Chapter 13

Earthquakes and Structural Damages

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Additional information is available at the end of the chapter

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Abstract

Earthquakes are the most destructive natural hazards throughout human history. Hundreds of thousand people lost their lives and loss of billions of dollars' properties occurred in these disasters. Occurred medium or high-intensity magnitude earthquakes in last twenty years showed that these loses continue. For reinforced concrete (R/C) buildings, inappropriate design such as soft and weak stories, strong beam–weak column, short column, hammering, unconfined gable wall and in-plane/out-of-plane movement of the walls causes damages. These are the main reasons. In addition to this, low quality of structural materials, poor workmanship, lack of engineering services, and construction with insufficient detailing of the structural elements are the another reasons of damages. Main reasons of masonry building damages in terms of design faults can be shown as heavy earthen roofs, inappropriate detailing of wall to wall connection and wall to roof connection, absence of bond beams, large openings. However, construction of buildings by using local materials with poor workmanship on the base of traditional rules is the other reason of failures for these buildings. In this book chapter, earthquakes and reasons of damages arose from earthquakes for reinforced concrete and masonry structures were presented. In addition to this, appropriate solutions are suggested.

Keywords: earthquakes, reinforced concrete buildings, masonry buildings, structural damages

1. Introduction

Earthquakes are one of the most destructive natural hazards that cause huge amount of loss of life and property. Nearly 10,000 people were killed every year because of these hazards. Moreover, annual economic loss is in the billions of dollars. In the last quarter century, severe earthquakes on the world like 1995 Kobe, Japan, 1998 Afghanistan, 1999 Kocaeli, Turkey, 2001

Gujarat, India, 2003 Bam, Iran, 2004 Indian Ocean, 2008 Wenchuan, China, 2009 L'Aqulia, Italy, 2010 Haiti, 2010 Chile, and 2011 Van earthquakes experienced construction industry to take severe measures to prevent collapse and to decrease damages of the structure; for example, after 1995 Kobe, Japan earthquake, it was reported that more than 6434 people lost their lives; nearly 4600 of them were from Kobe. In 1999 Kocaeli earthquakes, more than 17,000 people were killed and more than 40,000 people were injured and 300,000 people became homeless. In the year 2008, an earthquake hit the Sichuan China. Measured magnitude of earthquake from surface is 8.0. It was reported that nearly 70,000 people were dead, 95% of this death toll is in Sichuan province. In addition, more than 370,000 injured and 18,000 people missing. In Italy, 308 people were killed and more than 1500 people were injured after L'Aquila earthquake in 2009. However, total economic loss was 16 billion dollars during this earthquake. Many historical structures were collapsed and heavily damaged. The last earthquake tragedy for Turkey, very close to present time, is Erciş (Van) and Edremit (Van) earthquakes. These earthquakes struck Erciş (Van) district and Edremit (Van) district on 2011. After these earthquakes, 604 people were killed and 4852 people were injured, among of them 1301 people were seriously injured. A total of 2307 multistorey structures were collapsed. In addition, nearly 8% of the total province population became homeless.

The purpose of this chapter was to present earthquake characteristics and structural defects, damages, and possible solutions. The scope of the book chapter is depicted in the **Figure 1**.

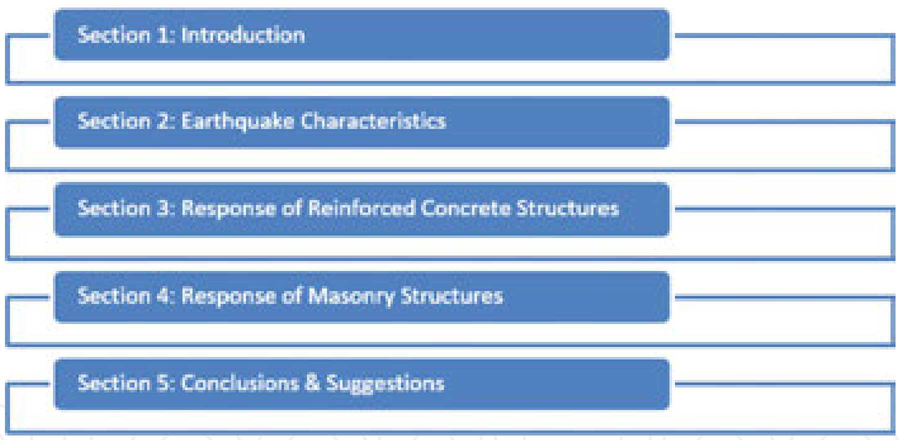

Figure 1. Scope of the book chapter.

Section 1 gives information about last destructive earthquakes.

Section 2 shows structure of the earth, plate tectonics, seismic waves, faults, and effects of earthquakes.

Section 3 gives failure reasons of reinforced concrete (R/C) buildings.

Section 4 presents failure reasons of masonry building damages.

Section 5 evaluates lessons learned from earthquake damages and failure experience from this type of natural hazards. Also in this part, suggestions were presented in order to prevent earthquake damages.

