-Elbistan (Kahramanmaraş), the damage levels in the first earthquake increased to a higher level, causing the rate of structural damage to be much higher. After this earthquake couple, where it is not possible to describe the destructiveness of earthquakes with photographic images, both public institutions/organizations and non-governmental organizations declared high-level mobilization and tried to carry out the necessary interventions after the earthquake in the earthquake area. The representation of $M \geq 6$ earthquakes that occurred in the instrumental period in Türkiye before the Kahramanmaraş earthquakes is given in Fig. 1. Earthquakes of this magnitude did not occur in the Eastern Anatolian Fault Zone (EAFZ), where the earthquake couple occurs, during the instrumental period. In addition, there is no other example of an earthquake couple in Türkiye with nine-hour intervals. In addition, the fact that both earthquakes are independent and very close to each other distinguishes these two earthquakes from all other earthquakes. The earthquake couple, which is called the disaster of the century in Türkiye, requires a detailed examination of all features from every manner.

After each earthquake in which significant loss of life and property occurred, the examinations and observations made in the field bring up the importance of the studies to be done in this regard and the measures that can be taken. Each post-earthquake work to be done by different disciplines is an integral part of post-earthquake disaster management. In this context, all kinds of studies are to be carried out within the scope of an earthquake, and structural engineering is a support tool for decision-makers in revealing the earthquake and structural risks of those regions. In addition, the earthquake hazard of the regions can be presented more realistically with structural damage and earthquake

data, and earthquake-resistant building design rules can be developed with the help of these data. Evaluating and managing all the data obtained together is important in terms of spatial planning and urban transformation (Bilgin et al. 2022; Bülbül et al. 2022; Işık et al. 2017; Hadzima-Nyarko et al. 2017; Ademović et al. 2020).

There are many articles in the literature discussing post-earthquake damage in Türkiye and the world. Especially 1975 Mexico, 1990 Luzon (Philippines), 1994 Northridge (USA), 1992 Erzincan (Türkiye), 1995 Hyogoken Nanbu (Kobe), 1999 Marmara (Türkiye), 1999 Düzce (Turkey), 2010 Maule (Chile), 2011 Van (Türkiye), 2011 Christchurch Tohoku (Japan) 2015 Gorkha (Nepal) and 2017 Puebla (México) earthquakes are important in this context. After these earthquakes, both superstructure and infrastructure damages were examined in detail. Post-earthquake field observations are carried out for various types of structures such as reinforced concrete and masonry buildings (Ozmen et al. 2014; Bayraktar et al. 2013; Kam et al. 2011; Zhao et al. 2009; Bruneau 2002; Inel et al. 2013; Temür et al. 2021; Ahmad et al. 2014; Xiong et al. 2015), bridges (Ko et al. 2023), industrial structures (Uckan et al. 2015), and historical buildings (Kumar et al. 2020; Kocaman 2023). Based on these observations, the causes of the identified damages are indicated, and various recommendations are provided to prevent such damages from occurring. These studies serve as an important source to understand how structures of this kind behave during earthquakes and to utilize scientific approaches in the restoration processes of special structures such as historical buildings.

There are many studies on earthquakes occurring in different countries of the world and the structural damage caused by them. Each of these studies can be considered as case studies. These studies, in addition to being a support tool for decision-makers, make significant contributions to practice and academia. Especially the 1999 Marmara and 2023 Kahramanmaraş Earthquakes have shown that more economic damage than superstructure damage is in the infrastructure. The fragility and importance of infrastructure has been pointed out in the studies carried out by different researchers around the world. In addition to superstructure damage, many researchers (Evans and McGhie 2011; Giovinazzi et al. 2011; Lemnitzer et al. 2021; Todd et al. 1994) have focused on infrastructure damage, which causes greater losses to the economy. Factors such as migration from rural to urban areas increase the cost of infrastructure in cities, and it can be said that possible damage to infrastructures in subsequent earthquakes may cause greater economic loss (Sathurshan et al. 2022). Some other studies conducted as a result of earthquakes in different countries of the world are shown in Table 1.

Considering the earthquake activity in Türkiye, the dense building stock in the earthquake zones, the wide variety of characteristics of the building stock, and the types of damaged superstructures and infrastructures, the results of field studies have always been interesting after the earthquakes in Türkiye. However, it is another irony that the country has highly developed earthquake codes (recently revised as TBEC-2018) there are dozens of universities providing earthquake and structural engineering education, and the damage is heavy despite the fact that world-class research is being carried out in these universities.

After the earthquakes in Türkiye, many studies have been carried out on the damage of reinforced concrete buildings, which constitute a significant part of the building stock Adalier and Aydingun (2001); Sezen et al. (2003); Kaplan et al. (2004); Yakut et al. (2005); Bakir et al. (2005); Inel et al. (2008); Arslan and Korkmaz (2007); Celep et al. (2011); Kaltakçı et al. (2008); Çelebi et al. (2013); Öztürk (2015); Korkmaz (2015); Doğan et al., (2021); Koç (2016); Damcı et al., (2015) and very recently Koçer and Ünal (2023); Ozturk et al (2023a, b).

Table 1 Post-earthquake studies in various countries of the world

Country	Earthquake	Date	Types of the structure	References
California (USA)	Northridge ($M_w=6.7$)	January 17, 1994	Steel	Mahin (1998)
Nepal	Gorkha ($M_w=7.8$)	April 25, 2015	Stone/Brick/RC	Goda et al. (2015)
New Zealand	Christchurch ($M_w=6.1$)	Earthquake series of 2010 to 2011	Steel	Clifton et al. (2011)
Wenchuan (China)	Sichuan, ($M_w=7.9$)	May 12, 2008 May 12, 2008	RC/Masonry Tunnel	Zhang and Jin (2008) Yu et al. (2016)
Albania	Durrës ($M_w=6.4$)	November 26, 2019	Masonry	Bilgin et al. (2022)
Italy	L'Aquila ($M_w=5.9$)	April 6, 2009	Masonry	Lagomarsino (2012)

Similarly, the damage to masonry and adobe buildings, which constitutes a significant part of the building stock in the rural area, has also been the focus of attention of researchers. The fairly new research by Isik et al. (2020), Işık et al. (2023); Dogan et al. (2021); Sayın et al. (2021); Bayraktar et al. (2016); Oyguc and Oyguc (2017); Korkmaz (2015); Celep et al. (2011) are some of these studies. Pioneering studies of concrete prefabricated building damage are Sezen and Whittaker (2006); Saatcioglu et al. (2001); Senel and Kayhan (2010); Arslan et al. (2006); Işık (2023). Similarly, in wooden and steel structures some researchers have conducted field studies such as Doğangün et al. (2006), Langenbach (2008), and Bruneau (2002).

In this study, observational evaluations were made by conducting field studies by the authors in order to reveal the effects of the February 6, 2023, Kahramanmaraş earthquake couples on both the ground and the structures. Damages in structures such as reinforced concrete and masonry buildings, prefabricated industrial buildings, minarets, and mosques have been evaluated in terms of earthquake and structural engineering. Since the area affected by both earthquakes is very large, the study is limited to only Kahramanmaraş and its districts. In the study, surface examinations were made and interpretations were made about the faults and the values at the strong ground motion measurement stations in Kahramanmaraş province and its districts were given separately for both earthquakes. For each of the geographical locations of the stations, the seismic parameters were compared, taking into account the last two earthquake hazards used in the country. Even the high peak ground acceleration values measured for Kahramanmaraş for both earthquakes are a sufficient indicator to show the extent of the earthquake's destructiveness.

1.1 February 6, 2023, earthquake couple and measured accelerations in Kahramanmaraş

The earthquakes that took place in the south of Türkiye on February 6, 2023, were the release of the accumulated energy of the Eastern Anatolian Fault Zone (EAFZ), one of the two important fault zones of Anatolia, with strong energy after a long time. EAFZ consists of seven different segments (Alkan et al. 2021). It shows a tearing mechanism from north to south, just like a zipper. Along this zone, major earthquakes had occurred in the first four segments from the north, and the fifth segment, Pazarcık, was waiting for its turn as a region with new earthquake potential. Since there has not been an earthquake of this

magnitude in this region since 1513, a rupture along the Pazarcık segment (approximately 80 km) was expected and an effect in a certain area in the probably expected earthquake, great energy was released in the earthquake that took place on February 6, 2023, at 04:17. The stress transfer process brought by this energy was shortened and not only in this segment but in total three different fault segments were torn one after the other. About 5–6 s after the earthquake that started in the Narlı segment, the EAF was triggered in the main fault segments, and the rupture in the northeast direction extended to Çelikhan and the southwest direction to Hatay. With the rupture of the Türkoğlu-Çelikhan and Türkoğlu-Hatay segments, apart from the Narlı fault, the total magnitude of the earthquakes in the three fault segments became $M_w=7.7$. Nine hours after this earthquake, again due to stress transfer, another $M_w=7.6$ earthquake occurred on the Çardak Fault, which is located in Elbistan-Ekinözü in the northwest and has not been active for about 10 thousand years. Earthquake activity continues in the region and more than 15 thousand aftershocks have occurred to date. Earthquakes greater than 5.5 M_w and fault lines occurring in the region are shown in Fig. 2.

The acceleration values of the first earthquake, $M_w=7.7$ Pazarcık (Kahramanmaraş) earthquake, measured at earthquake recording stations in Kahramanmaraş and its districts are given in Table 2.

The accelerations of the 2nd earthquake, $M_w=7.6$ Ekinözü-Elbistan (Kahramanmaraş) earthquake, measured at earthquake recording stations in Kahramanmaraş and its districts are given in Table 3.

The local field effect theory, which seems to be the foundation for the seismic codes adopted by the majority of nations, can be traced back to evidence gathered from earlier

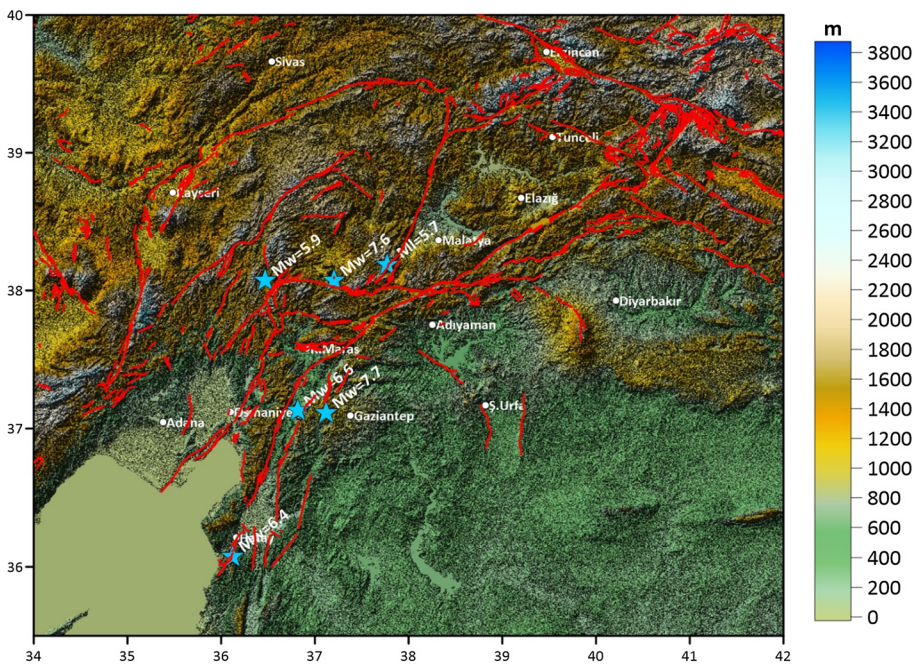


Fig. 2 Earthquakes and fault lines with $M_w > 5.5$ in the region (Alkan et al. 2023)

