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Evaluation of Earthquake-Related Damages on the Reinforced Concrete Buildings due to the February 6, 2023, Kahramanmaraş-Türkiye Earthquakes

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ABSTRACT

On February 6, 2023, two powerful quakes (with magnitudes of Mw7.7 and Mw7.6) struck the Eastern Anatolian Fault Zone (EAFZ), separated by around nine hours. Both earthquakes occurred in the Pazarcık and Elbistan districts of Kahramanmaraş province and were felt in many countries surrounding them. In addition, these quakes resulted in substantial losses of life and property in 11 provinces along the EAFZ. The purpose of this study is to evaluate the ground motions and discuss Reinforced Concrete (RC) buildings' performance in Hatay, one of the most earthquake-affected provinces. On-site investigations revealed that many buildings were damaged in the first Pazarcık earthquake (Mw7.7), and many of them collapsed following the second Elbistan earthquake (Mw7.6). Furthermore, many of the defects uncovered by scientists in previous earthquakes (e.g., Van, Izmir or Duzce) were also observed in these earthquakes. The study also recommended revising the latest Turkish response spectrum for the earthquake region.

Keywords: Kahramanmaraş earthquakes, Earthquake damage to RC buildings, Hatay province, East Anatolian Fault Zone, the 6 February 2023.

Betonarme Binalarda 6 Şubat 2023 Kahramanmaraş-Türkiye Depremleri Nedeniyle Oluşan Deprem Kaynaklı Hasarların Değerlendirilmesi

ÖZ

6 Şubat 2023 tarihinde Doğu Anadolu Fay Zonu'nda (DAFZ) yaklaşık dokuz saat arayla iki güçlü deprem (Mw7.7 ve Mw7.6 büyüklüğünde) meydana gelmiştir. Her iki deprem de Kahramanmaraş ilinin Pazarcık ve Elbistan ilçelerinde meydana gelmiş ve çevrelerindeki birçok ülkede hissedilmiştir. Ayrıca bu depremler, DAFZ boyunca uzanan 11 ilde önemli can ve mal kayıplarına yol açmıştır. Bu çalışmanın amacı, depremden en çok etkilenen illerden biri olan Hatay'daki yer hareketlerini değerlendirmek ve betonarme binaların performansını tartışmaktır. Yerinde yapılan incelemeler, ilk Pazarcık depreminde (Mw7.7) birçok binanın hasar gördüğünü ve ikinci Elbistan depreminin (Mw7.6) ardından birçoğunun yıkıldığını ortaya koymuştur. Ayrıca, bilim insanları tarafından önceki depremlerde (örneğin Van, İzmir veya Düzce) ortaya çıkarılan kusurların birçoğu bu depremlerde de gözlemlenmiştir. Çalışma ayrıca deprem bölgesi için Türkiye'nin en son tepki spektrumunun gözden geçirilmesini tavsiye etmiştir.

Anahtar Kelimeler: Kahramanmaraş depremleri, Depremin betonarme binalara verdiği hasar, Hatay ili, Doğu Anadolu Fay Zonu, 6 Şubat 2023.

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1. Introduction

The Mw7.7 and Mw7.6 Kahramanmaraş earthquakes consequently hit south-eastern Türkiye at 4:17 and 13:24 local times on February 6, 2023, respectively. The earthquakes happened in Kahramanmaraş province on the EAFZ. The first Pazarcık earthquake's epicenter had a focal depth of 10 km, and the second Elbistan earthquake's epicenter was about 175 km away from the first quake. On the Turkish seismic hazard map prepared based on the peak ground acceleration (PGA) values, the epicenters of the earthquakes are shown in white stars in Figure 1 on the EAFZ (black line). The seismic hazard map clearly shows locations that are highly susceptible to earthquakes along both the North Anatolian Fault Zone (NAFZ) and the EAFZ.

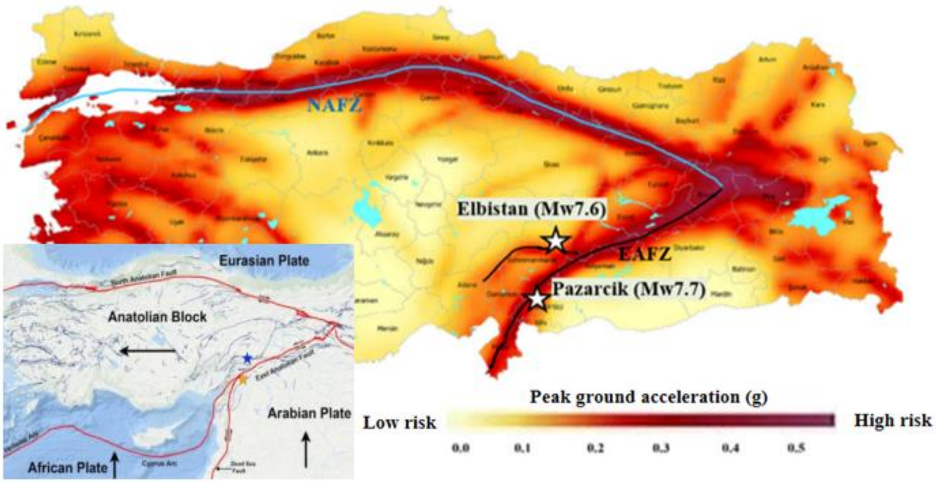


Figure 1. The epicenters of the 6 February 2023 Mw7.7 Pazarcık and Mw7.6 Elbistan earthquakes along the EAFZ on the Türkiye's seismic hazard map (adapted from (AFAD, 2018; USGS, 2023)).

In general, buildings are vulnerable to earthquake damage and can be subjected to shaking, vibration and displacement during seismic activity, which can cause structural damage, partial collapse, or even complete destruction (Ates et al., 2013; D'Angela et al., 2021; Sesli et al., 2022). Twenty earthquakes in Türkiye with a Mw greater than 7.0 have happened since 1900. Among these, the most severe earthquakes in terms of loss of life and severe damage were the 1939 Erzincan, 1999 Kocaeli and 2023 Kahramanmaraş earthquakes (Demir et al., 2024; Elnashai, 2000). Ulutaş (2024) investigated the causes of soft-storey and weak-storey formations in low-and mid-rise RC buildings in Türkiye. It was obtained that that buildings with no infill walls in one direction or with infill walls in only one of the exterior axes in one direction have a high risk of having weak storeys. In the history of seismology, it is rare for two strong earthquakes to occur on the same day. The consecutive February 2023 Kahramanmaraş earthquakes, which are uncommon in recent times regarding the magnitude and affected area, caused considerable damage to the densely populated areas, including infrastructure, residential buildings, bridges, transportation systems, industrial structures, lifelines and ports in the region. According to official records following the earthquakes, over 50,000 people lost their lives, more than one hundred thousand injuries, and over five hundred thousand buildings as well as infrastructure, including communications and electricity, were severely destroyed (SBT, 2023). In the region, the number of heavily damaged buildings that must be demolished and/or collapsed buildings are detected as around 156,000. While the number of buildings that have sustained medium and light damage amounts to roughly 43,000, the number of dwelling units within those collapsed and severely damaged structures is around 507,000 (Erdik et al., 2023). As the quantitative data becomes obvious, there has been a great loss of life as well as considerable economic damage, approximately 110 billion dollars, in the region (SBT, 2023).

Building regulations and codes have been implemented worldwide to help make sure that buildings are built to withstand seismic activity and reduce the risk of earthquake damage (Kiral & Gurbuz, 2024; Kurt & Tonyalı, 2020; Zhao et al., 2021). After 2023 Kahramanmaraş earthquakes, researchers started to investigate building damages and tried to find the causes of severe destructions (Mertol et al., 2023; Onat et al., 2023; Ozturk et al., 2023; Tonyali et al., 2024). They concluded that the reasons for such severe damage to the quality of concrete and to insufficient control of compliance with the Turkish earthquake regulations (TBEC, 2019; TEC, 1998, 2007) and standards in force (Ivanov & Chow, 2023). The construction is one of the most important industries for the Türkiye's economy, and RC buildings account for at least 80% of the construction industry. Most of these buildings were designed and constructed in accordance with the Türkiye Earthquake Codes (TECs), which were released in 1975 or after. The TECs were revised in the years 1998 (TEC, 1998), 2007 (TEC, 2007), and 2019 (TBEC, 2019). The rapid increase in migration from villages to cities has led to uncontrolled, multi-story development. Unluckily, this has resulted in a considerable number of structures not complying with earthquake regulations in existence at the time they were constructed. Furthermore, due to some conceptual shortcomings of the out-of-date regulations, there are issues with buildings constructed in compliance with seismic standards. For example, the 1970s version of the earthquake regulations in Türkiye was distant from the principles of ductile design and capacity design. This caused RC buildings built until the early 2000s to be inadequate in this context (Ozturk et al., 2023). In Türkiye, the concrete manufacturing industry is also quite important due to the widespread use of RC frame systems in the construction of buildings. In addition, qualified ready-mixed concrete and RC steel became commonly used in the construction industry towards the end of the 1990s. Nonetheless, RC structures have a low seismic vulnerability, which were built before the 2000s and are widespread in cities. In addition, twenty-five percent or so of RC buildings in the cities near the epicenter were heavily damaged or destroyed after two large earthquakes that occurred on the same days, which is not common in the seismological literature (Sucuoğlu et al., 2007). In fact, a similar demolition rate was detected in Kocaeli (Mw7.6) and Düzce (Mw7.2) earthquakes in 1999 (Bal et al., 2008). However, it is noteworthy that this collapse rate has not changed much despite the new buildings constructed in accordance with the TEC (1998), TEC (2007) and TBEC (2019) regulations, which have severe seismic design rules that came into effect after the 1999 earthquakes in Türkiye (Ozturk et al., 2023). In the site inspection, it was observed that thousands of RC buildings were damaged and collapsed, and some of these damaged buildings collapsed after frequent major aftershocks. Therefore, the primary inquiry of the on-site investigations following the February 6 earthquakes in Turkey is whether the current earthquake code has any problems in terms of seismic design.

