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Structural damage assessment of reinforced concrete buildings in Adıyaman after Kahramanmaraş (Türkiye) Earthquakes on 6 February 2023

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A R T I C L E I N F O

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A B S T R A C T

Two destructive earthquakes (Mw: 7.7 and Mw: 7.6) occurred in Kahramanmaraş, Türkiye, on February 6, 2023. The epicenters of these two earthquakes were very close to each other (approximately 90 km apart), and both took place on the same day. The first earthquake occured at 04:17 local time with a magnitude of 7.7 and a depth of 8.6 km, while the second earthquake occurred at 13:24 local time with a magnitude of 7.6 and a depth of 7.0 km. These two earthquakes caused extensive damage, particularly in 11 provinces, with Adıyaman being one of the hardest-hit areas. Most buildings in Adıyaman were severely affected or collapsed as a result of the earthquakes. Reports indicate that over 35,000 buildings collapsed in the aftermath. Furthermore, between February 6, 2023, and May 6, 2023, more than 30,000 aftershocks, ranging in magnitude from 0.2 to 6.6, were recorded. In this study, earthquake damages in reinforced concrete buildings in Adıyaman province were evaluated. The causes of damages in reinforced concrete buildings were evaluated in terms of material quality, design of building and reinforcement details. Field observations are also provided, along with accompanying pictures. The earthquake regulations in Türkiye, established in 1975, 1998, 2007, and 2018, which apply to a significant portion of the country's buildings, are discussed. An evaluation was conducted to assess whether the damaged buildings complied with the earthquake regulations in Türkiye. Field observations revealed that the earthquake regulations, particularly in relation to reinforcement details, were overlooked. In addition, designers should avoid design mistakes such as to make discontinuous of frames, to place most of vertical element strong axis in one direction, insufficient support condition of stairs and adjacent building effects.

1. Introduction

Türkiye has active earthquake fault zones, including the North Anatolian Fault, East Anatolian Fault, and West Anatolian Fault zones, which have the potential to cause destructive earthquakes. Türkiye has often been exposed to destructive earthquakes in the past. After these earthquakes, many studies about structural failures have been conducted and documented in the literature [1–12]. On 6 February 2023, two destructive earthquakes occurred in Kahramanmaraş provinces in Türkiye (Mw: 7.7 and Mw: 7.6). The first earthquake was occurred in Pazarcık (distinct of Kahramanmaraş) at 04:17 local time with a magnitude of Mw:7.7. The second earthquake was occurred in Elbistan (distinct of Kahramanmaraş) at 13:24 local time with a magnitude of Mw:7.6. These two

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Table 1
Studies about damages of building after Türkiye earthquakes.

RC buildings	Sezen et al. (2003), Doğangün (2004), Arslan and Korkmaz (2007), Celep (2011), Taskin et al.(2013), Dogan et al. (2020), Işık et al. (2020), Sayın et al. (2021), Demir and Altıok (2021), Mertol et al (2023), Ozturk et al. (2023)
Masonry and Adobe buildings	Celep (2011), Dogan et al. (2020), Günaydın et al. (2021), Sayın et al. (2021), Işık (2023), Işık et al. (2023), Kocaman (2023)
Industrial and precast buildings	Sezen and Whittaker (2006), Arslan et al. (2006), Sagbas et al. (2023),

Table 2
Kahramanmaraş earthquakes parameters.

Earthquake	Local time	Magnitude (Mw)	Latitude (°N)	Longitude (°E)	Depth (km)
Pazarcık	04:17	7.7	37.288	37.043	8.6
Elbistan	13:24	7.6	38.089	37.239	7.0

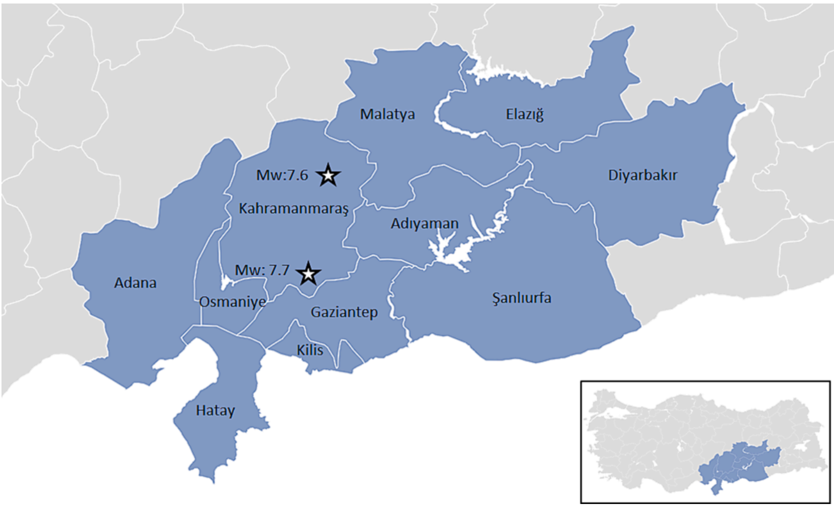


Fig. 1. Kahramanmaraş earthquakes and the most effected provinces.

earthquakes were occurred in same day (approximately nine hour apart) and there is approximately 90 km distance between epicenters of these earthquakes [13]. The pair of earthquakes resulted in significant structural damage, particularly impacting 11 provinces, including Kahramanmaraş, Hatay, Gaziantep, Malatya, Diyarbakır, Kilis, Şanlıurfa, Adıyaman, Osmaniye, Adana, and Elazığ, where many buildings either sustained severe damage or collapsed entirely.

According to official announcements from the Disaster and Emergency Management Authority (DEMA) on 2 June 2023, it was reported that over 35,000 buildings had collapsed after the earthquakes. Furthermore, during the period from February 6, 2023, to

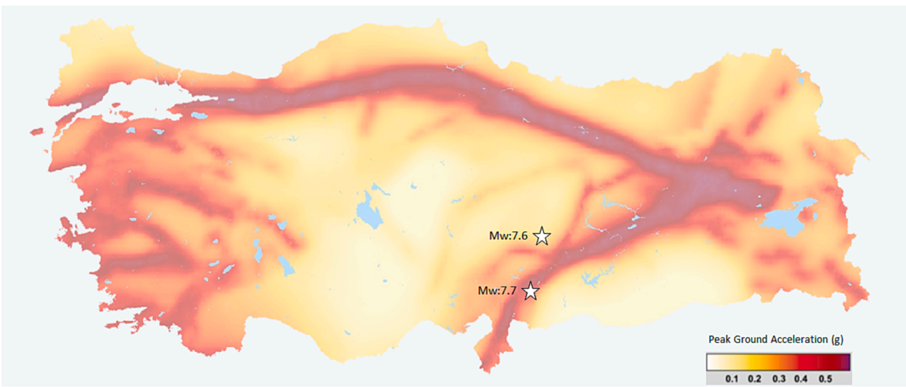
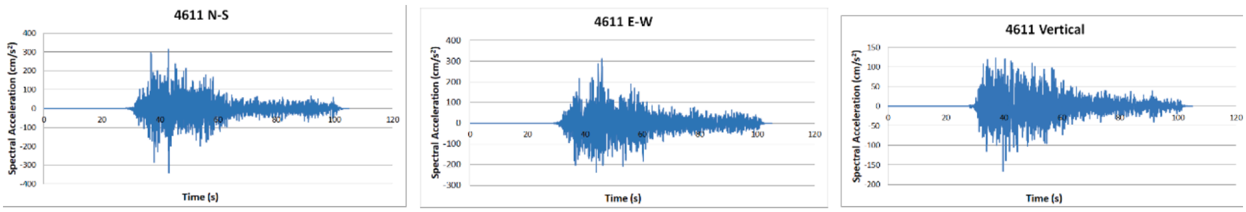


Fig. 2. Türkiye earthquake hazard map and epicenters of Kahramanmaraş earthquakes.

Fig. 3. Epicenters of Pazarcık earthquake and location of 4611 acceleration station.



(a) 0.354g (b) 0.327g (c)0.177g

Fig. 4. Component of ground acceleration records of Pazarcık Earthquake.

May 6, 2023, more than 30,000 earthquakes with magnitudes ranging from 0.2 to 6.6 were documented [13]. The Kahramanmaraş earthquakes had a profound impact on Türkiye, causing severe damage not only during the initial earthquakes but also due to subsequent aftershocks.

Following the Kahramanmaraş Earthquakes, extensive research has been conducted regarding various aspects, including reinforced concrete buildings, masonry structures, precast structures, and the distinctive characteristics of these seismic events. Işık et al. [14] examined masonry buildings in Adıyaman province, Mertol et al. [15] and Ozturk et al. [16] examined reinforced concrete structures, Işık et al. [17] examined mosques and minarets in Adıyaman province. Sagbas et al. [18] examined industrial structures and Kocaman [19] examined mosques and minarets after Kahramanmaraş Earthquakes. Ozturk et al. [20] examined school buildings performance after Kahramanmaraş Earthquakes. A literature summary about post-earthquake field investigations after past earthquakes and Kahramanmaraş earthquakes is listed in Table 1.