Table 2 Accelerometer stations and measured accelerations in Kahramanmaraş for the first earthquake (AFAD, 2023)

No.	District	Station Code	Latitude	Longitude	PGA (cm/s ²)			Repi (km)
					NS	EW	UD	
06.02.2023 04:17 M _w = 7.7 (Pazarcık-Kahramanmaraş)								
1	Çağlayancerit	4611	37.28426	37.7472	349.72	321.11	173.39	55.32
2	Göksun	4612	36.48187	38.024	140.97	122.22	54.31	95.59
3	Andırın	4613	36.35737	37.5701	146.93	153.52	75.03	68.19
4	Pazarcık	4614	37.29775	37.4851	2165.59	2178.71	1951.48	31.42
5	Pazarcık	4615	37.13803	37.3868	583.65	582.12	664.18	13.83
6	Türkoğlu	4616	36.83836	37.3755	652.76	502.87	397.27	20.54
7	Onikişubat	4617	36.8303	37.5855	145.33	115.16	110.59	38.04
8	Onikişubat	4618	36.87231	37.6001	125.66	159.42	134.42	37.84
9	Onikişubat	4619	36.86616	37.587	302.03	194.74	175.51	36.73
10	Onikişubat	4620	36.89845	37.5857	300.40	320.93	185.34	35.48
11	Dulkadiroğlu	4621	36.92909	37.5935	363.80	295.56	253.92	35.42
12	Onikişubat	4624	36.91765	37.5361	357.60	319.96	161.72	29.73
13	Dulkadiroğlu	4625	36.98187	37.5387	448.15	483.65	367.37	28.40
14	Onikişubat	4626	36.91505	37.5753	108.81	223.09	112.27	33.89
15	Afşin	4628	36.92281	38.2412	91.10	82.55	55.74	106.52
16	Türkoğlu	4629	36.78871	37.2874	338.93	248.20	124.36	22.50
17	Türkoğlu	4630	36.80604	37.3449	178.56	124.04	178.14	21.89
18	Nurhak	4631	37.42765	37.9663	22.21	19.34	32.95	82.68
19	Türkoğlu	4632	36.77369	37.256	359.46	299.25	200.23	24.09

earthquakes, particularly the earthquake that struck Mexico City in 1986. Settlements with basin structures are where this scenario is most obvious.

The spectral accelerations obtained from the acceleration values recorded at strong ground motion stations in 17 different locations are plotted in Fig. 3 according to different soil types. Accordingly, the expected acceleration values were exceeded for all soil types at seven stations. In ZC and ZD soil types, the number of stations exceeding the expected acceleration value was 10. The acceleration spectrum graphs obtained from the mentioned acceleration records and the design acceleration spectrum in the Turkish Building Earthquake Code (TBEC-2018) were compared for different soil classes (ZB-ZC-ZD-ZE). As it is known, the design acceleration spectrum is the spectrum that occurs every 475 years or that occurs with a probability of 10% during the economic life of the building. Spectrum curves plotted for 5% damping are shown in Fig. 3.

The M_w = 7.6 earthquake, which occurred nine hours after the first major earthquake, was recorded at strong ground motion stations located in 11 different locations in fewer numbers than the first earthquake in Kahramanmaraş, probably due to its further distance. Spectral accelerations obtained from the measured accelerations are plotted in Fig. 4 according to different soil types. Accordingly, the expected acceleration values were exceeded for all soil types at one station. In ZC and ZD soil types, the number of stations whose acceleration value exceeded the expected acceleration value was 2. The acceleration spectrum graphs obtained from the mentioned acceleration records and the design

Table 3 Accelerometer stations and measured accelerations in Kahramanmaraş for the Ekinözü-Elbistan (Kahramanmaraş) ($M_w = 7.6$) earthquake (AFAD, 2023)

No.	District	Station Code	Latitude	Longitude	PGA (cm/s^2)			Repi (km)
					NS	EW	UD	
06.02.2023 13:24 $M_w = 7.6$ (Ekinözü-Elbistan-Kahramanmaraş)								
1	Çağlayancerit	4611	37.28426	37.7472	194.40	139.04	72.57	38.21
2	Göksun	4612	36.48187	38.02395	635.45	52.321	494.91	66.68
3	Andırın	4613	36.35737	37.5701	80.61	78.25	75.74	96.56
4	Pazarcık	4614	37.29775	37.48513	160.82	206.05	89.21	67.35
5	Pazarcık	4615	37.13803	37.38676	44.47	73.75	41.67	78.59
6	Türkoğlu	4616	36.83836	37.37547	57.55	53.50	28.05	86.81
7	Onikişubat	4617	36.8303	37.58551	55.97	82.69	54.79	66.50
8	Onikişubat	4618	36.87231	37.60011	No measured value			
9	Onikişubat	4619	36.86616	37.58702				
10	Onikişubat	4620	36.89845	37.58568	66.82	81.33	57.03	63.46
11	Dulkadiroğlu	4621	36.92909	37.59347	No measured value			
12	Onikişubat	4624	36.91765	37.5361	65.00	79.75	38.61	67.65
13	Dulkadiroğlu	4625	36.98187	37.53872	73.46	50.68	38.15	65.22
14	Onikişubat	4626	36.91505	37.57532	No measured value			
15	Afşin	4628	36.92281	38.241198				
16	Türkoğlu	4629	36.78871	37.287373				
17	Türkoğlu	4630	36.80604	37.344912				
18	Nurhak	4631	37.42765	37.966325	337.38	388.61	610.04	21.43
19	Türkoğlu	4632	36.77369	37.256028	No measured value			

acceleration spectrum in TBEC-2018 were compared for different soil classes (ZB-ZC-ZD-ZE). Spectrum curves plotted for 5% damping are shown in Fig. 4.

2 Seismicity of Kahramanmaraş city and comparison of seismic parameters

The earthquake hazard map and earthquake regulation in Türkiye were updated in 2018. The previous earthquake zone map, which was used from 1996 to 2018, was prepared on a regional basis using probabilistic seismic hazard analysis. The standard earthquake ground motion level with a recurrence period and probability of exceedance of 10% was taken into account and five different earthquake zones were expressed. Again, with the map developed by using probabilistic seismic hazard analysis, the transition to geographical location-specific earthquake risk has been made instead of regional earthquake risk. In addition, the current map has been transformed into separate maps, taking into account four different earthquake ground motion levels, which were taken into account together with the TBEC-2018, which was also updated in 2018. These ground motion levels are given in Table 4.

In order to use the current earthquake map and code more practically, the Türkiye Earthquake Hazard Map Interactive Web Earthquake Application (TEHMIWA) was launched in 2018. With the help of the application, seismic parameters of any geographical location can

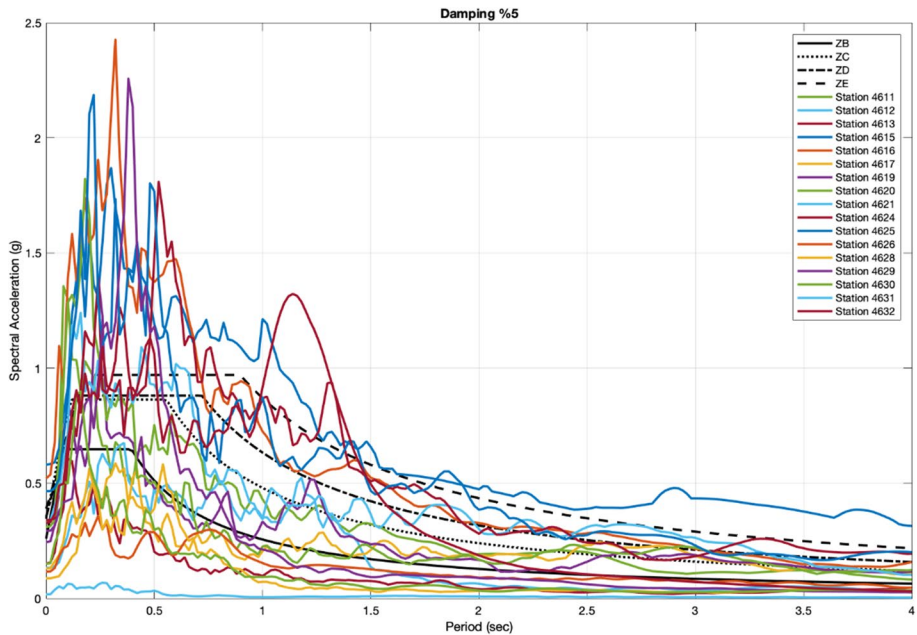


Fig. 3 Spectral acceleration graph for ZB, ZC, ZD, and ZE soil types of 17 acceleration stations installed in Kahramanmaraş for the Pazarcık Earthquake ($M_w=7.7$)

be obtained separately for different earthquake ground motion levels and soil classes. In the case given in TBEC-2018 where the soil properties are very bad (weak soil, low stiffness, and low permeability) and the local soil class is ZF, the application cannot be used and requires site-specific research. In this context, the peak ground acceleration (PGA) and the highest ground velocity (PGV) values, which are the most widely used Intensity measures, were obtained separately for the positions of the accelerometer in Kahramanmaraş. The PGA and PGV values obtained according to the different probabilities of exceedance are shown in Table 5.

The PGA for earthquakes with a 10% probability of exceedance in 50 years for 19 different locations considered in Kahramanmaraş is in the range of 0.24 g–0.470 g. While the largest PGA was obtained for the Pazarcık district, the lowest PGA value was obtained for the Afşin district. For earthquake level DD-1, PGA was obtained as 0.478 g–0.922 g. While the lowest PGA value was obtained for the Afşin district as 0.478 g, the highest PGA value was obtained in the Türkoğlu district as 0.922 g. For the same earthquake ground motion level, PGV was obtained in the range of 28,870 cm/s–62,034 cm/s. These resulting values are considered expected acceleration values, especially when compared with the ground properties of strong ground motion stations. The fact that the PGA value is high in stations such as Pazarcık, which is close to the focal point of the earthquake, is an expected result. On the other hand, very high PGA values were observed in remote settlements such as Antakya and Adıyaman due to excessive soil amplification. The PGV value range was obtained relatively high. Due to the source's high energy, the seismic wave's propagation speed was also high.