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2. Earthquake characteristics

2.1. Structure of the earth

The earth consists of layers which have different properties. The outer layer of the earth is called as “crust.” The thickness of this layer is between 35 and 70 km for continents, and this thickness varies between 5 and 10 km thickness for ocean floor. Mantle layer, existed under the crust, is divided as lower mantle and outer mantle. This layer is approximately 2900 km thickness. Convection current occurred in the mantle causes plate tectonics in the crust. Core is the innermost layer and divides into two parts as fluid outer core and solid inner core. The outer layer is 2300 km, and inner layer is 1200 km thickness [1]. The internal structure of the earth is shown in the **Figure 2**.

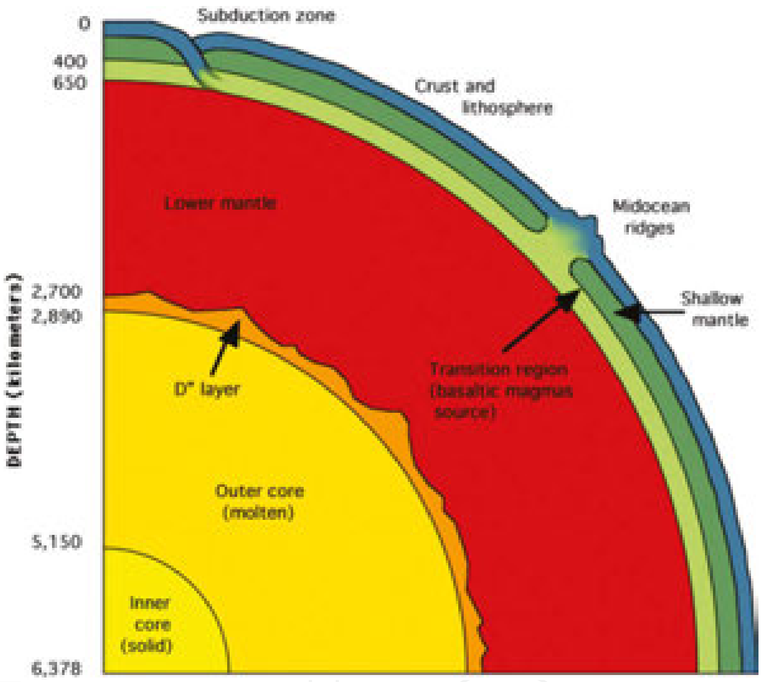

Figure 2. The internal structure of the earth [2].

2.2. Plate tectonics

Plate tectonic deals with movement and strain of earth crust. According to the state of the art of Plate tectonic, the earthquake occurs in some parts of the plate and these parts act relative to each other. Pressure shift arose from these action and cooling stages in mantle causes stresses in the earth crust. When the increased stresses reached to bearing capacity of the crust on faults, this event causes sliding (breakthrough). Sliding movement spreads outward starting from hypocenter. Strain energy, which cumulated for a long time, discharges with sliding and causes earthquake shaking. Propagation of wave from hypocenter that results surface sliding is perceived as earthquake [3]. **Figures 3** and **4** show the tectonic plates and worldwide earthquake distribution, respectively.

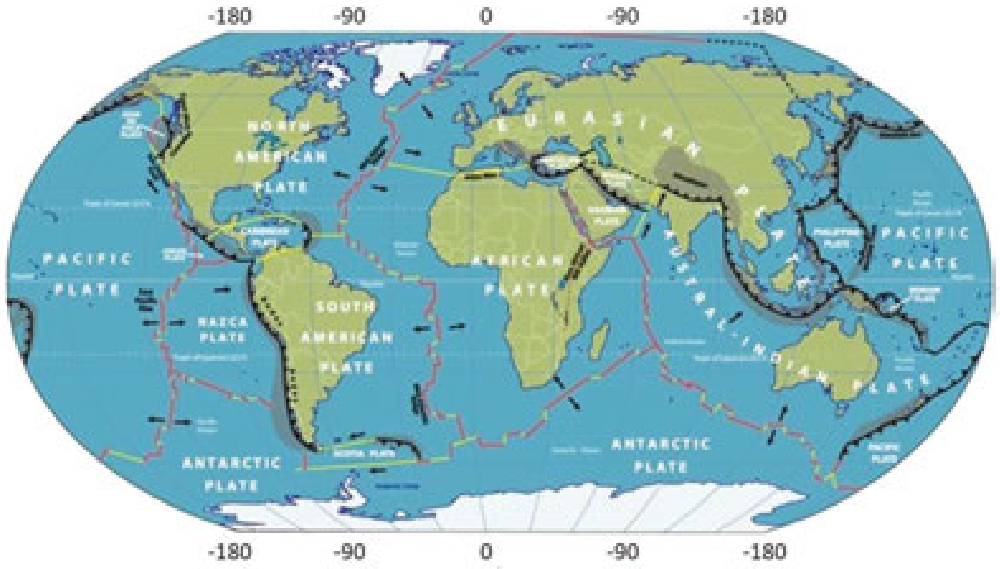

Figure 3. Tectonic plates [4].

