

PERFORMANCE OF REINFORCED CONCRETE BUILDINGS IN THE 2023 KAHRAMANMARAS EARTHQUAKES

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Abstract: *This paper provides initial observations and discussions on the severe damage inflicted on reinforced concrete residential buildings during the Kahramanmaras earthquakes (Pazarcik M7.7 and Elbistan M7.6). Particular attention is given to relatively modern buildings constructed in the past 40 years in the Hatay province, Turkey. The paper highlights the main shortcomings related to the material and construction quality as well as design issues and off-project modifications that led to significant damage and collapse. After a brief discussion of the strong ground motion characteristics of two earthquakes, on-site observations are presented by dividing the entire building stock into two categories according to the construction period. It is shown that buildings constructed prior to 2000 exhibited various deficiencies that contributed to their vulnerability during the seismic events. These included the adoption of deficient lateral resisting frame systems, use of smooth reinforcement bars with inadequate detailing and low reinforcement ratios, excessive corrosion of steel bars, low-quality concrete materials, substandard engineering design, and the utilization of ribbed slab systems with poor seismic performance. In the case of framed buildings constructed after 2000, several key issues were also identified. In addition to many of the design and construction issues observed in the pre-2000 buildings, seismic demands were typically underestimated, geotechnical site investigations were inadequate, and weak foundation designs were prevalent. Another common observation was the utilization of lower storeys as open commercial spaces with minimal infill walls, leading to soft-storey type failures. Many of the catastrophic building failures could also be attributed to non-engineered off-project modifications, such as column removals made in commercial spaces to create larger spaces. The overall assessment revealed that the building stock in parts of Turkey was ill-prepared to withstand extreme seismic events. It is shown that existing buildings, especially those constructed before 2000, need to be examined thoroughly to assess their seismic resilience as part of urban renewal policies. Furthermore, the establishment of a robust building inspection system is imperative to ensure structural integrity and mitigate the risks associated with future seismic events.*

Introduction

A devastating earthquake with a moment magnitude (M_w) of 7.7 struck the city of Pazarcik/Kahramanmaras in the southern part of Turkey on February 6, 2023, at 04:17 (01:17 GMT), causing widespread damage and casualties. The epicentre was located at coordinates of N37.288°, E37.043°, with a focal depth of 8.6 km as reported by the Turkish Ministry of Interior, Disaster and Emergency Management Presidency (AFAD) on their seismic database and analysis system (TADAS) with an event ID of 17966. Subsequently, another destructive earthquake with M_w of 7.6 hit the region approximately 9 hours later at 13:24 (10:24 GMT). The epicentre of the second earthquake was located in Elbistan/Kahramanmaras, Türkiye, with exact coordinates of N38.089°, E37.239°. The focal depth of the second event reported by AFAD was 7 km (TADAS) (event ID: 17969). Both seismic events occurred on the East Anatolian Fault (EAF), which connects the Anatolian Plate and the northward-moving Arabian Plate. The fault mechanism of the earthquakes was reported by different national and international research agencies as left-lateral strike-slip, which is consistent with the tectonic characteristics of EAF.

The two major earthquakes affected 11 provinces, including Kahramanmaras, Hatay, Malatya, Adiyaman, Osmaniye, Kilis, Gaziantep, Elazig, Adana, Sanliurfa, and Diyarbakir. As of May 17,

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2023, a total of 25222 aftershocks were recorded in 11 affected provinces. These included 3 aftershocks exceeding M_w of 6.0; 45 aftershocks between M_w of 5.0 and 6.0; and 488 aftershocks between M_w of 4.0 and 5.0. During the devastating earthquakes, more than 50,000 people died

and around 233,000 buildings either collapsed or were heavily damaged as reported by TCSBB (2023), prepared by the 'Presidency of Strategy and Budget, Turkey'. A more detailed discussion regarding seismic characteristics of the earthquakes and strong ground motion records is presented in the subsequent sections of this paper.