The majority of the building stock in Türkiye consists of multistory reinforced concrete buildings. The majority of these buildings were designed and built according to the Türkiye earthquake codes published in 1975 or later. Türkiye Earthquake Codes were updated in 1975 (TEC 1975), 1998 (TEC 1998), 2007 (TEC 2007) and 2018 (TBEC 2018) [21–24]. Currently, building design in Türkiye is governed by the Türkiye Buildings Earthquake Codes 2018 (TBEC-2018). Additionally, structures in Türkiye are required to adhere to TS500 (Requirements for Design and Construction of Reinforced Concrete Structures), which have been updated in 1975, 1984, and 2000 and are currently in use as the prevailing standards for construction and design [25–27].

Adıyaman province was severely impacted by these two earthquakes and experienced extensive damage. As a result of the two earthquakes occurring on the same day, no inspections or assessments could be conducted immediately following the first earthquake. Following the second earthquake, a thorough examination of the structures in Adıyaman province was carried out.

In the context of this research, field investigations were conducted in Adıyaman subsequent to the Kahramanmaraş earthquakes that occurred on February 6, 2023. The study focused on identifying earthquake-related damage in multi-story reinforced concrete buildings and assessing the underlying causes of such damage. Various factors that negatively impact the earthquake resistance of these buildings, including design aspects, material choices, and reinforcement details, were examined. Additionally, an evaluation was conducted to assess whether the examined reinforced concrete buildings were in accordance with the Türkiye Earthquake Codes. The primary aim of this study was to identify errors and shortcomings in buildings located in earthquake-prone areas and, crucially, to derive valuable lessons from these mistakes.

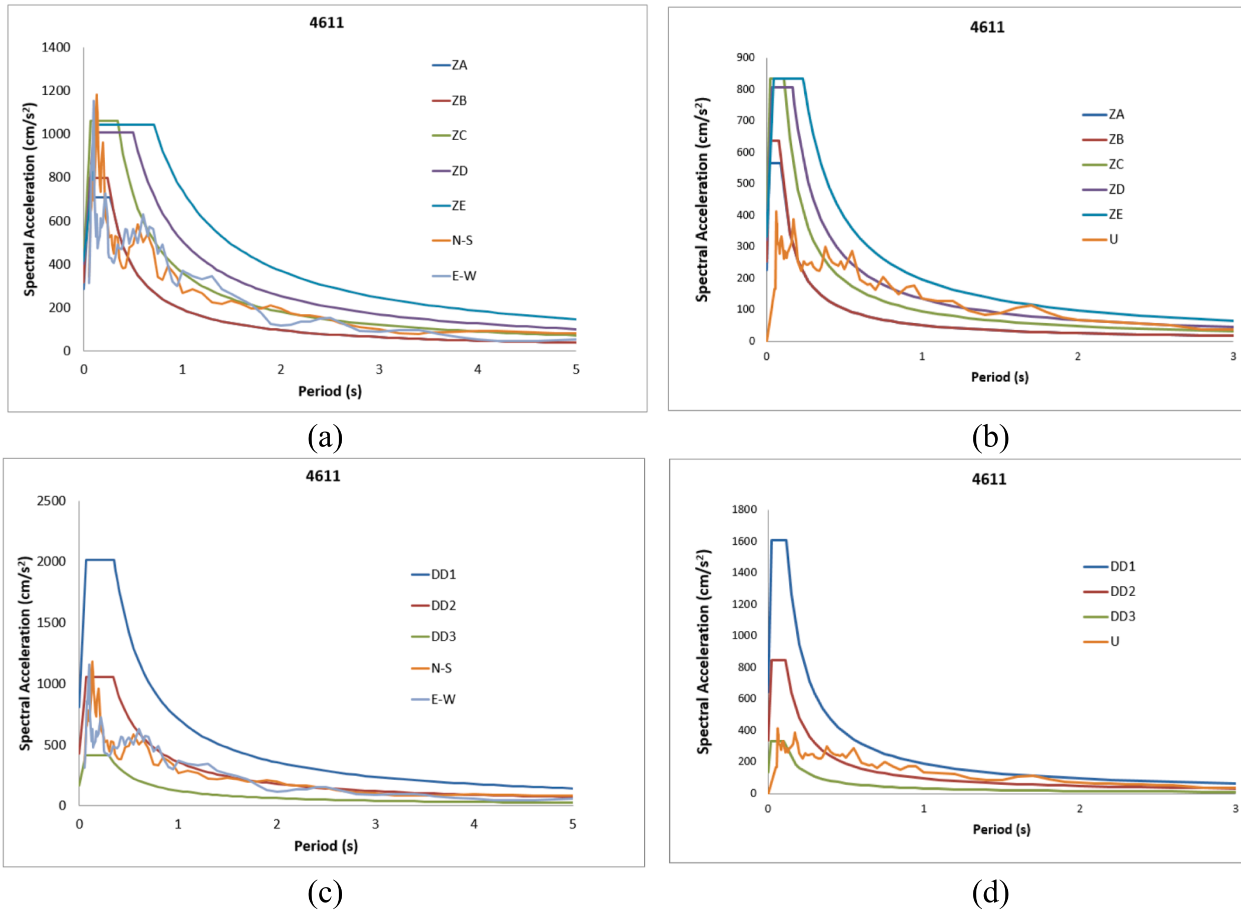


Fig. 5. Spectral acceleration of Pazarcık Earthquake and design spectrum of TBEC-2018 a) horizontal b) vertical c) horizontal for ZC soil d) vertical for ZC soil class.

Fig. 6. Epicenters of Elbistan earthquake and location of 0213 acceleration station.

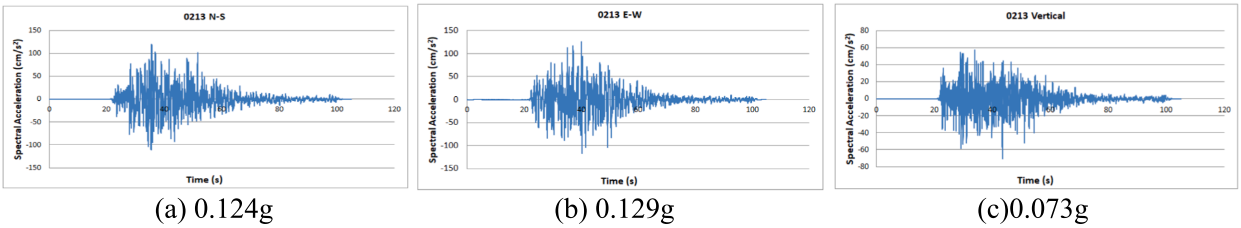


Fig. 7. Component of ground acceleration records of Elbistan Earthquake.