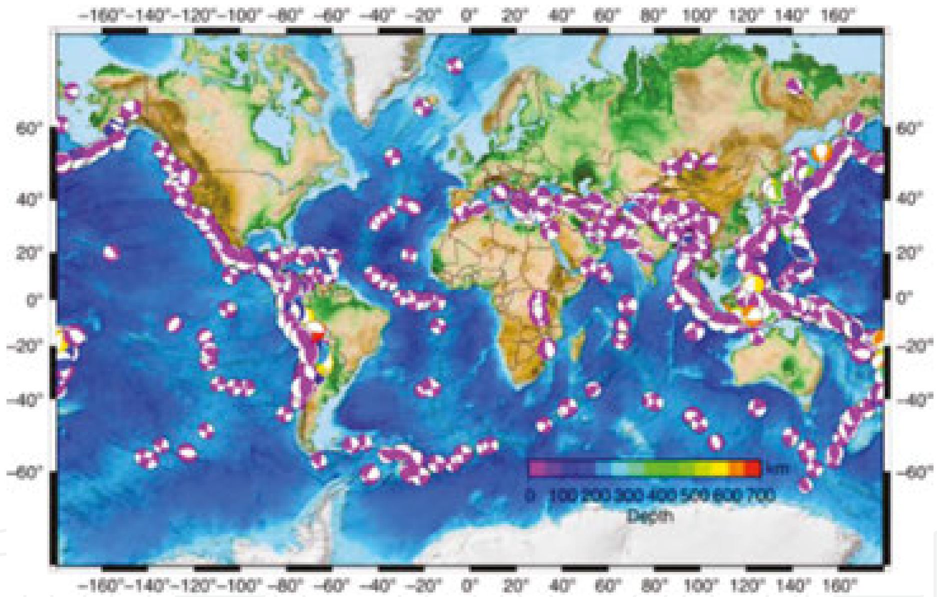

Figure 4. Geographical distribution of the 1700 earthquakes on the worldwide [5].

2.3. Faults

When two plates move with respect to each other, elastic strain energy is accumulated in results of tectonic processes. Thus, these two plates are released through the rupture of the interface zone. The shapeless blocks show immediate reaction towards equilibrium. As a result of this reaction, a seismic motion is produced. This process is called as “elastic rebound” theory. The resulting fracture in the crust of earthquake is defined as “fault”. **Figures 5–7** show fault mechanisms [6].

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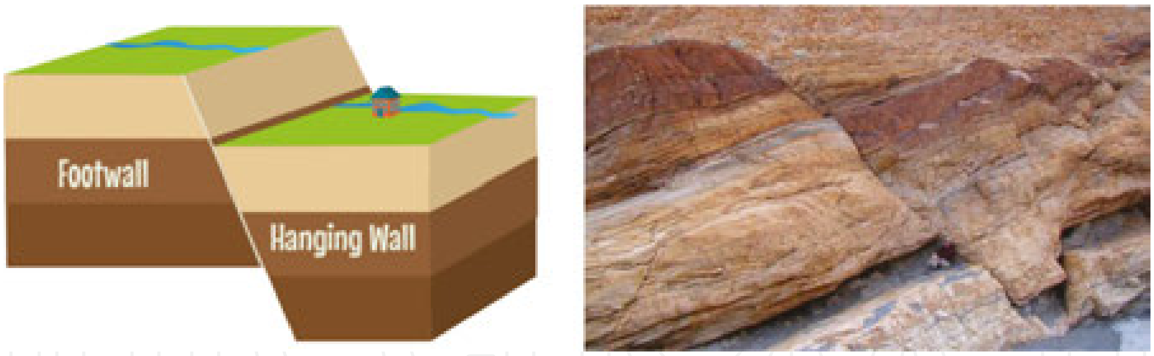

Figure 5. Normal fault graphical presentation and mechanism [7].

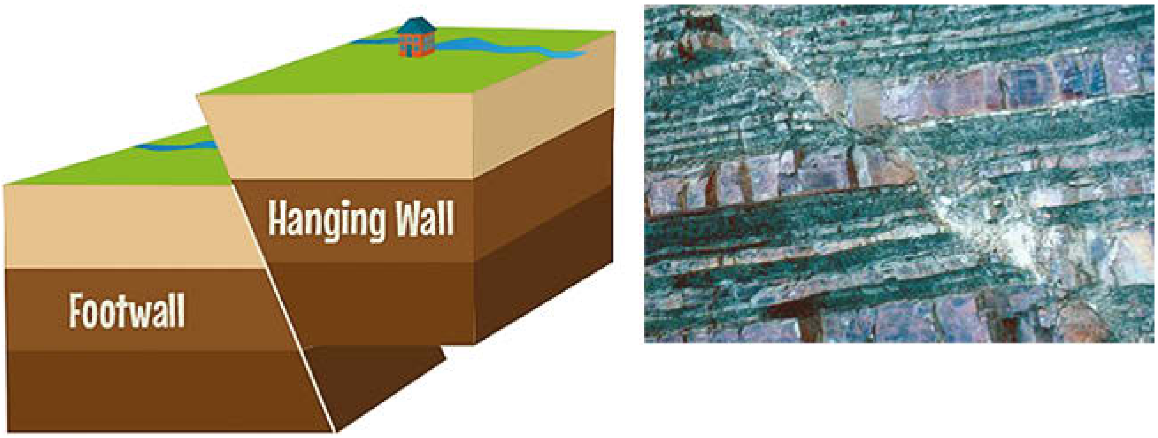

Figure 6. Reverse fault graphical presentation and mechanism [7].