Turkey is located in a seismically active region known as the Mediterranean Basin, and earthquakes are a recurring threat to the country. The most recent seismic hazard map prepared by AFAD (TDTH, 2018) is presented on Figure 1. Despite efforts to improve earthquake preparedness and response, earthquakes continue to pose a significant risk to Turkey's population and infrastructure. Nonetheless, Turkey has made significant progress in developing seismic design codes to improve earthquake resilience. The Turkish government first implemented seismic codes in the 1940s, which were then revised in 1953, 1961, 1968, 1975, 2007 and 2018 (AFAD, Işık, 2021, Soyuk and Harmankaya, 2012). These revisions were mainly made following a series of devastating earthquakes in the history of Turkey, and always adopted more strict requirements. However, after every significant earthquake, severe and devastating outcomes were observed. Whilst the codes reflected a high standard of seismic design knowledge, these catastrophic consequences were mostly due to poor implementation of design and construction in practice as well as lack of a proper inspection system. Therefore, in addition to the intensity of the ground motion, the structural system selection, design, and construction quality played a significant role in the seismic performance of building structures.

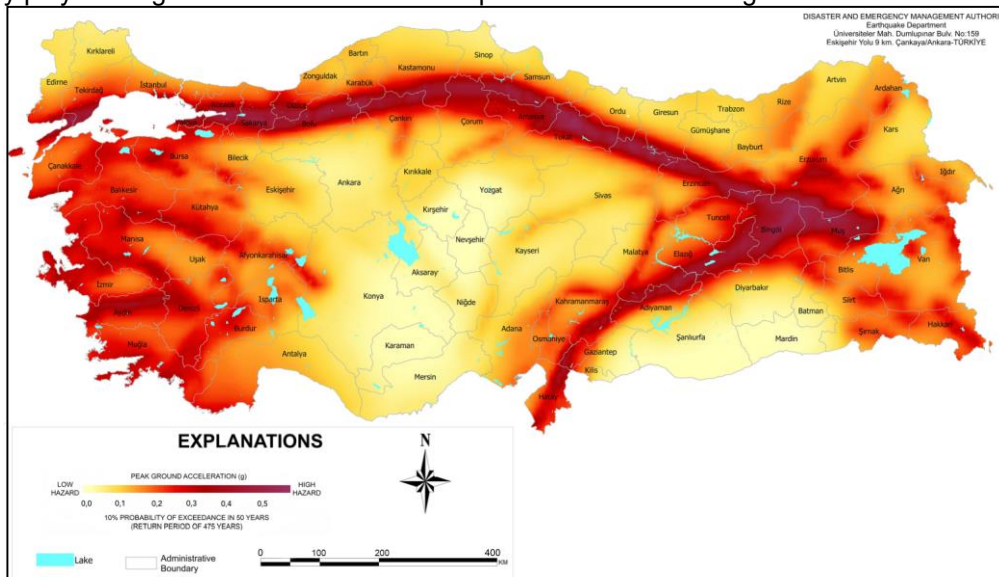


Figure 1. Earthquake hazard map of Turkey (TDTH, 2018).

This paper provides observations on collapsed or heavily damaged residential structures in the districts of Iskenderun, Belen, and Arsuz in the Hatay province, which led to a high number of casualties. The investigated building database was divided into two categories of pre- and post2000 construction date, on the basis of a perception of a significant improvement in the construction practice in Turkey between the late 1990s and early 2000s due to the following factors: (i) introduction of an improved seismic code in 1998, (ii) lessons learnt after two major 1999 earthquakes in Kocaeli and Duzce on August 17 and November 12, respectively, (iii) publication of new Turkish guidelines for design and construction of reinforced concrete structures (TS 500), and (iv) enactment of building inspection law in 2001 for 19 pilot provinces including Hatay, Gaziantep, and Adana (extended to the entire country in 2011). In subsequent sections of this paper, common observed problems leading to damage or collapse are summarised leading to discussions on the overall earthquake resistance quality of the building stock in Turkey.