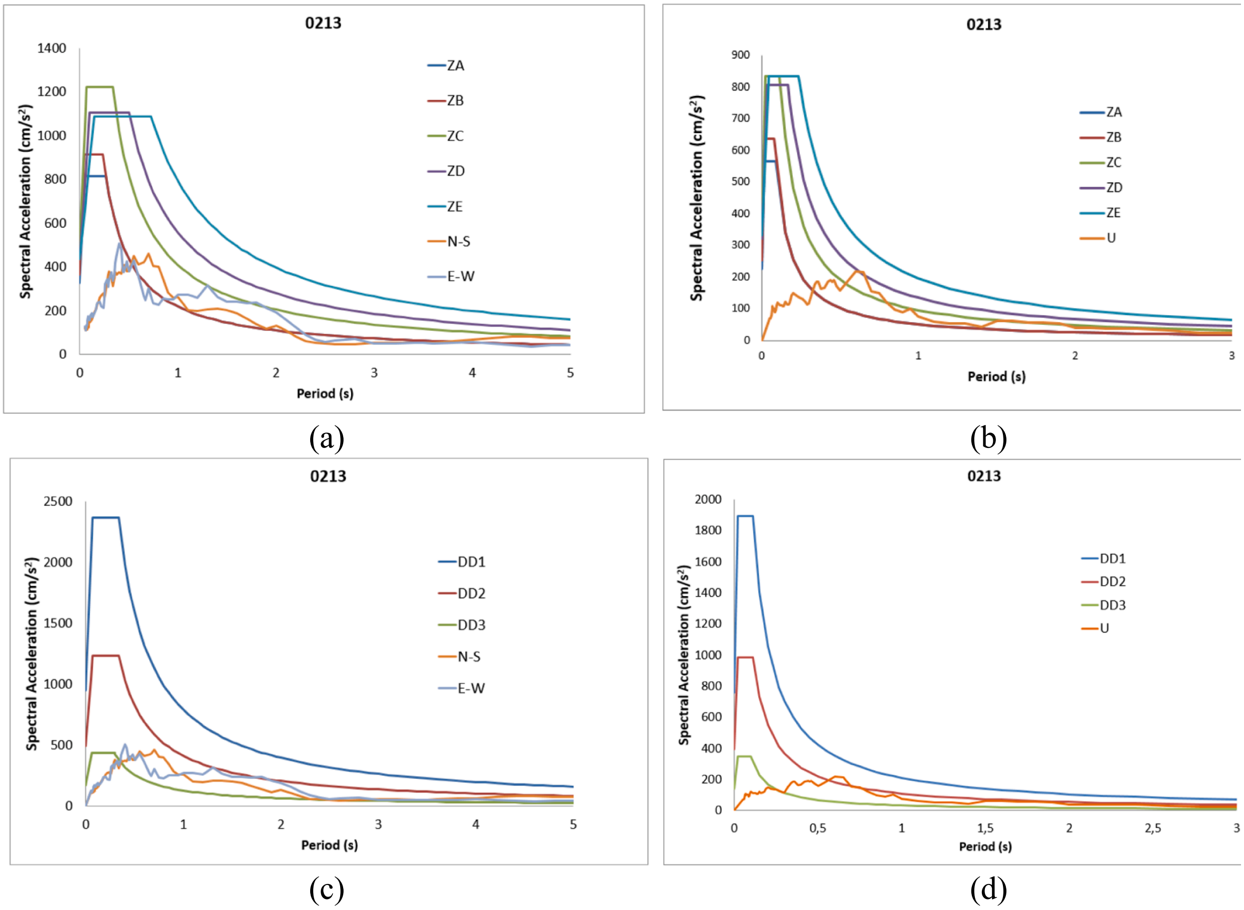


Fig. 8. Spectral acceleration of Elbistan Earthquake and design spectrum of TBEC-2018 a) horizontal b) vertical c) horizontal for ZC soil d) vertical for ZC soil class.

2. Characteristics of earthquakes

On 6 February 2023, two destructive earthquakes (Pazarcık and Elbistan) occurred in Kahramanmaraş provinces in Türkiye. Parameters of these earthquakes could be seen in Table 2. These two destructive earthquakes have severely affect buildings specially in 11 provinces (Kahramanmaraş, Hatay, Gaziantep, Malatya, Diyarbakır, Kilis, Şanlıurfa, Adıyaman, Osmaniye, Adana, Elazığ). Epicenters of earthquakes and most effected provinces could be seen in Fig. 1.

Türkiye have active earthquakes fault zones and these zones of Türkiye could cause severe earthquakes. Türkiye have North Anatolian Fault (NAF), East Anatolian Fault (EAF) and West Anatolian Fault (WAF) zones. Türkiye earthquake hazard map is formed considering by this fault zones. In Fig. 2 it can be seen Türkiye earthquake hazard map and epicenters of Kahramanmaraş earthquakes.

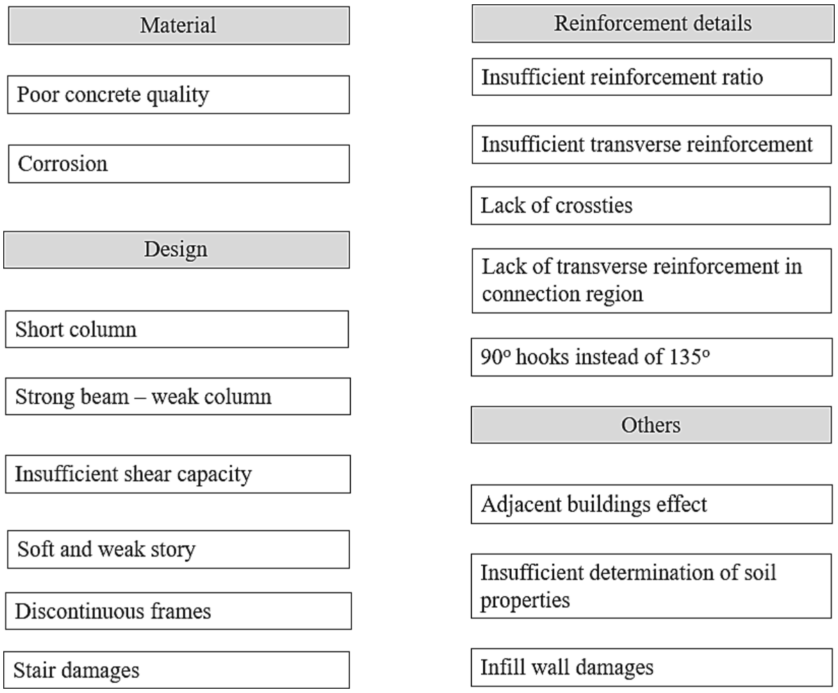


Fig. 9. Classification of damage reasons of RC buildings.

2.1. Pazarcık earthquake

On February 6, 2023, at 04:17 in Türkiye local time, an earthquake occurred at a depth of 8.6 km (Mw: 7.7). When the acceleration records given by DEMA are examined, it is seen that all records in Adıyaman early terminated. For this reason, records of 4611 acceleration station, located outside the Adıyaman province of the Pazarcık earthquake, but closest to Adıyaman, were given (Figs. 3-4). In addition, a comparison of the response spectra of this station with the TBEC-2018 spectrum was given in Fig. 5.

TBEC-2018 defines four earthquake levels called as DD-1, DD-2, DD-3 and DD4. Return period of these earthquakes are 2475, 475, 72 and 43 years, respectively. In addition, probability of exceedance of these earthquakes are 2 %, 10 %, 50 % and 68 % in 50 years, respectively. DD-1 earthquake level is the largest earthquake defined in TBEC-2018. DD-2 earthquake is the design earthquake for buildings. DD-3 and DD-4 earthquake levels are frequent earthquake and service earthquake, respectively. Comparison of the response spectra of acceleration station and different earthquake levels for ZC soil type was given in Fig. 5. It is seen that Pazarcık Earthquake loads exceed design earthquake loads (DD-2), especially for vertical direction.

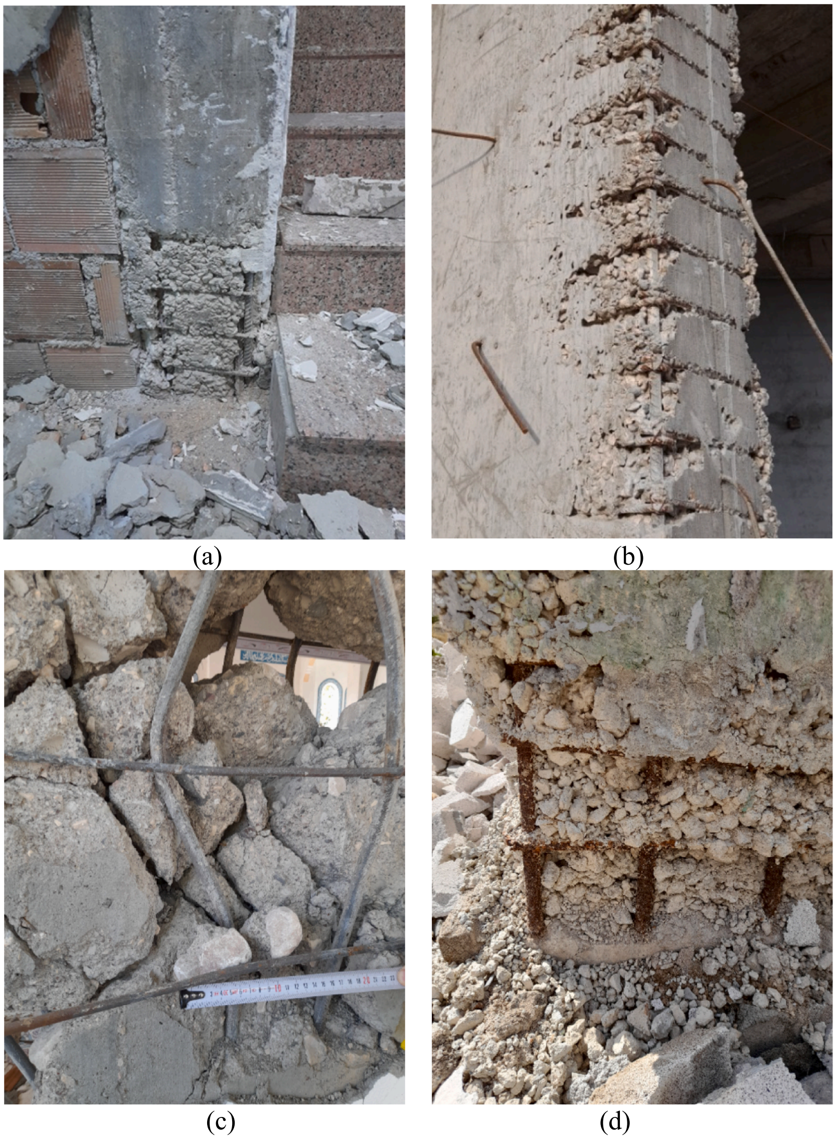
2.2. Elbistan earthquake

On February 6, 2023, an earthquake occurred at a depth of 7 km (Mw: 7.6) at 13:24 Türkiye local time. Acceleration records of station 0213, which is the closest acceleration station to the regions examined after the Elbistan earthquake, are given (Figs. 6-7). In addition, a comparison of the response spectra of this station with the TBEC-2018 design spectrum is given (Fig. 8). Comparison of the response spectra of acceleration station and different earthquake levels for ZC soil type was given in Fig. 8. It is seen that Elbistan Earthquake loads exceed design earthquake loads (DD-2), especially for vertical direction. The vertical acceleration components of earthquakes defined in TBEC-2018 should be more investigated.