Several recent studies (Altunişik et al., 2023; Atmaca et al., 2023; Avcil, 2023; Binici et al., 2023; Demir et al., 2024; Erdik et al., 2023; Erkek & Yetkin, 2023; Ibrahim et al., 2023; İnce, 2024; Ivanov & Chow, 2023; Kahya et al., 2024; Kiral & Tonyali, 2023; Mertol et al., 2023; Onat et al., 2023; Ozturk et al., 2023; Balaban et al., 2024; Tao et al., 2023) about these destructive earthquake doublets (Mw7.7 and Mw7.6) have been carried out. However, these studies mostly focused on the characteristics of the earthquake, the seismotectonic of the region, the damages observed in RC and other construction types in the region, and their causes. In this study, a site inspection was conducted to better identify the failures related to the design and construction of structures. Some evaluations are presented more specifically for Hatay Province, one of the most earthquake-affected provinces, regarding construction errors and reasons for RC buildings' damage. The assessments are based on field observations (damage levels in buildings), the acceleration and velocity spectra of the February 6, 2023, earthquakes and elastic acceleration spectra obtained from Turkish earthquake regulations. Considering the importance of the lessons to be learned from the huge destruction, the eventual aim of this study is to help those in the field establish better design requirements (i.e., updating response spectrum for the region), construction practices and produce more earthquake-resistant structures in the future.

2. Seismotectonic of the Region

One of the most active fault systems in the world is the Anatolian transform fault system. The tectonic structure of the eastern Mediterranean is complicated, including many plates, such as the African, Eurasian, Aegean, and Anatolian plates. Most of Türkiye is situated on the Anatolian microplate, which is being forced toward the Eurasian plate by the Arabian plate, with a northward movement of approximately 2.5 cm/y (Yilmaz, 2007). Due to the massive weight of the Eurasian plate, the Anatolian microplate is forced westward, which leads to the formation of the complicated left-lateral EAFZ and the right-lateral NAFZ (Duman & Emre, 2013), as shown in Figure 2. On February 6, 2023, two earthquakes happened on the EAFZ. The first earthquake (Mw7.7) occurred on the Pazarcık segment of the main strand of the EAFZ, while the second (Mw7.6) happened on the Nurhak-Cardak segments of the northern strand of the EAFZ (Duman et al., 2023), as illustrated in Figure 2.

Figure 2. Plate movements around Türkiye and epicenters of Kahramanmaraş earthquakes (adapted from (Ozturk et al., 2023)).

The main part of EAFZ is a left lateral strike-slip fault line extending approximately 580 km between the Arabian and Anatolian plates in shout-eastern Turkey (Bulut et al., 2012). It is located between Karliova district of Bingöl province in the northeast and Samandag district of Hatay province in the southwest. It is represented by a simple fault trace between Karliova and Çelikhan districts and is divided into two branches as north and south branches in the south of Çelikhan (Duman & Emre, 2013), as illustrated in Figure 3. The main line of the EAFZ, which is defined on the southern branch, has seven segments, namely Karliova, Ilıca, Palu, Pütürge, Erkenek, Pazarcık and Amanos. The northern branch called the Sürgü-Misis fault system, which connects the districts of Çelikhan and Karatas, is approximately 380 km long. It is composed of the Sürgü, Çardak-Goksun, Savrun, Çokak, Toprakkale, Yumurtalık, Karatas, Düziçi-Osmaniye segments (Duman et al., 2020) (Figure 3b). The Figure also shows historical earthquake activities along these segments and epicenters of Kahramanmaraş earthquakes.

According to historical earthquake catalogs, the fault segments extending north-eastern to Çelikhan were reactivated by a series of Ms>7 earthquakes (Figure 3b). In the last century, many earthquakes above Mw6.0 have occurred on the

EAFZ, such as the 1986 Sürgü (Mw6.1), 1998 Ceyhan (Mw6.2), 2003 Bingöl (Mw6.4), 2010 Sivrice-Elazığ (Mw6.1), and 2020 Sivrice-Elazığ (Mw6.8) earthquakes. The last Sivrice-Elazığ earthquake in 2020 most recently ruptured the Pütürge segment, which is located about 230 km northeast of the first February 6, 2023, mainshock epicenter (Pousse-Beltran et al., 2020). Before the 2023 Kahramanmaraş earthquakes, Pazarcık segment of the fault was last ruptured by the last devastating earthquake in 1513 (Mw7.8) (Duman & Emre, 2013).

The first earthquake (Mw7.7) occurred on the main EAFZ between Çelikhan and the Amik Basin and its epicenter was located near Pazarcık district. It happened at a depth of 8.6 km at 37.288°N, 37.043°E and this caused a rupture exceeding 270 km in Pazarcık segment (Karabacak et al., 2023). When this rupture was investigated, it showed that the first earthquake was produced by the simultaneous rupture of three separate earthquake forming parts (Utkucu et al., 2023). The extent of this catastrophic earthquake experienced can be better understood, as compared to 1999 Kocaeli Earthquake in Türkiye, which created nearly 130 km surface rapture. Following almost nine hours, a second earthquake (Mw7.6), probably triggered by the first earthquake, hit the region again. This occurred at a depth of 7.0 km at 38.089°N, 37.239°E, and its epicenter was located near Elbistan district on the Sürgü-Çardak segment. This second earthquake caused a rupture on the Sürgü-Çardak segment, whose rupture length was over 160 km with large surface displacements between the range of 2–8 m (Çetin et al., 2012).

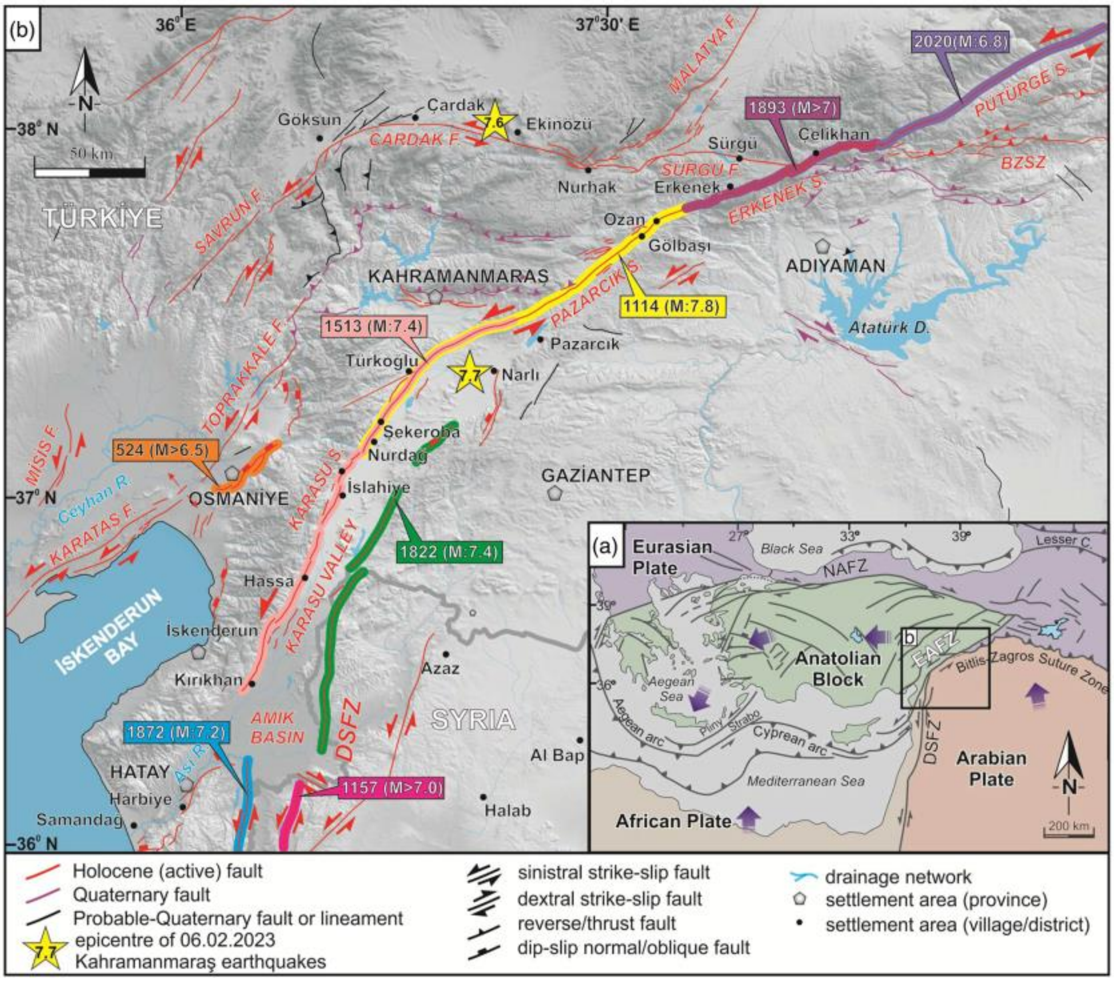


Figure 3. (a) The location of the EAFZ between the Eurasian, African, Arabian and Anatolian plates (Özkaymak, 2015), **(b)** Geometric fault segments of the EAFZ between the Bitlis–Zagros Suture Zone and Amik Basin and historical earthquake activities along these (Denaro, 2005; Karabacak, 2007).