The comparison of the values obtained for the last two earthquake maps and regulations used in Türkiye for the geographical locations of all accelerometers in

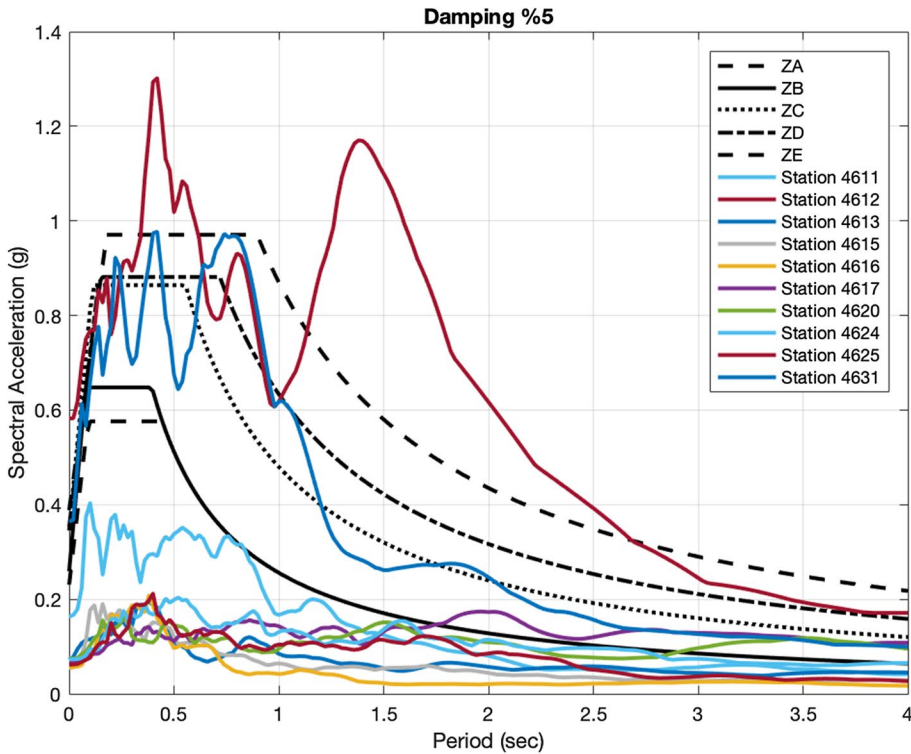


Fig. 4 Spectral acceleration graph for ZB, ZC, ZD, and ZE soil types of 17 acceleration stations installed in Kahramanmaraş for Ekinözü-Elbistan Earthquake ($M_w = 7.6$)

Table 4 Earthquake ground motion levels (TBEC-2018)

Earthquake ground motion level	Repetition Period (year)	Probability of exceedance (in 50 years) (%)	Definition
DD-1	2475	2	Largest earthquake ground motion
DD-2	475	10	Standard design earthquake ground motion
DD-3	72	50	Frequent earthquake ground motion
DD-4	43	68	Service earthquake movement

Kahramanmaraş is shown in Table 6. In the comparisons, the standard earthquake ground motion level with a recurrence period of 475 years in both earthquake maps and regulations was taken into account.

While the map in 1996 was prepared on a regional basis, the current map in 2018 was prepared specifically for the geographical location. In the previous earthquake zone map, Göksun, Andırın, and Afşin districts are in the 3rd-degree earthquake zone, while Nurhak district is in the 2nd-degree earthquake zone, while all other settlements are in the 1st-degree earthquake zone. The current earthquake hazard map and PGA value have changed for all settlements. While the biggest increase occurred in Göksun, the biggest decrease occurred in Onikisubat, where the earthquake recording station

Table 5 PGA and PGV values obtained for the locations of the accelerometers in Kahramanmaraş

No.	Location	PGA (g)				PGV (cm/s)			
		2%	10%	50%	68%	2%	10%	50%	68%
1	Çağlayancerit	0.691	0.376	0.142	0.097	44.878	23.334	8.379	5.625
2	Göksun	0.624	0.296	0.086	0.056	38.71	17.561	5.359	3.584
3	Andırın	0.568	0.292	0.104	0.070	34.022	17.040	6.066	4.154
4	Pazarcık	0.853	0.470	0.157	0.100	60.085	31.854	9.164	5.743
5	Pazarcık	0.840	0.448	0.151	0.100	54.902	28.161	8.923	5.791
6	Türkoğlu	0.883	0.462	0.155	0.105	59.338	29.640	8.958	5.915
7	Onikişubat	0.609	0.328	0.127	0.089	39.433	20.285	7.570	5.263
8	Onikişubat	0.620	0.333	0.129	0.089	40.097	20.672	7.656	5.299
9	Onikişubat	0.631	0.340	0.131	0.091	40.910	21.091	7.753	5.358
10	Onikişubat	0.658	0.356	0.135	0.093	42.625	22.076	7.961	5.461
11	Dulkadiroğlu	0.672	0.364	0.137	0.094	43.510	22.620	8.074	5.511
12	Onikişubat	0.784	0.422	0.149	0.101	51.158	26.373	8.612	5.752
13	Dulkadiroğlu	0.870	0.470	0.158	0.105	56.405	29.368	9.062	5.894
14	Onikişubat	0.688	0.373	0.140	0.096	44.584	23.185	8.176	5.563
15	Afşin	0.478	0.242	0.081	0.054	28.870	14.629	5.240	3.559
16	Türkoğlu	0.878	0.453	0.153	0.104	58.942	28.923	8.843	5.882
17	Türkoğlu	0.853	0.448	0.154	0.105	57.253	28.614	8.853	5.885
18	Nurhak	0.820	0.408	0.128	0.084	52.784	26.119	7.824	4.982
19	Türkoğlu	0.922	0.467	0.153	0.104	62.034	29.869	8.861	5.882

numbered 7 is located. While the design spectral acceleration coefficients decreased in Onikişubat where stations 7, 8 and 9 are located, they decreased at all other station locations. The biggest increase occurred for Göksun.

3 Impact of the 2023 Kahramanmaraş earthquakes

The earthquake codes (TEC-1998, TEC-2007 and TBEC-2018), which came into force in Türkiye especially in 1998 and later, include the seismic detailing, earthquake load calculation procedures and seismic design control criteria required by the era. With TEC-1998; ductile structure design was prioritized with some criteria such as capacity design, ductility, plasticization, shear failures etc. In addition, heavy sanctions have been imposed especially on column sections due to rigidity concerns. Minimum longitudinal reinforcement ratios and lower limits of the mechanical properties of the reinforcement are also included in the codes due to strength concerns. There are heavy confinement reinforcement requirements for ductility. For this reason, the upper limit for beam and column longitudinal reinforcement is also included in the code. Having an upper limit of column axial load level is also a ductility concern.

In TBEC-2018, which is currently in force, necessary seismic design principles are available for all building types. Naturally, since reinforced concrete building systems are quite common, the requirements for reinforced concrete structure design are given in more detail. Details of all building systems are given. Also high buildings, buildings

Table 6 Comparison of the obtained values within the scope of the last two regulations

No.	Location	TEC-2007 Seismic Zone	TEC-2007 PGA (g)	TBEC- 2018 PGA (g)	PGA 2018/ 2007	S_{DS} 2007	S_{DS} 2018	S_{DS} 2018/2007
1	Çağlayancerit	1	0.400	0.376	0.94	1	1.076	1.08
2	Göksun	3	0.200	0.296	1.48	0.50	0.843	1.69
3	Andırın	3	0.200	0.292	1.46	0.50	0.835	1.67
4	Pazarcık	1	0.400	0.470	1.18	1	1.352	1.35
5	Pazarcık	1	0.400	0.448	1.12	1	1.284	1.28
6	Türkoğlu	1	0.400	0.462	1.16	1	1.324	1.32
7	Onikişubat	1	0.400	0.328	0.82	1	0.934	0.93
8	Onikişubat	1	0.400	0.333	0.83	1	0.95	0.95
9	Onikişubat	1	0.400	0.340	0.85	1	0.971	0.97
10	Onikişubat	1	0.400	0.356	0.89	1	1.018	1.02
11	Dulkadiroğlu	1	0.400	0.364	0.91	1	1.044	1.04
12	Onikişubat	1	0.400	0.422	1.06	1	1.205	1.21
13	Dulkadiroğlu	1	0.400	0.470	1.18	1	1.339	1.34
14	Onikişubat	1	0.400	0.373	0.93	1	1.069	1.07
15	Afşin	3	0.200	0.242	1.21	0.50	0.725	1.45
16	Türkoğlu	1	0.400	0.453	1.13	1	1.292	1.29
17	Türkoğlu	1	0.400	0.448	1.12	1	1.282	1.28
18	Nurhak	2	0.300	0.408	1.36	0.75	1.153	1.54
19	Türkoğlu	1	0.400	0.467	1.17	1	1.33	1.33

with insulators, light steel buildings etc. Design principles are included in separate sections for different types of special structures such as steel, prefabricated reinforced concrete, wood, masonry etc.

TBEC-2018 has given the force and deformation-based calculation procedure in the design of structures depending on some special conditions. In addition, in the analysis of structural systems according to seismic strength, there are sections related to single-mode, multi-mode and methods in the time history analysis.

Along with TEC-2007, the performance analysis of existing structures was explained in the earthquake code and the principles of strengthening were mentioned. Therefore, earthquake safety of existing buildings has been included in the code with TEC-2007. With TBEC-2018, the earthquake performance of both existing and new structures has been explained with a similar procedure.

After the 2023 Kahramanmaraş Earthquake couples, which were effective in 11 provinces in Türkiye, moderate and heavy damage occurred in many types of structures, especially reinforced concrete, and total collapse occurred in some of the structures. In some provinces, the rate of totally collapsed buildings in the building inventory has reached 25%. A similar statistic was obtained from the relevant region after the 1999 Düzce Earthquake ($M_w = 7.2$). This situation shows that the effect of a similar magnitude earthquake that occurred 25 years later on the building stock is the same. Only 10% of the heavily damaged buildings, which constitute about 25%, were built after the 1998 code. This shows that the collapse rate of buildings built after TEC-1998 is 2%. In fact, this theoretically very high ratio (normally 10^{-6}) shows the importance of not

only designing the building stock comply with the code, but also constructing it appropriately. However, the influence of the local ground is an undeniable fact. In the section described below, the damages that occur in these building types and the causes of damage are summarized.

Damage assessment studies were carried out in 1,712,182 buildings in 11 provinces affected by the earthquake until the report was written. According to this report; It was determined that 35,355 buildings were destroyed, 17,491 buildings needed to be demolished urgently, 179,786 buildings were heavily damaged, 40,228 buildings were moderately damaged and 431,421 buildings were slightly damaged. According to the researches, 86.7 percent of the buildings in the earthquake zone are reinforced concrete. 2.4 percent of the buildings are steel, 3.5 percent masonry, and 3.6 percent prefabricated. The rest has a different structural system.

While the damages caused by the earthquake on the superstructure can be noticed immediately, since the facilities providing the drinking water and sewerage infrastructure are mostly underground, it is very difficult to determine the damage in these structures. Damages in infrastructure systems that will be affected by the earthquake can cause many problems, especially epidemic diseases. For this reason, it should be checked whether the water and wastewater infrastructure is safe after an earthquake. In order to ensure the safety of the infrastructures to be built in earthquake zones, the necessity of considering the soil properties in the infrastructure design and construction has also emerged as a result of these earthquakes. In addition, it has been observed that the design acceleration spectra in the Turkish Building Earthquake Code are far below the values measured in some regions (ODTÜ-DMAM 2023). In addition to housing damages, damages to public institutions buildings and infrastructure facilities constitute the second largest cost item. As a result of the field studies carried out in 11 provinces after these earthquakes, it was observed that many reinforced concrete highway bridges were damaged (KTU 2023). However, it was stated by the researchers that no debris or fatal outcome was reported on the highway bridges and tunnels in Kahramanmaraş city after the two earthquakes. Also, in the researches carried out by the relevant institutions, the following data on infrastructure damage are shared as shown in Table 7 (TC SBB 2023).

