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Comprehensive analysis of the damages in Hatay due to the February 2023 Pazarcık and Elbistan earthquakes

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Professional paper

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On 6 February 2023, two major earthquakes with magnitudes of 7.7 and 7.6 Mw struck the Pazarcık and Elbistan districts of Kahramanmaraş in Turkey. These earthquakes affected 11 provinces and were felt in neighbouring countries including Syria, Iraq, Egypt, and Iran. Although the epicentres were approximately 200 km and 300 km away from Hatay, respectively, Hatay province was among the most affected provinces, where many buildings were severely damaged or collapsed. In this study, we present field observations of earthquake-induced damage in Hatay by investigating the behaviour of reinforced concrete buildings under earthquake conditions, including the causes and consequences. The results indicate that the main causes of damage were the high velocity and acceleration of earthquakes, which exceeded design expectations of the Turkish Building Earthquake Code-2018 as well as issues associated with ground amplification, liquefaction, and building design. Additional contributing factors included zoning plans, illegal construction, poor workmanship, and the use of inadequate materials. Based on these insights, the study proposes several recommendations for earthquake-resistant building designs and construction practices.

Key words:

earthquake sequence, field observations, the behaviour of reinforced concrete buildings, liquefaction, structural irregularities

Stručni rad

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Detaljna analiza šteta nastalih u pokrajini Hatay uslijed potresa u Pazarcıku i Elbistanu u veljači 2023.

Dana 6. veljače 2023. dva snažna potresa magnitude 7,7 i 7,6 Mw pogodila su Pazarcık i Elbistan u pokrajini Kahramanmaraşu u Turskoj. Ti su potresi pogodili 11 pokrajina, a osjetili su se u susjednim zemljama Siriji, Iraku, Egiptu i Iranu. Iako su epicentri potresa bili otprilike 200 km odnosno 300 km udaljeni od pokrajine Hataya, upravo je ona bila među najviše pogođenima, s velikim brojem teško oštećenih ili potpuno srušenih građevina. U ovome istraživanju prikazana su terenska opažanja o štetama uzrokovanim potresom u Hatayu te analize ponašanja armiranobetonskih zgrada uslijed potresa, uključujući uzroke i posljedice. Rezultati pokazuju da su glavni uzroci oštećenja bile velike brzine i ubrzanja tijekom potresa, koja su premašila projektirane vrijednosti definirane Turskim pravilnikom o potresima za zgrade iz 2018., te problemi povezani s pojačanim gibanjem tla, likvefakcijom i projektiranjem zgrada. Dodatni čimbenici koji su pridonijeli štetama odnose se na urbanističke planove, nelegalnu gradnju, lošu izgradnju i uporabu neadekvatnih materijala. Na temelju tih spoznaja u istraživanju predložen je niz preporuka za projektiranje i izgradnju zgrada otpornih na potrese.

Ključne riječi:

potresna sekvenca, terenska opažanja, ponašanje armiranobetonskih zgrada, likvefakcija, konstrukcijske nepravilnosti

1. Introduction

On 6 February 2023, two earthquakes struck Turkey: the first at 4:17 a.m. with a magnitude of 7.7 Mw and an epicentre in the Pazarcık district of Kahramanmaraş and the second at 1:24 p.m. with a magnitude of 7.6 Mw and an epicentre in the Elbistan district of the same province [1]. These devastating earthquakes caused severe damage in the cities of Kahramanmaraş, Hatay, Malatya, Gaziantep, Diyarbakır, Şanlıurfa, Adıyaman, Osmaniye, Kilis, Adana, Elazığ, Bingöl, Kayseri, Mardin, Tunceli, Niğde, and Batman. Approximately 52,000 people died and 115,000 people were wounded. Thousands of aftershocks following these events increased the damage to reinforced concrete structures. In this study, the damage in Hatay, one of the most severely affected provinces, was comprehensively investigated and supported by field observations.

