Earthquakes, Structural Defects, Structural Damages, and Possible Solutions

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Introduction

Earthquakes are the most destructive natural hazards throughout human history. Hundreds of thousands of people lost their lives and the loss of billions of dollars in properties occurred in these disasters. Occurred medium or high-intensity magnitude earthquakes in the last twenty years showed that these losses 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 damage. 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 another reason of damages. The 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, and large openings. However, the construction of buildings by using local materials with poor workmanship on the base of traditional rules is the other reason of the failures for these buildings. In this course, earthquakes and reasons of damages that arose from earthquakes for reinforced concrete and masonry structures were presented. In addition to this, appropriate solutions are suggested.

Idea & Aims of the Course

The purpose of this course was to present earthquake characteristics and structural defects, damages, and possible solutions. The content of the course is divided into five sections as follows:

Section 1: gives information about the last destructive earthquakes.

Section 2: shows the 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 the failure reasons of masonry building damages.

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

Section 1: Destructive Earthquakes

Earthquakes are one of the most destructive natural hazards that cause huge amounts 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 in 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. The measured magnitude of an earthquake from the 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 were injured, and 18,000 people missing. In Italy, 308 people were killed and more than 1500 people were injured after the L'Aquila earthquake in 2009. However, the 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 the present time, is Erciş (Van) and Edremit (Van) earthquakes. These earthquakes struck Erciş (Van) district and Edremit (Van) district in 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 multistory structures were collapsed. In addition, nearly 8% of the total province population became homeless.

Section 2: Earthquakes 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. The internal structure of the earth is shown in the Figure 1.

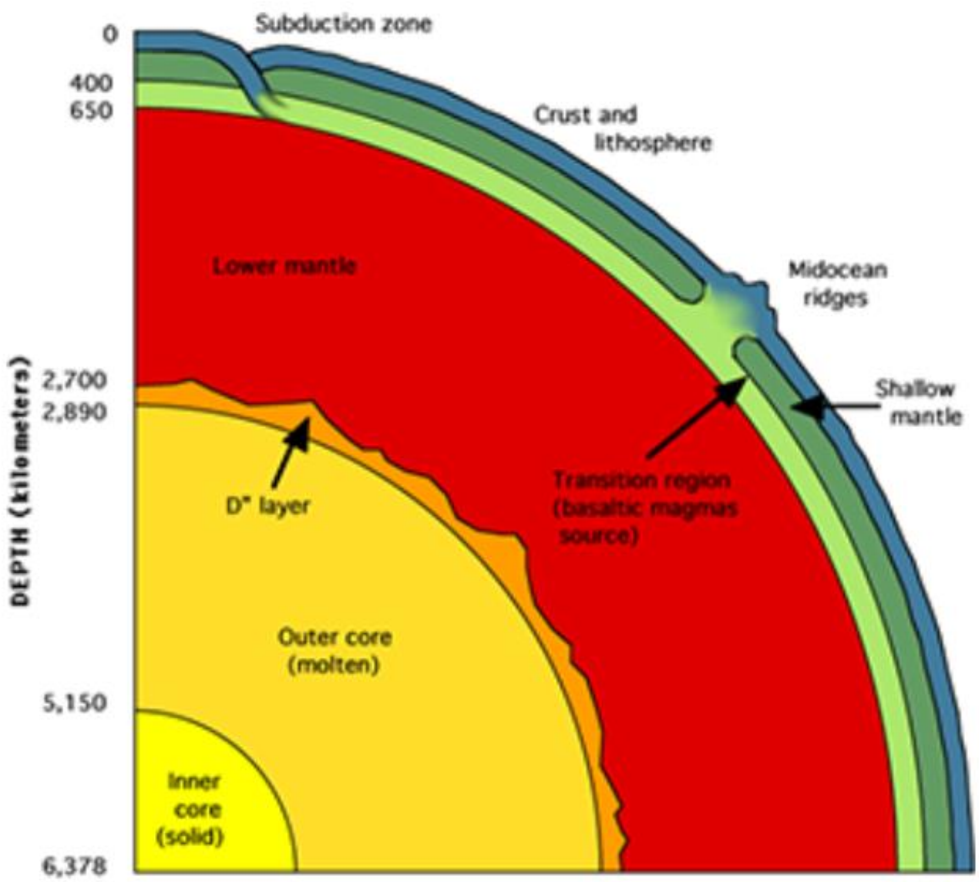


Figure 1. Earth Internal Structure.

