# THE INTERACTION OF REINFORCED CONCRETE SKELETON SYSTEMS AND ARCHITECTURAL FORM SUBJECTED TO EARTHQUAKE EFFECTS

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# ABSTRACT

## THE INTERACTION OF REINFORCED SKELETON SYSTEMS AND ARCHITECTURAL FORM SUBJECTED TO EARTHQUAKE EFFECTS

The interaction of architectural form and structural configuration has become a serious issue in the building industry because of the poor seismic performance of reinforced concrete buildings in Turkey. Therefore, it has a determinative role on earthquake behaviour of buildings.

The study focuses on R/C skeleton systems which are commonly constructed in building industry of Turkey. In this study, structural irregularities in plan and vertical direction have been investigated in detail based on Turkish Earthquake Code, 2007. Four main cases are generated based on each structural irregularity in plan. These cases consist of 29 main parametric models and totally 265 models with sub models. They are designed as to have symmetrical or asymmetrical plan geometry and regular or irregular rigidity distribution. All models are analyzed by using the structural analyzing software, IdeCAD Static 6.0055. The changes in the earthquake behaviour of buildings were examined according to the number of stories, number of axes, configuration of structural elements, floor openings, projections in plan and vertical direction.

Many findings are obtained and assessed as a result of the analysis for each structural irregularity. The most remarkable result shows that structural irregularities can be observed in completely symmetric buildings in terms of plan geometry and rigidity distribution due to the inaccurate structural system selection. Moreover, it has emerged that symmetry in the rigidity distribution is more important than the symmetry in the plan geometry.

# ÖZET

## DEPREM ETKİLERİNE MARUZ KALAN BETONARME İSKELET SİSTEMLERİN VE MİMARİ FORMUN ETKİLEŞİMİ

Mimari form ve strüktürel konfigurasyonun etkileşimi Türkiye'deki betonarme binaların kötü deprem davranışı nedeniyle inşaat sektöründe ciddi bir sorun haline gelmiştir. Bu nedenle binaların deprem davranışları üzerinde belirleyici bir role sahiptir.

Bu çalışma Türkiye'de inşaat sektöründe yaygın olarak inşa edilen betonarme iskelet sistemler üzerine odaklanmıştır. Plan düzlemindeki ve düşey doğrultudaki yapı düzensizlikleri 2007 Türk Deprem Yönetmeliğine dayandırılarak detaylı bir biçimde incelenmiştir. Plan düzlemindeki her yapı düzensizliği baz alınarak dört ana örnek çalışma oluşturulmuştur. Bu örnek çalışmalar 29 ana parametrik model ve alt modelleri ile beraber toplam 265 modelden oluşmaktadır. Modeller simetrik veya asimetrik plan geometrisi ve düzenli veya düzensiz rijitlik dağılımına sahip olacak şekilde tasarlanmıştır. Tüm modeller, IdeCAD Statik 6.0055 yapı analiz programı ile analiz edilmiştir. Binaların, kat sayısı, aks sayısı, taşıyıcı elemanların konfigurasyonu, döşeme açıklıkları, plan ve düşey doğrultudaki çıkma durumlarına göre deprem davranışları incelenmiştir.

Yapı düzensizlikleri için yapılan analizlerin sonucunda birçok bulgu elde edilmiş ve değerlendirilmiştir. En dikkat çekici sonuç, plan geometrisi ve rijitlik dağılımı bakımından tamamen simetrik binalarda dahi, yanlış taşıyıcı sistem seçiminden dolayı yapı düzensizlikleri görülebilmektedir. Ayrıca rijitlik dağılımındaki simetrinin, plan geometrisindeki simetriden daha önemli olduğu ortaya çıkmıştır.

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| | |
|---|---|
| A | Storey gross area |
| A1 | Torsional Irregularity |
| A2 | Floor Discontinuity |
| A3 | Projections in Plan |
| A4 | Nonparallel Axes |
| A(T) | Spectral Acceleration Coefficient |
| $A_{fo}$ | Floor opening area |
| $\frac{A_{fo}}{A}$ | The ratio of floor opening |
| $\Sigma A_e$ | Effective Shear Area at any storey for the earthquake direction considered |
| $\Sigma A_g$ | Sum of section areas of structural elements at any storey behaving as structural walls in the direction parallel to the earthquake direction considered |
| $\Sigma A_k$ | Sum of masonry infill wall areas (excluding door and window openings) at any storey in the direction parallel to the earthquake direction considered |
| $A_o$ | Effective Ground Acceleration Coefficient |
| $\Sigma A_w$ | Sum of effective web areas of column cross sections |
| B1 | Weak Storey |
| B2 | Soft Storey |
| B3 | Discontinuity of Vertical Structural Elements |
| $D_i$ | Enlargement factor to be applied to ± 5 % additional eccentricity at i'th storey of an irregular buildings in terms of torsion |
| e | eccentricity |
| ERD | Earthquake Resistant Design |
| Fi | Design seismic load acting at i'th storey in Equivalent Seismic Load Method |
| g | Acceleration of Gravity (9.81 $m/s^2$) |