86.7% of the buildings are RC buildings. 2.4% of the buildings are steel, 3.5% are masonry, and 3.6% are prefabricated in the earthquake region. In the other category, there are wooden, mixed or unidentified structural systems, and the share of other structural systems is quite low. The level of masonry structures, which is the most problematic category in terms of earthquake resistance, remains low. On the other hand, it is seen that the steel

Table 7 Infrastructure damages

Infrastructure	Unit	Amount
Drinking water pipeline	km	354
Drinking water treatment plant	piece	2
Water tank	piece	45
Drinking water network	km	729
Sewerage network	km	1842
Wastewater treatment plant	piece	7
Pumping station	piece	5
Water catchment facility	piece	5

Fig. 5 Distribution of the structural System of buildings in the earthquake region (%)

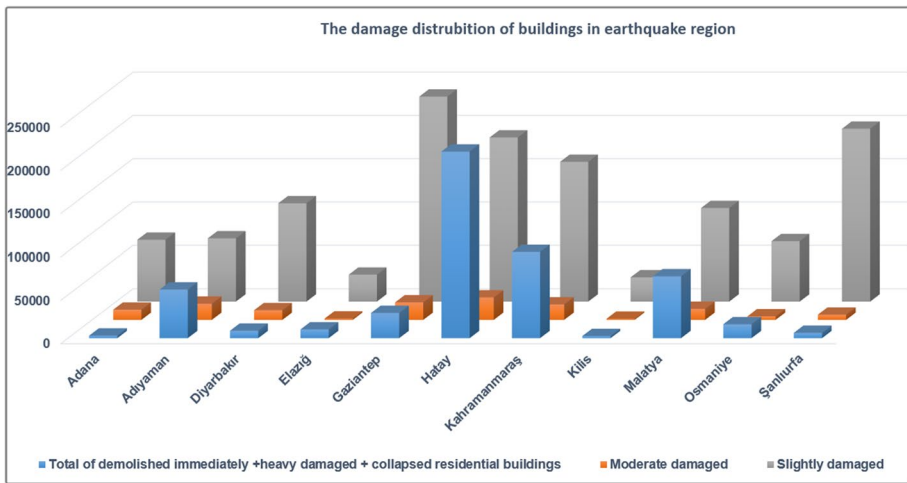
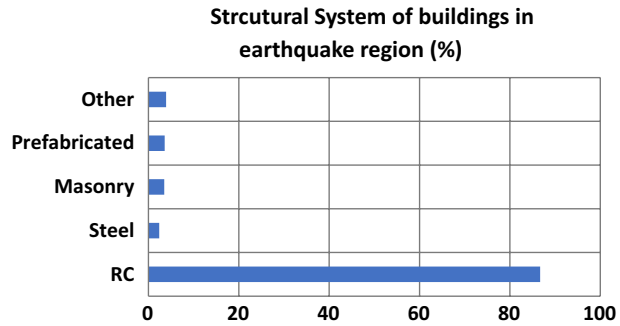


Fig. 6 The damage distribution of buildings (March 06, 2023) (T.R. Presidency, 2023)

construction structures, which are generally accepted to be resistant to earthquakes despite their high cost, are also quite low. The data shown in Fig. 5 are valid for buildings with a building permit, but buildings without a building permit are not taken into account. Therefore, data collection is also required for buildings that do not have a building permit (T.R. Presidency, 2023).

According to the results of the damage assessment study carried out by the relevant ministry as of March 06, 2023, the total of demolished immediately + heavy damaged + collapsed residential buildings was determined as 518,009. The number of moderately damaged buildings was estimated to be 131,577 and the number of slightly damaged houses to be 1,279,727 (T.R. Presidency, 2023). This damage distribution for the entire earthquake zone is shown in Fig. 6.

According to these damage assessments, the greatest structural damage occurred in the provinces of Hatay, Kahramanmaraş, Malatya and Adiyaman. From this point of view, Kahramanmaraş province, which is the epicenter of both earthquakes, is worth examining. Kahramanmaraş, which is one of the provinces most affected by the earthquake, has a total of 481,362 houses and the total population of the province is 1,177,436 according to the data in 2022. In Kahramanmaraş, 99,326 collapsed or heavily damaged buildings, 17,887

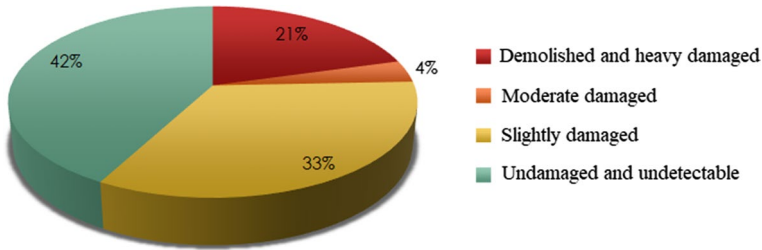


Fig. 7 Damage distribution of buildings in Kahramanmaraş (SBB 2023)



Fig. 8 Surface fractures observed in Çiğli and Kuyumcular villages

moderately damaged 161,137 slightly damaged buildings were identified. Other structures are either undamaged or it was not possible to determine whether they were damaged or not due to different reasons as shown in Fig. 7.

3.1 Fault outcrops and soil-related damage

Earthquakes cause damage to the ground surface as well as structural damage. Ground damage was observed extensively in Çiğli Village, 12 km from the epicenter, and Kuyumcular Village, 18 km from the earthquake epicenter. Cracks were formed in the land and the fault progressed in a traceable direction in a certain direction. Fault outcrops are shown in Fig. 8.

Kahramanmaraş Çiğli village was one of the places most affected by the earthquake. The effects of the fractures, which reached 2 m in width and observed in the center of Çiğli village with approximately 350 households, one of the villages most of which were destroyed in the earthquakes, are shown in Fig. 9.

Kahramanmaraş Kuyumcular village, which is one of the villages in the direction of its fault line like Çiğli village, was one of the places most affected by the earthquake. Only 3 houses survived in the village where there are 40 houses. The damage to the roads at the village entrance and inside the village or the closure of the roads due to collapsed buildings caused delays in aid and intervention. The surface damages observed in Kuyumcular village are shown in Fig. 10.



Fig. 9 Damages caused by the earthquake in Çiğli village center



Fig. 10 Earthquake-induced surface damage in Kuyumcular village

As a result of both earthquakes, transportation structures, energy, and communication facilities were also damaged significantly. Earthquakes have caused significant damage to the intercity highway network, especially bridge settlements and asphalt splits, and many connection roads have been closed to vehicle traffic due to collapses. In addition, the railway network in some parts of 11 different provinces in the earthquake zone was affected by the earthquake couple. One of them was observed around Kahramanmaraş Türkoğlu. The length of the railway line for which repair and maintenance work was carried out after the earthquakes is 1204 km (SBB, 2023). These damaged structures are shown in Fig. 11. Due to the strong ground motion, not only in the areas where there is construction but also in the open areas, major faults have occurred on the surface. Surface faulting is clearly observed and visualized (Fig. 12).

3.2 Damages in reinforced concrete structures

The fact that the reinforced concrete building stock in Turkey is very high compared to other building types, it is obvious that causing the damage to be concentrated more on



Fig. 11 Damages in transportation and communication facilities after the earthquake (Kahramanmaraş)

Fig. 12 Aerial view of surface faulting



reinforced concrete structures. This issue has been emphasized many times in the post-EQ field studies (Saatcioglu and Bruneau 1993), which started with the 1992 Erzincan (M_w 6.8) earthquake and was discussed in a wide perspective with the 1999 Marmara earthquake (M_w 7.4). What is important here is to fully understand what kind of deficiency in reinforced concrete structures causes the structures to collapse.

Before evaluating earthquake damages specifically for the load-carrier system, it is necessary to first mention the deficiencies in the design and production process of the

reinforced concrete carrier system type, which constitutes the majority of the structures in the building stock.

- (1) In reinforced concrete buildings, it is necessary to select the zoning area suitable for earthquake-resistant building design and to determine the number of floors according to the soil profile of the selected area. It experienced heavy destruction in Adapazarı and its surroundings during the 1999 Marmara Earthquake, the structures built on alluvial agricultural lands showed very poor earthquake performance. Unfortunately, although this earthquake was not very effective in the Kahramanmaraş region, this situation was clearly observed in Adıyaman, Nurdağı, and Hatay.
- (2) The lack of necessary micro studies in the construction of structures that are built on suitable soil and have the frequency feature that can overcome the earthquake without resonance, considering the characteristic corner periods (T_A and T_B) of the soil, has increased the price of demolition.
- (3) Architectural plans should also be created according to earthquake risk. It is necessary to avoid penalty parameters (especially irregularities) that will negatively affect the structural performance in TBEC-2018 and have a direct negative impact on the vulnerability of the structures. For example, the plan and vertical discontinuities in TBEC-2018 will cause poor seismic performance for earthquake-prone regions. In other words, it is beneficial for the architectural plan to be as bare as possible in this respect.
- (4) The civil engineer who will create the structural system model must be experienced in earthquake performance of buildings. The important thing here is safe design rather than economical design. It is known that the impact of the carrier system on the total cost of a reinforced concrete structure is around 35% (Öztürk et al. 2023a). According to the design to be made according to the DD-1 and DD-2 earthquake levels specified in TBEC-2018, the difference in construction cost will be around 5% (Öztürk et al., 2023b). This difference is a negligible level when the repair/strengthening and especially the loss of life after possible earthquakes in the future are considered.
- (5) It is extremely important to design the superstructure and infrastructure together. As mentioned in the previous section, soil amplification further triggered the damage to the load-bearing systems. It is extremely important to strengthen the existing ground and ensure that the foundation system fully meets the built-in conditions.
- (6) The maintenance of the structure after it is produced is the responsibility of the user. Unfortunately, changes in the structure, leaving the structure unattended against the effects of the external environment, users unconsciously damaging the structure, etc. negatively affect structural performance (Öztürk et al. 2023a, b).

In this broad perspective, although it is actually a bit difficult to evaluate the earthquake performance of a structure based only on the reinforced concrete behavior, why damages occur in reinforced concrete structures by ignoring other factors within the framework of structural engineering is explained in the following section.

Soft/weak story is an important irregularity that must be avoided due to capacity design. Totally collapse occurs especially with the hinging of ground story columns. Damages observed in reinforced concrete structures in previous earthquakes have also been observed widely in Kahramanmaraş and its districts. One of these damages is the formation of soft/weak story due to the difference in strength and stiffness between floors. A sample of such

damage is shown in Fig. 13. This type of irregularity, which is frequently encountered in residential buildings, is caused by the fact that the entrance floors of the buildings are high and the infill walls are not made in order to make the buildings more functional for commercial purposes, causing more horizontal displacement of the lower floors during the earthquake. As a result, the carrier system is severely damaged. In short, the difference in strength and/or stiffness between floors in the building is the main reason for such damages.

Non-compliance with the capacity design in the column-beam connection areas; It can occur in two situations, i) the size and moment carrying capacity of the beams at the node (joint) are greater than those of the columns and ii) Insufficient shear capacity in the column-beam connection area. Collapses in multi-story reinforced concrete structures fail as a result of an earthquake, causing floors to fall on top of each other is the most serious type of damage. As a result of factors such as insufficient RC frame connection (especially column-beam joints), faulty reinforcement, and strong beam-weak column, column-beam connections weaken and complete collapses occur. Examples of such structural damage are shown in Fig. 14. These collapses, which occur as a result of the failure of the load-bearing elements to show the necessary resistance against lateral loads (earthquake load) and their rupture or breakage from the column-beam connection points, are also called complete



Fig. 13 Buildings collapsed as a result of soft/weak story mechanism



Fig. 14 Sample of pancake total collapse

collapses in the form of stacking of floors called "pancakes." As a result of the articulation of the columns in the building, all floors collapsed by piling on top of each other.

Hammering (pounding) possibilities due to adjacent structures; Buildings may collide and collapse, especially due to reasons such as insufficient dilatation gaps between adjacent buildings, the floors in the load-bearing system being at different elevations, and the natural vibration frequencies of the buildings being different. In the case of adjacent reinforced concrete buildings having different floor levels, the shear forces that will occur create additional shear forces on the vertical structural elements of the other structure, causing the shearing capacities of these columns to be exceeded. Likewise, if one of the neighboring structures collides with other structures as a result of the collapse, an extra shear force may also occur. Examples of column damage where the predicted shear capacity is exceeded due to the additional shear forces formed in the columns due to the pounding effect are shown in Fig. 15.