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. Figures 2 and 3 show the tectonic plates and worldwide earthquake distribution, respectively.

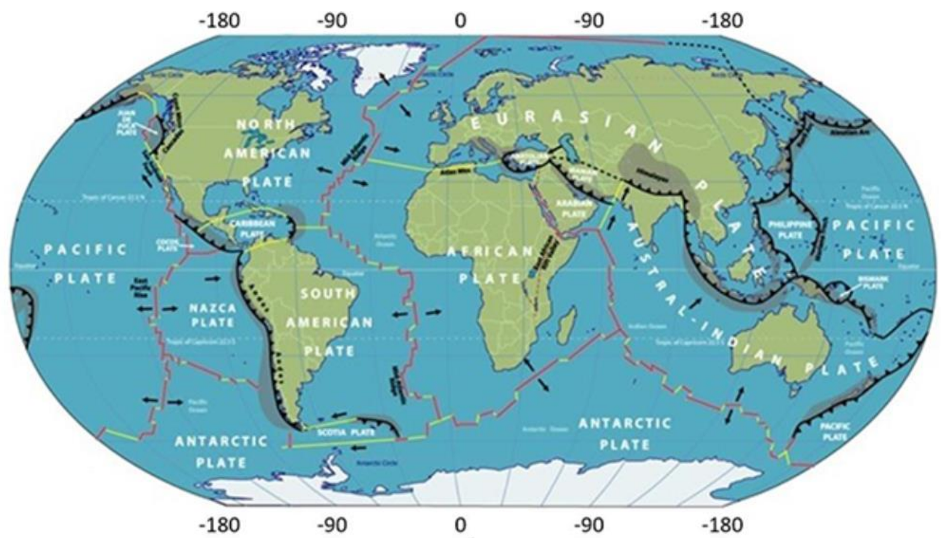


Figure 2. Tectonic plates.