Strong motion characteristics

Strong motion data in the two Kahramanmaras earthquakes were recorded in an extensive region by accelerometer stations operated by AFAD. The placement of stations and measured peak

ground accelerations (PGA) for both the 1st (Pazarcik, M_w 7.7) and 2nd (Elbistan, M_w 7.6) events are illustrated in Figure 2a and 1b, respectively. The triangles represent accelerometer stations, yellow stars indicate the epicentres of the earthquakes. The highest PGA of 2178.71 cm/s^2 (E-W direction) for the first event was recorded at Station 4614 located in the Pazarcik district of Kahramanmaraş with an epicentral distance (R_{epi}) of 31.42 km. In the second event, the highest PGA was 635.45 cm/s^2 (N-S direction) and recorded at Station 4612 in Goksun, Kahramanmaraş. The entire strong ground motion data for the two events is available at AFAD's earthquake database and analysis system (TADAS). For brevity, only the dataset from the stations with the highest PGAs as well as the ground motion from the nearest stations to the investigated region (Iskenderun, Arsuz and Belen districts of Hatay) are presented herein.

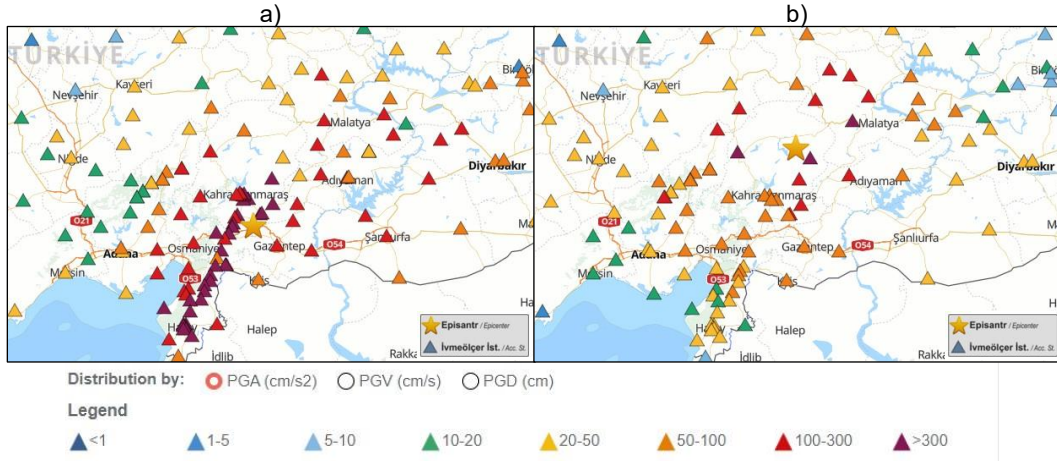


Figure 2. Distribution of strong ground motion stations and recorded PGAs: a) M_w 7.7 (event ID: 17966), b) M_w 7.6 (event ID: 17969) (figures from (TADAS)).

Figure 3 shows the strong ground motion records at the stations with the highest PGAs recorded for both earthquakes. Since the evaluated region was mostly affected during the 1st event (Pazarcik, M_w 7.7), the strong ground motion data recorded in the 1st event are evaluated in this paper. The records were obtained from the stations within the region and compared to the corresponding elastic design spectra according to Turkish seismic design code (TBDY-2018, 2018). For this purpose, 4 strong ground motion stations are selected, and their information are given in Table 1. The table shows the location of the stations, their distance to the epicentre (R_{epi}), V_{s30} , peak ground accelerations (PGA) in three directions, and the site classes. Site classes ZB and ZC correspond to NEHRP Site Classes B and C, respectively (NEHRP, 2020).