3. Evaluation of Strong Ground Motions

The February 6 earthquakes are one of the largest earthquakes in historical records to ever occur on this fault. In the region, there were 390 aftershocks above Mw3.5 following the first mainshock until March 15, 40 of which were above Mw5.0. The largest aftershock with Mw6.7 occurred 17 minutes after the first mainshock. Two weeks later, the southern part of Hatay province was struck by another Mw6.4 aftershock (AFAD, 2023). Considerably powerful earthquakes occurred in a short period of time in both the north and south strands of the EAFZ.

Table 1 shows earthquakes basic information of the two mainshocks and some of the largest aftershocks in the region.

According to the United States Geological Survey's (USGS, 2023) PAGER system, the first Pazarcık earthquake's Modified Mercalli Intensity (MMI) reached IX (violent shaking), which exposed around 70,000 people to this intensity, whereas the second Elbistan earthquake's MMI was at least VIII (severe shaking), which exposed around 133,000 people, as shown in Table 2. In Figure 4, the isoseismal maps of the two main earthquakes' instrumental intensities were illustrated. It was seen that the largest intensity of the Pazarcık earthquake is distributed along the Amonos segment of the south strand of the EAFZ, from the district of Hassa to Antakya.

Table 1. The basic information of the two mainshocks and some of the largest aftershocks

Motion ID	*Date (m/d/y h)*	*Station No*	*Province /District*	*Lati.* [º]	*Long.* [º]	*Mw*	*Depth* [km]	*Vs30* [m/s]	*PGA* [g]
543428	02.06.2023 01:17	4614	K.maraş /Pazarcık	37.288	37.043	7.7	8.6	541	2.18
543431	02.06.2023 01:28	2712	Gaziantep /Nurdağı	37.304	36.920	6.6	6.2	NA	0.45
543430	02.06.2023 01:36	2708	Gaziantep /Islahiye	37.128	36.639	5.7	11.19	523	0.36
543593	02.06.2023 10:24	4612	K.maraş /Elbistan	38.089	37.239	7.6	7.0	246	0.53
551067	02.20.2023 17:04	3125	Hatay /Antakya	36.037	36.021	6.4	21.73	448	0.78

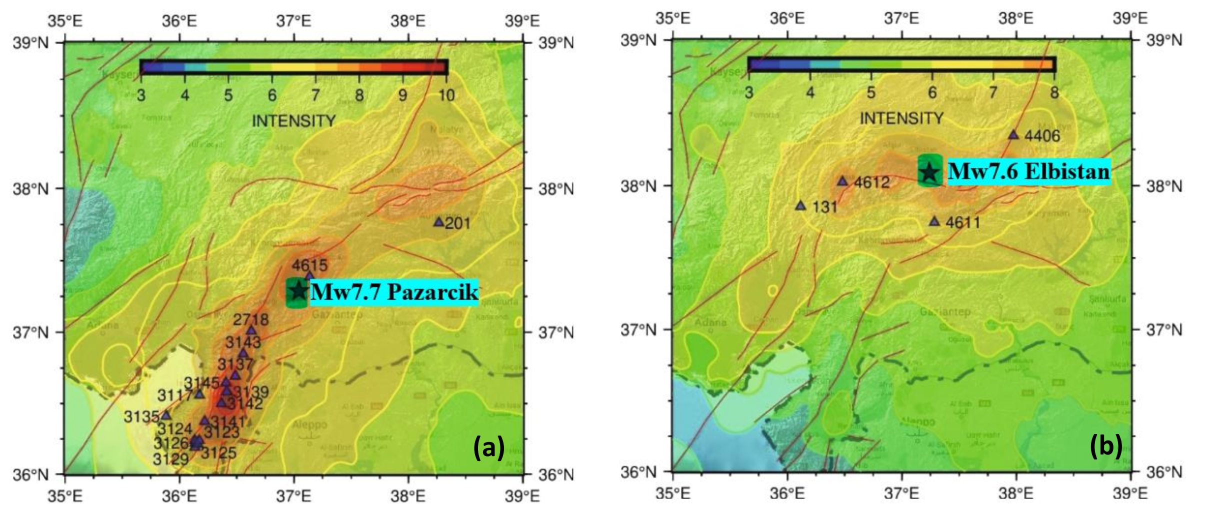


Figure 4. Seismic intensity of February 6, 2023, Türkiye earthquakes on the Isoseismal map, according to MMI, **(a)** Mw7.7 Pazarcık earthquake, **(b)** Mw7.6 Elbistan earthquake (adapted from (Tao et al., 2023)).

Table 2. Ranges of ground motions for MMI scale (data sourced from (Wald et al., 1999))

<table>
<tr><td>Perceived Shaking</td><td>Not felt</td><td>Weak</td><td>Light</td><td>Moderate</td><td>Strong</td><td>Very Strong</td><td>Severe</td><td>Violent</td><td>Extreme</td><td rowspan="5">Kahraamanmaraş, Pazarcık</td><td rowspan="5">Violent
Heavy
2.18g
169.88cm/s
MMI IX-X+</td></tr>
<tr><td>Potential Damage</td><td>none</td><td>none</td><td>none</td><td>very light</td><td>light</td><td>moderate</td><td>moderate/ heavy</td><td>heavy</td><td>very heavy</td></tr>
<tr><td>PGA (%g)</td><td><0.17</td><td>0.17-1.4</td><td>1.4-3.9</td><td>3.9-9.2</td><td>9.2-18</td><td>18-34</td><td>34-65</td><td>65-124</td><td>>124</td></tr>
<tr><td>PGV(cm/s)</td><td><0.1</td><td>0.1-1.1</td><td>1.1-3.4</td><td>3.4-8.1</td><td>8.1-16</td><td>16-31</td><td>31-60</td><td>60-116</td><td>>116</td></tr>
<tr><td>Instrumental Intensity</td><td>I</td><td>II-III</td><td>IV</td><td>V</td><td>VI</td><td>VII</td><td>VIII</td><td>IX</td><td>X+</td></tr>
</table>

Numerous stations operated by the Disaster and Emergency Management Presidency of Türkiye (AFAD) recorded ground shaking associated with the mainshocks and the aftershocks of the Kahramanmaraş earthquakes. These data are available in the official AFAD (2023) database.

Figure 5 shows some of the largest ground motion records at the selected stations as of March 31. In the figure, SN denotes station numbers operated by AFAD; those of them are 4614 Pazarcık station, 3125 and 3126 Antakya stations, and 3129 Defne station. Acceleration records at the selected stations are very close to or above 1g in each direction, but around 2g at the Pazarcık station. The peak ground accelerations (PGA) were recorded at 4614 Pazarcık station, and those of them were 2.18g, 2.12g, and 1.95g in the E-W (east-west), N-S (north-south), and Up (vertical) directions, respectively. The peak ground velocities (PGV) of both horizontal directions (E-W and N-S) were between around 70cm/s and 170cm/s, but between around 30cm/s and 65cm/s in the up direction, as can be seen in Figure 5. It means that these velocity ranges are associated with the potential to cause heavy and very heavy damage to structures in the region, according to the Modified Mercalli Intensities (MMI), as shown in Table 2. The peak ground displacements (PGD) of both horizontal directions (E-W and N-S) were between around 50cm-95cm, but the largest displacement occurred in up direction, which was 100.31cm at 4614 Pazarcık station. Also, the two earthquakes (Mw7.7 and Mw7.6) lasted for about 105s.

In Figure 6, the 5%-damped horizontal response spectra of the recorded motion during the earthquakes were compared with the site-specific design basis spectra according to the most recent Turkish building seismic code (TBEC, 2019). The horizontal response spectra and their geometric means of the Pazarcık earthquake (Mw7.7) at chosen stations were compared to DD-1, DD-2, DD-3, and DD-4 earthquake ground motion levels. The return periods for them are 2475 years, 475 years, 72 years, and 43 years, respectively. DD-1 ground motion level is regarded as the largest earthquake ground motion. Residential buildings are generally designed considering the 475-year return period spectrum. To put it differently, residential buildings are designed according to the DD-2 design earthquake ground motion level. The recorded spectra must be converted to the 5%-damped horizontal response spectra to compare the recorded motion from the recent earthquakes with the spectra used to construct the building regulations. Residential buildings that are built to be earthquake-resistant are designed using the 5% damping ratio as the base, therefore, 5% damping was considered in response spectra.