3. Reinforced concrete structures

During the field investigations in Adıyaman, it was observed that the majority of reinforced concrete buildings had been designed and constructed in accordance with earthquake regulations published in 1975 or later. Earthquake regulations in Türkiye were revised in 1975, 1998, 2007, and 2018. In this section, the design rules given for reinforced concrete buildings in the Earthquake Regulations used in Türkiye are discussed. In addition, the damages encountered in reinforced concrete buildings and the causes of these damages are detailed.

One of the causes of damage mentioned earlier includes material defects, such as poor concrete quality and reinforcement corrosion, which were widely observed during the field investigations and have a detrimental impact on building performance. In addition, problems such as insufficient transverse reinforcements, the absence of crossties, the absence of transverse reinforcements in column-beam connection and making transverse reinforcement hooks at 90 degrees instead of 135 degrees were commonly



(a) (b) (c) (d)

Fig. 10. Poor concrete quality and corrosion.

encountered in terms of reinforcement details.

Deficiencies during the design phase can potentially harm reinforced concrete buildings. Many damages have been observed due to reasons such as the discontinuity of the frames, the inability to provide strong column-weak beam condition, soft and weak story effect, short column effect and low shear strength of the elements. In addition, serious damage was observed in many buildings due to the adjacent buildings, which was not taken into account during the design phase. Under this title, the reasons that adversely affect the earthquake performance of reinforced concrete buildings are examined in detail and figures of the field investigations are given (Fig. 9).

3.1. Poor concrete quality and corrosion

In the design of a reinforced concrete building, the design is made by assuming that the concrete provides the project strength, is homogeneous and works together with the reinforcements. However, during field observations, concrete strength is reduced by segregation in concrete, use of unsuitable aggregate in granule, inability of concrete to settle due to dense reinforcement have been encountered frequently (Fig. 10).

The minimum concrete classes that should be used for buildings are specified in the earthquake regulations applied in Türkiye. According to the 1975 earthquake code, the concrete strength in buildings should be minimum 14 MPa (18 MPa if in the 1st and 2nd degree earthquake zones). According to the 1998 earthquake code, the concrete strength in buildings should be a minimum of 16 MPa

Fig. 11. Insufficient transverse reinforcement in RC elements.

(20 MPa if the building importance factor is greater than one 1.4 or high ductility in 1st and 2nd degree earthquake zones). In the 2007 earthquake code, the minimum concrete strength should be 20 MPa. In the current 2018 earthquake code, the minimum concrete strength is limited to 25 MPa. However, in the field investigations, it has been observed that many buildings have insufficient concrete strength in Türkiye. Ready mixed concrete started to be used widely after 2000. However, before this date, the use of handmade concrete without a vibrator is a situation that is frequently encountered and causes the concrete strength to be lower than expected.

Corrosion of the reinforcement due to insufficient concrete cover causes a weakening of the bond between the concrete and the reinforcement. With the progression of the corrosion level, the diameter of the reinforcing bar decreases, thus reducing the bearing capacity of the reinforced concrete element. In addition, the volume of rusting steel increases, causing cracks in the shell concrete of the reinforced concrete element. During the field investigations, reinforcement corrosion was frequently encountered in reinforced concrete elements.

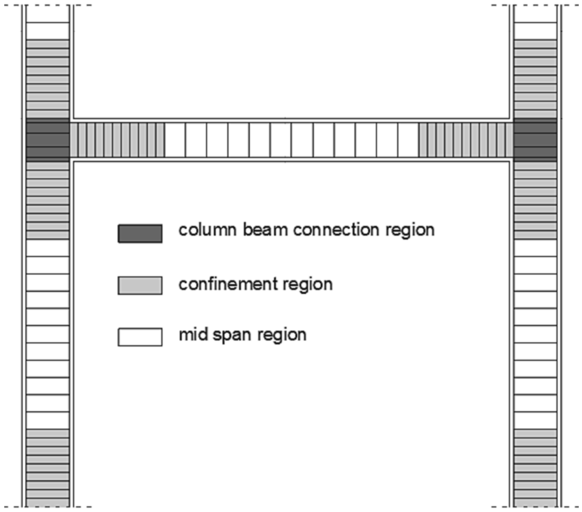


Fig. 12. Regions of transverse reinforcement for RC elements.

Fig. 13. Lack of transverse reinforcement in column-beam connection.

3.2. Insufficient transverse reinforcement in structural member

Transverse reinforcement used in reinforced concrete elements to resist shear forces and ensure that the element behaves ductility. While designing reinforced concrete buildings according to Türkiye Earthquake Regulations, earthquake forces are reduced by R coefficient (structural system behavior factor) and it is aimed that the buildings will show sufficient performance against earthquakes by absorbing energy. However, insufficient shear capacity of element causes brittle shear failure contrary to ductile behavior. Ductile behavior is the ability of making deformation. In order to ensure ductile behavior in reinforced concrete buildings, structural element should reach their all capacity without brittle failure. For this reason, reinforced concrete elements (columns, beams and column-beam connection) should have sufficient shear capacity. Therefore, to provide ductile behavior, transverse reinforcement details should be

Fig. 14. Opened transverse reinforcement and buckling of longitudinal bars.

proper and sufficient. In addition, there are more precautions to be taken in order to provide ductile behavior during extreme loading situations such as strong column-weak beam and avoiding short column effects. It is necessary to increase the transverse reinforcement ratio in the plastic hinge region with crossties and 135° hook angle. However, in the field observations, it was frequently observed that severely damaged buildings have up to 40 cm spacing of transverse reinforcement even in plastic hinge region (Fig. 11).

Türkiye Earthquake Codes (TEC-1975, TEC-1998, TEC-2007 and TEC-2018) defines there region for reinforced concrete elements. Column-beam connection region, confinement region and mid-span region is defined in these codes (Fig. 12). Türkiye Earthquake Codes requires that column transverse reinforcements should be continued within the column beam connection area. However, even in buildings constructed after 2010, lack of transverse reinforcement of column-beam connection was frequently observed (Fig. 13).

Transverse reinforcement hooks must be 135° and their lengths must be sufficient to effective working (TECs). Otherwise, the transverse reinforcements are opened under the effect of earthquake loads because of 90° hooks and insufficient hook lengths (Fig. 14). In cases where the transverse reinforcement spacing is insufficient in the plastic hinge regions of the columns and column-beam connection region, it is frequently observed that the longitudinal reinforcements buckling and the thrown out of cover concrete

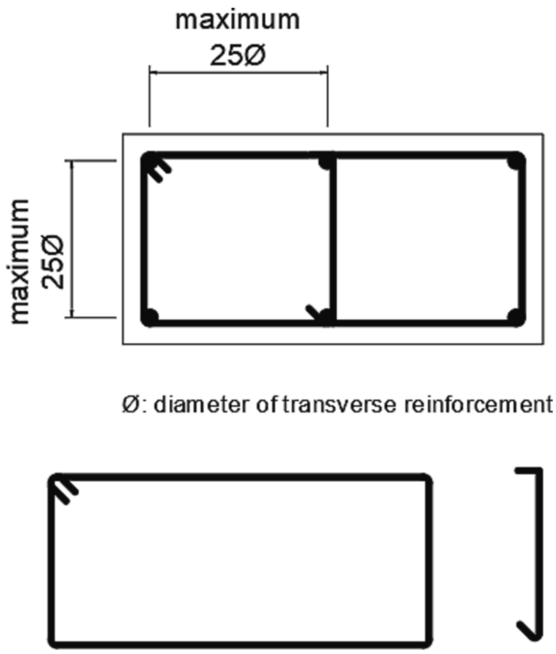


Fig. 15. Detail example of transverse reinforcement.

Fig. 16. Lack of crossties in columns.

(Fig. 14).

Türkiye Earthquake Codes requires that distance between transverse reinforcement arms should not exceed 25Ø (Ø: diameter of transverse reinforcement) (Fig. 15). However, in field observations, transverse reinforcement generally observed only around of column (Fig. 16).