An RC structure example of a collapsed to the side, with an insufficient reinforced concrete frame, and plastic hinge formed primarily at the lower ends of the ground floor columns, is shown in Fig. 16.

An example of damage in the type of partial collapse of the RC structure in the vertical direction is shown in Fig. 17. Vertical collapse or heavy damage occurred in the same area on each floor of the building. Torsion effect, plastic hinge starting at ground floor columns



Fig. 15 Examples of RC columns heavily damaged by the impact of pounding



Fig. 16 Example of a building collapsing to the side

Fig. 17 The collapse of a part of the structure in the vertical direction



and continuing to upper floors, beam-column discontinuities, strong beam-weak column, and low-strength reinforced concrete are among the main causes of this type of damage.

The collapse mechanism in the form of lateral collapse is caused by the formation of plastic hinges primarily in the columns, insufficient reinforcement, low-strength material, and RC frame insufficiency. An example of this damage mechanism is shown in Fig. 18. The main reason for this damage, which can classify as slumping damage, is that the system reaches the lateral collapse mechanism as a result of the formation of plastic hinges in the columns (construction of strong beams, weak columns, not paying attention to the confinement of stirrups, poor concrete quality).

Short column formation is a structural weakness situation specified in TBEC-2018, and sudden shear damage occurs, especially in ground floor columns. Short column damage caused by the change of column height due to different reasons in the building has also been observed widely. Short column damage, especially due to the use of band-type windows, is shown in Fig. 19. In this case, buckling problems in longitudinal reinforcement were clearly observed as a result of crushing in low-strength core concrete. Short columns,

Fig. 18 Lateral collapse (accordion) damages



Fig. 19 Short column damages due to band-type windows

which are created in the design phase or later in building structures, are structural elements with high rigidity and low ductility. Due to their high rigidity, they are exposed to small displacements despite large horizontal forces during earthquakes. This situation causes the columns to collapse by losing strength due to shear failure.

Infill wall placement, if done properly, is a great gain for structural performance. Otherwise, a soft and weak story situation may be triggered and building torsion may occur. In addition, displacement controls for the frames must be made separately depending on whether these elements are adjacent to the frame or separate in the design. In RC structures, X-shaped shear cracks are commonly encountered in the infill walls, which are built to separate spaces and due to external effects, have low shear and tensile stress capacity. Such damage is shown in Fig. 20. In addition, out-of-plane failure-type damages were observed on these walls with insufficient connections.

Column directions in the plan should have equal stiffness as much as possible. This is also important in the context of strong column-weak beam. Rigidity, strength and ductility are the main factors to consider in the design of reinforced concrete structures. One of the conditions required to meet these principles is sizing. Dimensional compatibility



Fig. 20 Examples of infill wall damage

of load-bearing elements with each other has an important place in earthquake-resistant building design specifications. The load-bearing structural elements with size compatibility between them perform the load transfer in a healthier way. Columns are recommended to be stronger than beams in earthquake design codes. Because the beams only carry self-weight together with the loads coming from the slabs and walls on the floors they are located. However, in addition to all these loads, the columns also carry self-weight and the loads coming from the upper floors. In this case, the hinges are formed at the upper ends of the columns, causing the columns to separate from the beams, resulting in damage (Fig. 21).

Structural member detailing must comply with TBEC-2018. Inadequate or unsuitable use of reinforcements used to resist tensile stresses in reinforced concrete buildings at column-beam joints and poor workmanship also cause structural damage at various levels. In such damages, the concrete cover is damaged first, followed by a buckling of the longitudinal reinforcements, where inadequate transverse reinforcement is not used. (Fig. 22).

In the last two seismic design codes used in Türkiye, the conditions related to the transverse reinforcement to be used in the RC columns are shown in Fig. 23.



Fig. 21 Damages caused by strong beams and weak columns



Fig. 22 Damages due to low-strength concrete and lack of reinforcement

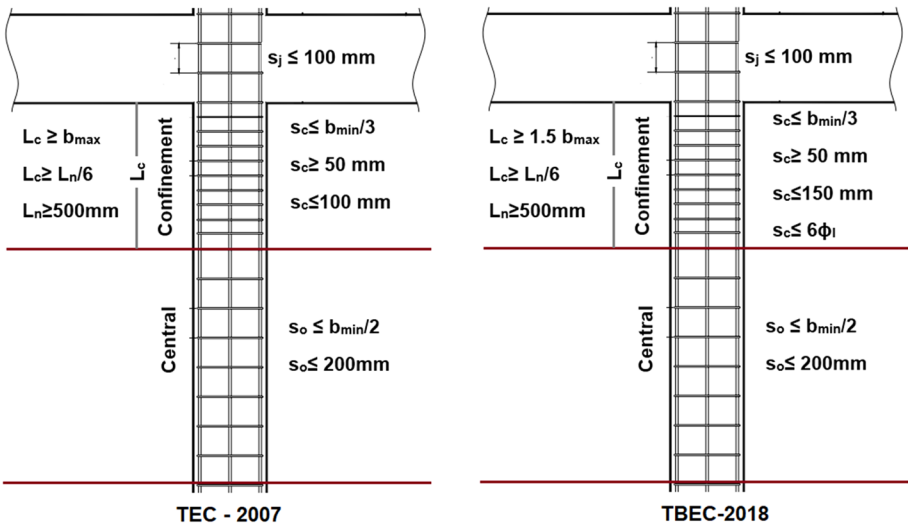


Fig. 23 The requirements of transverse reinforcement for columns in TEC-2007 and TBEC-2018

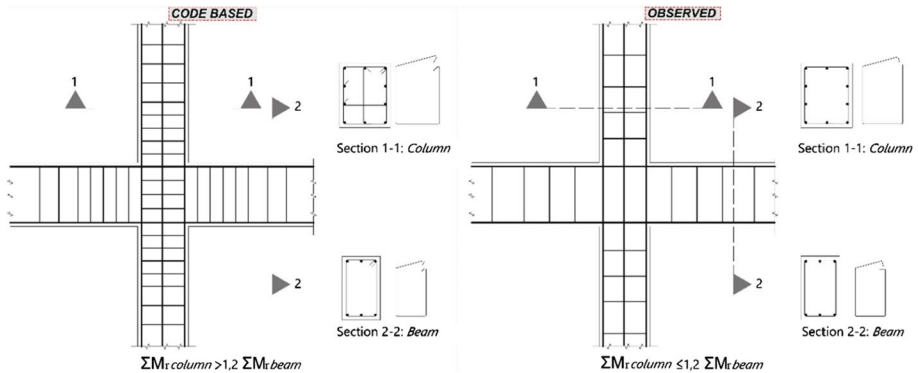


Fig. 24 Comparison of the reinforcement detail according to the code and observed in the field

As seen in Fig. 24, it is seen that the transverse reinforcement gaps in the beam-column joint, confinement, and middle region are exceeded. It has been observed that in some regions of the columns, the transverse reinforcements are not used at all. In addition, it has been determined that the special earthquake stirrups, which are obligatory in TBEC-2018, are not used at all. In addition to these, the transverse rebar's fixed to the longitudinal rebar at 90° instead of 135° . This prevented the transverse and longitudinal reinforcements from working together during the earthquake and caused them to separate from each other. In addition, although a strong column-weak beam is foreseen in the regulation, the weak column-strong beam is created in practice. A comparison of the code and observed conditions in the field of all these cases is shown schematically in Fig. 24.

The main causes of damage in reinforced concrete buildings are inadequate concrete quality, use of non-ribbed (flat) reinforcement, construction on unsuitable floors, design of the carrier system as hollow slab, heavy and long cantilever protrusions, and stores/shops with higher story heights on the lower floors of the buildings were determined. The main causes of damage in masonry buildings were determined as insufficient material properties of binders and masonry units, weak bearing walls due to lack of bond-beam and lintel, and inappropriate connection details. In addition, poor workmanship and lack of application details in reinforced concrete caused the development and progression of damages.

Finally, the provinces that are expected to generate the most earthquake waste are Hatay, Kahramanmaraş, Malatya, Gaziantep, and Adıyaman, which were most affected by the earthquake. Therefore, the need for temporary and final storage space for earthquake wastes is highest in these provinces. In this respect, the capacity of the existing fields should be determined primarily, and if necessary, new temporary and final storage areas should be determined. Necessary occupational health and safety measures should be taken in the process of demolition of buildings, transportation, and management of waste.

The schematic representations of structural damage observed in reinforced concrete structures in general are shown in Fig. 25.

3.3 Observed damages in masonry structures

In this part of the study, the typical damages that occur in masonry structures as a result of field observations are taken into account. The damages are examined as damage to the window and door openings, load-bearing wall damages, structural damage that occurred at

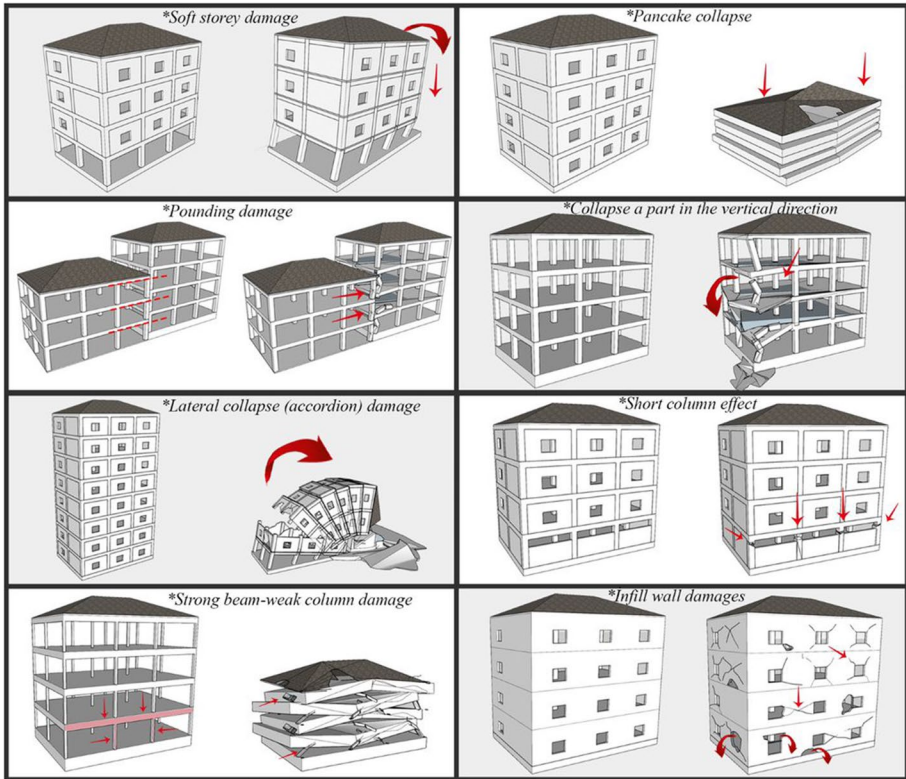


Fig. 25 The schematic representations of the structural damage in RC structures

different levels due to the separation of the load-bearing wall corners, and damage to the non-structural building members. One of the frequently encountered problems in masonry structures under the effect of seismic load is cracking in window openings. These cracks often involve weaker sections such as corners or junctions of structural members. In the examinations made after the earthquakes, it was observed that most of the masonry structures in Kahramanmaraş were structurally damaged due to cracks in these regions. These findings play an important role in better understanding the behavior of masonry structures in earthquakes and determining the measures to be taken to strengthen the structures. Damages caused by window openings are shown in Fig. 26.