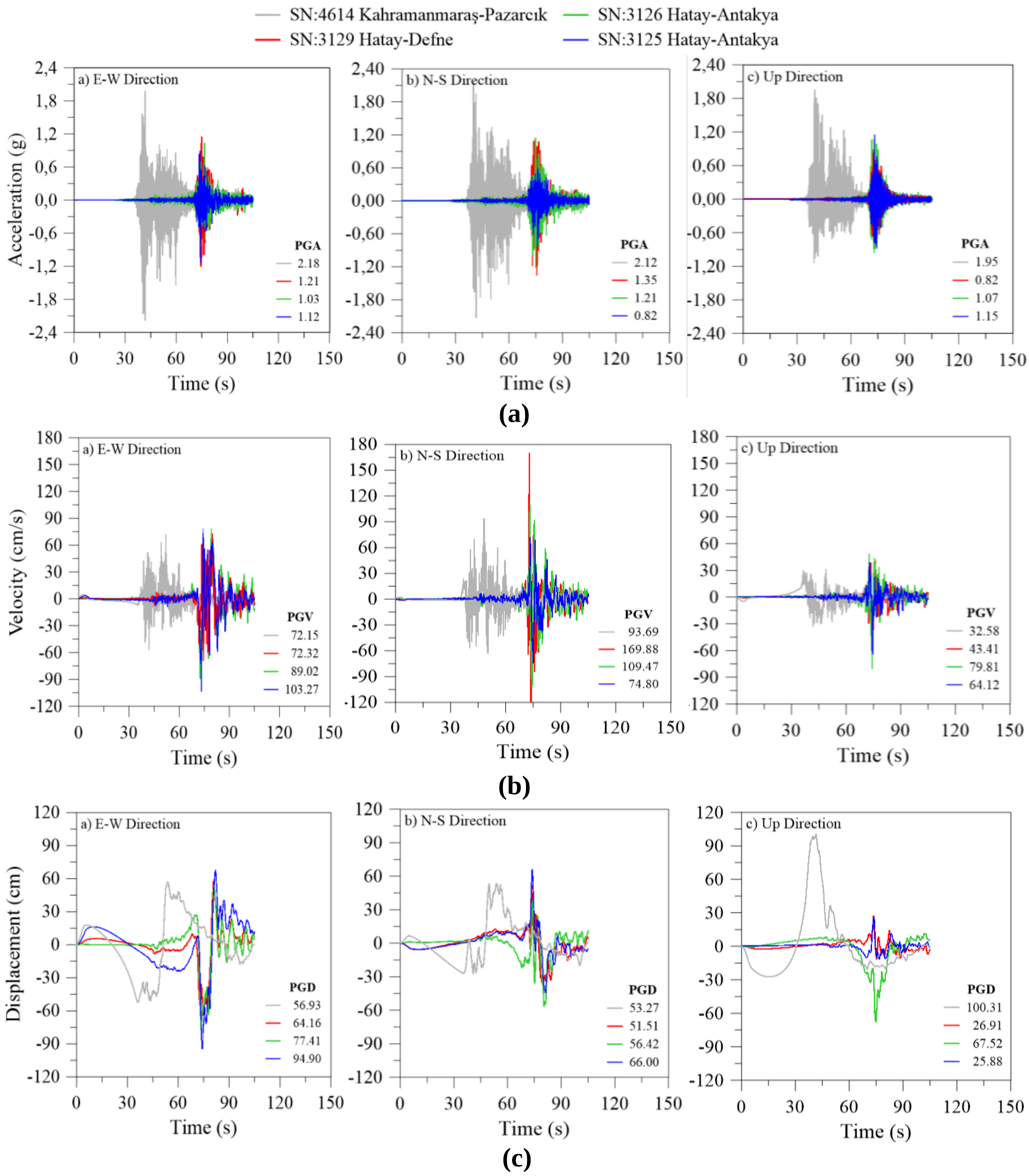


Figure 5. Some of the largest time-history records at selected stations, (**a**) acceleration time histories of E-W, N-S and Up directions, (**b**) velocity time histories of E-W, N-S and Up directions, and (**c**) displacement time histories of E-W, N-S and Up directions

In Figure 6a, b, and c, the ground-based spectra for 4614 Pazarcık, 3129 Defne, and 3126 Antakya stations are well above even the 2475-year code-based spectra (DD-1 ground motion level), especially in the period range of 0.05 and 0.5 seconds. Ground-based spectra for periods greater than 0.05 seconds at selected stations were well above even the design spectrum of 475 years of code-based spectra (DD-2 ground motion level), especially 4614 Pazarcık station for small periods and 3129 Defne station for small and long periods. In Figure 6d, the ground-based spectra at 3125 Antakya station located in Hatay Province more closely resemble the site-specific design basis spectra according to the most recent Turkish seismic code. This means that even if the buildings were constructed according to code, there were some locations where the shaking was greater than what they could sustain.

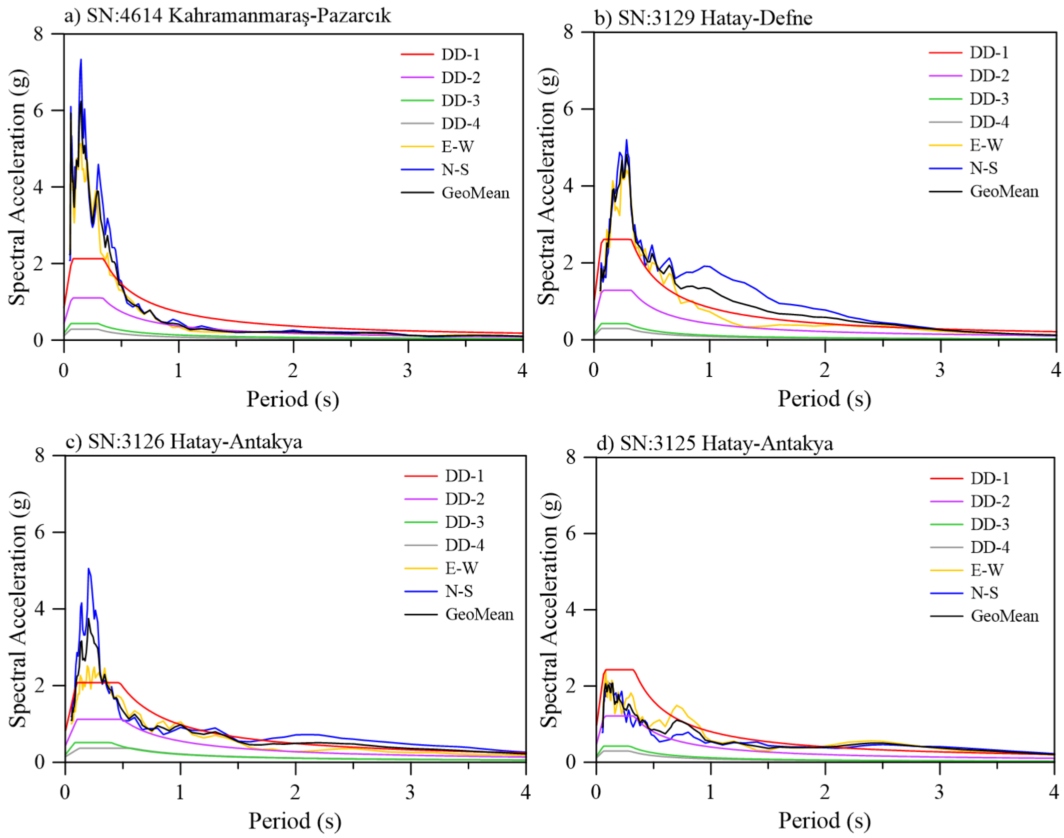


Figure 6. Comparison of the 5% damped acceleration response spectra with the latest seismic code-(TBEC, 2019) based spectra at (a) 4614 Kahramanmaraş-Pazarcık station, (b) 3129 Hatay-Defne station, (c) 3126 Hatay-Antakya station, and (d) 3125 Hatay-Antakya station due to Pazarcık earthquake (Mw7.7).

4. The Assessment of Building in Hatay Following the Earthquake

The Kahramanmaraş earthquakes affected a total of 11 provinces covering the equivalent of roughly 14% land area of Türkiye. There are around 2.6 million buildings in the region, of which 90% are residential buildings, 3% are public buildings, and 6% are places of employment. The percentage of reinforced concrete (RC) structures in the area is around 86.7%, followed by 2.4% steel, 3.5% masonry, 3.6% prefabricated, and 3.8% other kind of construction. (PoSB, 2023). As can be seen from these data, most of the building stock in the region consists of RC buildings. The building stock in Hatay, which is one of the provinces most affected by the earthquake compared to other earthquake-affected provinces, is quite high, and approximately 15% of the buildings in the earthquake-affected region are in Hatay province.

Figure 7 is based on data from Presidency of the Republic of Turkey, Presidency of Strategy and Budget (PoSB) and Turkish Statistical Institute (TURKSTAT). Figure 7a displays the total number of buildings in the province of Hatay. Accordingly, there are 406849 buildings, and roughly 88% of them are residential buildings. The total number of buildings by damage state is illustrated in Figure 7b, based on damage assessment studies carried out in the earthquake-affected provinces. As of March 6, 2023, damage assessment investigations have been carried out for 1712182 structures in 11 provinces affected earthquakes. In this regard, it was determined that 35355 buildings collapsed, 17491 buildings should be demolished urgently, 179786 buildings were severely damaged, 40228 were moderately damaged, and 431421 were lightly damaged. Figure 7c shows the number of buildings according to damage levels considering the damage control report of Hatay province. Figure 7d illustrates the buildings in Hatay province, based on the number of floors. In the process of evaluating the aftermath of an earthquake, this statistic is thought to be significant. Accordingly, it was seen that almost half of the buildings in the Hatay province are 1-to-2 story. The buildings can also be categorized according to their year of construction. Figure 7e illustrates the buildings' percentile distribution according to the construction year in the province of Hatay. The buildings were divided into four categories: pre-1980, 1981 to 2000, 2001 to present, and unknown construction years.