| | |
|---|---|
| $H_i$ | Height of i’th storey of building measured from the top foundation level |
| JICA | Japan International Cooperation Agency |
| L waves | Love Waves |
| n | Live Load Participation Elements |
| P waves | Primary Waves |
| R waves | Rayleigh Waves |
| R | Structural Behaviour Factor |
| R/C | Reinforced Concrete |
| S waves | Secondary Waves |
| S(T) | Spectrum Coefficient |
| Sae(T) | Elastic spectral acceleration ($m/s^2$) |
| T | Building normal period |
| $T_A$, $T_B$ | Spectrum Characteristic Periods |
| TEC | Turkish Earthquake Code |
| TS | Turkish Standards |
| USGS | United State Geological Survey |
| V | Base shear force |
| $V_t$ | Total Equivalent Seismic Load acting on the building (base shear) in the Earthquake Direction considered |
| $w_i$ | Storey weight |
| Z1 | A type of Local Site Class |
| $\Delta_i$ | Reduced storey drift of i’th storey of building |
| $(\Delta_i)$avg | Average reduced storey drift of i’th storey of building |
| $(\Delta_i)$max | Maximum storey drift of i’th storey of building |
| (δi)max | Maximum effective storey drift of i’th storey of building |
| ηbi | Torsional irregularity Coefficient defined at i’th storey of building |
| ηci | Weak Storey irregularity Coefficient defined at i’th storey of building |
| ηki | Soft Storey irregularity Coefficient defined at i’th storey of building |
| θi | Second Order Effect indicator defined at i’th storey of building |

# CHAPTER 1

# INTRODUCTION

This chapter includes the main statement and the aim of the thesis together with the scope of the problem definition and the scientific methodology. It introduces the background of the main argument, dispositions and finally the outline of the thesis.

## 1.1. Statement of the Problem

Turkey is situated in a seismically active region and suffers from earthquakes at frequent intervals, which cause considerable loss of life and property, and has negative impacts on the national economy (Öztekin & Yıldırım, 2007; Gönençen, 2000). It is expected that it faces with earthquakes in the future as well which are presumably turn to disasters by the collapses of the structures. Accordingly, it is too significant to design earthquake resistant buildings in order to defend the structures against significant earthquake loads. This statement supports the general objective of the study that earthquake resistant design of buildings is a vital need for Turkey.

This study focuses on reinforced concrete (R/C) skeleton buildings which are the mainstream construction system in Turkey. Many reasons can be asserted for this condition such as its cheapness, availability, sufficiency in qualified personnel, etc. In spite of containing various structural irregularities, today the vast majority of urban population in Turkey living in multi-storey R/C apartment blocks. Furthermore, the majority of the built environment consists of typical five storey R/C buildings. Düzce Municipal Government conducted a building damage survey after 1999 Marmara earthquakes on relating damage grade to building height. These results are illustrated in Figure 1.1. It is evident that building vulnerability remarkably increases with the number of stories. The percentages of damage grades are given for each total storey number separately. Especially four and five story buildings appear to be more vulnerable than the others (Sucuoğlu & Yılmaz, 2000).

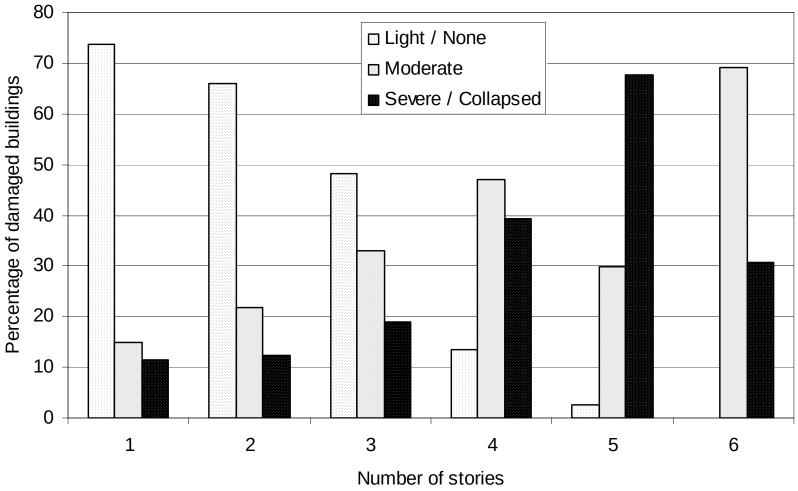


Figure 1.1. Distribution of building damage with the number of stories after 1999 earthquakes in Düzce (Source: Sucuoğlu & Yılmaz, 2000)