Another common type of damage seen in masonry structures is the type of damage caused by the out-of-plane movement of the wall. The reason for the out-of-plane behavior is due to the low resistance of the load-bearing walls against out-of-plane forces. By making the connection of the walls with the foundation and the roof and wall connections strong, it can help to transmit lateral loads to the structure better and make the wall more resistant to damage caused by out-of-plane movements. Damages caused by out-of-plane movement on load-bearing walls are shown in Fig. 27.

Splitting damage is a damage that is usually seen at the corner points where two walls join. Cracks or splits can occur when masonry structures are subjected to horizontal or vertical loads in areas such as joints or corners. Insufficient connection or



Fig. 26 Damages caused by window openings



Fig. 27 Out-of-plane movement damages load-bearing walls

clamping at the corner points of the load-bearing walls is the main reason for this damage. Especially as a result of the concentration of horizontal loads at these points and exceeding the bearing capacity, cracks or separations can be seen at the wall joints or corners. Examples of such damage are shown in Fig. 28.

Examples of damaged structures containing mixed materials are shown in Fig. 29. This type of damage was caused by the lack of sufficient connections during the layering of different wall materials.



Fig. 28 Splitting damage at the wall corners



Fig. 29 Damages caused by the use of different wall materials and insufficient connection

Damages were also observed in the confined masonry structures. The difference in strength/rigidity between floors was caused by the soft-story mechanism. An example of such damage is shown in Fig. 30. Since the gap between the load-bearing walls on the left side of the building is less than on the right side of the building, the building has reached the collapse mechanism from the right side.

As a result of the observations made in rural areas after the Kahramanmaraş earthquakes, it was seen that the structure collapsed as a result of the damage to some heavy earthen roofs. Such heavy earthen roofs under the influence of the earthquake, together with the vertical acceleration component of the earthquake, push the load-bearing walls out/inside the plane. In this case, these walls, which do not have sufficient connection



Fig. 30 Soft-story damage in a confined masonry structure

with the roof and have poor in-plane/out-of-plane rigidity, cannot transfer the load correctly, experience a sudden loss of strength and the walls collapse together with the roof. In buildings with heavy earthen roofs, the rate of destruction is higher when combined with factors such as the use of materials with low strength, the inability to provide the necessary and sufficient connection between the walls, and the excess of door and window openings. Examples of damage that caused the total collapse of the structure as a result of additional earthquake forces due to heavy earthen roofs are shown in Fig. 31.

Un-reinforced masonry buildings are the most common type of masonry structure in the rural areas in the earthquake region. In order to produce the rigid diaphragm effect in such buildings, reinforced masonry buildings, and enclosed masonry buildings, RC slabs with a thickness of at least 100 mm will be made according to TBEC-2018. This slab will be supported by horizontal beams with a minimum section height of 300 mm and reinforcing in the lengths of $6 \Phi 12$ and $\Phi 8/150$ mm. The width of the horizontal beams will be at least as much as the wall thickness. The vertical spacing of the horizontal beams shall not exceed 4 m. RC lintels will be built above the door and window spaces. The length of

Fig. 31 Heavy damage due to heavy earthen roofs





Fig. 32 The schematic representations of the structural damage in masonry structures



Fig. 33 Examples of industrial structures after the failure of the pinned beam-column connection

the parts of the lintels that rest on the wall shall not be less than 200 mm. The lintel height shall not be less than 150 mm (TBEC 2018). In addition, if the height of the gable walls of the roof resting on the horizontal beam on the top floor is greater than 0.80 m, vertical and inclined beams should be made. It can be seen from the visuals about the masonry building damages that these rules are not followed in these structures, which are already built without any engineering service.

The schematic representations of the structural damage observed in masonry structures in general are shown in Fig. 32.

3.4 Observed precast building damages

The majority of prefabricated buildings in Türkiye have 10–25 m beam spans and double slope roof beams and typically have a rectangular plan. Typically, columns are quite thin (especially in the direction perpendicular to the main axis), and beam-column connections lack mechanical connectors. At mid-span, the main beams’ cross-sectional depth may reach 2 m. When the prefabricated structures damaged during the earthquake are examined, it is seen that the resistance against horizontal earthquake forces remains low due to the weaknesses in the joint of the structural members. Prefabricated structures, which are the most common beam-column connections with steel dowels (pinned connections) in industrial buildings, have been heavily damaged. Especially the prefabricated structures in which wide span and heavy roof beams are used have been damaged due to the inadequate

anchorage of the beam to the column as shown in Fig. 33. The dapped-ended purlin beams collapsed together with the roof beams.

The most important advantages of prefabricated reinforced concrete structures are that they are produced in a factory environment and a controlled manner. However, their biggest weakness is that they are assembled in the field and the connections are not controlled as meticulously as the production in the factory. For this reason, the lack of detailing in the joint areas and insufficient control in the field constitute the weakest link of these structures. In these structures, which are very close to isostatic systems in terms of structural setup, the energy that will emerge in the event of an earthquake can only be damped in the column-socket joint areas. In these structures, which have lower global rigidity than conventional reinforced concrete structures due to the joints formed generally at the roof plane and the mezzanine level, the high displacement demand that occurs in the event of an earthquake causes plastic deformation in the column bases and many structures become hinged from these regions and become plastic hinge mechanisms. Figure 34 shows a column-socket joint with such a mechanism. The absence of damage to the socket system shows that this foundation provides fixed boundary conditions like other single foundations. However, field observations have shown separations in the tie beams connecting the socket tops. In this case, it caused the foundation system to move independently and thus the columns to displace independently from each other. This is one reason why roof beams are disconnected from the short cantilever connection. In prefabricated structures, especially the precast panels on the outer axes increase the rigidity of the outer perpendicular to the frame, while the absence of any walls in the inner axes due to manufacturing reduced their rigidity, and more displacements in the inner columns and separations in the roof plane occurred. Apart from this, the half-precast panels on the outer axes and the shear walls caused the formation of short columns in these regions. The fact that the coatings (usually double layered sandwich) on the roof plane and the purlin beams were not



Fig. 34 Plastic hinges formed at the base of the column

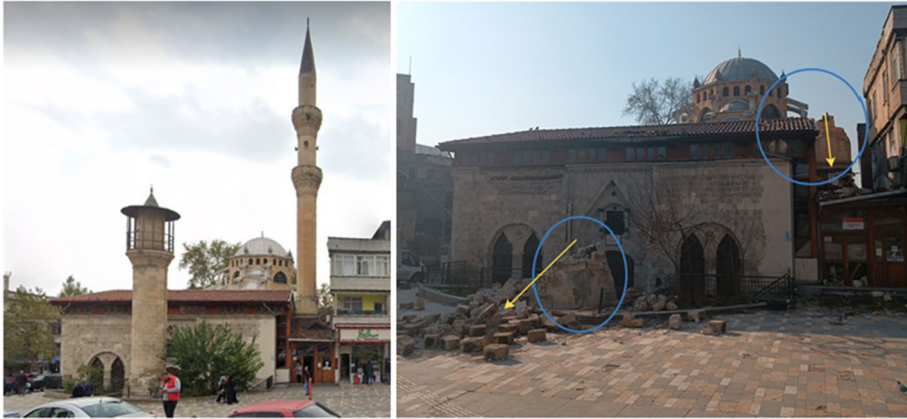


Fig. 35 Arasa Mosque and its minaret before the earthquake (google earth), after the earthquake (by authors)



Fig. 36 Examples of minarets damage

connected to the purlin beams with the number and quality of tie rods specified in TBEC-2018 also caused insufficient rigid diaphragm formation.

3.5 Observed minarets and mosques damages

The most damaged structures in Kahramanmaraş and its districts are minarets and mosques. Many structures of this type have suffered significant damage and have become unusable. The images of the Arasa mosque and minaret before and after the earthquake are shown in Fig. 35. Both minarets of the mosque have been destroyed from the areas where the cross-sections changed. Minarets generally have circular or polygonal cross-section geometries. They consist of different sections, and these regions, where geometric changes in different regions occur, cause stress concentrations under lateral loading such as earthquakes. As a result, stress accumulates in those regions and when the bearing capacity exceeds, damages and often collapses occur in those regions. Therefore, by ensuring that the transitions between these regions are smooth, stress concentration can be reduced and damage can be prevented with a more balanced stress distribution. In addition, the selection of materials

with high durability and flexibility may enable them to be more resistant to stresses that may occur under earthquake loads. Significant damage occurred on the load-bearing walls of the mosque. Various minaret damages are shown in Fig. 36.

The mosque and its shadirvan, which were built as reinforced concrete, collapsed during the earthquake (Fig. 37). Insufficient reinforced concrete frames, low-strength concrete, and transverse reinforcement have caused this damage.

4 Discussion

If the seismic performance of an existing building is not sufficient (if the structure cannot adequately respond to the related seismic activity demand in terms of both strength and displacement), the structure must be strengthened. Re-construction cost of the structure is an important criterion in retrofitting/strengthening processes. It may be considered appropriate to retrofit, especially if the re-construction cost does not exceed 35–40%.

How to do the strengthening is not defined in past dated codes such as TEC-1975 and TEC-1998. In TEC-2007, a new section was created for retrofitting/strengthening and determination of the seismic performance of the structure. With TBEC-2018, the relevant section has been further developed.

In TBEC-2018, necessary controls are requested in terms of both deformation-displacement and force. In retrofitting, in accordance with the philosophy of earthquake engineering, it should be aimed to eliminate the ductility, strength and rigidity concerns. However, it is clear that only gaining rigidity will not be sufficient in a building where ductility-related measures are not taken. Similarly, while an increase in strength occurs, a sufficient increase in ductility must also be achieved.

It has been observed that the capacity design principles are not complied with in all of the buildings that were heavily damaged or totally collapsed in the 2023 Kahramanmaraş Earthquakes. According to the capacity design principle, in order to respond to the earthquake displacement demand, the structures must first reach sufficient strength without



Fig. 37 The partial and total collapse of the mosque and its Shadirvan

reaching brittle damage, and then be able to respond to the displacement demand of the earthquake by forming plastic hinges in appropriate places.

These principles should also be taken into consideration in the strengthening of buildings that have somehow survived the earthquake. However, since the characteristics of each building are different from each other, it is clear that much more analysis and field control is required in retrofitting than in new construction.

Strengthening processes should be preferred in accordance with the existing characteristics of the building, ground condition and usage situation. Conventionally, jacketing the columns with reinforced concrete, adding shear walls to the load-carrier system (external or internal), increasing the thickness of the foundation system are well-known methods. The effect of these on performance is undoubtedly very positive and there are many studies on this subject in the literature. In addition, the addition of steel systems to the existing structure, the use of FRP materials, etc. can be preferred in methods such as time and architectural reasons. Their construction cost and construction time should be optimized. In addition, the additional costs of the elements that may require continuous maintenance after construction should be considered.

Unfortunately, the recent earthquakes once again reinforced the impression that heavy damage occurred after the earthquake, even in newly constructed buildings, especially due to insufficient field controls (engineering services). For this reason, the probability of achieving the desired performance is low in case of insufficient design and especially field control in retrofitting/strengthening operations.

5 Conclusions and suggestions

The earthquakes that occurred on the Eastern Anatolian Fault on February 06, 2023, caused very significant loss of life and structural damage in 11 different provinces. The highest acceleration values for these earthquakes were measured in Kahramanmaraş and its districts. In Kahramanmaraş, where the districts of Pazarcık and Elbistan are located, which are the epicenters of both earthquakes, great destruction, and damage occurred in all kinds of structures. Kahramanmaraş, which is located on the Eastern Anatolian Fault, which is one of the main tectonic elements of Türkiye and where the earthquake risk is very high, is not very sensitive to earthquakes. Reinforced concrete, prefabricated, and masonry structures have suffered very significant damage due to structural defects, and as a result, a large-scale loss of life and property has been caused. However, the fact that both earthquakes were large earthquakes and very close to the surface, and more importantly, occurred at intervals of 9 h, greatly affected the level of structural damage.