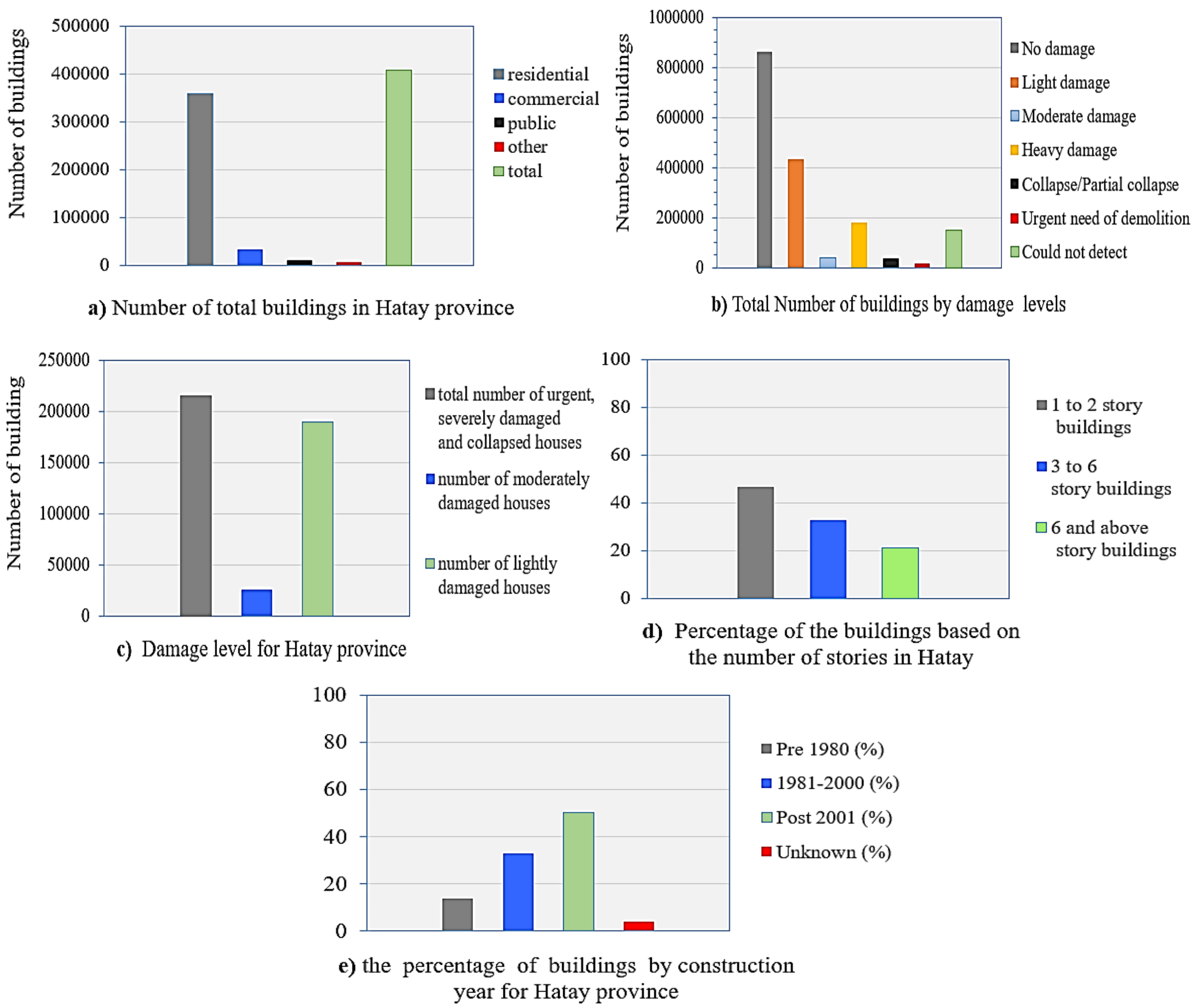
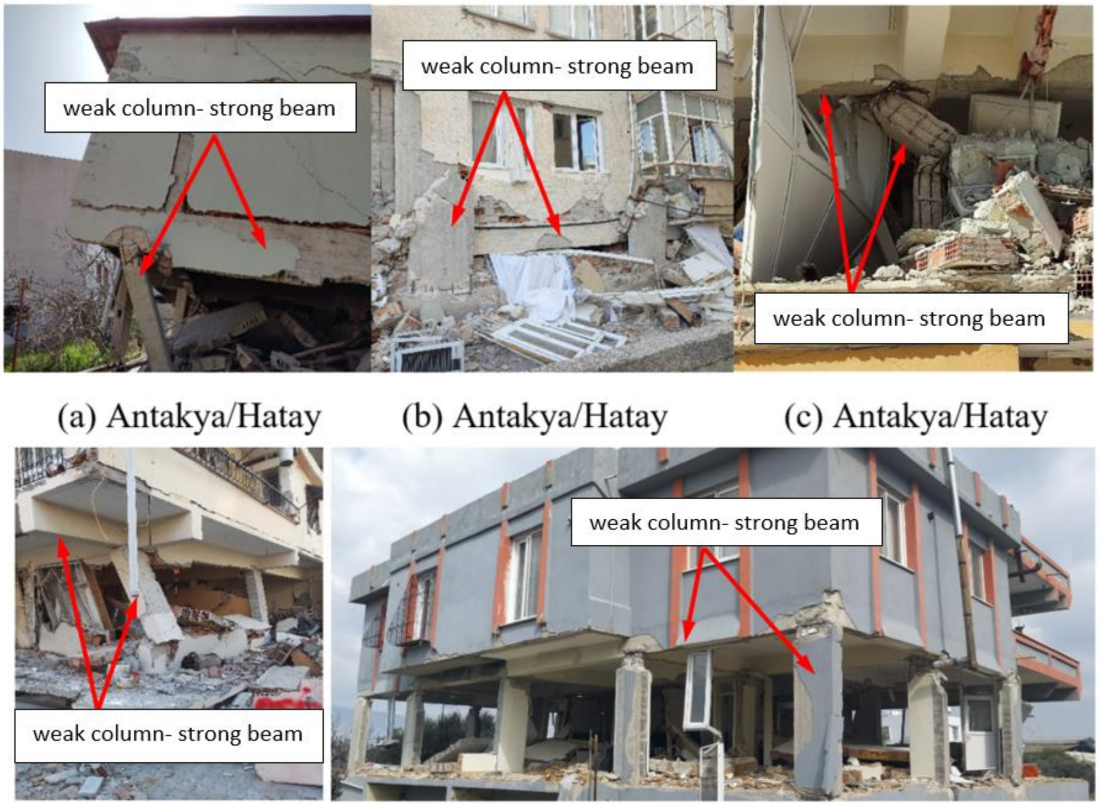


Figure 7. (a) Number of total buildings in Hatay province, (b) Number of buildings per damage levels in damage assessment studies, (c) Number of buildings per damage levels for Hatay province, (d) Percentage of the buildings based on number of stories in Hatay, (e) Buildings' percentile distribution according to the years of construction in Hatay (data sourced from (PoSB, 2023; TURKSTAT, 2021))

5. Field Investigations: Common Defects Identified in RC Buildings Following the Earthquakes

5.1. Weak Column-Strong Beam

Türkiye's older RC buildings were constructed utilizing a strong beam and weak column design before the development of the current earthquake regulations. These structures have deep, strong beams while the columns are flexible and weak. Flexible columns thus collapse before the beams. When an earthquake hits, the strong beams in this type of design behave elastically, whereas the weak columns suffer brittle failures due to compression crushing or shear failure. Buildings' full and partial collapse during the February 6, 2023, Kahramanmaraş-Türkiye earthquakes, was mostly caused by the strong beam-weak column design. The collapses of several structures that suffered from this type of design are seen in Figure 8. Current and previous seismic regulations (TBEC, 2019; TEC, 2007) mandate that total moment resistance of beams at beam-column joints be at least 20% smaller than total moment resistance of columns at the same joints in order to prevent this sort of damage and brittle collapses of columns.



(a) Antakya/Hatay (b) Antakya/Hatay (c) Antakya/Hatay

(d) Antakya/Hatay (e) Antakya/Hatay

Figure 8. Observed structural damages in Antakya/Hatay

5.2. Corrosion, Inadequate Concrete Cover and Concrete Quality

One of the key components needed for RC buildings to operate as anticipated during earthquakes is concrete compressive strength. However, it was observed through field inspections that many collapsed, or severely damaged structures did not have adequate concrete quality. Insufficient concrete cover, and corrosion of the reinforcement bars were also other types of structural material defects which were observed in the earthquake sites. The reinforcing bars' diameters decreased due to corrosion caused by insufficient concrete cover. Following the Kocaeli earthquake in 1999, ready-mix concrete use spread across Türkiye. Concrete that was prepared by hand was commonly utilized prior to this earthquake without the use of a vibrator. This incorrect application prevented a uniform mixture of concrete and thus the anticipated compressive strength from it. According to the old seismic code TEC [14], minimum allowed compressive strength of concrete was 20MPa for all RC buildings, however the latest seismic code TBEC (2019), demands that this must be at least 25MPa. Buildings damages having poor-quality concrete and corroded reinforcement bars due to insufficient concrete cover are shown in Figure 9.