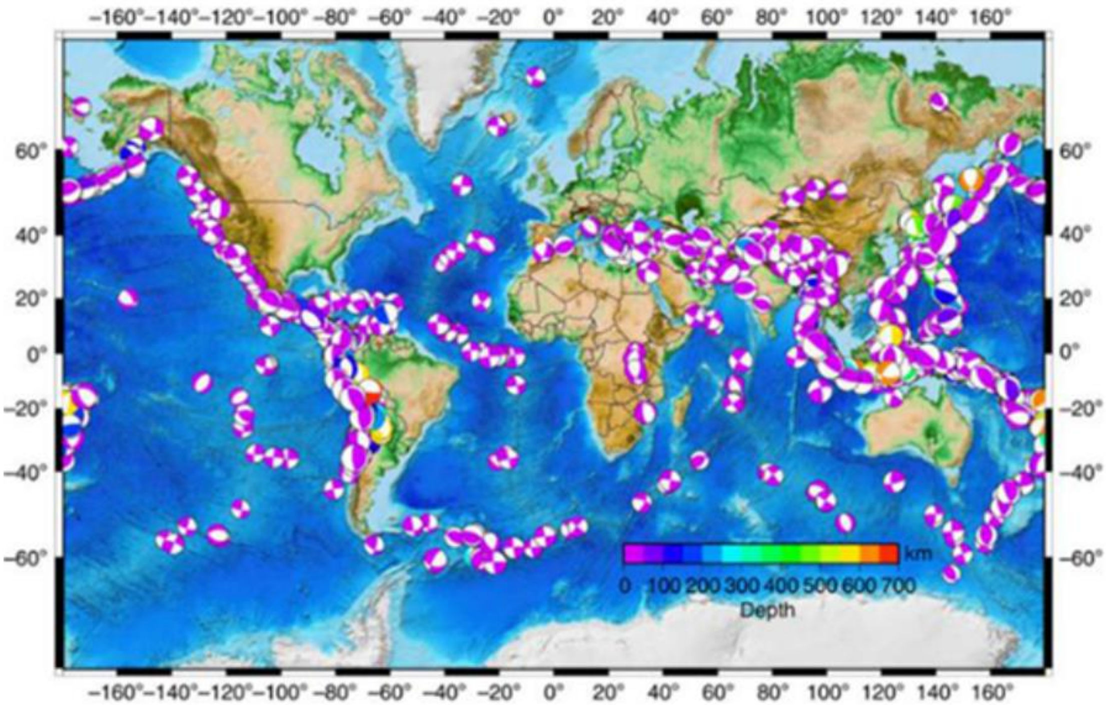


Figure 3.Geographical distribution of the 1700 earthquakes worldwide.

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 4–6 show fault mechanisms.

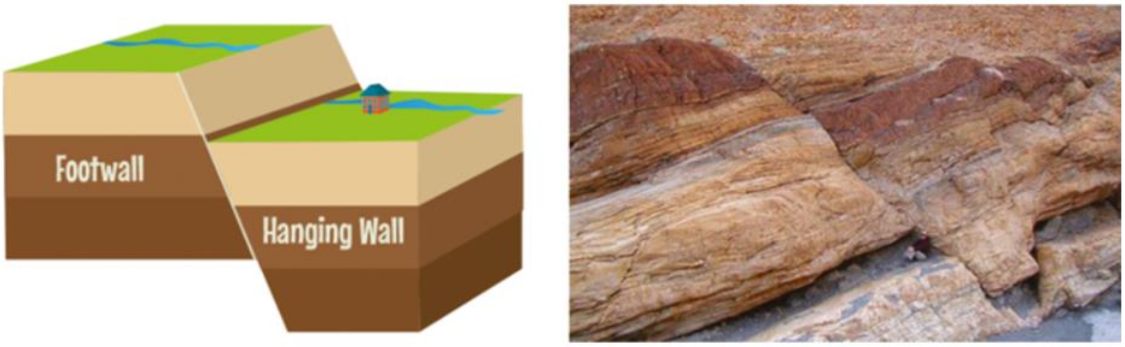


Figure 4- Normal fault graphical presentation and mechanism.

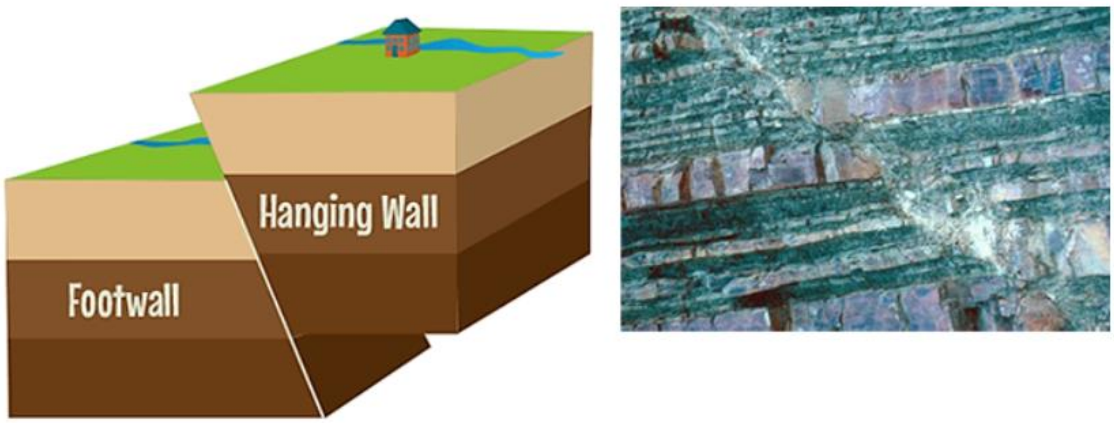


Figure 4. Reverse fault graphical presentation and mechanism.