2. Earthquake activity of the region

The Eastern Anatolian Fault Zone (EAFZ), which extends from the Karlıova district of Bingöl in the north to the Mediterranean Sea in the south, has experienced many destructive earthquakes throughout history. Major historical earthquakes along the EAFZ include Hatay–Antakya (7.5 Mw) in 1822, Karlıova (7.2 Mw) in 1866, Hatay–Antakya (7.2 Mw) in 1872 [2], Sivrice (6.7 Mw) in 1875, Çelikhan (7.1 Mw) in 1893, Malatya (6.8 Mw) in 1905 [2, 3], Erzincan (7.8 Mw) in 1939 [4, 5], Adana (6.0 Mw) in 1945, Malatya (6.0 Mw) in 1964, Bingöl (6.7 Mw) in 1971, Bingöl (6.1 Mw) in 2003, Elazığ (6.1 Mw), Elazığ (6.8 and 7.1 Mw) in 2010 [2, 3], Van (7.1 Mw) in 2011 [6, 7], and Sivrice (6.8 Mw) 2020 [8]. The fault segments of the EAFZ that broke during the earthquakes on 6 February 2023 are marked with rectangular boxes in Figure 1. Rectangular boxes indicate the fault segments (1: Pazarcık–Erkenek Segment, 2: Amanos Segment, 3: Çardak Segment, 4: Cyprus–Antakya Transform (CAT) and Antakya Triple Junction (ATJ)) where the February 2023 earthquakes occurred [2].



Figure 1. Map showing DAFZ with Eurasian, Anatolian, African, Arabian plates

Figure 2 displays examples of the destructive results of the earthquakes. Hatay Province is located between the left-striking Dead Sea, the Amanos Mountain segment (the southern part of the EAFZ), and the Cyprus–Antakya Transform Fault [2], as indicated by rectangular boxes 2 and 4 shown in Figure 1.

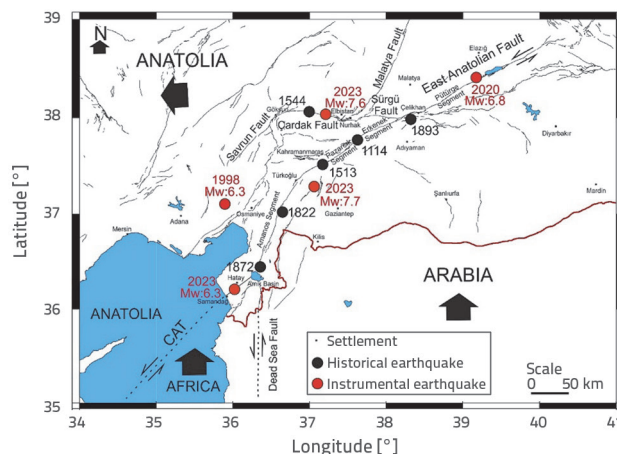


Figure 2. Map showing destructive earthquakes that occurred in the region both historically and in instrumentally measurable periods [2]

3. February 6 earthquake: characterisation, surface fractures, Seismic record analysis

Analysing focal mechanism solutions revealed that these earthquakes struck left-lateral strike-slip faults following the characteristics of the EAFZ. Some of these analyses showed normal and reverse fault mechanisms due to local changes in fault geometry along the fracture line [1, 4]. Surface fractures were reported on the Pazarcık, Amanos, Erkenek, Türkoğlu, and Narlı parts of the EAFZ in the 06 February 2023 Pazarcık earthquake (7.7 Mw). The Amanos Fault (Figure 1, rectangular box 2) extends toward Hatay, with separate ruptures observed through Türkoğlu, toward Hassa and Kırıkhan [2]. This fault, which stretches from the south of Türkoğlu to Antakya, is reported to have ruptured because of the first Pazarcık earthquake. Along the surface fracture of the Narlı segment, including parts of Hatay, left-lateral displacements ranging from 10–700 cm were observed. Left-lateral strike-slip surface fractures occurred 19 km from the Serinyol segment and a 122.5 km stretch from the Amanos segment. The Çardak Fault extending from Nurhak east to Göksun and the Doğanşehir Fault in the Doğanşehir district of Malatya were observed to have ruptured in the region between the Göksun district of Kahramanmaraş and the Doğanşehir district of Malatya (indicated by box 1 in Figure 1) during the second earthquake (7.6 Mw) [2]. The left lateral displacements in this region ranged from 25 to 880 cm [9]. Surface ruptures and translational movement traces have been extensively observed in Hatay since the earthquake in February 2023. These ruptures caused height differences ranging from 1 m–3 m. Figure 3 shows the surface fractures and deformations [10].