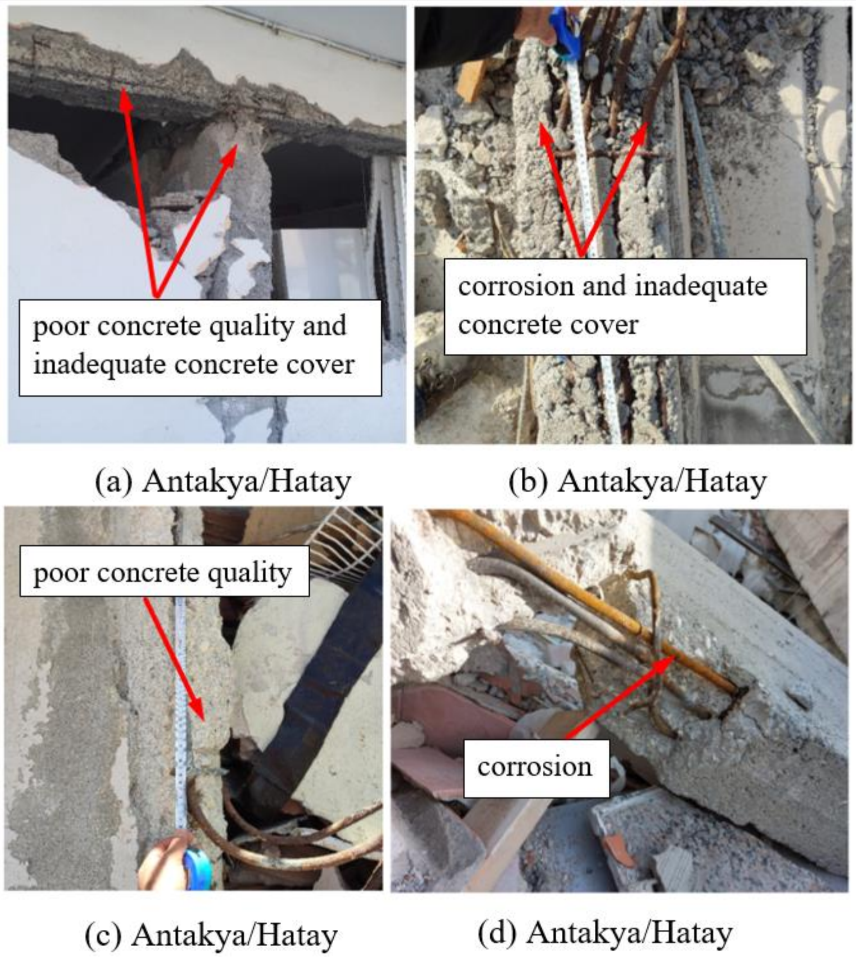


Figure 9. Observed structural damages in Antakya/Hatay, (**a**) poor concrete quality and inadequate concrete cover, (**b**) corrosion and inadequate concrete cover, (**c**) poor concrete quality, and (**d**) corrosion failures

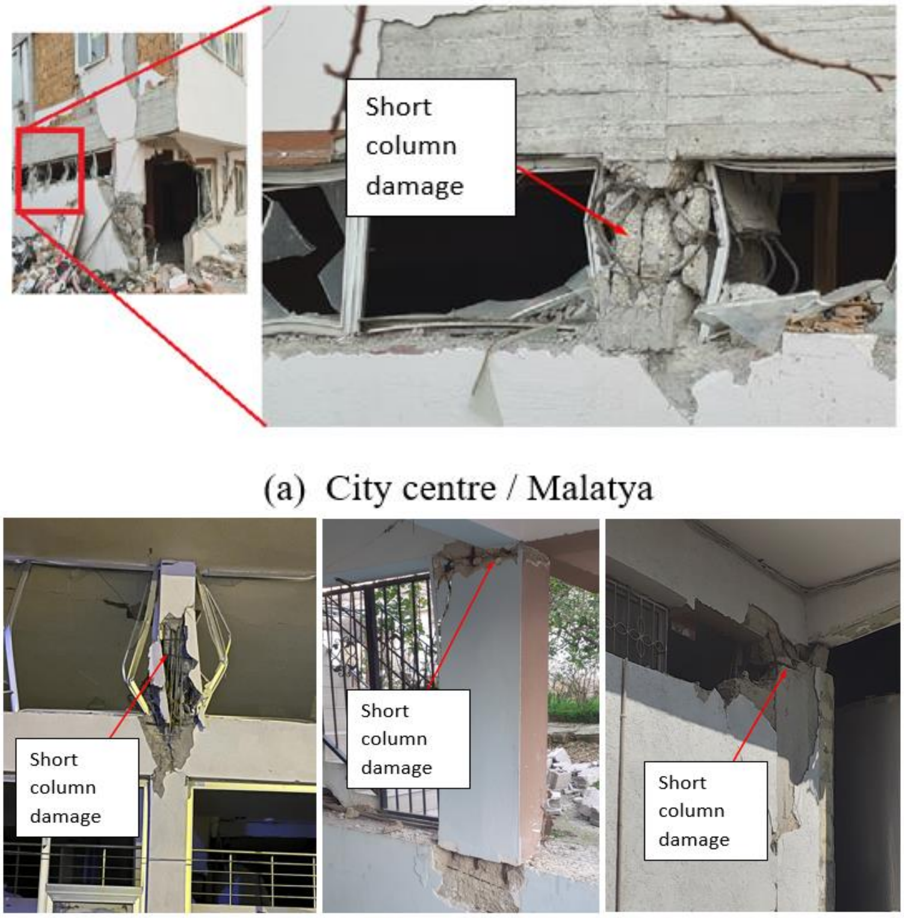
5.3. Inadequate Distances between Neighboring Buildings

As a result of insufficient land availability in the city centers, adjacent buildings are built. As a result, one or two building facades are in touch with one another or there is a small space between them. Hence, during an earthquake, these structures crash into one another. Unaligned floor levels between adjacent structures make the situation even riskier. In cases like these the floor of one building could hit the columns of the neighboring building, causing brittle fractures. A sufficient gap between adjacent buildings is necessary to prevent such damage. It is recommended that gaps between adjusted structures be 3cm up to a height of 6m, according to the latest seismic code TBEC (2019). For every 3m height increment, 1cm should be added gap to between adjacent buildings. In view of the requirement defined in the previous statement, gaps cannot be lower than the total of the absolute values of the average storey displacements times the coefficient (α). The amount of gap is $a = 0.25(\frac{R}{I})$ and $a = 0.50(\frac{R}{I})$ if neighboring floor levels of buildings at all storeys are the same and not the same, respectively. I and R stand for the building's importance factor and the response modification factor, respevtively. In Figure 10, structural damages are shown that have occurred as a result of insufficient spacing between buildings.

Figure 10. Observed structural damages in Antakya/Hatay. Damages due to adjacent buildings' lateral displacement. **(a)** A 7-story building collided with a 2-story building. **(b** and **c)** 4-story new and old buildings collided with each other. **(d, e** and **f)** 2-story old buildings collided with each other.

5.4. Short Column

An exterior band window, which is aimed at lighting basements of buildings, leads to short columns. With this application, a column's effective length is reduced, it becomes stiffer and is subjected to considerable dynamic shear forces, leading to shear cracking, and ending in brittle failure. This type of critical failure is shown in Figure 11. Calculating the shear force for transverse reinforcement in accordance with TBEC (2019) is given in 12, where $M_{bottom} = 1.4M_{ra}$, $M_{top} = 1.4M_{rü}$, V_e and l_n indicate calculated shear force and the length of the short column, respectively.



(b) Nurdağı/Gaziantep (c) Narlıca/Hatay (d) Narlıca/Hatay

Figure 11. Observed structural damages in the earthquake region. RC building damage related to **(a)** shear force (or called short column damage) in City centre/Malatya, **(b)** Nurdağı/Gaziantep, **(c)** Narlıca/Hatay and **(d)** Narlıca/Hatay.

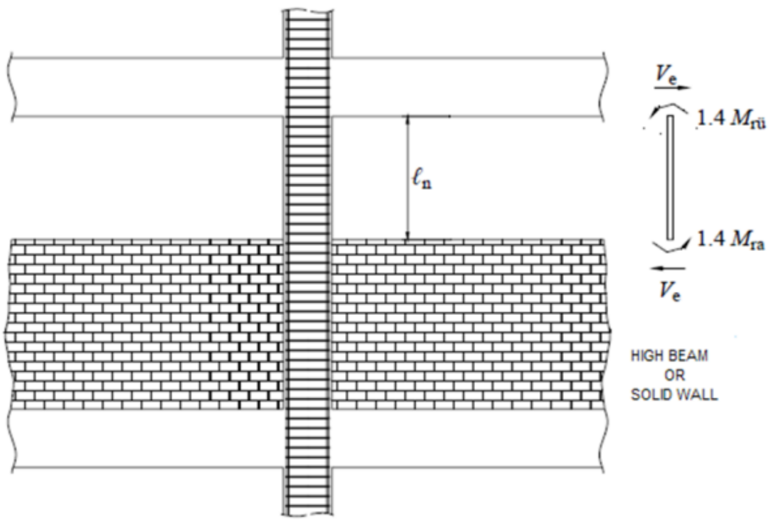


Figure 12. Shear force calculation for transverse reinforcement in accordance with the latest Turkish code (TBEC, 2019)

5.5. Transverse and Longitudinal Reinforcing Related Damage

For structures to be sufficiently ductile all structural elements need to be ductile. Transverse reinforcement plays a crucial role in shear resistance as well as the flexural ductility of beams and columns. The ends of beam, column and column-beam junctions are particularly impacted by shear forces under lateral forces. From the site investigations, it was observed that the distance between the transverse reinforcement in over 90 percent of severely damaged structures was not in accordance with the regulations. This was especially the case in the plastic hinge regions of structural members where the spaces were ranging from 20cm to 35cm. The incorrect application of this construction resulted in buckling of the longitudinal reinforcement bars under compression, caused by the moment reversals during the earthquake. Finally, the columns failed to handle axial forces and were severely damaged. As a result, transverse reinforcement details should be clearly specified in the project and must be carefully checked during construction.

Another observed issue was bond failure, also leading to brittle failures. It is strictly recommended by the design codes that smooth reinforcement should not be used and the bars should be properly anchored. The bending degree be not less than 135° for seismic hooks and ties and that the reinforcement bar be not damaged while being bent. However, site investigations revealed smooth transverse reinforcement, which causes less adherence with concrete (bond-slip), and 90° bent seismic tie hooks on damaged buildings. Apart from these, some collapsed buildings had smooth and ribbed bars within the same column (Figure 13c).