Figure 4 shows acceleration response spectra of ground motions recorded at the selected stations for 5% damping in comparison with the elastic design spectrum obtained from the latest version of the code (TBDY-2018, 2018). In order to define the elastic design spectra, the ground coefficients need to be carefully selected for the specific sites at the location of the investigated stations. The design spectral acceleration coefficients for both short period and 1.0 s period are the products of the mapped spectral acceleration coefficients and local site amplification coefficients. The former is stipulated as: "Map spectral acceleration coefficients corresponding to the geometric mean of earthquake effects in two perpendicular horizontal directions are defined as dimensionless coefficients by dividing the map spectral accelerations by the gravitational acceleration for a 5% damping ratio based on the reference ground condition ($V_{s30} = 760$ m/s) for a given earthquake ground motion level" in (TBDY-2018, 2018). The local site amplification coefficients are determined from Tables 2.1 and 2.2 in TBDY-2018 with respect to the site class and map spectral acceleration coefficient. Map spectral acceleration coefficients were obtained for the exact locations of the selected stations via the interactive version of earthquake hazard map shown in Figure 1 (TDTH, 2018). The elastic design spectra were determined for two levels of ground motion as DD1 and DD2. The former refers to very rare earthquakes with a return period of 2475 years whilst the latter corresponds to rare events with a return period of 475 years.

The maximum horizontal PGA of 1.40 g is recorded at Station 3135, located in Arsuz, Hatay, on a site with NEHRP Class C (ZC of TBDY-2018) in the E-W direction, while the vertical PGA is 0.60g. The response spectra of both the horizontal and vertical components exceed the design spectrum for both return periods of 475 and 2475 years for periods larger than around 1 second. The response of all other stations, apart from Station 3146 located in Belen, Hatay, in which the N-S

component exceeds the design spectra for a return period 475 year at very short period ranges, are consistent with the elastic design spectrum for a return period of 475 years.