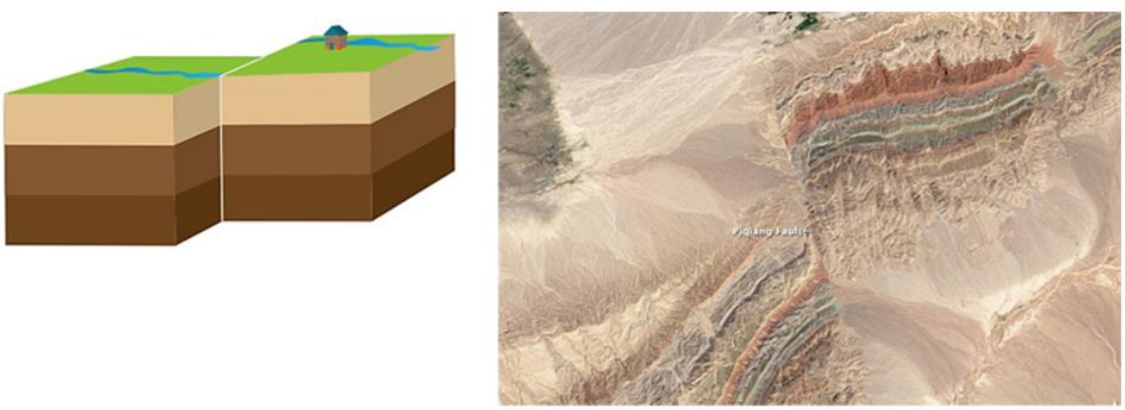


Figure 5. Strip slip fault graphical presentation and mechanism.

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. 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 7a. 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 as shown in Figure 7b.

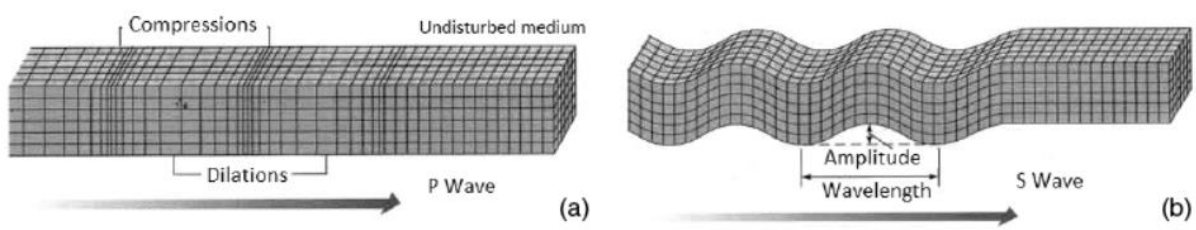


Figure 6. (a) Primary (P) wave and (b) Secondary (S) wave

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. Figure 8a and b shows these types of waves.

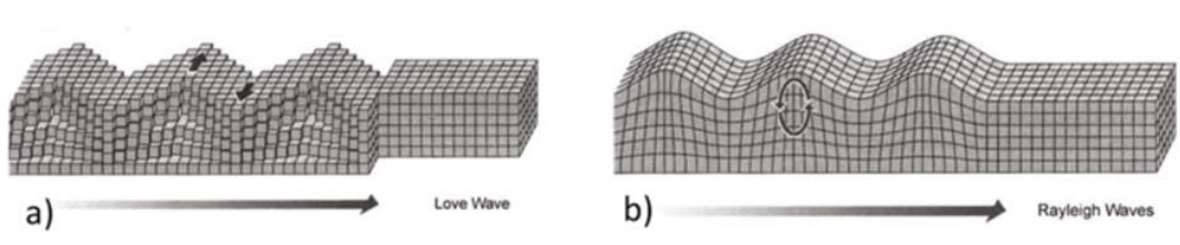


Figure 7. (a) Love (L) wave and (b) Rayleigh (R) wave.

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 worldwide.

Section 3: Reinforced concrete (R/C) structures response

3.1. Soft and weak story mechanism

Soft-story failure was responsible for nearly half of all homes that became uninhabitable in California's Loma Prieta earthquake of 1989 and was projected to cause severe damage and possible destruction of 160,000 homes in the event of a more significant earthquake in the San Francisco Bay Area. As of 2009, few such buildings in the area had undergone the relatively inexpensive seismic retrofit to correct the condition. In 2013, San Francisco mandated screening of soft-story buildings to determine if retrofitting is necessary or not.
The 2023 Turkey–Syria earthquake destroyed many buildings. The presence of many soft-story buildings greatly increased the amount of damage and number of casualties.