Figure 3. Surface fractures in agricultural land and forested areas after the earthquakes in Hatay [10]

Large cracks occurred in the fields of Tepehan village oin the Altınözü district of Hatay owing to seismic activity (Figure 4). Ruptures with left lateral displacement split the land, causing 300 cm displacements. Additionally, as shown in Figure 5, deep pits of approximately 30 m deep and 200 m wide formed a 35-decare olive orchard in Altınözü [11, 12].



Figure 4. Large surface fractures in agricultural land after the earthquake in Altınözü [11,12]



Figure 5. Deep pits in olive groves after earthquakes in Hatay–Altınözü district [7]

Although Pazarcık and Elbistan are located approximately 200 and 300 km from Hatay, respectively, the largest ground

motion was recorded in Hatay. Table 1 presents the distances from the earthquake epicentres to the stations in Hatay (Figure 6), the maximum ground acceleration values recorded in each direction at these stations, and the shear wave velocities [13–16]. The spectral curve plots of the 5% damped elastic response spectra at the selected stations were compared with the design spectra specified in the Turkish Building Earthquake Code–2018 [17, 18].

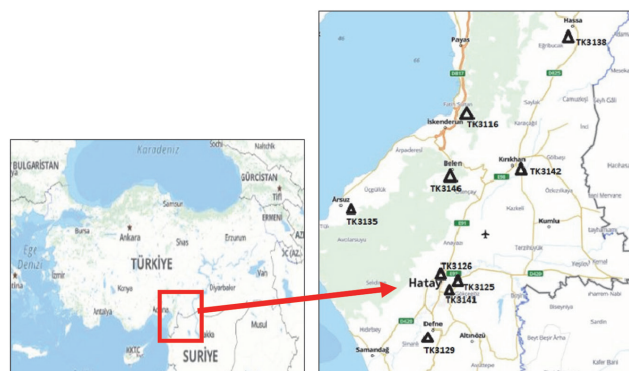


Figure 6. Some accelerometer stations in Hatay during the 6 February Kahramanmaraş earthquakes

According to TBEC-2018, local soil classifications used for defining earthquake design spectra are determined through ground investigations and classified into six categories ZA: solid, hard rock soils; ZB: poorly weathered, moderately solid rock soils; ZC: very tight sand, gravel, and stiff clay layers or very cracked weak rocks; ZD: moderately tight sand, gravel or very stiff clay layers; ZE: loose sand, gravel or soft to stiff clay layers; and ZF: soils with the risk of collapse and potential collapse under earthquake effect, clays with a total thickness over 3 m, high plasticity clays with a total thickness over 8 m, very thick (> 35 m), soft or medium stiff clays [17]. Local soil types classified as ZC, ZD, and ZE were selected to represent the study region (Figure 7). TBEC-2018 defines earthquake ground motion level 2 (DD-2) as ground motion with a 10% probability of exceedance in 50 years, which corresponds to a 475-year period. This level is used for designing non-specific structures. Based on in Figure 7, evaluations were made based on DD-2.

According to the data obtained from stations numbered 3125, 3126, 3129, 3135, 3138, and 3141 in Hatay, which were established by the Turkish Accelerometric Database Analysis System (TADAS) [19] and the Turkey Disaster and Emergency Management Presidency (AFAD) to record earthquakes, horizontal and vertical spectral acceleration values higher than the design values stipulated in TBEC-2018 were obtained during the Pazarcık earthquake (7.7 Mw) at 0–1 s intervals. All three components (east–west, north–south, and up–down) exhibited high spectral acceleration values, which contributed to a high degree of damage in that region. The DD-2 spectrum (representing