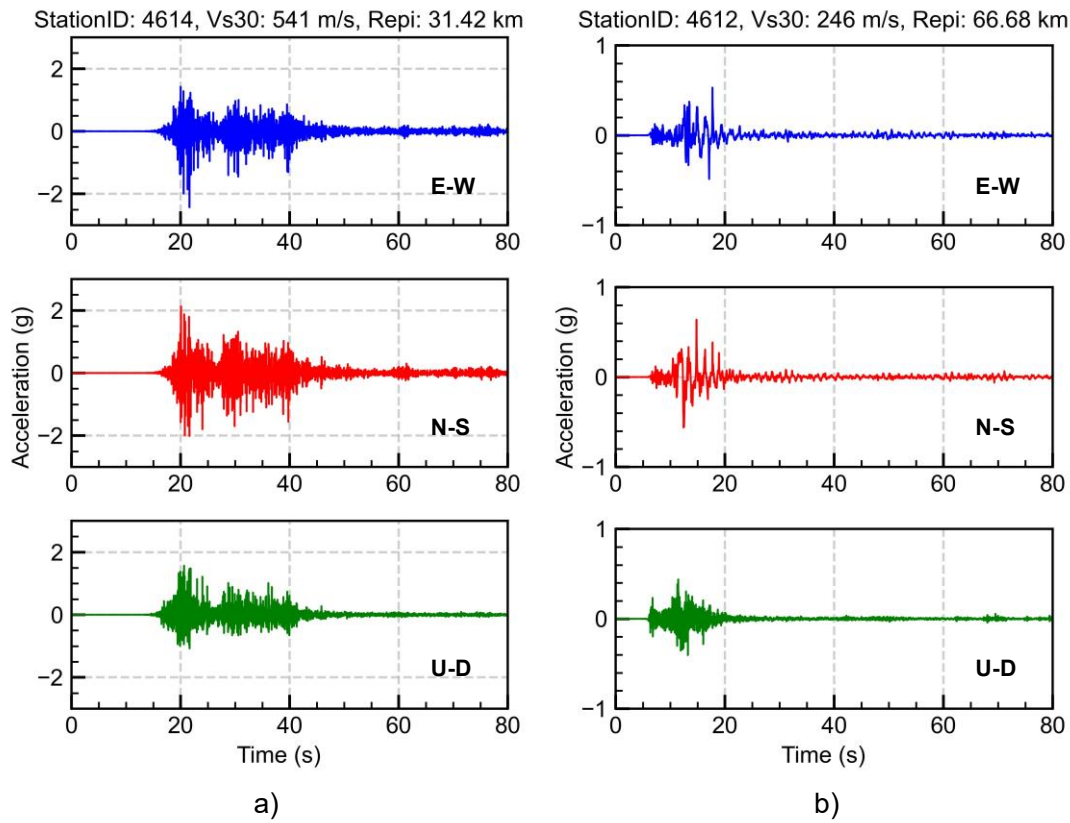


Figure 3. Strong ground motion records at the highest PGAs recorded stations for the events: a) M_w 7.7, b) M_w 7.6 (data from (TADAS)).

| StationID | City | District | R_{epi} , km | V_{s30} , m/s | Direction | PGA, g | Site Class* |
|-----------|-------|------------|----------------|-----------------|-----------|--------|-------------|
| 3135 | Hatay | Arsuz | 142.15 | 460 | E-W | 1.40 | ZC |
| | | | | | N-S | 0.76 | |
| | | | | | U-D | 0.60 | |
| 3146 | Hatay | Belen | 114.57 | NA | E-W | 0.35 | NA |
| | | | | | N-S | 0.50 | |
| | | | | | U-D | 0.35 | |
| 3115 | Hatay | Belen | 113.57 | 424 | E-W | 0.25 | ZC |
| | | | | | N-S | 0.30 | |
| | | | | | U-D | 0.22 | |
| 3116 | Hatay | Iskenderun | 105.38 | 870 | E-W | 0.17 | ZB |
| | | | | | N-S | 0.17 | |
| | | | | | U-D | 0.17 | |

*Site classes are given according to the classification in TBDY-2018 (2018). NA denote 'not available'.

Table 1. Information on ground motion records for stations within investigated region (TADAS).