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 story 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-story mechanism, particularly at the first story. Failures can be concentrated at any story called as weak story 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 stories. These types of damages can be seen in Figures 9 and 10.

Figure 8. Unexpected inter-story drift due to soft story during the Van earthquake.

Figure 9. Weak story mechanism during the Bingöl earthquake.

Soft stories, in the technical point of view, having low stiffens in the lateral direction when compared to the other floors can be considered as the soft story effect.

When the lateral loads from the earthquakes are applied, floors with high lateral safeness will be able the bear the forces and control the lateral deflections. However, soft story will have excessive lateral deformation leading the failure of the floor. <u>These kinds of failures result in collapse of the structures.</u>

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 11 shows this failure below.

Figure 10. 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.

Special attention is required for short columns and hence recommended to avoid in building design especially for earthquake-prone areas. The effect of a short column is disastrous as they undergo brittle shear failure. Short column failure is given in Figure 12.

Remedies for Short Column Effect

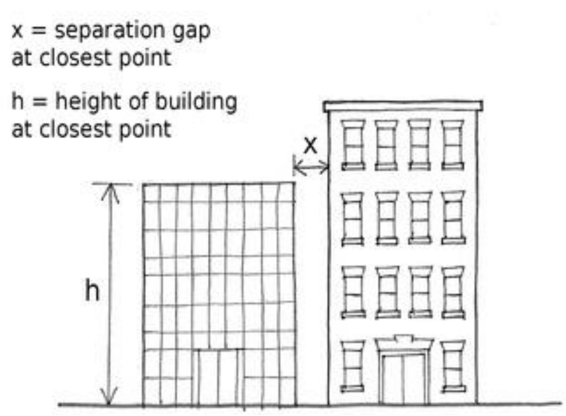
1) The first possible solution is to avoid the use of a short column in the architectural design stage itself.
2) If short columns cannot be ignored, special design requirements are followed. As per ACI 318 code, for those columns that have chances to undergo short column effect will require special confining reinforcement called the ductile reinforcement. The reinforcement provided must extend to the columns below and above by a certain amount as stated in standards.
3) In order to reduce the short-column effect on an existing building. The openings are closed by constructing a full-height wall.

4) If wall building is not possible, the short columns have to be retrofitted by any existing methods. A quality structural engineer who has sufficient experience in this area have to implement this.

Figure 11. Short column damages during the 2003 Bingöl earthquake.

3.4. Inadequate gaps between adjacent buildings

Insufficient or no seismic separation gap between buildings thus allowing them to pound and damage each other. A building can have pounding potential if the gap between buildings is less than 4% of the height (h) of the lower building see to figure below.



If x is less than 4% of h, the buildings can have pounding potential.

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 13 shows this type of damage during the 2003 Bingöl earthquakes.

Figure 12. Collapse of adjacent buildings during the Bingöl earthquake.

Damage due to pounding in reinforced concrete buildings with floors at different elevations in the 1999 Athens earthquake.

Pounding damage in adjacent buildings of different heights affected by the 1999 Turkey earthquakes

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 14.

Figure 13. 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 causing 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 15.

Figure 14. 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 aggregates that have improper granulometry, corrosion which decreases reinforcement bar area, and using smooth steel reinforcement affected the strength of concrete. This type of damages is given in Figure 16.

Figure 15. 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 for life and economic loss during the earthquake is the 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 phenomenon. 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 in accelerations. To prevent this problem, the 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 the detachment of infill walls from reinforced concrete elements and will increase the stiffness of the total structural system. Figure 17 shows out-of-plane and in-plane damages.