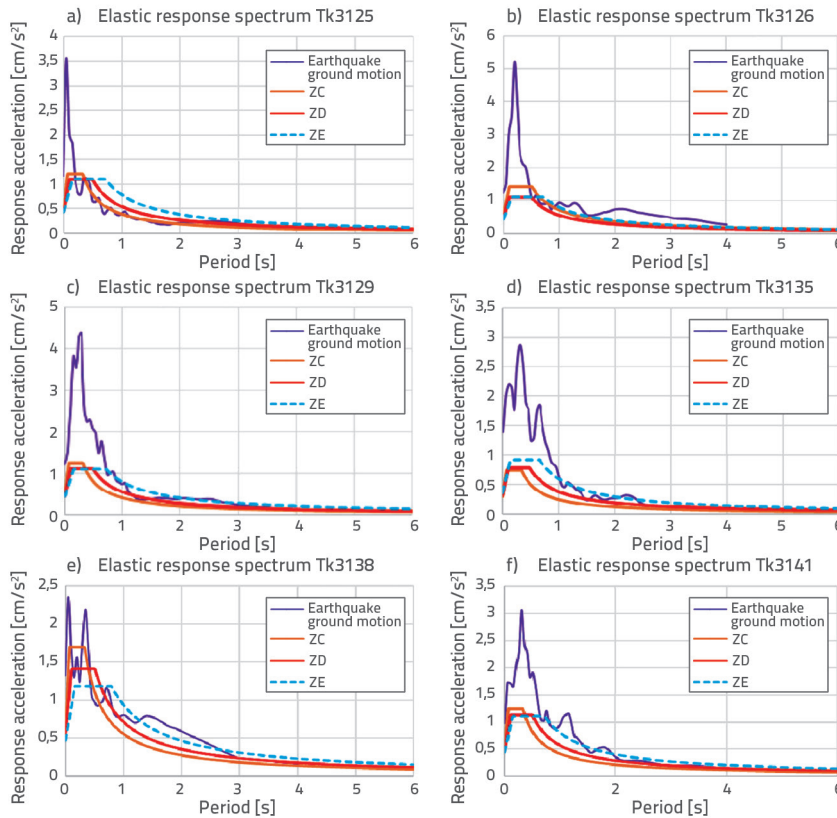


Figure 7. Comparison of elastic acceleration spectra of stations Tk3125, Tk3126, Tk3129, Tk3135, Tk3138, and Tk3141 in Hatay with TBEC-2018 design acceleration spectrum graphs

an earthquake with a 10% probability of occurrence over 50 years) was lower than the recorded spectral acceleration

severe earthquakes is rare in the literature and increases the degree of damage to buildings.

values. For example, in the February 2023 earthquakes, the largest acceleration value measured at station 3126 was 1.2 g, whereas the design-level prediction was only 0.41 g. Specifically, the observed acceleration was approximately three times larger than expected value (Figure 7.b).

Many researchers have examined the effects of shear wave velocities on ground motion [20-23]. The shear wave velocity at a depth of 30 m, denoted as $V_{s(30)}$, was strongly correlated with ground magnification. On 6 February 2023, $V_{s(30)}$ values recorded at various stations in Hatay ranged from 300–500 m/s during the first earthquake (7.7 Mw) and from 400 to 500 m/s during the second earthquake (7.6 Mw). Accordingly, the soil amplification factor was estimated to be 2 to 3, reaching 3.5 to 4 in regions with alluvial soils [24] in microzonation studies, with magnification values in the range of 2 to 4 and 4 to 6.5. This indicated medium-high hazards that cause an increase in the severity of destruction during the earthquake [25].

The successive occurrence of two severe earthquakes is rare in the literature and increases the degree of damage to buildings.

Table 1. Distance of Pazarcik earthquake (Mw:7.7) centre to stations in Hatay, measured acceleration records, and shear wave velocities [19]