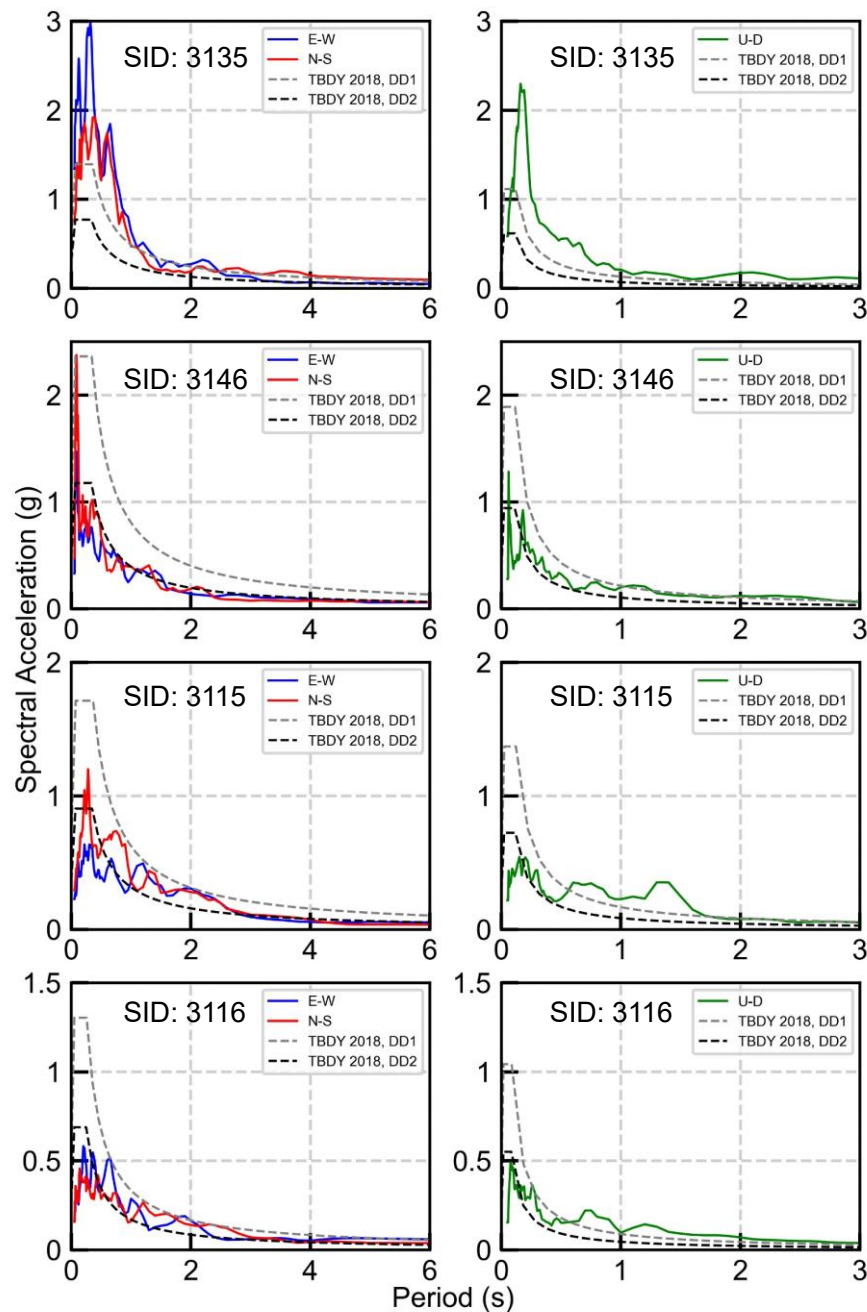


Figure 4. Response spectra with 5% damping compared to most recent code (TBDY-2018, 2018) at selected stations for Pazarcik (M_w 7.7) earthquake (data from (TADAS)).

Observations on collapsed or heavily damaged RC buildings

The two events, Pazarcik and Elbistan of the Kahramanmaraş earthquakes were one of the most significant in the past century in Turkey; 11 provinces were severely affected during these earthquakes. The least affected provinces were Adana, Diyarbakir, Elazig, Kilis, Osmaniye, and Sanliurfa. On the other hand, Hatay, Kahramanmaraş, Gaziantep, Adiyaman, and Malatya had the highest damage and casualties due to the proximity of these provinces to the faults. Therefore, collapsed or heavily damaged residential buildings located in Iskenderun, Arsuz, and Belen provinces of Hatay are considered herein. The building inventory intentionally consists of the buildings with a high number of casualties and is divided into two categories with respect to their construction periods of pre- or post-2000. Around 90 collapsed or heavily damaged buildings, predominantly consisting of framed RC framed buildings were examined.

Buildings constructed before 2000

Common shortcomings in frame-type buildings constructed prior to 2000 included the inadequate stiffness and strength within lateral resisting systems, utilization of smooth-surfaced reinforcement bars, poor detailing of steel reinforcement especially within the beam-column connection regions,

excessive corrosion of steel, and low concrete material strength, leading to severe damage and many collapses. Figure 5 shows examples of common issues related to steel reinforcement and concrete material. As indicated in the figures, the amount of steel reinforcement is relatively low and rebars are excessively corroded, whilst concrete is segregated and contains coarse smooth-surfaced aggregates with around 7-8 cm diameter. These reduce significantly the bond capacity between the rebars and concrete material as shown in Figure 5.