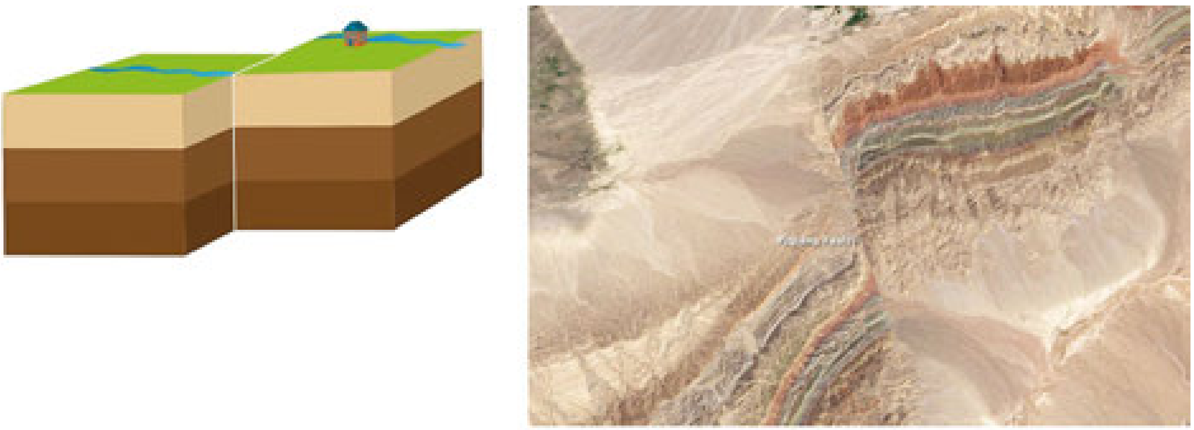

Figure 7. Strip slip fault graphical presentation and mechanism [7].

2.4. Seismic waves

2.4.1. Body wave

Seismic activity that results in earthquake generates two types of seismic waves: body and surface. Body waves move through the interior layers of earth's. Body waves include primary waves (known as P-waves) and secondary waves (also called as S-waves). P-waves generate sequential push (or compression) and pull (or tension) in soil as shown in below **Figure 8a**. P waves have relatively little damage potential. On the contrary, S-wave propagates horizontal and vertical motion. S-waves produce shear stresses in the soil along their paths [6] as shown in **Figure 8b**.

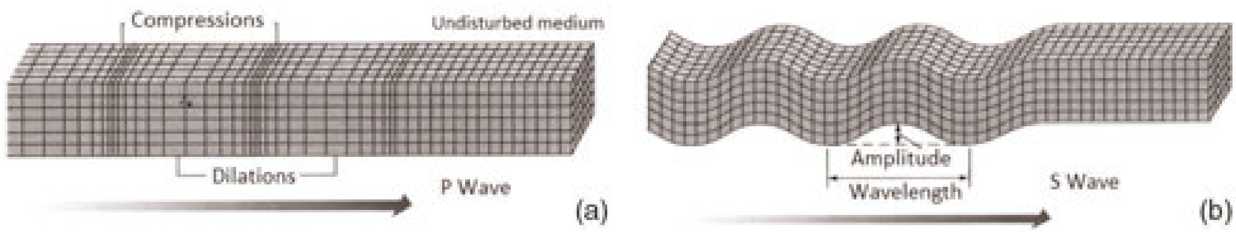

Figure 8. (a) Primary (P) wave and (b) Secondary (S) wave [8].

2.4.2. Surface waves

Surface waves include Love (L) and Rayleigh (R) waves that propagate through the outer layers of the crust. These waves are generated by body waves move through parallel to the ground surface and various underpass the layer boundaries. These waves cause large displacements. These types of waves take various forms at a further distance away from the earthquake source. Surface waves are occurred during shallow earthquakes; on the other hand, body waves take place at all depths. Surface waves cause serious damage to structures due to their long duration [6]. **Figure 9a** and **b** shows these types of waves.

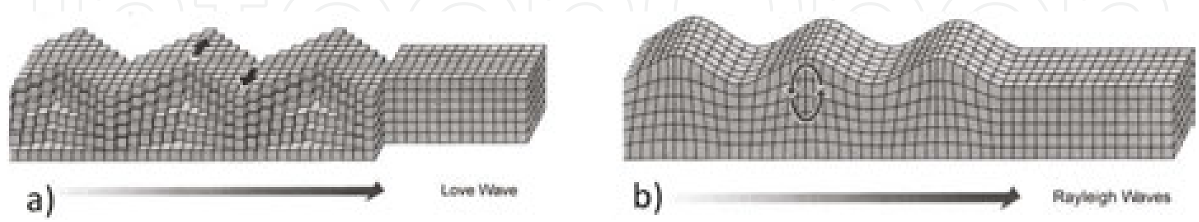

Figure 9. (a) Love (L) wave and (b) Rayleigh (R) wave [8].