3.3. Soft and weak story

Soft and weak story irregularities are caused by the lower horizontal stiffness of any story than the other stories in multi-story buildings. Generally, in story used for commercial purposes, increasing the height of the first floors (up to 5.5 m) and removing the infill walls significantly reduces the rigidity of this floor. Earthquake damages are concentrated in this floor, which shows weak

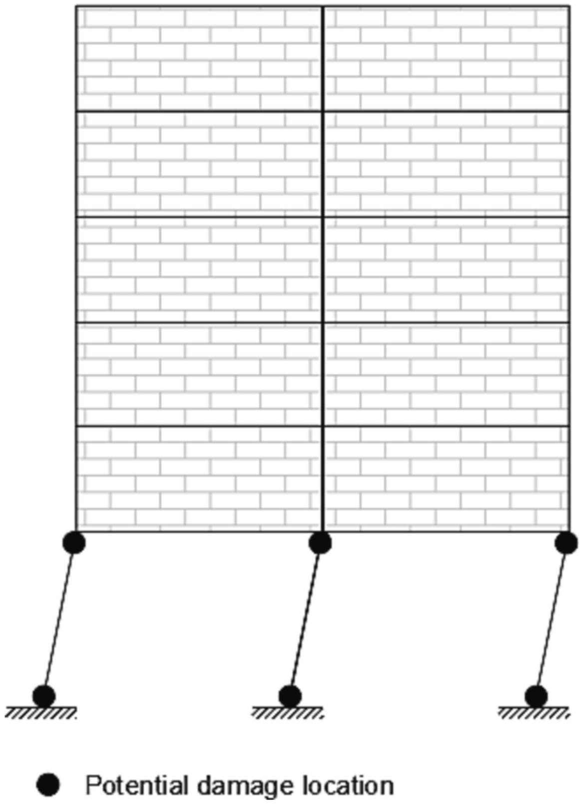


Fig. 17. Soft and weak story damage mechanism.

strength and more displacements (Fig. 17).

TBEC-2018 define soft story which is defined as the ratio of the relative story drift of a story to relative story drift of the story immediately above or below is greater than 2. Also TBEC-2018 define weak story which is defined as the ratio of the effective shear area (sum of column area, shear wall area and 15 % of infill wall area) of any story to the effective shear area of the story immediately above is less than 0.8.

In the Fig. 18, the height of the first floor of building was increased and the infill walls were removed in the first floor. While significant damage was not observed on the upper floors of a 5-storey building, plastic hinges were formed in the ground floor columns.

TBEC-2018 defines soft story and weak story and resist the lateral drift ratio of buildings. However this regulation does not prohibit increasing story height and removing infill wall. TBEC-2018 defines some penalties to buildings that have soft and weak story irregularities. Existing of soft story has an effect on the selection of the method of seismic analysis. Existing of weak story increases R coefficient (structural system behavior factor), increases earthquake design loads. To decrease negative effect of soft and weak story, increasing of story height in a story should limited. Also to prevent buildings from soft and weak story effect, shear walls or larger column sections should be used in buildings to increase lateral load carrying capacity and stiffness of buildings.

3.4. Strong beam – Weak column

In reinforced concrete buildings, columns are designed stronger than beams. Thus, it is aimed that beams are damaged before columns to prevent building from brittle failure or totally collapse. Also to ensure ductile behavior columns are designed stronger than beams. TBEC-2018 is requires that sum of ultimate moment resistances of columns should be at least 20 % more than the sum of ultimate moment resistances of beams. However, in the field investigations, it has been observed that in many buildings, the columns were damaged before the beams and even collapse of the building floors (Fig. 19).

3.5. Short column

During an earthquake, it is expected that columns will displace freely along the story height. However, reasons such as building an infill wall adjacent to a column to a certain height or supporting the stair landings to the column restrict the displacement of the column and reduce the effective height of the column. Column with decreasing effective height behaves more rigid and additional shear forces come to this column during earthquake. In field observations damages based on short column effect was often observed (Fig. 20).

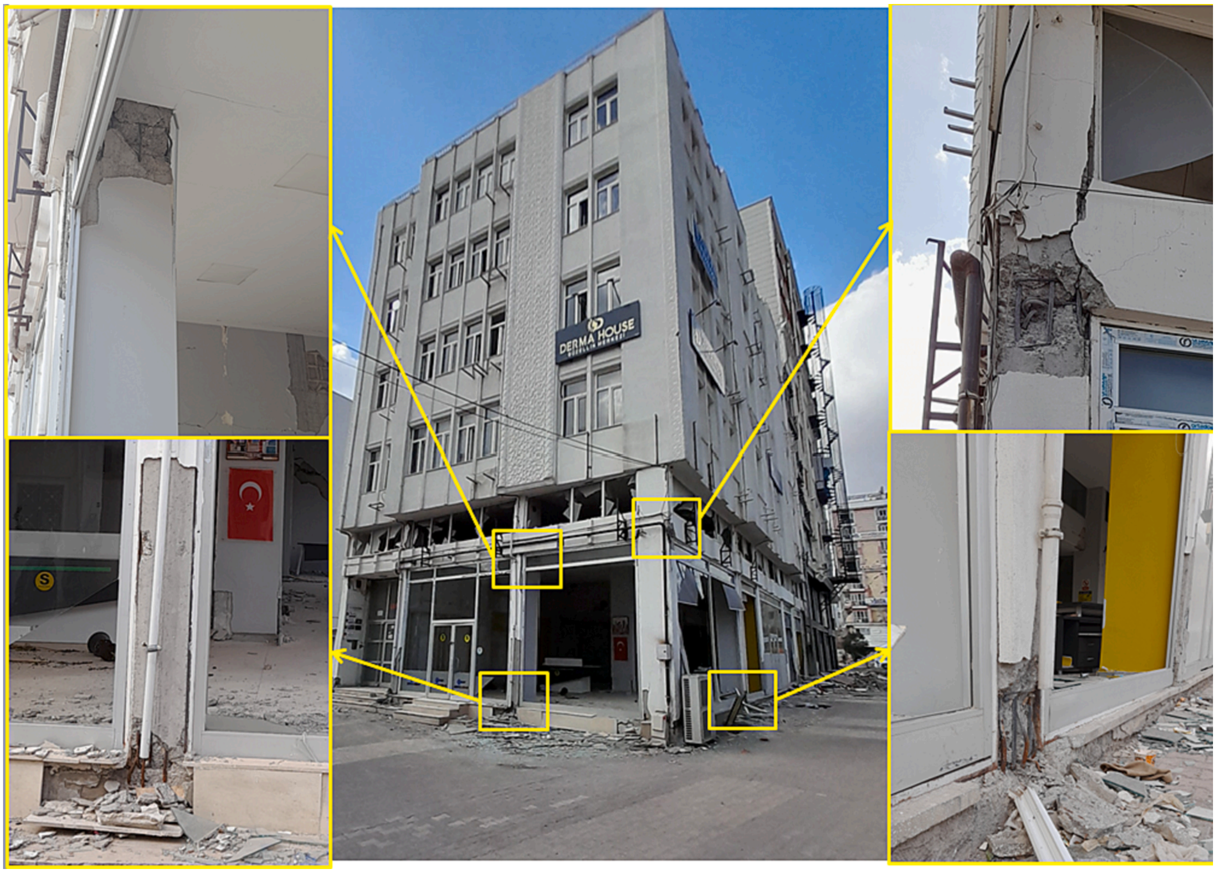


Fig. 18. A damaged building because of soft and weak story.

3.6. Inadequate gaps between adjacent buildings

Buildings design is made by assuming that reinforced concrete buildings can freely make displacement during an earthquake. In case of insufficient space between two buildings, these buildings collide and damage each other. Especially in adjacent buildings with different floor levels, it can cause serious damage to the column of another building at the floor level of one building. Although Türkiye Earthquake Regulations requires gap between adjacent buildings, buildings are often constructed adjacent, especially in city centers. According to Türkiye Earthquake Codes, minimum distance of buildings should be 30 mm up to 6 m building height and from there on a minimum 10 mm should be added for each 3 m height increment. This value should not less than the square root of the sum of their squares of the average story displacement multiplied by the coefficient α. If adjacent floor levels of buildings at all stories are the same then $\alpha = 0.25(R/I)$ otherwise $\alpha = 0.50(R/I)$. In these equations, R represent structural behavior factor and I represent building importance factor.

In field investigations, adjacent buildings with same floor height were widely observed (Fig. 21). Also damaged buildings because of different floor level were widely observed (Fig. 22). Design of buildings with span longer than 40 m should have expansion joints. However, in field observations, it was seen that many building expansion joints have not enough gap distance (Fig. 23). In many case, collapsed buildings severely damaged next to the building by impact effect (Fig. 24).

3.7. One way joist slab system with wide beam column connection

One way joist slab system is widely used in Türkiye, thanks to its advantages such as obtaining a plain ceiling surface, effective use of floor height, fast construction time and low formwork cost (Fig. 25). In this floor system, the floors consist of a thin slab layer of 7–10 cm thick, with joist placed parallel to each other at a height of about 32–40 cm. In this floor system, beam heights are taken the same as joist. In order to provide sufficient rigidity in these low height beams (shallow beams), the beam widths are increased and even exceed the column width. Although this situation causes problems in the transmission of the loads of the beam reinforcement passing outside the column, this situation is not taken into account in the Türkiye Earthquake Codes regulations. In addition, due to the use of shallow beams, building lateral displacements increase and building stiffness decreases compared to buildings with conventional beams. Since beams with low rigidity cannot keep the column rotations at a sufficient level, severe damage may occur in the columns

Fig. 19. Strong beam- weak column damages.