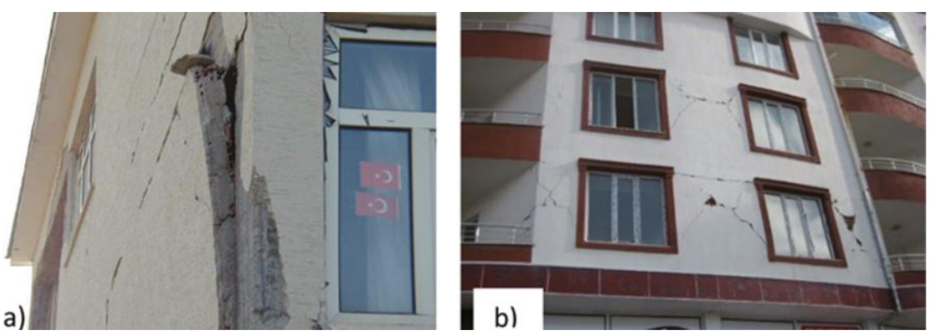
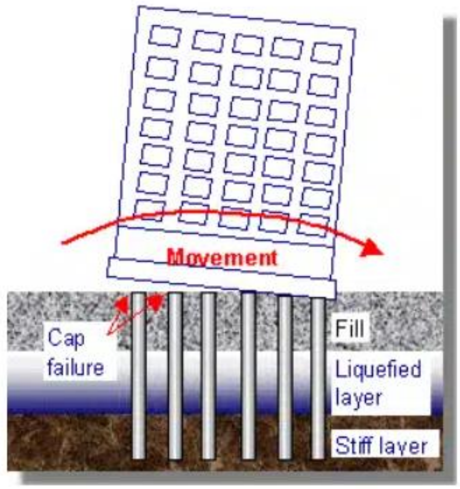


Figure 16. (a) Detachment of infill wall during the Bingöl earthquake and (b) In-plane damage of during the Van earthquake

3.9. Pile Cap Failure due to earthquake

When buildings are overturned due to the lateral loads applied from earthquakes, failure of the pile caps could occur in addition to other structural damages to the superstructure (see figure below).

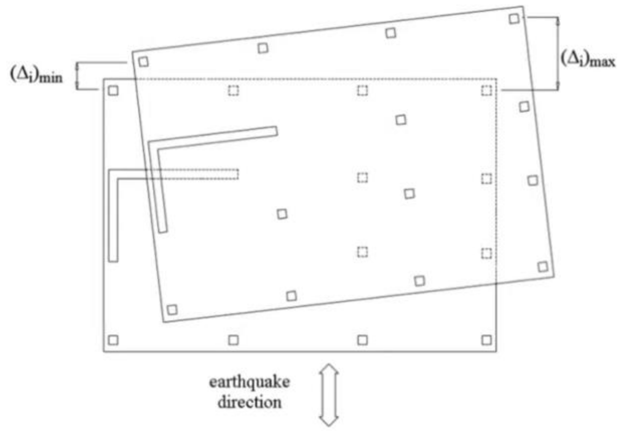


At the connection of the pile cap, the failure may occur with excessive loads applied. Since the pile cap together with the ground beams has very high stiffness, the connection of the pile and pile cap would become a weak location to fail. In addition, the interaction of the soil and structure would worsen the situation further.

3.10. Irregularity in Floor Plans and Stiffness

Designers are preferring to have the first two modes in the two translational directions. It avoids the dominancy of the torsional behavior of the structure.

The torsional behavior of a structure in an earthquake would cause severe damage to the structure if it is not considered during the structural design. <u>The most common practice is to modify the stiffness of the structure to avoid the torsional modes becoming dominant</u>.



As indicated in the above figure lateral deformation of the area having low stiffness has higher lateral deflection when compart to the shear wall area. The geometric center and the center of the stiffness are not coinciding.

The columns in an area subjected to higher lateral deflection could develop high bending movement and shear forces. If the structural capacity of the columns is not adequate to bear these forces, the column could fail leading to the collapse of part of the structure or whole structures.

3.11. Insufficient Ductility

The ductility of the structure is a very important factor considered in the design of structures against seismic loading. The right structure absorbs more energy and could cause failure. However, when the structure is ductile, it has more deformations.

The ductility of the structure is controlled by the reinforcement detailing. There is a special requirement to be met when the detailing of the reinforced concrete element is made. Further, failure of the connection of the beam and columns, column, and foundation could cause structural failure.