2.5. Effects of earthquakes

Earthquakes can cause devastating effects in terms of life and property. The destructive potential of earthquakes depends on many factors such as focal depth, epicenter distance, and local site conditions. But the causes of fatalities and the extent of damages depend on lack of engineering service, design faults, material quality, and workmanship.

Many researchers studied and evaluated structural damages of reinforced concrete (R/C) and masonry buildings after the past earthquakes in different regions. Watanabe studied the behavior of R/C buildings during the Hyougoken-Nanbu earthquake and evaluated the damage reasons of reinforced concrete buildings [9]. Adalıer and Aydıngün evaluated the structural damages and the geological conditions for 1998 Adana–Ceyhan earthquake in Turkey [10]. Humar et al. evaluated the performance of masonry and reinforced concrete buildings during the Bhuj earthquake in India on January 26, 2001 [11]. Bruneau investigated the seismic behavior of structures after August 1999 Kocaeli earthquake and listed some general lessons obtained from this earthquake [12]. The structural damages of buildings were investigated during the December 26, 2003, Bam earthquake in Iran by Ahmadizadeh and Shakib [13]. Doğangün carried out a study about the reasons of damages of reinforced concrete structures during the May 1, 2003, Bingöl, Turkey, earthquake [14]. Ghobarah et al. conducted a field investigation in Thailand after December 26, 2004, Southeast Asia earthquake and tsunami. For this purpose, they evaluated the effects of the event on buildings, bridges, and infrastructure [15]. Bayraktar et al. evaluated the performance of stone masonry buildings during the Aşkale andErzurum earthquakes in Turkey on March 25 and 28, 2004 [16]. Arslan and Korkmaz carried out a study about R/C buildings during recent earthquakes in Turkey [17]. Zhao et al. focused on description of building performance after the May 12, 2008, Wenchuan earthquake in China [18]. Rossetto and Peiris evaluated the performance of government, commercial, and residential buildings after the October 8, 2005 Kashmir earthquake in Pakistan. Also, seismic design provisions of Pakistan were compared with seismic requirements of UBC (1997) and EC8 (1998) [19]. Maqsood and Schwarz (2010) carried out a study about the damages to rural buildings after Baluchistan earthquake that occurred in Pakistan in 2008 [20]. Augenti and Parisi evaluated the seismic performance of reinforced concrete and unreinforced masonry (URM) buildings during the L'Aquila earthquake that struck Italy in 2009 [21]. Chiou and Wang investigated the traditional Chinese residences after Chi-Chi earthquake that occurred in Taiwan on September 21, 1999 [22]. Celep et al. assessed the damages of concrete and masonry buildings after the March 8, 2010, Elazığ earthquakes in Turkey [23]. Ricci et al. conducted a study about the behavior of R/C buildings after L'Aquila earthquake which occurred on April 6, 2009, in Italy [24]. Braga et al. investigated the behavior of non-structural elements, particularly masonry infills in reinforced concrete frames at the 2009 L'Aquila earthquake [25]. Kam and Pampanin assessed the performance of R/C buildings during February 22, 2011, Christchurch earthquake in New Zealand [26]. Mahmood and Ingham assessed the seismic vulnerability of unreinforced masonry buildings in Pakistan using three empirical (New Zealand, United States, and Indian) methods [27]. Calayır et al. studied the damages of various structures during the March 8, 2010, Elazığ-Kovancılar earthquake in Turkey [28]. Yön et al. investigated the seismic performance of reinforced concrete and masonry buildings after 2011 Simav (Turkey) earthquake [29]. Taskin et al. evaluated strong ground motion and geotechnical and structural damages during the 2011 Van Turkey earthquakes [30]. Sayın et al. studied the failures of masonry and adobe buildings during the June 23, 2011, Maden, Elazığ earthquake in Turkey [31]. Bayraktar et al. and Ates et al. evaluated the reinforced concrete building damages during the 2011 Van earthquakes [32, 33]. Hermanns et al. investigated the performance of buildings with masonry infill walls after the 2011 Lorca, Spain, earthquakes. They described and analyzed the failure patterns in reinforced concrete frame buildings with masonry infill walls [34]. Manfredi et al. focused on damage observations and analyzed the emphasizing typical weaknesses of R/C buildings after the 2012 Emilia, Italy, earthquake [35]. Lemnitzer et al. assessed the behavior of reinforced concrete buildings after 2010 Chile earthquake [36]. Yön et al. conducted a field observation after the 2011 Van, Turkey, earthquakes. They investigated failure mechanisms and damage patterns of reinforced concrete buildings and presented their observations in the study [37]. Pinilla et al. carried out a study after the 2011 Lorca, Spain, earthquake. They determined the earthquake damages in reinforced concrete buildings and presented in their study [38]. Sharma et al. carried out a field investigation after the April 25, 2015, Gorkha earthquake in Nepal. They investigated the damaged buildings and the failure mechanisms in their study [39].