Fig. 20. Damaged columns because of short column effect.

Fig. 21. Adjacent buildings with same floor level.

Fig. 22. Adjacent buildings with different floor level.

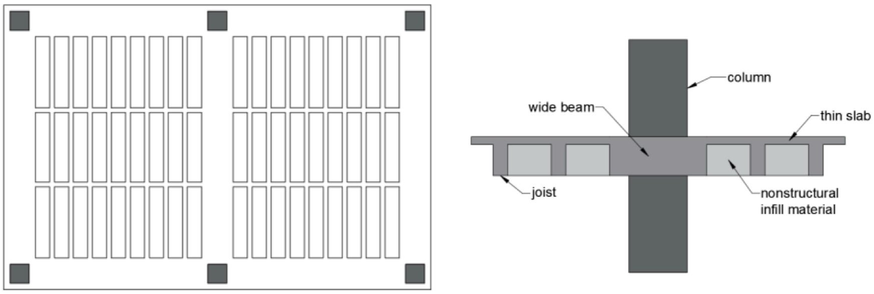
Fig. 23. Expansion joints with insufficient gap distance.

Fig 24. A damaged building because of impact effect of collapsed building.

(Fig. 26).

Using of one way joist slab is limited by Türkiye Earthquake Codes. TEC-1968 prohibited the construction of reinforced concrete buildings with one way joist slab in 1st and 2nd degree earthquake zones [28]. TEC-1975 allows to using of this slab type, in case the building height exceed certain limit, shear walls should used in this building. TEC-1998 and TEC-2007 allow to using of one way joist slab with condition of high ductility design or using of shear wall in 1st and 2nd degree earthquake zones. TBEC-2018 limits height of building designed with one way joist slab.

Reinforced concrete buildings with shallow beams are frequently used in Adıyaman. In field observations, it is seen that



(a) (b)

Fig. 25. One way joist slab.

(a) (b) (c) (d)

Fig. 26. A damaged building with one way joist slab.

nonstructural infill material used in one way joist slab is generally chosen as heavy materials instead of light material. Using of the heavy filling material increases the weight of the building and thus negatively affects the earthquake performance.

In the field investigations, it has been observed that many buildings with one way joist slab show good performance despite the negativities of the wide beams. When the common features of these buildings are examined, it is seen that they are designed with shear walls, and these shear walls are mostly placed on the outer axes and the outer axes are designed with deep beams. Also these buildings have regular column axes.

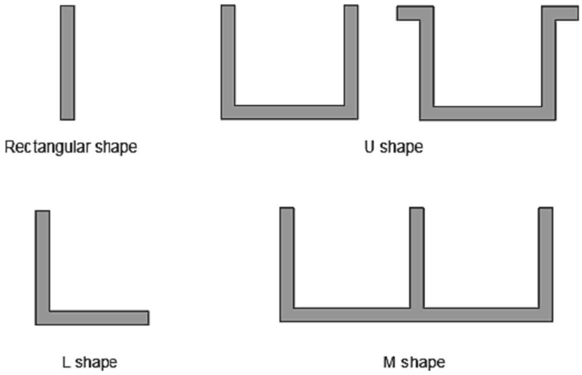


Fig. 27. Shear walls shapes commonly used in Türkiye.

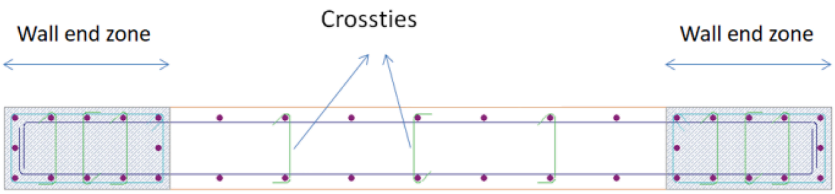


Fig. 28. A example of rectangular shape shear wall (adapted from ideCAD software).

3.8. Shear wall damages

Shear walls carry most of lateral loads and decrease lateral displacement of building thanks to their high moment of inertia. According to the 2018 Türkiye Earthquake Code, vertical bearing elements which ratio of the long side to the short side is equal to or greater than 6 are called shear walls. This value was taken as 5 in TEC-1975, 7 in TEC-1998 and TEC-2007. Türkiye Earthquake Codes Require wall end zone in shear walls to increase ductility and strength (Fig. 28). Also TECs requires crossties in shear walls. However, lack of wall end zone and lack of crossties was commonly observed in field observations.

Shear walls shapes commonly used in Türkiye can be seen in Fig. 27. U shaped shear walls generally preferred for elevator in buildings. Shear wall damages in buildings were commonly seen in U shape shear walls used for elevator. Because, these building commonly have only U shape shear wall for elevator. Therefore these wall carries most of lateral load.

In field investigations shear wall damages commonly observed (Figs. 29-33). One of the main problem of damaged shear walls are low shear capacity due to insufficient transverse reinforcement and poor material quality.

3.9. Infill wall damages

Although the stiffness of infill walls is lower than reinforced concrete elements, they carry horizontal force during an earthquake. When infill walls work together with a reinforced concrete frame, damage similar to a diagonal X shape occurs in the infill wall (Fig. 34). Due to the lack of adequate connection of the infill walls with the frame, out-of-plane collapse may occur in the infill walls due to the perpendicular effect of the earthquake to the wall plane. It has been observed that infill wall damage is concentrated in the lower floors where relative story drifts are high (Fig. 35).

Infill wall damages are undesired brittle damages. Flexible joints should use between infill walls and the load-bearing structural elements to prevent these brittle damages. However, precautions are required to prevent the infill wall from collapsing out of plane.

3.10. Damages because of insufficient soil information

The soil examination must be carried out before a building design phase. However, soil examination is sometimes neglected or disregarded. TBEC-2018 defines 6 soil class as ZA, ZB, ZC, ZD, ZE and ZF (ZA is the best soil class and ZF is the worst soil class). In ZF soil class, site-specific soil behavior analysis should be performed. Also precaution should be taken in weak soils that have a significant risk in terms of soil liquefaction. In these weak soils, deep foundations (such as pile foundations) or soil improvements (such as jet grouting) should be used for earthquake resistant building design. In field observations it is seen that many buildings damaged because of soil liquefaction that is soil layers below the groundwater level temporarily lose their strength because of the earthquakes (Fig. 36).

Fig. 29. Damaged rectangular shape shear walls.