The hinge form closes to the beam-column connection. That area shall be detailed in a way that it does not fail due to the cyclic loading applied seismic excitations, and to have adequate ductility.

3.12. Inadequate Lateral Stiffness

Lateral loads applied on the structure will be shared by the reinforced concrete frame structure and the shear walls. When there are shear walls and frame structure, shear wall, and frame interaction can be considered for the design as it enhances the lateral load resisting capacity.

Correcting locating the shear walls and having provided adequate wall area to bear the applied loads is a must to avoid failure.

Section 4: Response of masonry structures

4.1. Earthen roof damages

One- and two-story masonry buildings are common in rural areas because they require easy workmanship. These buildings are constructed with thick adobe and stone walls and are 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. These structures are constructed with traditional techniques using locally available materials. Nearly no engineering services are used in these buildings. Adobe blocks are produced from local material containing mixed soil with straw and leaves dried under the sun. These units are easily broken into small pieces as they have very low strength. As adobe blocks have low strength, the 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. 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 earthquakes. During horizontal displacements, these heavy roofs are very vulnerable since they can easily slide over the walls. Figure 18 shows the damaged masonry buildings arising from heavy earthen roofs at various earthquakes.

Figure 17. Damage to adobe structures due to the heavy earthen roof during the Van earthquake

4.2. Corner damages

Corner damages are common in 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 the 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 to each other, the intensity of the cracks increases and these cracks spread along the height of the wall. Similar cracking may have been observed at adobe buildings. Poor connections between adjacent walls and the absence of bond beams cause serious damage. 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 19. Due to reduced compression stress and increased 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 the roof level, top corners are more sensitive to failure because of cantilever-like behavior.

Figure 18. Corner damage of briquette masonry buildings

4.3. Out-of-plane mechanism

Out-of-plane mechanisms 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 20 shows the out-of-plane mechanism of the adobe and briquette masonry buildings, respectively.

Figure 19. Out-of-plane mechanism of the briquette buildings

4.4. In-plane mechanism

The seismic performance of the masonry buildings relates to the in-plane stiffness of the walls. The 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 buildings don't have sufficient and proper bond beams that distribute the lateral forces uniformly and enhance the lateral strength of the walls. During earthquakes, excessive bending and shear can produce in-plane failures depending on the aspect ratio of the unreinforced masonry elements. 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 21a–b), sliding consisting of straight failure at the horizontal bed joints (Figure 21c), and stepped failures from the head to bed or bed to head joints (Figure 21d).

Figure 20. Diagonal shear (a-b), horizontal (c) and stepped (d) failures wall

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. In these walls, stones are placed in a random order. These walls have two exteriors 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 22 presents this failure in stone masonry buildings.

Figure 21. Disintegration in stone masonry buildings

Section 5: Earthquake damages and failure lessons learned

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

For reinforced concrete structures,

- The reason for soft story collapse is occurred due to the low rigidity of reinforced concrete structural members on the ground floor. In case of the absence of the infill wall, the rigidity of the ground floor is lower than the upper stories. Thus, this failure mechanism is triggered by the earthquake. This type of failure is prevented during the design phase by designing with more detail.

- Inadequate transverse reinforcement and no bending of hooks or ties in structural elements cause damage. This problem can be solved by using close-spaced stirrups and 1350 bent hooks to increase the shear resistance of structural elements.

- Failures reason of short columns 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 the first shake, different natural vibration periods cause a 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, a weak column–strong beam failure mechanism is developed. To refrain this type of problem, the sum of moments at the column connected to any of the joints should be bigger than the sum of moments at the 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 for in-plane, out-of-plane, and gabble wall failures is the lower strength of infill materials than the reinforced concrete frames. To prevent this type of failure, adequate connection and high-strength mortar between the wall and reinforced concrete frame should be used.

For masonry structures,

- Thick and heavy earthen roofs are one of the reasons for the damage. 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 a lack of horizontal and vertical bond beams. This problem can be eliminated by using the proper connection defined in current codes. Moreover, bond beams should be used.

- Another reason for the damage 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 the 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 increases 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.

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

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

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