Code	Longitude	Latitude	Province	District	Maximum ground acceleration in the north-south direction PGA_NS [cm/s ²]	Maximum ground acceleration in the east-west direction PGA_EW [cm/s ²]	Maximum ground acceleration in the vertical direction PGA_UD [cm/s ²]	$V_{s(30)}$ [m/s]	Distance from the epicenter of the earthquake [km]
3138	36.511	36.803	Hatay	Hassa	888.73	746.66	1296.27	618.0	71.70
3116	36.207	36.616	Hatay	İskenderun	164.28	168.86	165.84	870.0	105.38
3142	36.366	36.498	Hatay	Kırıkhan	651.69	739.29	456.90	539.0	106.49
3146	36.227	36.491	Hatay	Belen	483.85	346.93	341.39	430.0	114.57
3141	36.220	36.373	Hatay	Antakya	961.12	868.82	722.66	338.0	125.42
3135	35.883	36.409	Hatay	Arsuz	740.97	1372.07	588.97	460.0	142.15
3126	36.138	36.222	Hatay	Antakya	1178.12	999.38	921.57	350.0	143.54
3129	36.134	36.191	Hatay	Defne	1351.50	1198.74	716.94	447.0	146.39
3125	36.133	36.238	Hatay	Antakya	822.62	1121.95	1151.56	448.0	142.15



Figure 8. Liquefaction and sand slides observed in İskenderun–Hatay due to earthquake



Figure 9. Highway cracking in Hatay



Figure 10. Settlement damage detected along the Hatay coastline



Figure 11. Approximately 60 cm subsidence and some settlements detected in Iskenderun after the earthquake

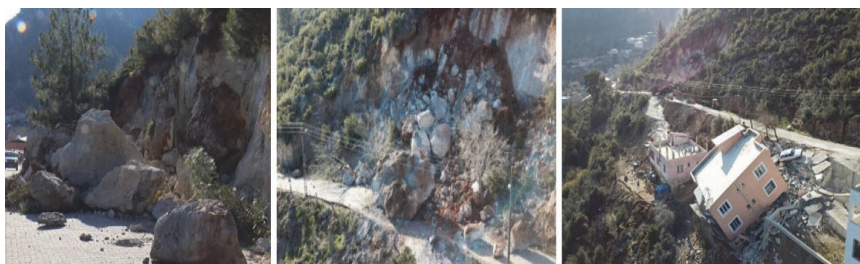


Figure 12. Landslides and rockfalls were triggered by earthquakes in Kırıkhan [34]

4. Investigation of earthquake damages from the perspective of ground and foundation engineering

Severe tremors have caused various problems in soil and foundation engineering in Hatay, including liquefaction, lateral spreading, sand boils, settlements, collapse/heaving, and differential settlements [26–30]. Cracks and crevices were observed in areas affected by sand boils. Evidence of liquefaction and sand boils was documented near Atakaş Mosque following the February 2023 earthquakes, particularly in the coastal region of Iskenderun (Figure 8). Figure 9 shows the cracks and wide splits on the highways.

In buildings near the coastal zone, the bearing capacity decreases owing to liquefaction in the ground, while settlement occurs (Figure 10).

Although collapses and settlements of up to 80 cm were observed in structures along the coastal areas of İskenderun for a span of approximately 6 km after the earthquakes, complete collapse/demolition did not occur [31, 32]. Cases where soil liquefaction does not transmit high acceleration values (1.2 to 1.3 g) to structures are rare and warrant further investigation. Many coastal buildings are old, constructed on very soft or poor soils, and lack deep foundations such as pile-based slab foundations. Although this initially appears counterintuitive, the high average shear wave velocity ($V_s(30)$) decreased in loose sand during the earthquake and contributed to the survival of the buildings. The foundations of the buildings near the beach, located on the ground that liquefied owing to seismic movement, were damaged following a 50–60 cm settlement in Iskenderun–Hatay (Figure 11).

The dynamic movements caused by earthquakes can mobilise weak layers and large masses with the contribution of gravity [33]. The February 2023 earthquake triggered scarps, which caused landslides and landfalls. Rocks breaking off from the mountain fell on houses, and 49 people lost their lives in the village of Bektaşlı in the Kırıkhan district of Hatay (Figure 12).