Structural damage at different levels has occurred in masonry structures built without any engineering service, especially in rural areas. The low strength of the stone walls used in masonry structures was the main reason for the damage. Heavy earthen roofs, insufficient clamping at the corners, insufficient adherence between different material layers, low-strength mortar, poor masonry, and not using the necessary horizontal and vertical bond beams have increased the damage levels.

In the RC buildings examined by the authors, the main causes of damage can be listed as; beams in which plastic hinges are formed by exceeding the bearing capacity, buckling of longitudinal reinforcement due to insufficient confinement reinforcement, use of plain reinforcement rebar as reinforcement in general old type structures, not using special earthquake confinement bar, the used aggregate is taken from the stream and used without any

processing, excessive segregation in concrete, use of low-strength concrete, not bending of confinement bar by 135° , insufficient use of reinforced concrete (reinforcement and concrete), not using RC shear-wall, no confining reinforcement is used in column-beam joint areas, almost no crossties are used in shear walls and columns, etc. In short, it has been observed that the capacity design and ductile detailing principles mentioned in earthquake regulations since 1998 (TEC-1998, TEC-2007, and TBEC-2018) have not been complied with. In addition to these, failure to take the necessary care in the construction phase and not complying with the project negatively affect the damage levels.

Minarets are built by local minaret masters without any engineering service. These high and slender structures have been damaged especially at the points where the cross-section geometry changes.

The use of prefabricated buildings is increasing day by day in both industrial and residential buildings. Prefabricated building elements, which are produced with high strength in the factory, are put into use by being assembled in the places where they will be located. In the examinations made in the disaster area after the earthquake, it was observed that some prefabricated structures were destroyed and damaged at various levels. The most important reason for the failure in the examinations is that the structural elements cannot carry the earthquake load due to connection weaknesses. Especially in TBEC-2018, a limited number of buildings with special design criteria and conditions required for prefabricated structures were observed. In this situation, it has been seen that this type of building, which requires more special design principles unlike conventional reinforced concrete buildings, requires expertise in both the design and manufacture of this building and that the number of buildings that receive this service in practice is limited.

As a result of the damage observations made by the authors in the field, their suggestions are presented below:

Masonry structures, which make up the majority of the building stock in rural areas, should be eligible for engineering services. Because the construction of such structures is frequently done subconsciously, without taking into account earthquake loads and other important factors. One method of minimizing damage from future earthquakes will be to demolish extremely old masonry structures, regardless of their level of damage, and replace them with projects that offer the best design principles for each rural region.

It is important for buildings designed in accordance with earthquake-resistant building design rules to receive the necessary engineering services in practice. Under the influence of this earthquake, the importance of the concept of strength and dimension for reinforced concrete structures has appeared once again.

Appropriate foundation design should be made as a result of knowing all the details of the local soil conditions and if necessary, soil and foundation strengthening.

It would be beneficial to make the basement mandatory in buildings with 3 and higher stories.

Adjacent structures should be abandoned and dilatation joints suitable for the technique should be used in cases of necessity. In addition, care should be taken to ensure that the floor levels in adjacent structures are at the same level as neighboring structures.

The construction of buildings with heavy overhangs should be abandoned.

Prohibition of making floor height changes in the mezzanine and inside the building in order to prevent the formation of soft/weak stories in buildings other than buildings with commercial and industrial structures will provide additional benefits in preventing loss of property and life during the earthquake.

It should be made mandatory for the masters who have the Professional Competence Certificate to take part in the building inspection system, and the signatures of these

masters should be obtained for the sections that concern them. In this way, it will be possible to produce according to the project with a sense of responsibility.

In the current earthquake code, the use of shear walls is mandatory only in basements. Consideration should be given to the creation of reinforced concrete shear walls at the rates to be determined in all kinds of reinforced concrete buildings to be built in the new design phase.

For concrete casting; in order to pay maximum attention to vital issues such as concrete preparation, transportation, temperature, weather conditions, pouring time, compaction, taking test samples, post-casting maintenance and curing, building inspection organizations, municipal engineers, and site supervisors should be warned and adequate inspections should be made.

With the health monitoring of the building, any changes to be made after the use of the building should be followed.

The high stock of existing buildings does not make detailed performance analyses of such structures possible in terms of time, economy, and personnel. Therefore, regional risk priorities can be determined for existing structures by using rapid assessment methods. Thus, there will be a significant reduction in the number of buildings to be examined in detail.

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References

- Adalier K, Aydingun O (2001) Structural engineering aspects of the June 27, 1998 Adana-Ceyhan (Turkey) earthquake. *Eng Struct* 23(4):343–355. [https://doi.org/10.1016/S0141-0296\(00\)00046-8](https://doi.org/10.1016/S0141-0296(00)00046-8)
- Ademović N, Kalman Šipoš T, Hadzima-Nyarko M (2020) Rapid assessment of earthquake risk for Bosnia and Herzegovina. *Bull Earthq Eng* 18:1835–1863. <https://doi.org/10.1007/s10518-019-00775-1>
- Ahmad N, Ali Q, Crowley H, Pinho R (2014) Earthquake loss estimation of residential buildings in Pakistan. *Nat Hazards* 73(3):1889–1955. <https://doi.org/10.1007/s11069-014-1174-8>
- Alkan H, Büyüksaraç A, Bektaş Ö (2023) Investigation of earthquake sequence and stress transfer in the Eastern Anatolia Fault Zone by Coulomb stress analysis. *Turk J Earth Sci* (in press)
- Alkan H, Büyüksaraç A, Bektaş Ö, Işık E (2021) Coulomb stress change before and after 24.01.2020 Sivrice (Elazığ) Earthquake (Mw= 6.8) on the East Anatolian Fault Zone. *Arab J Geosci* 14(23):1–12. <https://doi.org/10.1007/s12517-021-09080-1>
- Arslan MH, Korkmaz HH (2007) What is to be learned from damage and failure of reinforced concrete structures during recent earthquakes in Turkey? *Eng Fail Anal* 14(1):1–22
- Arslan MH, Korkmaz HH, Gulay FG (2006) Damage and failure pattern of prefabricated structures after major earthquakes in Turkey and shortfalls of the Turkish Earthquake code. *Eng Fail Anal* 13(4):537–557. <https://doi.org/10.1016/j.engfailanal.2005.02.006>
- Bakır BS, Yılmaz MT, Yakut A, Gülkan P (2005) Re-examination of damage distribution in Adapazarı: geotechnical considerations. *Eng Struct* 27(7):1002–1013. <https://doi.org/10.1016/j.engstruct.2005.02.002>
- Bayraktar A, Altunışık 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. <https://doi.org/10.1016/j.soildyn.2013.06.004>
- Bayraktar A, Altunışık AC, Muvafık M (2016) Field investigation of the performance of masonry buildings during the October 23 and November 9, 2011, Van Earthquakes in Turkey. *J Perform Constr Facil* 30(2):04014209. [https://doi.org/10.1061/\(ASCE\)CF.1943-5509.0000383](https://doi.org/10.1061/(ASCE)CF.1943-5509.0000383)

- Bilgin H, Shkodrani N, Hysenlliu M, Ozmen HB, Isik E, Harirchian E (2022) Damage and performance evaluation of masonry buildings constructed in 1970s during the 2019 Albania earthquakes. *Eng Fail Anal* 131:105824. <https://doi.org/10.1016/j.engfailanal.2021.105824>
- Bruneau M (2002) Building damage from the Marmara, Turkey earthquake of August 17, 1999. *J Seismolog* 6:357–377. <https://doi.org/10.1023/A:1020035425531>
- Bülbül MA, Harirchian E, Işık MF, Aghakouchaki Hosseini SE, Işık E (2022) A hybrid ANN-GA model for an automated rapid vulnerability assessment of existing RC buildings. *Appl Sci* 12(10):5138. <https://doi.org/10.3390/app12105138>
- 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. <https://doi.org/10.1007/s11069-012-0478-9>
- Celep Z, Erken A, Taskin B, Ilki A (2011) Failures of masonry and concrete buildings during the March 8, 2010 Kovancilar and Palu (Elazığ) earthquakes in Turkey. *Eng Fail Anal* 18(3):868–889. <https://doi.org/10.1016/j.engfailanal.2010.11.001>
- Clifton C, Bruneau M, MacRae G, Leon R, Fussell A (2011) Steel structures damage from the Christchurch earthquake series of 2010 and 2011. *Bull N Z Soc Earthq Eng* 44(4):297–318. <https://doi.org/10.5459/bnzsee.44.4.297-318>
- Damcı E, Temur R, Bekdaş G, Sayin B (2015) Damages and causes on the structures during the October 23, 2011 Van earthquake in Turkey. *Case Stud Constr Mater* 3:112–131. <https://doi.org/10.1016/j.cscm.2015.10.001>
- Dogan G, Ecemis AS, Korkmaz SZ, Arslan MH, Korkmaz HH (2021) Buildings damages after elazığ, Turkey earthquake on January 24, 2020. *Nat Hazards* 109(1):161–200. <https://doi.org/10.1007/s11069-021-04831-5>
- Doğan GG, Yalçınar AC, Yuksel Y, Ulutaş E, Polat O, Güler I, Şahin C, Tarih A, Kânoğlu U (2021) The 30 October 2020 Aegean Sea tsunami: post-event field survey along Turkish coast. *Pure Appl Geophys* 178(3):785–812. <https://doi.org/10.1007/s00024-021-02693-3>
- Doğangün A, Tuluk Ö, Livaoglu R, Acar R (2006) Traditional wooden buildings and their damages during earthquakes in Turkey. *Eng Fail Anal* 13(6):981–996
- Evans NL, McGhie C (2011) The performance of lifeline utilities following the 27th February 2010 Maule Earthquake Chile. In: *Proceedings of the ninth Pacific conference on earthquake engineering building an earthquake-resilient society*, pp. 14–16
- Giovinazzi S, Wilson TM, Davis C, Bristow D, Gallagher M, Schofield A, Villemure M, Eiding J, Tang A (2011) Lifelines performance and management following the 22 February 2011 Christchurch earthquake New Zealand: highlights of resilience. *Bull New Zealand Soc Earthq Eng*. <https://doi.org/10.5459/bnzsee.44.4.402-417>
- Goda K, Kiyota T, Pokhrel TM, Chiaro G, Katagiri T, Sharma K, Wilkinson S (2015) The 2015 Gorkha Nepal earthquake: insights from earthquake damage survey. *Front Built Environ* 1:8. <https://doi.org/10.3389/fbuil.2015.00008>
- Hadzima-Nyarko M, Mišetić V, Morić D (2017) Seismic vulnerability assessment of an old historical masonry building in Osijek, Croatia, using Damage Index. *J Cult Herit* 28:140–150. <https://doi.org/10.1016/j.culher.2017.05.012>
- Inel M, Ozmen HB, Bilgin H (2008) Re-evaluation of building damage during recent earthquakes in Turkey. *Eng Struct* 30(2):412–427. <https://doi.org/10.1016/j.engstruct.2007.04.012>
- Inel M, Ozmen HB, Akyol E (2013) Observations on the building damages after 19 May 2011 Simav (Turkey) earthquake. *Bull Earthq Eng* 11(1):255–283. <https://doi.org/10.1007/s10518-012-9414-3>
- Işık E (2023) Structural failures of adobe buildings during the February 2023 Kahramanmaraş (Türkiye) earthquakes. *Appl Sci* 13(15):8937. <https://doi.org/10.3390/app13158937>
- Işık E, Işık MF, Bülbül MA (2017) Web based evaluation of earthquake damages for reinforced concrete buildings. *Earthq Struct* 13(4):423–432
- Işık E, Avcil F, Büyüksarac A, İzol R, Arslan MH, Aksoylu C, Harirchian E, Eysüren O, Arkan E, Güngür MŞ, Günay M, Ulutaş H (2023) Structural damages in masonry buildings in Adiyaman during the Kahramanmaraş (Türkiye) earthquakes (Mw 7.7 and Mw 7.6) on 06 February 2023. *Eng Fail Anal* 151:107405. <https://doi.org/10.1016/j.engfailanal.2023.107405>
- Isik E, Aydin MC, Buyuksarac A (2020) 24 January 2020 Sivrice (Elazığ) earthquake damages and determination of earthquake parameters in the region. *Earthq Struct* 19(2):145
- Kaltakci MY, Arslan MH, Yilmaz US, Arslan HD (2008) A new approach on the strengthening of primary school buildings in Turkey: an application of external shear wall. *Build Environ* 43(6):983–990
- Kam WY, Pampanin S, Elwood K (2011) Seismic performance of reinforced concrete buildings in the 22 February Christchurch (Lyttleton) earthquake. <https://doi.org/10.5459/bnzsee.44.4.239-278>