3. Response of reinforced concrete (R/C) structures

3.1. Soft and weak storey mechanism

In some R/C buildings, especially at the ground floor, walls may not be continuous along to height of building for architectural, functional, and commercial reasons. While ground floor generally encloses with glass window instead of brick infill walls, partition walls are constructed above from this storey for separating rooms for the residential usage. This situation causes brittle failures at the end of the columns. In mid-rise reinforced concrete buildings, the most common failure mode is soft-storey mechanism, particularly at the first storey. Failures can be concentrated at any story called as weak storey in which the lateral strength changes suddenly between adjacent stories due to lack of or removing of partition walls or decreasing of cross section of columns. Thus, during an earthquake, partial and total collapses occur in these storeys. These types of damages can be seen in **Figures 10** and **11**.

Figure 10. Unexpected inter-storey drift due to soft storey during the Van earthquake.

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3.2. Inadequate transverse reinforcement in columns and beams

Shear forces increase during an earthquake especially at columns and beam–column joints. Consequently, special attention should be paid to construction and design of beam–column joints and columns. Seismic design requires increasing of ductility of structures for performance-based design approach. In particular, columns of buildings can be having insufficient transverse reinforcement in the plastic hinge region. Therefore, structural elements which have such details show low performance against to dynamic loads and lost their shear and axial load carrying capacity. **Figure 12** shows this failure below.

Figure 11. Weak storey mechanism during the Bingöl earthquake.

Figure 12. Damaged structure due to inadequate spacing between shear reinforcements during (a) Van earthquake and (b) Bingöl earthquake.

3.3. Short column

This type of mechanism can be developed due to structural adjustments and/or to continuous openings at the top of infill walls between columns. Lateral forces that occurred by an earthquake are carried by columns and shear walls. Length of column is an important factor for dissipation of these loads. When the length of column decreases, the column becomes stiffer and brittle than the other columns and this column attracts more shear forces. Thus, shear failure which is a critical type of concrete column damage occurs at these columns. Short column failure is given in **Figure 13**.

Figure 13. Short column damages during the 2003 Bingöl earthquake.

3.4. Inadequate gaps between adjacent buildings

Buildings are sometimes constructed adjacent because of the lack of building lots. In this layout plan, one or two faces of two buildings are in contact to each other. Consequently, the buildings that have not adequate gaps pound to each other during the earthquake. If the floors of the buildings are not at the same level, pounding effect of the buildings becomes more dangerous. **Figure 14** shows this type of damage during the 2003 Bingöl earthquakes.

Figure 14. Collapse of adjacent buildings during the Bingöl earthquake.

3.5. Strong beam–weak column

Deep and rigid beams are used with flexible columns in type of buildings. Therefore, these beams resist more moments, occurred by dynamic loads, than weak columns. In such a design during an earthquake while deep and rigid beams show elastic behavior, shear failure or compression crushing causes plastic hinges at flexible columns. Failure mechanism of strong beam–weak column can be seen in **Figure 15**.

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Figure 15. Failure of a building due to strong beam–weak column effect during the Van earthquake.

3.6. Failures of gable walls

The most common failure mode at gable walls is out-of-plane collapse in the earthquakes. Although failures of gable walls are not structural damages, these damages may be cause loss of lives and properties. Stability problems and large unsupported wall lengths cause damages at these walls. Failure of gabble wall is presented in **Figure 16**.

Figure 16. Failure of gabble walls on top of the building during the Van earthquake.

3.7. Poor concrete quality and corrosion

The other main reasons of damages are low concrete strength and workmanship. Concrete quality is an important factor for building performance against to earthquakes. Handmade concrete is used to without using vibrator in construction of old buildings. Thus, homogeny mixing was not obtained and expected compressive strength was not provided in these buildings. In addition to this, using of aggregates which have improper granulometry, corrosion which decreases reinforcement bar area, and using of smooth steel reinforcement effected strength of concrete. This type of damages is given in **Figure 17**.

Figure 17. Failure of column due to poor concrete quality during; (a) Van earthquake and (b) Bingöl earthquake.

3.8. In-plane/out-of-plane effect

One of the most important reasons of life and economic loss during the earthquake is combined effect of in-plane and out-of-plane movement of the wall. In-plane and out-of-plane interaction is very complicated and should be analyzed well for this phenomena. For low-rise and mid-rise unreinforced masonry (URM) infilled R/C frames, ground story infill walls are expected to be damaged firstly, because they are subjected to the highest in-plane demands. However, under the effect of bidirectional loading, where the two components of a ground motion are equally significant, infill walls of the upper stories may fail under the combination of in-plane and out-of-plane effects. The in-plane demand reduces at the upper stories, while that of out-of-plane forces increases due to the increase of accelerations [40]. To prevent this problem, in-plane carrying capacity of the wall should increase and out-of-plane ductility should increase with possible and applicable developments like bed-joint reinforcements and wire mesh. These listed applications will prevent detachment of infill wall from reinforced concrete elements and will increase the stiffness of the total structural system. **Figure 18** shows out-of-plane and in-plane damages.