Figure 5. Typical material and detailing deficiencies in pre-2000 buildings; a) Smooth-surfaced rebars with 90° hooks at the ends of stirrups and deficient detailing; b) Anomalous size and shape of aggregates; c) Excessive corrosion and poor reinforcement detailing.

Another key issue is the common use of ribbed floor slabs due to architectural preferences by the end of 2010s. In this type of floor, beams are hidden within the slab, resulting in a flat ceiling without any obstructions. An example of its application is shown in Figure 6. The thickness of this type of slab varies between 30-40 cm. Therefore, in order to hide the beams within the slab, the designer needs to use shallower beams which significantly decrease the bending capacity. Depending on the filling material between the ribs, the weight of the slab can increase notably, leading to heavier buildings hence higher seismic forces. Whilst ribbed slabs can provide rigid diaphragm behaviour in the direction parallel to the ribs, it is quite weak in the direction perpendicular to the ribs and, in most cases, a relatively rigid diaphragm is hard to obtain. Due to their poor seismic performance, their adoption is restricted in the most recent Turkish seismic code (TBDY, 2018), with respect to the type of building, seismic zone, and use of shear walls. As observed in the building inventory, the vast majority of pancake-type failures as illustrated in Figure 7, has been observed in buildings incorporating ribbed floor slabs,



Figure 6. Examples of ribbed floor slabs construction.



Figure 7. Failures of buildings with ribbed slab.

Examples of deficient design were also commonly observed. A typical example is the inadequacy or even absence of a proper lateral resisting frame system. Mostly due to architectural purposes or restrictions by construction law, mushroom-type buildings are quite common in Turkey, despite it being undesirable in such high seismic risk regions. The current construction law does not allow the use of the entire site to construct the building, as in many countries. However, it allows the floor areas to be increased for storeys above the ground floor. As for the architectural side, designers usually move beams connecting external columns to the façade to avoid having drop beams visible within the flat floor, as illustrated in Figure 8. Proper frame action is therefore not obtained on the storeys above the ground floor. This also remained a common issue in buildings constructed after 2000. Due to the severity of this problem, this type of construction is under consideration for prohibition in the near future by building codes in Turkey.

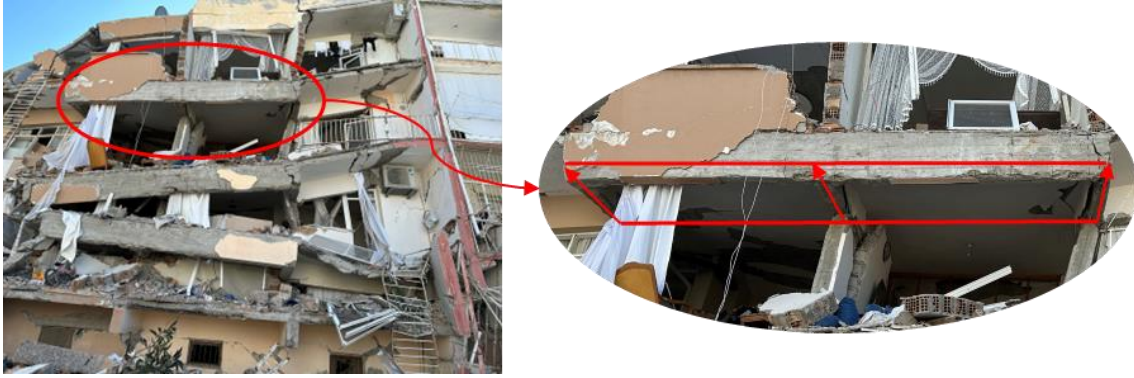


Figure 8. Example of inadequate lateral resisting frame system.



Figure 9. Failures of two identical buildings.

Another type of repeatedly observed failure is shown in Figure 9, which shows typical failures of two identical buildings. The poor design of the bridge between the blocks is clear. There is no seismic expansion joint, and the bridge is connected to the blocks via a fixed support. When considering the short length of the beam members, the shear failure as seen in the figure is evident. Also, the quality of connection design and reinforcement detailing is quite low, all leading to a soft storey failure.