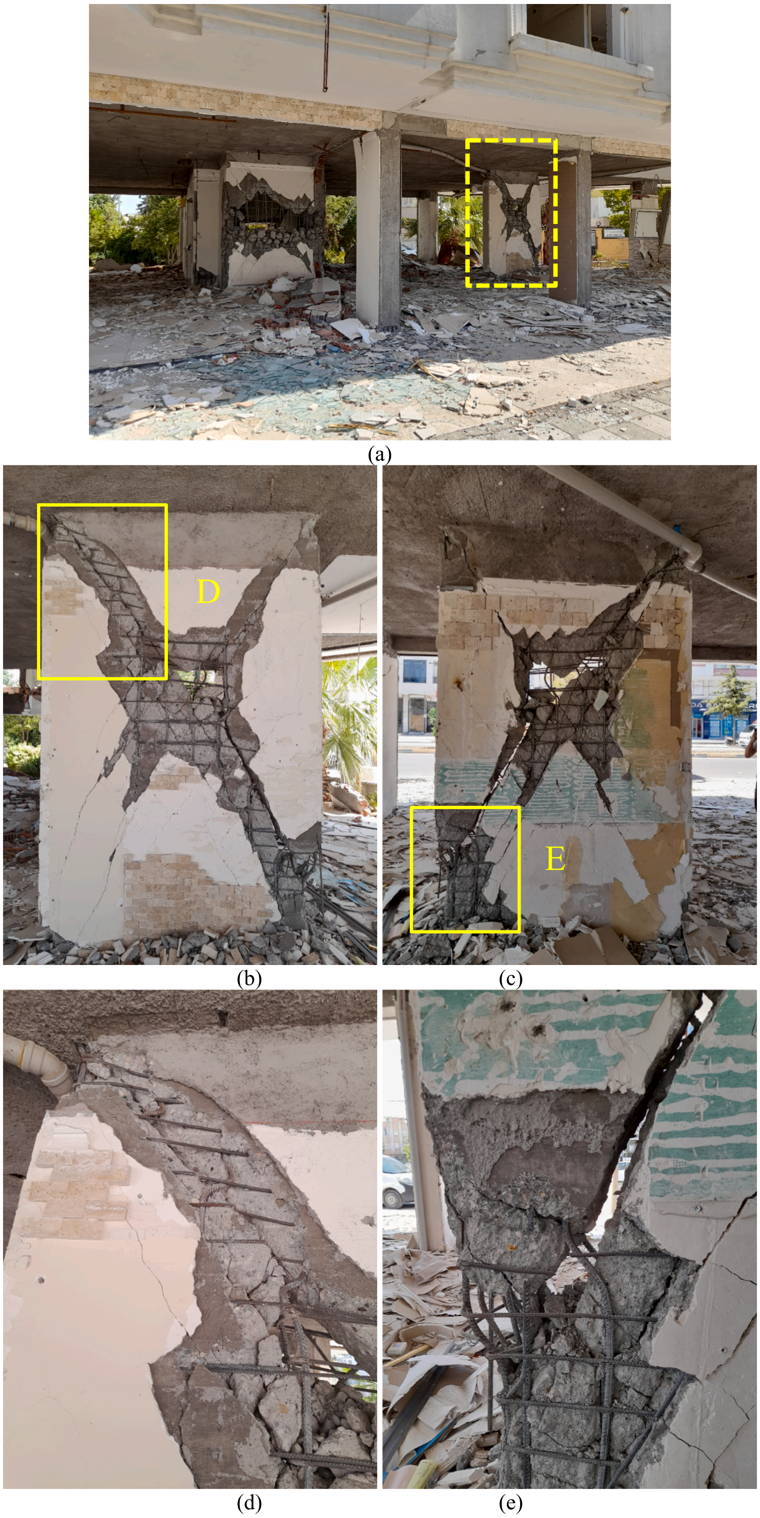


Fig. 30. A Damaged I shape shear wall due to insufficient shear capacity with dimension of 25x200 cm.

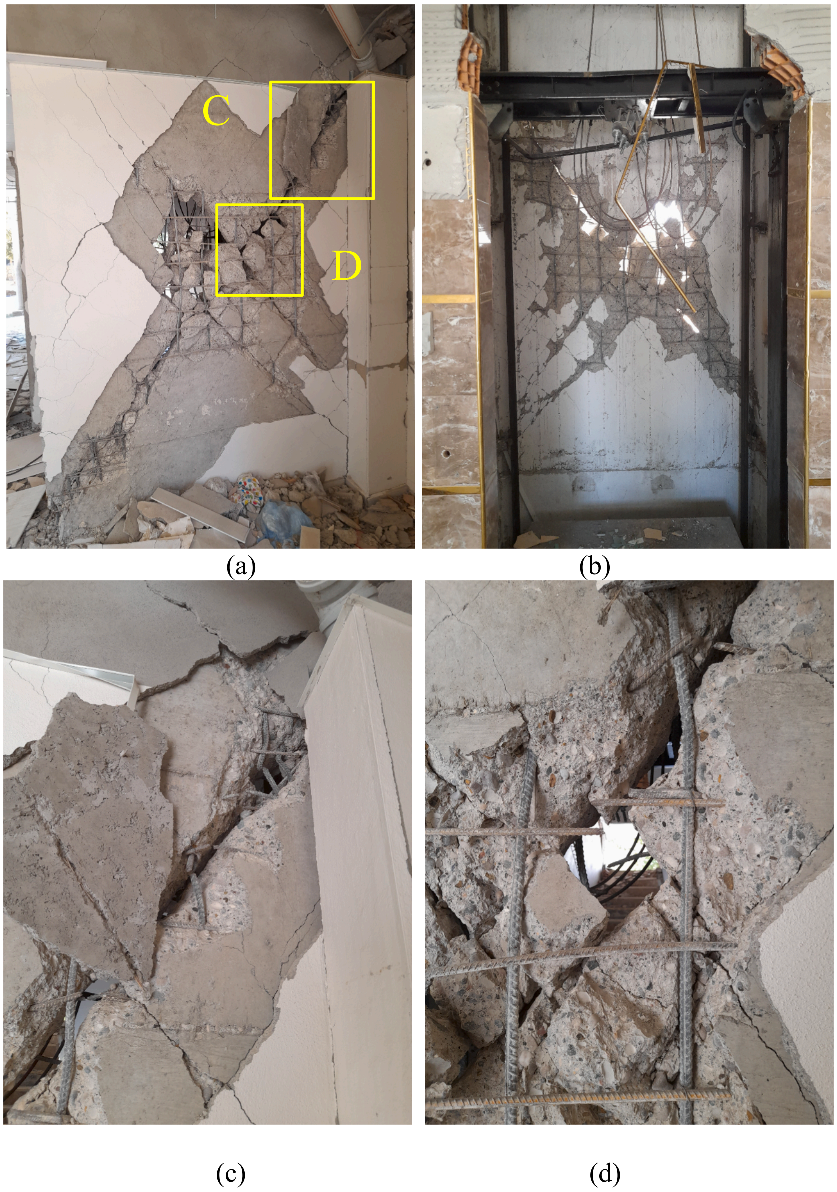


Fig. 31. A Damaged U shape shear wall due to insufficient shear capacity and rupture of reinforcement bars.

3.11. Design mistakes

For earthquake resistant building design, Irregularities should be avoided. TBEC-2018 defines irregularity in plan and in elevation (Fig. 37). As depicted in Fig. 37, irregularities in plan divided in three sub-sections, torsional irregularities, floor discontinuous and projections in plan. The other type of irregularity is defined as irregularities in elevation which is detailed in the sub titles of soft and weak story and also discontinuity of vertical elements. Except these irregularities, there are some design mistakes that have a negative effect on earthquake performance of buildings such as discontinuous of frame elements.

In TBEC-2018, there is not an obligation about discontinuity of frames. During an earthquakes, it is assumed that structural load bearing elements work together. To cooperate vertical structural element effectively (columns and shear walls), these element should be connected with beams to each other. However, in field observations buildings with discontinuous frames are commonly observed (Figs. 38-39).

During an earthquake, buildings should show nearly same performance for both direction. To provide this situation, the strong axis of vertical bearing elements (especially shear walls) should be oriented in both directions. However, buildings that have mostly strong axis in one direction widely observed.

Fig. 32. A Damaged U shape shear wall.

3.12. Stair damages

Reinforced concrete stairs are widely used in buildings from one floor to another. Stair landings should be supported by vertical bearing element to transfer their loads properly. Insufficient support condition could cause damages to stair or vertical element. In Fig. 40, it can be seen that a damaged shear wall because of stair. Also stair reinforcement details should be designed as in Fig. 41 to effective working of reinforcement. Incorrect reinforced details cause separation between concrete and reinforcement. In field investigations, stair damages widely observed by incorrect reinforcement detail (Figs. 42-43).

4. Discussion

Examination of earthquake damages and causes of these damages provide valuable information about earthquake resistant building design. The obtained data from field observation shows the deficiency of building stock in the region and contributions to the development earthquake regulations. Türkiye have active earthquake fault zones (North Anatolian Fault, East Anatolian Fault, and West Anatolian Fault zones) that have potential to cause severe earthquakes. Earthquake resistant building design is one of the most important issue for the country. In this study, performance of reinforced concrete structures in Adıyaman province were examined during Kahramanmaraş earthquakes (Pazarcık and Elbistan) on 6 February 2023.

In the design of reinforced concrete building, it is assumed that buildings show ductile behavior and high-energy absorption capacity. Türkiye Earthquake Regulations reduces earthquake forces by R coefficient (structural system behavior factor) to rely on ductile behavior. In ductile behavior, structural elements should reach their entire capacity without brittle failure. However, brittle damages disrupts this ideal behavior. Brittle damages such as shear damages, weak column-strong beam damages, short column damages and buckling of longitudinal bars are commonly encountered in field observations. For earthquake resistant building design more attention should be paid for ductile behavior.

One of the main problem in reinforced concrete buildings is the transverse reinforcement details. All Türkiye Earthquakes Codes after 1975 require using of transverse reinforcement in column-beam connection region, increasing the transverse reinforcement ratio in the plastic hinge region, using crossties and 135° hook angle. However, most of reinforced concrete buildings do not meet these rules. More attention should be paid to construction process for accordance between construction and project. Figs. 11-16 gives detail information about transverse reinforcement deficient.

For earthquake resistant building design, it is essential to avoid irregularities. TBEC-2018 defines some irregularities mentioned in Fig. 37. Except to these irregularities, discontinues frames are commonly encountered problem in reinforced concrete building. To cooperate vertical structural element (columns and shear walls), these element should be connected with beams to each other. Fig. 38 shows the discontinues frames in reinforced concrete buildings.

Reinforced concrete buildings should freely make displacement during an earthquake to show their expected design capacity. Insufficient gap between adjacent buildings cause undesired brittle damages or collapse of buildings. Fig. 21-24 show earthquake damages due to insufficient gap between buildings. New buildings should be constructed with sufficient gap between adjacent buildings for earthquake resistant design.

5. Conclusions

Two destructive earthquakes occurred in Pazarcık (Mw: 7.7) and Elbistan (Mw: 7.6), Kahramanmaraş, Türkiye. These earthquakes severely affected 11 provinces (Kahramanmaraş, Hatay, Gaziantep, Malatya, Diyarbakır, Kilis, Şanlıurfa, Adıyaman, Osmaniye, Adana,

Fig. 33. Damaged U shape shear walls due to insufficient shear capacity.