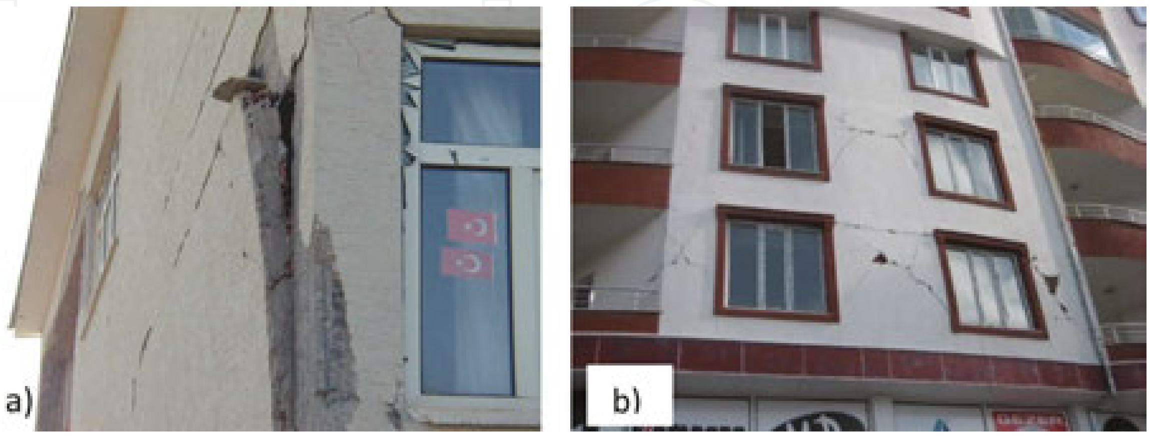

Figure 18. (a) Detachment of infill wall during the Bingöl earthquake and (b) In-plane damage of during the Van earthquake.

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4. Response of masonry structures

4.1. Earthen roof damages

One- and two-story masonry buildings are common in the rural areas because they require easy workmanship. These buildings are constructed with thick adobe and stone walls and mostly vulnerable to strong ground motions. But masonry buildings are preferred because of the advantages such as thermal properties and simple construction by using local materials [31]. These structures are constructed with traditional techniques using locally available materials. Nearly no engineering services are used in these buildings [20]. Adobe blocks are produced from local material contains mixed soil with straw and leave dried under the sun. These units are easily broken into small pieces as they have very low strength. As adobe blocks have low strength, walls of masonry buildings are thick and massive.

Generally, earthen roofs are constructed over wooden logs supported by two main walls of the buildings to provide thermal and water insulation. Also, heavy earthen roofs are constructed by the residents because a thick roof keeps the house cool or warm according to the seasons. However, these roofs lose their effectiveness because of weather conditions, such as rain and snow. Therefore, the residents place a new earthen cover on top of the existing roof to repair these roofs [16]. Thus, the weight and thickness of the roof increase over time. As a result of these heavy roofs, the structures are subjected to larger inertia forces during the earthquakes [41]. During the horizontal displacements, these heavy roofs are very vulnerable since they can easily slide over the walls [30]. **Figure 19** shows the damaged masonry buildings arising from heavy earthen roof at various earthquakes.

Figure 19. Damage to adobe structures due to heavy earthen roof during the Van earthquake [42].

4.2. Corner damages

Corner damages are common in the adobe and masonry buildings. This type of mechanism generally occurs at wall-to-wall and wall-to-roof connections when subjected to out-of-plane displacements. During an earthquake, the stress concentrations increase at intersection of the walls. In this way, vertical or inclined cracks appear in the corners of masonry buildings. If bond beams are not used in the corners or connection, two walls are not properly anchored each other, intensity of the cracks increases and these cracks spread along the height of the wall. Similar cracking may have been observed at adobe buildings [41]. Poor connections between adjacent walls and the absence of bond beams cause serious damages. In addition, there are no appropriate connections at the corner of the walls in damaged buildings. This type of damage for adobe and masonry buildings is shown in **Figure 20** [42]. Due to reduced compression stress and increase seismic acceleration at upper stories, the common failures are seen at the corners of the roof level. When there is no slab with some in-plane rigidity at roof level, top corners are more sensitive to fail because of cantilever-like behavior [43].

Figure 20. Corner damage of briquette masonry buildings [42].

4.3. Out-of-plane mechanism

Out-of-plane mechanism may appear from the combination of several deficiencies. A lack of bond beams, poor connections among the walls and the roofs, and large unsupported wall lengths cause the separation of walls and cause damage to occur via the of out-of-plane mechanism. Thus, the whole or the significant parts of the wall fall down during the earthquake. Wooden logs that bear the weight of the floor of the building are generally placed on load-bearing walls in only one direction. Thus, earthquake loads are transferred to perpendicular walls by wooden logs. Therefore, the walls that are not supported by the wooden logs may easily overturn to out-of-plane direction during the earthquake. This failure mechanism can be commonly observed in the earthquake region. **Figure 21** shows the out-of-plane mechanism of the adobe and briquette masonry buildings, respectively.