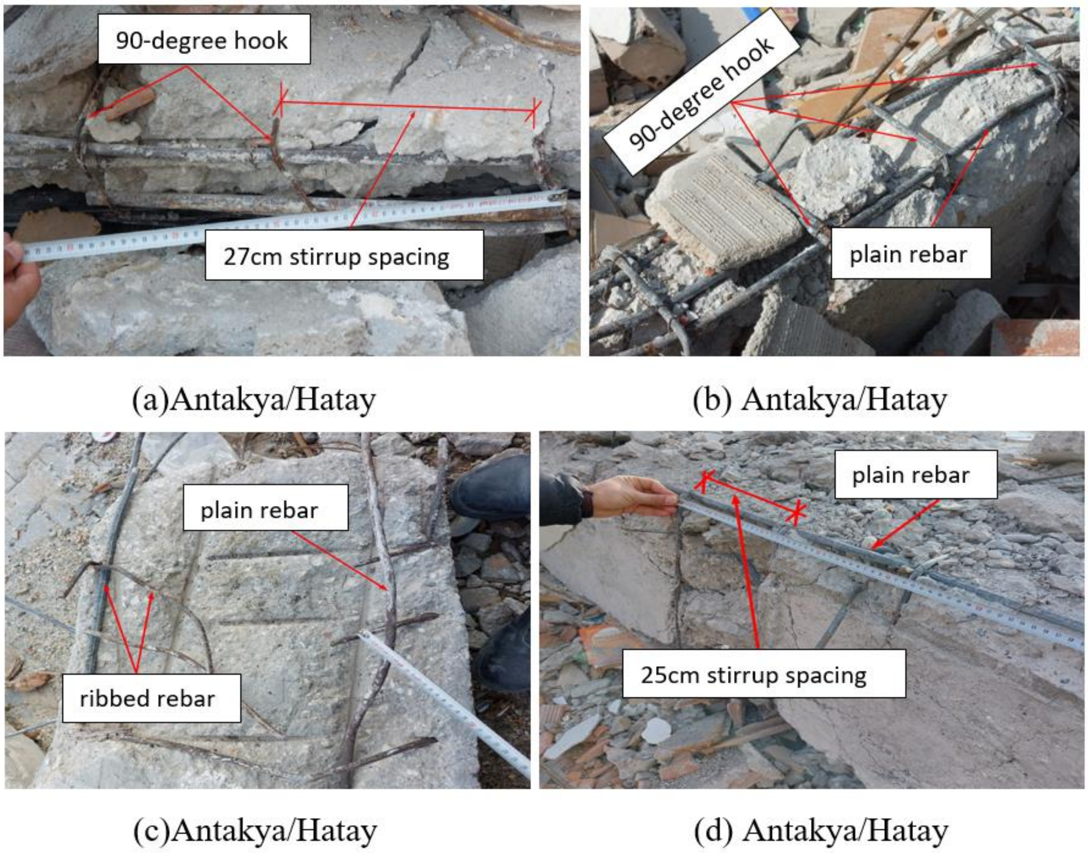


Figure 13. Observed structural damages in Antakya/Hatay. RC building damage related to deficiencies in materials and workmanship. **(a)** 90-degree hook angle instead of 135 and 27 cm stirrup space, which is larger than the Turkish code requirement; **(b)** smooth steel bars instead of ribbed rebar; **(c)** having both plain and ribbed rebar in the same column; and **(d)** having plain rebar and inadequate stirrup space.

It was also observed that the ground floor of some buildings had smooth steel bars, whereas the upper floor had ribbed steel bars. It is considered that some floors were added to these old weak buildings after 2000 because it is the date when ribbed steel bars became common in the country. Such non-uniform material distribution in the building causes the ground floor to be the weakest point in a building, with the upper floors acting as a rigid box, which leads to concentration of damage at ground floor and a total collapse of the building. Some transverse and longitudinal bars details from the sites are given in Figure 13.

Because of improperly designed beam-column joints, buildings' structural performance significantly decreases during earthquakes. To avoid catastrophic failures following an earthquake, the joints must be kept in an elastic zone. The distribution of force and moment depends heavily on these joints. The most frequent reasons for these joints to fail are the bond and shear mechanisms. Several RC structures suffered significant damage during the 2023 Kahramanmaraş and Hatay earthquakes because of the failures of these joints. From site observations, it was found that the major causes of these collapses were poor craftsmanship, inadequate materials, and deficient detailing at column-beam joints. Joint failure also results from a lack of anchoring bars and transverse reinforcements and seismic cross-ties for columns and beams in RC components. According to TBEC (2019), in places where lap joints will be made, special earthquake stirrups will be used along the lap joint, and the spacing of these stirrups will be a maximum of 100 mm. Besides, TBEC (2019) in RC frame systems, the total ultimate moment resistances of beams at a column-beam joint must be at least 1.2 times lower than the sum of ultimate moment resistances of columns at the same joint. This design approach facilitates beams to yield before the columns reach their ultimate strength point. Figure 14 shows structural damages related to column-beam joint failures.

(a) Antakya/Hatay (b) Antakya/Hatay

(c) Antakya/Hatay (d) Antakya/Hatay

Figure 14. Observed structural damages in Antakya/Hatay. RC building damage related to deficiencies in materials and workmanship. **(a, b** and **c)** Lack of stirrup tightening in the beam-column joint and corrosion in the rebar; and **(d)** lack of anchoring bars in the joint and corrosion.

5.6. Weak and Soft Story Formations

It is a usual situation for the ground floor of the buildings to be used as business spaces for commercial gain. Business owners frequently remove some of the infill walls from the ground floor, and in some cases, excavate the ground to make more space, even remove the vertical load-bearing element when converting ground floors to business premises. They do not, however, account for the risk of structural collapse during an earthquake. While designing structures, walls' contributions to building lateral resistance are not usually considered. They are considered structural dead loads at the design stage. Nevertheless, the initial rigidity of buildings is greatly influenced by partition walls as they behave like a shear wall before getting damaged. The ground floor, where the partition walls are removed, deforms more than the above floors after such an incorrect application. The increase of the ground floor hight is another factor causing soft-story mechanisms. Floor stiffness is reduced by increasing its height. During an earthquake, large displacements and thus extremely large second-order moments happen on this floor, which leads to a total collapse of the building on the top of this floor. For preventing soft story damage in buildings, ground floor drift should be limited by using RC shear walls or/and increasing column sizes. The collapses related to a soft story mechanism during the earthquakes are depicted in Figure 15.

Figure 15. Observed structural damages in the earthquake region. RC building damage related to the soft-story mechanism. **(a)** Building, located in Antakya / Hatay, collapsed on the ground floor with no damage to the upper floors; **(b)** Building's ground floor, located in Narlıca / Hatay, was heavily damaged, yet the upper floors had only in-plane wall damage; **(c)** In Antakya / Hatay, the ground floor of the building was heavily damaged, while the upper floors only suffered out-of-plane damage; and **(d)** The ground floor of the building, located in Antakya / Hatay, was severely damaged, while only the walls were damaged on the upper floors.

When the upper floors went up in old Turkish buildings, the dimensions of the lateral resistant elements (columns or curtain walls) decreased. Shear walls were sometimes used on only lower floors. The remaining floors of the building were completed with columns. Mezzanine floors can sometimes be removed by building owners to create larger spaces. The design of earthquake-resistant buildings is incompatible with such an approach. Due to excessive earthquake displacement demands, a floor with reduced stiffness may collapse. Also, from the site investigations of slum areas, it was observed that a constructed building was one-storey at first, but in subsequent years, two or more storeys were added to that building with higher strength concrete, higher yielding strength of steel and larger column cross sections than the existing ground floor. Such incorrect applications lead to a weak storey on the ground floor. TBEC (2019) and TEC (2007) recommend that the effective shear area of the i^{th} storey to the effective shear area of the $(i+1)^{th}$ story shall not be less than 0.80 in each of the orthogonal seismic directions for avoiding weak storey mechanisms in buildings. Some examples of weak storeys observed in the earthquake site are given in Figure 16. One of common observed construction misapplication in Hatay city (given in Figure 16b-d) was adding stories to old and weak ground floor. This can easily violate the ratio of 0.8 given by the latest code TBEC (2019).

(c) Narlıca /Hatay (d) Narlıca/Hatay

Figure 16. Observed structural damages in the earthquake region. RC building damage related to the weak storey mechanism. **(a)** Building, located in Antakya/Hatay, collapsed on the ground floor, while the upper floors had only wall damage; **(b)** Building, located in Antakya/Hatay, collapsed on the ground floor, yet the upper floor had no damage in beam-column joints; **(c)** Building, located in Narlıca/Hatay, collapsed on the second floor; and **(d)** Building, located in Narlıca/Hatay, collapsed on the first and second floors.

5.7. Foundation Failure

Because of seismic soil liquefaction initiation in the regions of Adıyaman-Gölbaşı, Hatay-İskenderun and Hatay-Antakya, the bearing capacity failures, and excessive settlements in the foundation of many residential buildings were observed (Figure 17). The size of the foundation settlements in the earthquake was observed to vary from a couple of cm and up to 80cm (Cetin et al., 2023). As well as 30cm of differential settlements, from 5 to 10 degrees rotation has been also observed in buildings. Figure 17d shows a severe example of liquefaction-induced bearing capacity failure-the toppling of an apartment (which had a raft foundation thickness of 80cm) in Adiyaman-Gölbaşi.

Figure 17. The foundation failure in **(a)** Antakya-Hatay, (b) İskenderun-Hatay (Cetin et al., 2023)), (c) Gölbaşı-Adıyaman(Cetin et al., 2023)) and **(d)** Gölbaşı-Adıyaman (adapted from (Bilgin, 2023; Cetin et al., 2023)).