Table 2. Structural damage by province from the 6 February 2023 Pazarcık and Elbistan earthquakes [35]

Province	Total emergency heavy destroyed number of residences	Number of structures with moderate damage	Number of slightly damaged buildings
Adana	2952	11768	71072
Adıyaman	56256	18715	72729
Diyarbakır	8602	11209	113223
Elazığ	10156	1522	31151
Gaziantep	291555	20251	236497
Kahramanmaraş	99326	17887	161137
Malatya	71519	12801	107765
Hatay	215255	25957	189317
Kilis	2514	1303	27969
Osmaniye	16111	4122	69466
Şanlıurfa	6163	6041	199401
Total of region	518009	131577	1279727

5. Investigations of structural damages

According to data reported by the Presidency of the Republic of Turkey Strategy and Budget Directorate [35], a total of 5,649,317 houses in 11 provinces were affected by earthquakes. Of these buildings, 518,009 were "heavily damaged, collapsed, and to be demolished immediately." In Hatay, one of the provinces most affected by the disaster, 215,255 houses were classified as "heavily damaged, collapsed, and to be demolished immediately." Approximately 24 percentage of buildings damaged by earthquakes in the region were located in Hatay (Table 2).

It is inaccurate to attribute the damage and destruction of structures to a single parameter. There are numerous reasons for damage to reinforced concrete structures [36, 37]. For example, over 50% of the building stock is composed of reinforced concrete structures that complete their structural life, or the use of coarse gravel aggregate and lack of gradation, the use of non-ribbed reinforcement, low quality of concrete, soft floors, short column effects, weak columns but strong beams, hammering effects in adjacent buildings, incomplete/incorrect applications in the column–beam joint area, presence of short beams, segregation, and corrosion [38–40].

5.1. Structural collapses caused by adjacent zoning (hammering)

When appropriate joints or gaps between two neighbouring buildings are not provided, structures with different dynamic movements can hit each other during an earthquake and cause


Figure 13. Buildings whose structural elements were damaged by adjacent constructions

damage; this is known as the hammering effect. Given Hatay's zoning status, contiguous construction is widespread, and many buildings have been damaged and collapsed from hammering (Figure 13). The elevation differences between buildings and different construction characteristics (year of construction, type of material, and quality) significantly cause damage.

5.2. Structural damages due to short column irregularities

Short-column irregularity refers to a situation in reinforced concrete structures where the free columns are shorter than the calculated length for various reasons, such as the case where the shear wall in the basement does not continue up to the height of the floor, or when band-type windows are placed right next to the columns (typically windows open for ventilation and light are left in the basements) or building mezzanines, resulting in excessive shear force. The horizontal forces on the columns caused the short columns to be subjected to shear stresses beyond their capacity and induced ruptures during earthquakes. Damage caused by short columns has been detected in many buildings in Hatay (Figure 14).



Figure 14. Damage due to short-column irregularities in Antakya–Hatay

5.3. Collapses caused by soft storey irregularities

Soft-story effects refer to differences in rigidity between the floors of a building. According to TBEC-2018, type B2 is a vertical irregularity type. The regulation states that for two earthquake directions perpendicular to each other, if the ratio of the relative drift on any floor, except ground floors, divided by the ratio of the relative drift on the upper or lower floor is >2 , soft floor irregularity is expected to occur. The columns in the mezzanine above the ground floor were crushed during the earthquake owing to the soft floor irregularity, and a building in Iskenderun was severely damaged (Figure 15).



Figure 15. Previous and post-earthquake damage to a building in Iskenderun–Hatay



Figure 16. Soft-story buildings in Antakya–Hatay collapsed during the earthquake

In contrast to other floors, soft stories cause significant displacement. In this case, second-order effects, which are not considered in the design, occur on a soft floor, and the earthquake damage is felt more intensely on this floor. Accordingly, before the vertical load-bearing elements on the other upper floors reach half of their capacity under the earthquake effect, collapse and overturning can occur on the lower floors (Figure 16).

5.4. Structural problems due to poor material quality

Many buildings in Hatay have deficiencies regarding construction material quality. Some of the issues detected in these structures include the corrosion of structural elements, lack of aggregate gradation, use of river gravel aggregate, deficiencies in the production and casting of concrete, inadequate cement use, lack of maintenance, use of concrete poured manually, lack of testing for fresh concrete, lack of stirrups and stirrup hooks, use of flat reinforcement, segregation, inadequate adherence, ruptures in reinforcements, inadequate concrete cover, and use of poor- or low-quality materials [41].