Buildings constructed after 2000

Newer buildings, which were assumed to have been designed and constructed in accordance with modern seismic codes (Elghazouli, 2016), exhibited better performance compared to pre-2000 buildings. Nevertheless, unexpected numbers of new buildings suffered collapse or heavy damaged, indicating a failure to meet the prescribed performance objectives outlined in the seismic design code. The main deficiencies of framed post-2000 buildings were: (i) poor design and construction quality, as in pre-2000 buildings, (ii) underestimation of seismic demands, (iii) inadequate geotechnical site investigations and weak foundation design. These deficiencies are largely attributed to the lack of a proper inspection system rather than the inadequacy of the code.

Figure 10 shows an example of a recently constructed 17-storey RC building in Iskenderun, including basement, ground floor, and roof. The figure includes photos during construction, when completed, after the 1st earthquake and the full collapse after the 2nd event. As clearly shown in the figure, the lateral resisting system is inadequate. Whilst the frame system seems to be formed in one direction, there are no beams connecting the columns in the other direction. This type of multi-storey buildings both in plan and elevation requires the use of proper lateral resisting systems in orthogonal directions, with adequate stiffness, strength and ductility. However, in this case, the stiff elements are formed around the lift shaft. These shear walls prevented half of the structure in plan from collapse during the first earthquake.



Figure 10. Example of post-2000 building collapses; a), b), and c) Before the earthquakes; d) After first earthquake; e) and f) After second earthquake.



Figure 11. Illustration of collapses in post- 2000 buildings; a) Front view; b) Back view with softstorey mechanism; c) View of ribbed floor slab.

Another example failure of a building constructed after 2000, is shown in Figure 11. The building was designed as an RC framed building with ribbed floor slabs. The ground floor was used for commercial purposes as a showroom with little or no infill walls which, unless coupled with adequate design and detailing, often leads to soft storey failures as illustrated in the figure. The floor area of the storeys above the ground floor is also increased, and ribbed floor slabs with poor seismic performance, as discussed earlier, were utilised in the building. All these factors, individually or in combination, led to the collapse of many buildings in the affected areas.

Conclusions

This paper has provided initial observations on collapsed or heavily damaged residential structures in the districts of Iskenderun, Belen, and Arsuz in the Hatay province, which led to a high number of casualties. Following a discussion on the strong motion characteristics of the two large Kahramanmaraş earthquakes, on-site observations were presented by dividing the investigated building inventory into two categories of pre- and post-2000 construction date. The paper then investigated common issues related to material and construction quality as well as engineering design that may lead to poor performance of buildings. The main observations are summarised below.

The use of smooth reinforcement bars with poor detailing and low reinforcement ratio, excessive corrosion of steel bars, low concrete material quality, substandard engineering design, lack of proper formation of lateral resisting frame systems, and the utilisation of ribbed slab systems with very low seismic performance represent the main deficiencies in pre-2000 buildings. The primary

issues observed in framed post-2000 buildings included: (i) poor design and construction quality, as in those constructed prior to 2000, (ii) underestimation of seismic demands, (iii) inadequate geotechnical site investigations and weak foundation design. The use of lower storeys as commercial stores with limited infill walls and lack of proper design and detailing led to numerous soft storey failure. Many catastrophic failures of building were also attributed to off-project modifications such as column removals or reductions in commercial stores of buildings.

Overall, it was concluded that the building stock in Turkey was highly vulnerable to the extreme seismic demands experienced in the two large Kahramanmaras events. The current building stock, particularly pre-2000 buildings, need to be assessed thoroughly to examine their seismic resilience as part of urban renewal policies. Furthermore, the establishment of a robust building inspection system is imperative to ensure structural integrity and mitigate the risks associated with future seismic events.

Acknowledgement

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