5.8. Observed Other Types of Structural Damages

Besides these defects, several different types of structural damage were observed at the sites. For example,

- A rigid partition wall between column and window lead to shear failure in the column (Figure 18a).
- The columns of upper floors did not end in the ground (Figure 18b). They were hanging over first floor. The column on the

ground floor failed by punching through the slab. From site observations, the author think that the above three floors were added to a single storey later without getting engineering help.

- Damage related to flexible joist slabs as a diaphragm was observed in a newly constructed multi-storey building (Figure 18c).
- Most of the buildings with a shear wall from bottom to top did not get severely damaged based on the buildings observed in the region. In these buildings, there was little or no damage to the beam-column joints (Figure 18d). This proved the impotence of shear wall construction in earthquake-prone regions.

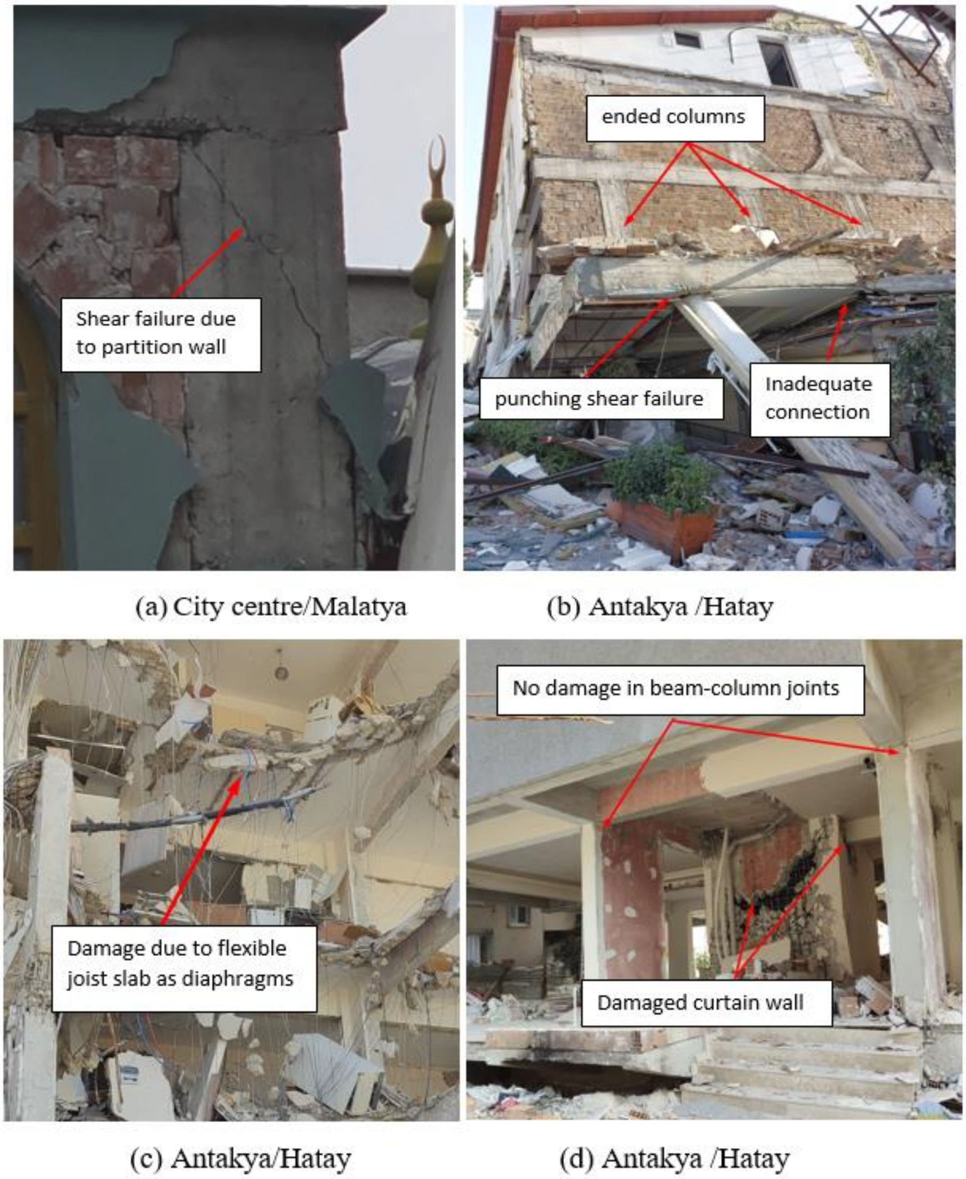


Figure 18. Other types of structural damage observed on the site. **(a)** Shear failure in the column due to partition wall in City centre/Hatay; **(b)** deficiencies in construction and material in Antakya/Hatay; **(c)** damage due to flexible joist slab as diaphragm; **(d)** shear wall damage with no damage in the beam-column joint.

5.9. Damages to Infill Walls

Observations in the field presented different types of infill damage. There is a complexity between in-plane and out-of-plane interactions and such complexity is fully dependent on load-transferring mechanisms in reinforced concrete elements interacting with infill walls. As a result of being subjected to the highest in-plane demand in infilled reinforced concrete buildings, ground floor walls are first expected to break (Figure 19a). Examples of shear cracks in the plane of the walls are given in Figure 19b.

On the other hand, when upper stories are subjected to both in-plane and out-of-plane strong seismic loadings, which consider N–S and E–W acceleration parts, the infill walls may get damaged.

Figure 19 Figure 19c-d display examples of the total and partial out-of-plane failure mechanisms. Most wall damages observed from the site were out-of-plane due to the complexity of earthquakes (Mw7.7 and Mw7.6) which hit the region.

Figure 19. Infill wall damage observed in Antakya/Hatay

7. Conclusions and Recommendations

On February 6, 2023, a series of earthquakes hit the Kahramanmaraş province of Turkiye with magnitudes of Mw7.7 and Mw 7.6, affecting a total of 11 different provinces and approximately 14 million people (16.5% of the total population of Turkiye) along the East Anatolian Fault Zone. These were one of the strongest earthquakes ever recorded in the country's southeast region in the last century and produced the largest ground motions in instrumental times. Accordingly, a wide region was severely affected, covering Cyprus, Egypt, Lebanon, Syria, and the east coast of Turkey on the Black Sea, and that caused a catastrophic disaster in the region. According to the official authorities of AFAD, as of March 20, 2023, these had caused over 50 thousand fatalities and over 100 thousand injuries. One of the most striking features of the February 6 earthquakes is that they happened strongly and consecutively on the same fault line in a relatively short amount of time-roughly nine hours. In the region, more than 50 aftershocks with a magnitude of Mw > 5.0 have occurred as of March 14, and these aftershocks have also caused the destruction of heavily damaged buildings (AFAD, 2023).

This study aims to evaluate the extent of the damage to the structures caused by the consecutive earthquakes on the EAFZ and the structural imperfections that cause these damages with on-site investigations in the region. This study briefly summarizes the history and present seismicity of the EAFZ and especially reveals the dynamic properties of specific ground motion records that happened on February 6, 2023. All significant earthquake-induced failures and defects of RC buildings on the site identified during site examinations are described. The following conclusions can be drawn based on the results of the study:

- The results of this study revealed that a percentage of buildings suffered severe damage due to a lack of transverse reinforcement spacing, insufficient anchoring bar, the use of non-ribbed reinforcement, a lack of stirrup tightening in the beam-column joint, building construction on poor ground, poor concrete quality, the presence of inadequate distance between adjacent buildings, a short column formation, a strong beam-weak column mechanism, and having 90-degree stirrup bending. These observed deficiencies prove a lack of materials, applications (i.e., workmanship), and monitoring by local authorities.
- The latest TBEC 2019 code must be used in conjunction with the Turkish Seismic Hazard Map to identify earthquake-resistant design requirements for any given region in Turkiye. The province of Hatay is frequently characterized by ZC and ZD soil types. According to the seismic map, the horizontal PGA values are the same for the ZC and ZD soil classes, and their PGA values are 0.43g and 0.85g for DD-2 and DD-1 ground motion levels, respectively. In the investigated area, the PGA recorded at most of the accelerometer stations is over 1.0g. The PGA values recorded at stations far exceed the design values on Turkiye's seismic hazard map. Therefore, the buildings in the region were thought to have been subjected to significantly larger PGAs, which was one of the causes of the severe damage. Reassessing the PGA values on the seismic map for all major fault zones in Turkiye is recommended, considering these outcomes.

Following the major structural damages and loss of life in the mentioned earthquakes in the region, we are once again aware of the importance of building settlements and infrastructure that are resistant to disaster risks. It should also not be forgotten that each of the stages of pre-examination, design, construction, and control has the same importance in structural engineering. Each department should meticulously fulfil its own duties. In addition, especially in earthquake zones, after the buildings are built, local administrations should periodically check whether the earthquake performance of the buildings is adequate or not, especially in old buildings built with old earthquake regulations. It is recommended to make a risk assessment in the settlement area in places located on the active fault line, to carry out earthquake risk studies on buildings based in high seismic areas, to identify and demolish buildings that are weak in terms of earthquakes, and to create new settlement centers with strong ground conditions away from the fault zone. Also, in the consecutive Kahramanmaraş earthquakes, the PGA values of the earthquake are seen to greatly exceed the design values on the Turkiye Seismic Hazard Map. Therefore, it is recommended that the PGA values along the significant fault zones (i.e., EAFZ) in Turkiye be reconsidered.

Author Contributions

All authors contributed to the study's origin and plan. Material preparations were performed by [Zeliha TONYALI]. Data collection from the site was conducted by [Adnan KIRAL]. The first draft of the manuscript was partially written and specifically reviewed by [Adnan KIRAL] and[Zeliha TONYALI] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Conflict of Interest

All the authors declare no conflict of interest.

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