The damage investigation of a two-story building in Hatay Belen revealed that the column sections were inadequate ($20\text{ cm} \times 20\text{ cm}$), concrete covers were inadequate, reinforcements were corroded, their diameters were thinned, stirrup hooks were produced at a 90° angle, and the stirrup spacing was 30 cm. Additionally, different diameters and numbers of flat reinforcements without ribs were used, and coarse aggregates were used in the concrete, which resulted in poor concrete quality (Figure 17).



Figure 17. Structural defects in a damaged multi-story building in Hatay after an earthquake

Corrosion-induced structural damage was high owing to the presence of seawater near Hatay, particularly in the coastal areas (Figure 18).



Figure 18. Loss of concrete reinforcement adherence and thinning of reinforcement diameter (cross-sectional loss)

5.5. Shear, diagonal, out-of-plane bending damages in shear walls

Shear and bending damage to shear walls in buildings that occurred during the Hatay earthquake on 6 February 2023 were examined. Damage occurred in the shear walls because of significant displacement and sectional stresses caused by severe shaking in a tall building in the Iskenderun district of Hatay (Figure 19). The concrete cover cracked, the concrete was shattered, exceeding its compressive capacity, the stirrups opened, the longitudinal reinforcements were shifted by 10 cm, and some longitudinal reinforcements and stirrups were broken.



Figure 19. Plastic deformation and out-of-plane bending damage in Iskenderun–Hatay shear wall



Figure 20. Diagonal cracks and loss of sections in structural walls

Diagonal cracks occurred in load-bearing shear elements in response to excessive cross-sectional pressures or insufficient cross-sectional dimensions (Figure 20).

5.6. Structural damages caused by strong beam-weak column formation

The TBEC-2007 [42] stipulates that columns must be stronger than beams and that the sum of the bearing moments of the columns joining each column-beam joint must be at least 20% greater than the sum of the bearing moments of the beams joining the joint on the column face in structural systems consisting of frames or a combination of shear walls and frames. Otherwise, the case is referred to as a weak column-strong beam irregularity (Figure 21). The endpoints of the columns were stressed beyond their maximum strength capacity, which caused brittle cracking, soft floor formation, and even total collapse.



Figure 21. Strong beam-weak column behaviour in Antakya and Iskenderun

5.7. Structural damages due to workmanship defects

Poor workmanship contributes to damage caused by earthquakes. Some stirrups were not bonded to the longitudinal reinforcement in the carriers of collapsed or severely damaged buildings. The stirrups cannot provide sufficient adherence to the core concrete and open immediately because of the dynamic movement (Figure 22).



Figure 22. Inadequate transverse reinforcement

5.8. Reinforced concrete beams damaged during earthquake

Beam damage was common in these earthquakes and was observed in short beams connected to shear or column elements. There was also significant damage to short beams connected to the elevator concrete wall and to short beams built to fulfil architectural requirements (Figure 23).



Figure 23. Examples of short-beam cracks connected to elevator shear walls

5.9. Damage caused by unrelated (irrelevant) substances in concrete

Irrelevant materials have also been found in the concrete when examining damaged buildings. Many systems, such as plumbing pipes and electrical cables, pass through structural elements, reducing the cross-sections of that element and thus the strength, causing more damage to the structure. As shown in Figure 24-a and b, electrical cables passing through the carrier reduced the strength of that section, and in Figure 24-c, plumbing pipes passing through the carrier reduced the cross-section in that area of the section, causing cracks to occur during the earthquake.

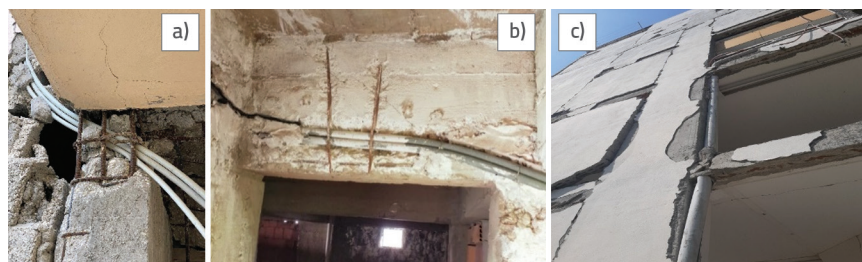


Figure 24. Materials that cause section losses in structural elements

6. Conclusion

This study comprehensively assessed the earthquake damages in Hatay, one of the provinces in Turkey that was devastated by the first earthquake of Mw 7.7 with epicentre in Pazarcık (Kahramanmaraş) in February 2023 and the second earthquake of Mw 7.6 with epicentre in Elbistan (Kahramanmaraş) approximately 9 h later.