4.4. In-plane mechanism

The seismic performance of the masonry buildings relates to the in-plane stiffness of the walls. In-plane mechanism is generally observed in most of the masonry buildings that are affected by shear cracking. Earthquake loads increase the shear force. It can damage walls and their connections. These damages generally occur near openings, because most of the masonry

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buildings don't have sufficient and proper bond beams that distribute the lateral forces uniformly and enhance the lateral strength of the walls. During the earthquakes, excessive bending and shear can produce in-plane failures depending on the aspect ratio of the unreinforced masonry elements [41]. In the areas struck by earthquake, three failure modes of the shear damages in masonry buildings are generally observed, namely diagonal shear failures that proceed through masonry units and mortar (**Figure 22a–b**), sliding consisting of straight failure at the horizontal bed joints (**Figure 22c**), and stepped failures from the head to bed or bed to head joints (**Figure 22d**).

Figure 21. Out-of-plane mechanism of the briquette buildings [42].

Figure 22. Diagonal shear (a-b), horizontal (c) and stepped (d) failures wall [42].

4.5. Disintegration of stone masonry walls

Most of the masonry buildings are constructed with thick stone walls. As the thickness of the walls is relatively large, these stone walls are constructed by using more than one stone along the thickness direction [28]. In these walls, stones are placed in a random order. These walls have two exterior vertical wythes of large coarse stones. However, smaller rubble stones with mud mortar are used between two exterior layers. Using mud mortar instead of cement mortar causes insufficient adherence between the layers. Thus, the interior and exterior layers of the wall behaved independently and separated each other during the earthquake. Some reasons such as the quality of construction, poor workmanship, and the use of improper materials increase the intensity of the disintegration. **Figure 23** presents this failure in stone masonry buildings.

Figure 23. Disintegration in stone masonry buildings [28].

5. Conclusions and suggestions

In this book chapter, reasons of damages for reinforced concrete and masonry structures arose from earthquakes are presented. According to information that obtained from investigated buildings, the main reasons of failures of are presented below.

For reinforced concrete structures,

- The reason of soft storey collapse is occurred due to low rigidity of reinforced concrete structural members at ground floor. In case of the absence of the infill wall, the rigidity of

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the ground floor is lower than the upper storeys. Thus, this failure mechanism is triggered by earthquake. This type of failure is prevented during design phase by designing with more detail.

- Inadequate transverse reinforcement and no bending of hooks of ties in structural elements cause damages. This problem can be solved by using close-spaced stirrups and 1350 bended hooks to increase shear resistance of structural elements.
- Failures reason of short column is especially occurred due to partially filled infill walls in R/C frame system. These failures can be prevented by increasing of shear strength of this part of the column.
- During the earthquake, after first shake, different natural vibration periods cause hammer effect and then result in total collapse. To prevent this problem, adequate gaps according to current codes should be left between the adjacent buildings.
- When deep and rigid beams are used with flexible columns, weak column–strong beam failure mechanism is developed. To refrain this type of problem, sum of moments at column connected to any of joint should be bigger than sum of moments at beam connected to the same joint.
- Low concrete strength, workmanship, and corrosion of steel bars decrease the lateral stiffness of the structural system. This important reason can be eliminated by inspecting concrete and workmanship.
- The reason of in-plane, out-of-plane, and gabble wall failures is lower strength of infill materials than reinforced concrete frame. To prevent this type of failure, adequate connection and high-strength mortar between wall and reinforced concrete frame should be used.

For masonry structures,

- Thick and heavy earthen roofs are one of the reasons for the damages. The walls of the buildings could not support heavy mass during an earthquake, and the heavy roof partially or completely collapsed. This type of application should be refrained.
- Corner damages are developed due to insufficient wall-to-wall connections and lack of horizontal and vertical bond beams. This problem can be eliminated by using proper connection defined in current codes. Moreover, bond beams should be used.
- Another reason for the damages is the out-of-plane mechanism. The main reasons for this mechanism are the lack of bond beams, poor connections among the walls and roofs, and large unsupported wall lengths. Also, the gable walls of some masonry buildings are affected negatively by the out-of-plane mechanism. This problem can be eliminated by using proper connection defined in current codes. Constructing long and unsupported walls should be refrained. In addition to this, vertical and horizontal bond beams should be used.
- However, a lack of bond beams and large openings that decrease the stiffness of the walls increase the shear effects and cause in-plane failures, such as diagonal shear failures, sliding consisting of straight cracks, and stepped failures. It should be refrained to construct large

window and door openings. In addition to this measure, vertical bond beams should be constructed near the openings.

- Construction of multilayer walls with inadequate connections causes the disintegration at stone masonry buildings along the wall thickness. This application should be prevented while constructing stone masonry wall.

According to listed damages and possible solutions above, it is strongly advised to obey current seismic codes. Furthermore, construction workers should be trained about earthquakes and construction of earthquake-resistant buildings. Process of construction should be controlled by the local government and professional civil engineers.

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