Fig. 34. In-plane damaged infill walls.

Fig. 35. Out-of-plane damaged infill walls.

Elazığ). Adıyaman is one of the provinces most affected by the earthquakes. Due to these two earthquakes occurring on the same day (nearly 9 h apart), damaged buildings were only examined after the second earthquake. This study focuses on examining the damaged reinforced concrete buildings in Adıyaman. Structural damages and the reasons for these damages are examined in comparison with Türkiye Earthquake Codes.

Conclusions and recommendations are listed below:

- Poor concrete quality is one of the most common defects found in the investigated buildings. Greater attention should be paid to the diameter and granulometry of the aggregate used in concrete. To prevent segregation in concrete, the concrete should be carefully settled using a vibrator. Additionally, corrosion is another issue affecting the buildings. To prevent steel corrosion, the concrete cover should provide sufficient protection against corrosion.
- Insufficient spacing of transverse reinforcement, especially in the plastic hinge region, the absence of transverse reinforcement in column-beam connections, and the lack of crossties (insufficient spacing of transverse reinforcement arms), have caused serious damage to buildings. Additionally, more attention should be given to the 135° hook angle and ensuring a sufficient hook length for the effective performance of transverse reinforcement.

Fig. 36. Damaged buildings because of soil liquefaction.

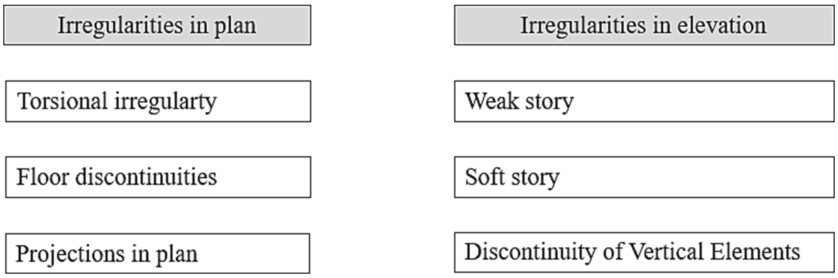


Fig. 37. Buildings irregularities defined in TBEC-2018.

- To ensure a more ductile and stronger structural behavior and to prevent the total collapse of reinforced concrete buildings, it is essential for columns to be stronger than beams. This consideration becomes even more critical in buildings that are vulnerable due to soft or weak stories.
- In the design of reinforced concrete buildings, it is crucial to prevent brittle damages. To achieve this, it is important to avoid the short column effect. To this end, a gap can be left between infill walls and structural elements. Additionally, in the basement, windows should be positioned away from the column sides.
- In the design of reinforced concrete buildings, it is assumed that the building can freely displace during an earthquake. Therefore, an adequate gap should be left between buildings. However, in the case of adjacent buildings, they can collide and cause damage to each other. This situation is particularly hazardous for buildings with different floor levels. To prevent such damages, a sufficient gap should be maintained between buildings.
- Due to the shallow beams in one-way joist slab construction, the low lateral stiffness of these buildings should be taken into consideration during the design stage. Therefore, the outer axes should be designed with deep beams, and shear walls should be positioned along these axes. Additionally, it is advisable to avoid the use of heavy nonstructural infill materials in these buildings.
- Shear walls carry the majority of lateral loads during earthquakes and are essential for resisting displacements. In most cases, the performance of these elements determines the overall building performance. Therefore, greater attention should be paid to these elements in aspects such as workmanship, concrete quality, reinforcement details, and the design of wall end zones.

Fig. 38. Under construction multi-story RC buildings with discontinuous frames.

Fig. 39. A Damaged beam due to discontinuous frames.

Fig. 40. A damaged shear wall due to stair.

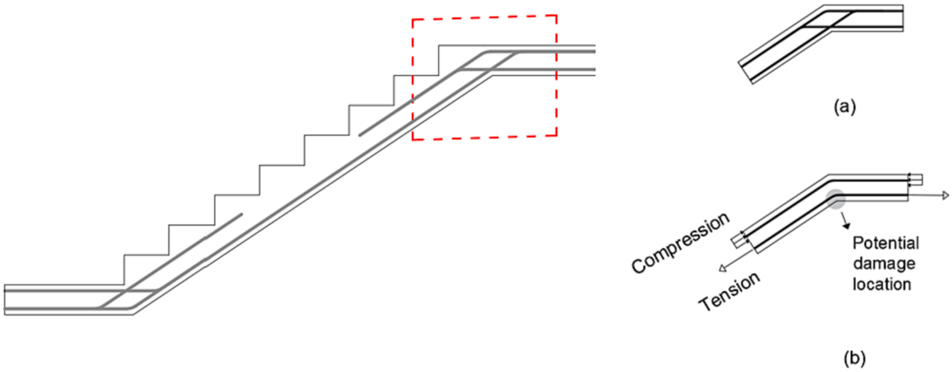
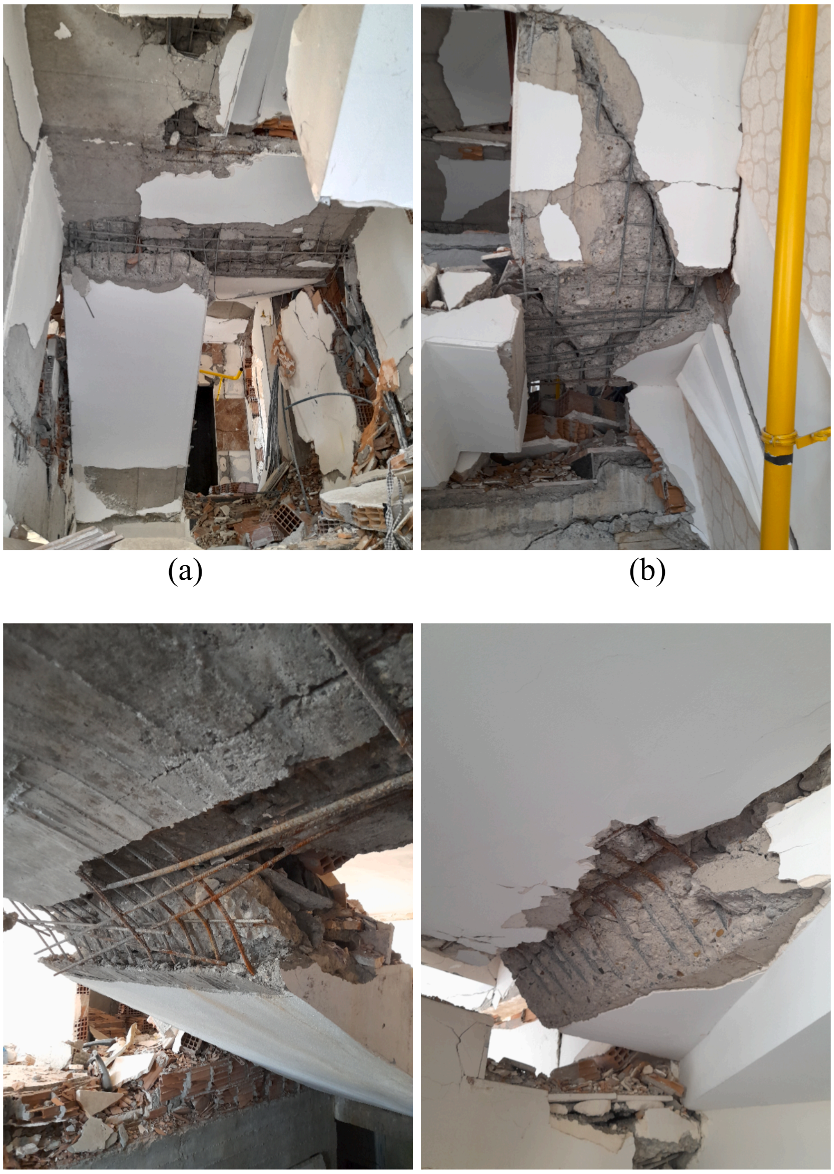


Fig. 41. Stair reinforcement detail a) proper b) incorrect.

Fig. 42. A damaged reinforced concrete stair.



(a) (b)

(c) (d)

Fig. 43. Damaged stairs because of incorrect reinforcement details.

- To prevent brittle infill wall damages, it is advisable to use flexible joints between infill walls and structural elements. This technique also helps avoid the short column effect, as well as the soft and weak story effects. However, precautions are required to prevent the infill wall from collapsing out of plane.
- In the design of a structure, it is crucial to understand the properties of the soil. Particularly in weak soils that pose a significant risk of soil liquefaction, precautionary measures should be taken. In weak soils, deep foundations or soil improvements should be used for earthquake resistant building design.
- For a safe design against earthquake loads, it is essential to avoid irregularities. The strong axis of vertical bearing elements should be oriented in both directions, and vertical bearing elements should be interconnected with beams.
- More attention should be paid to stair support conditions and stair reinforcement details. Stairs should be supported by vertical bearing element to transfer their loads. Stair reinforcement details should be designed to effective working of reinforcement.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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