Turkey is located on three active major fault lines, namely the EAFZ, North Anatolian Fault, and West Anatolian Fault, as well as several other faults, including the Karlıova, Yumurtalık, Cyprus, and Ölüdeniz faults. Moreover, the EAFZ is tectonically active and expected to produce medium- and high-intensity earthquakes. According to the geological and tectonic damage investigations, the Amanos segment, one of the DAFZ segments, which is a left lateral strike-slip fault, was broken, and surface ruptures could be traced as far as the Kırıkhan and Altınözü districts. In Hatay, which is a basin, the damage was mainly concentrated in the districts of Antakya (central district), İskenderun, and Kırıkhan.

Although Kahramanmaraş was the epicentre of one of the earthquakes that occurred on 6 February 2023 the devastation in Hatay, located 180 km away from the epicentre, was particularly high. Given that the shear wave velocity ($V_s(30)$) was low in loose soil, the intensity of the earthquake increased in the soil and affected the structures. Furthermore, the soils liquefied under seismic motion and could no longer support buildings. Therefore, structures built on plains, soft soils, and agricultural lands in the Antakya and Kırıkhan districts were the most damaged. Geotechnical investigations have revealed that landslides and sand spouts are caused by seismic ground liquefaction, which leads to cracks, heaving, and lateral spreading on the ground surface. Settlement and different settlement-related problems also arise in structures because of liquefaction.

As stated by many researchers, damage to buildings after the 6 February earthquakes was caused by structural irregularities, poor quality of building materials, poor workmanship practices, practices contrary to earthquake regulations, and a lack of relevant legislation [33, 35, 36]. Many restrictions and new rules were added to earthquake regulations in Turkey after the 1999 Marmara earthquake.

Most buildings in Hatay were constructed according to the 1975 regulations on structures to be built in disaster zones (TEC 1975) [43]. In contrast to the TBEC 1998 [44], the application of stirrup hooks at 90° instead of 135° played a crucial role in the collapse or damage to structures during the February 2023 earthquakes [45].

During field investigations, the use of short columns [46] in buildings in Hatay, the construction of soft floors on the ground floors for commercial purposes (shops), or the application of sudden or variable elevation differences between floors for various uses, such as utility floors, pools, and gymnasiums, caused sudden changes in stiffness, displacements, and dynamic response. According to TBEC-2007, ensuring that columns are stronger than beams is an important principle in the design of earthquake-resistant buildings (TBEC 2007) [42]. Weak column-strong beam irregularity, an irregularity in the vertical direction, causes brittle ruptures, collapse of multiple floors on top of each other, and total collapse.

Shear forces exceeding capacity limits, insufficient concrete cover and use of spacers or stirrups in column-beam, shear beam, or column-foundation joints were among the causes of damage in shear or column cross sections that were not constructed according to design or code requirements. Bearing elements cannot resist severe ground motions. The columns were subjected to tensile stresses, the reinforcements broke, and the integrity of the concrete was disrupted owing to the reverse acceleration during the earthquakes.

Additionally, shear and flexural damage occurred in buildings where shear walls [47] were not used or where they were used only in one direction and with a small number of shear walls. Shear walls are critical for preventing the total collapse of structures by absorbing a critical portion of the base shear forces.

Significant damage occurred in the beams, particularly in short beams connected to the elevator shear wall and those constructed to satisfy architectural requirements. Under the

effects of earthquakes, structural elements with small free lengths are subjected to shear forces above their capacity. This caused excessive stresses in the cross-sections and damage, especially in short beams, owing to static and dynamic effects. Investigations also showed that electrical cables and plumbing pipes pass through structural elements during construction [48]. These erroneous applications decrease the strength of the structural elements and may have contributed to more damage during earthquakes.

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