- Kaplan H, Yılmaz S, Binici H, Yazar E, Çetinkaya N (2004) May 1, 2003 Turkey—Bingöl earthquake: damage in reinforced concrete structures. *Eng Fail Anal* 11(3):279–291
- Ko YY, Tsai CC, Hwang JH, Hwang YW, Ge L, Chu MC (2023) Failure of engineering structures and associated geotechnical problems during the 2022 ML 68 Chihshang earthquake, Taiwan. *Nat Hazards*. <https://doi.org/10.1007/s11069-023-05993-0>
- Koç V (2016) Deprem sonrası ağır hasarlı bina hasarlarının sınıflandırılması, (Classification of heavy damaged building damages after earthquake). *Artvin Çoruh Univ Nat Disast Appl Res Center J Nat Hazards Environ Turkish* 2(1):46–65
- Kocaman İ (2023) The effect of the Kahramanmaraş earthquakes ($M_w = 7.7$ and $M_w = 7.6$) on historical masonry mosques and minarets. *Eng Fail Anal* 149:107225. <https://doi.org/10.1016/j.engfailanal.2023.107225>
- Koçer M, Ünal A (2023) RC structural damages observed after October 30, 2020, Seferihisar—İZMİR earthquake and analytical evaluation of existing sample RC buildings. *Nat Hazards* 117(1):237–265. <https://doi.org/10.1007/s11069-023-05858-6>
- Korkmaz SZ (2015) Observations on the Van earthquake and structural failures. *J Perform Constr Facil* 29(1):04014033. [https://doi.org/10.1061/\(ASCE\)CF.1943-5509.0000456](https://doi.org/10.1061/(ASCE)CF.1943-5509.0000456)
- KTU (2023) 6 Şubat 2023 Kahramanmaraş-Pazarcık $M_w=7.7$ ve Elbistan $M_w=7.6$ Depremleri ve Artçıları, Saha Gözlemlerini, Yapısal Hasarları ve İleriye Yönelik Önerileri İçeren Değerlendirme Raporu
- Kumar A, Hughes PN, Sarhosis V, Toll D, Wilkinson S, Coningham R, Maskey PN (2020) Experimental, numerical and field study investigating a heritage structure collapse after the 2015 Gorkha earthquake. *Nat Hazards* 101:231–253. <https://doi.org/10.1007/s11069-020-03871-7>
- Lagomarsino S (2012) Damage assessment of churches after L'Aquila earthquake (2009). *Bull Earthq Eng* 2009(10):73–92. <https://doi.org/10.1007/s10518-011-9307-x>
- Langenbach R (2008) Resisting earth's forces: typologies of timber buildings in history. *Struct Eng Int* 18(2):137–140. <https://doi.org/10.2749/101686608784218806>
- Lemnitzer A, Arduino P, Dafni J, Franke KW, Martinez A, Mayoral J, El Mohtar C, Pehlivan M, Yashinsky M (2021) The September 19, 2017 MW 7.1 CENTRAL-Mexico earthquake: immediate observations on selected infrastructure systems. *Soil Dyn Earthq Eng* 141:106430. <https://doi.org/10.1016/j.soildyn.2020.106430>
- Mahin SA (1998) Lessons from damage to steel buildings during the Northridge earthquake. *Eng Struct* 20(4–6):261–270
- ODTÜ-DMAM (2023) 6 Şubat 2023 Kahramanmaraş-Pazarcık $M_w=7.7$ ve Elbistan $M_w=7.6$ Depremleri Ön Değerlendirme Raporu, Deprem Mühendisliği Araştırma Merkezi.
- Oygun R, Oygun E (2017) 2011 Van earthquakes: lessons from damaged masonry structures. *J Perform Constr Facil* 31(5):04017062. [https://doi.org/10.1061/\(ASCE\)CF.1943-5509.0001057](https://doi.org/10.1061/(ASCE)CF.1943-5509.0001057)
- Ozmen HB, Inel M, Akyol E, Cayci BT, Un H (2014) Evaluations on the relation of RC building damages with structural parameters after May 19, 2011 Simav (Turkey) earthquake. *Nat Hazards* 71:63–84. <https://doi.org/10.1007/s11069-013-0900-y>
- Ozturk M (2015) Field reconnaissance of the October 23, 2011, Van, Turkey, earthquake: lessons from structural damages. *ASCE J Perform Constr Facil* 29(5):04014125. [https://doi.org/10.1061/\(ASCE\)CF.1943-5509.0000532](https://doi.org/10.1061/(ASCE)CF.1943-5509.0000532)
- 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. <https://doi.org/10.1016/j.engfailanal.2023.107521>
- 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. <https://doi.org/10.1016/j.job.2023.107810>
- Saatcioglu M, Bruneau M (1993) Performance of structures during the 1992 Erzincan earthquake. *Can J Civ Eng* 20(2):305–325. <https://doi.org/10.1139/I93-035>
- Saatcioglu M, Mitchell D, Tinawi R, Gardner NJ, Gillies AG, Ghobarah A, Lau D (2001) The August 17, 1999, Kocaeli (Turkey) earthquake damage to structures. *Can J Civ Eng* 28(4):715–737
- Sathurshan M, Saja A, Thamboo J, Haraguchi M, Navaratnam S (2022) Resilience of critical infrastructure systems: a systematic literature review of measurement frameworks. *Infrastructures* 7(5):67. <https://doi.org/10.3390/infrastructures7050067>
- Sayın E, Yon B, Onat O, Gör M, Öncü ME, Tunç ET, Bakır D, Karaton M, Calayır Y (2021) 24 January 2020 Sivrice-Elazığ Turkey earthquake: geotechnical evaluation and performance of structures. *Bull Earthquake Eng* 19:657–684. <https://doi.org/10.1007/s10518-020-01018-4>
- Senel SM, Kayhan AH (2010) Fragility based damage assessment in existing precast industrial buildings: a case study for Turkey. *Struct Eng Mech* 11(1):39

- Sezen H, Whittaker AS (2006) Seismic performance of industrial facilities affected by the 1999 Turkey earthquake. *J Perform Constr Facil* 20(1):28–36
- Sezen H, Whittaker AS, Elwood KJ, Mosalam KM (2003) Performance of reinforced concrete buildings during the August 17, 1999 Kocaeli, Turkey earthquake, and seismic design and construction practise in Turkey. *Eng Struct* 25(1):103–114. [https://doi.org/10.1016/S0141-0296\(02\)00121-9](https://doi.org/10.1016/S0141-0296(02)00121-9)
- TC SBB, 2023 Kahramanmaraş ve Hatay Depremleri Raporu (2023), <https://www.sbb.gov.tr/wp-content/uploads/2023/03/2023-Kahramanmaraş-ve-Hatay-Depremleri-Raporu.pdf> (date of access: 06 Haziran 2023)
- Temür R, Damcı E, Öncü-Davas S, Öser C, Sarğın S, Şekerci Ç (2021) Structural and geotechnical investigations on Sivrice earthquake (M w= 6.8), January 24, 2020. *Nat Hazards* 106(1):401–434. <https://doi.org/10.1007/s11069-020-04468-w>
- Todd DR, Carino NJ, Chung RM, Lew HS, Taylor AW, Walton WD (1994) 1994 Northridge earthquake: performance of structures, lifelines and fire protection systems
- Uckan E, Akbas B, Shen J, Wen R, Turandar K, Erdik M (2015) Seismic performance of elevated steel silos during Van earthquake, October 23, 2011. *Nat Hazards* 75:265–287. <https://doi.org/10.1007/s11069-014-1319-9>
- Xiong F, Xie L, Ge Q, Pan Y, Cheung M (2015) Reconnaissance report on buildings damaged during the Lushan earthquake, April 20, 2013. *Nat Hazards* 76:635–650. <https://doi.org/10.1007/s11069-014-1511-y>
- Yakut A, Gülkan P, Bakır BS, Yılmaz MT (2005) Re-examination of damage distribution in Adapazarı: structural considerations. *Eng Struct* 27(7):990–1001. <https://doi.org/10.1016/j.engstruct.2005.02.001>
- Yu H, Chen J, Bobet A, Yuan Y (2016) Damage observation and assessment of the Longxi tunnel during the Wenchuan earthquake. *Tunn Undergr Space Technol* 54:102–116. <https://doi.org/10.1016/j.tust.2016.02.008>
- Zhang M, Jin Y (2008) Building damage in Dujiangyan during Wenchuan earthquake. *Earthq Eng Vib* 7(3):263
- Zhao B, Taucer F, Rossetto T (2009) Field investigation on the performance of building structures during the 12 May 2008 Wenchuan earthquake in China. *Eng Struct* 31(8):1707–1723. <https://doi.org/10.1016/j.engstruct.2009.02.039>

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Authors and Affiliations

Fatih Avcil¹ · Ercan Işık¹ · Rabia İzol²  · Aydın Büyüksaraç³ · Enes Arkan⁴ · Musa Hakan Arslan⁵ · Ceyhun Aksoylu⁵ · Onur Eyisüren⁶ · Ehsan Harirchian⁷

✉ Rabia İzol
rizol@metu.edu.tr

Fatih Avcil
favcil@beu.edu.tr

Ercan Işık
eisik@beu.edu.tr

Aydın Büyüksaraç
absarac@comu.edu.tr

Enes Arkan
earkan@beu.edu.tr

Musa Hakan Arslan
mharslan@ktun.edu.tr

Ceyhun Aksoylu
caksoylu@ktun.edu.tr

Onur Eyisüren
onureyisuren@gmail.com

Ehsan Harirchian
ehsan.harirchian@uni-weimar.de

- ¹ Department of Civil Engineering, Bitlis Eren University, 13100 Bitlis, Turkey
- ² Department of Civil Engineering, Middle East Technical University, 06800 Ankara, Turkey
- ³ Çan Vocational School, Çanakkale 18 Mart University, 17400 Çanakkale, Turkey
- ⁴ Department of Architecture, Bitlis Eren University, 13100 Bitlis, Turkey
- ⁵ Department of Civil Engineering, Konya Technical University, 42075 Konya, Turkey
- ⁶ Çanakkale Municipality, TR-17000 Çanakkale, Turkey
- ⁷ Institute of Structural Mechanics (ISM), Bauhaus- Universität Weimar, 99423 Weimar, Germany