After the Marmara Earthquake, an investigation was made on ten heavily or severe destroyed buildings in 1999, August 17, the Marmara earthquake in the province of Düzce (Bakar, 2003). They have been investigated in terms of their structural irregularities and it is observed that they are all multi-storey R/C skeleton buildings which are commonly used for commercial or dwelling purposes. Based on Bakar's study the number of buildings which have the structural irregularity is summarized in Table 1.1. The table draws attention to the (A1) torsional irregularity and (B2) soft storey.

Table 1.1. An investigation of commonly experienced structural irregularity types in heavily damaged buildings after the Marmara Earthquake

| | Reviewed Project Number | Non- existing | Existing |
|---|---|---|---|
| A1 | 10 | - | 10 |
| A4 | 10 | 2 | 8 |
| B2 | 10 | - | 10 |

The structural irregularities are described in the Turkish Earthquake Code, 2007 (TEC, 2007). But, in practise it is quite significant and required to gain an understanding of the problems in projects at least in terms of structural irregularity, and then manage to solve the problems using problem-oriented solutions. Earthquake is a common and significant research field ranging from social sciences to technical sciences. However, the structural problems caused by an earthquake are generally seen as an engineering problem even though they can be eliminated through the design phase. Safety precautions should have a significant position in architectural design. Bayulke (2001b) states that the safety of a building is strongly related to its architectural design and its structural system. For this reason, architects should have an awareness of the problems about structural irregularities in terms of both problems in plan and structural configuration in order to achieve the reasonable and logical solutions.

Architecture is a profession which exists to solve the shelter problems of humanity in a way that is in harmony with nature and the force of nature (Işık, 2003). Producing safety built environment is one of the duties of architectural design. For that reason, this study aims to explore architectural problems in ERD to underline and understand architectural faults, and then its interaction with structural configuration to develop basic knowledge and perspective. If earthquake effects on existing buildings from the past destructive earthquakes are considered, it can be clearly seen that failures on buildings start at the beginning of the architectural design phase. Therefore, there exists a strong relationship between the architectural design of building and its earthquake safety. Besides, all types of damages are partly rooted, to a greater or lesser extent, in architectural design decisions.

Architectural design decisions have a significant effect on earthquake behaviour of structure that influences the seismic performance of the building due to the particularly building and structural system configuration issues. According to Erman (2002), “earthquake resistant architectural principles are not the provisions that could be inserted by the structural engineer after the completion of architectural design. They should be applied to the project during the architectural design phase”(p.102). Architectural design process plays an active role in the earthquake behaviour of structures.

Regular configuration and appropriate design decisions should be developed to provide better seismic behaviour, which means ideal or optimum configuration for overcoming with devastating earthquake loads. Furthermore, these loads have to calculate should be applied on both horizontal (plan) and vertical direction (Naeim, 2001). However, sometimes functional requirements, customer demands, environmental factors, etc determine the design decisions. On the other hand, regularity does not mean a symmetric and repetitive solution, which is limited by a series of principles. It searches appropriate solutions for better seismic behaviour of buildings that are in harmony with technological innovations (Mezzi, Parducci, & Verducci, 2004).

Architects are primary responsible from the overall picture observed after earthquakes due to the being the designer of the buildings. It is important to underline that ERD should not be seen just as an engineering calculation issue. Nevertheless, there is still hope for earthquake resistant R/C structures. This thesis verifies that it is possible to prevent structural irregularities without significant concessions.

## 1.2. Objectives and Scope

The main objective of this thesis is to explore the effective factors on structural irregularities to develop a substantial guide for architects and students of architecture in order to design earthquake resistant buildings. The earthquake resistance of a building is strongly related to architectural design and its interaction with structural configuration. In Turkey, the mainstream type of structural system is R/C. Therefore, in this study the behaviour of the R/C skeleton buildings is investigated on the bases of the structural irregularities that defined in the TEC (2007). Four cases having different structural irregularities are created and analyzed by IdeCAD structural analysis software. From the IdeCAD earthquake analysis reports, structural irregularities are obtained. The analyses focus on three basic aims. The first aim of the analysis is to assess the effective factors leading to structural irregularities. The second aim is to contribute to the general understanding and perception of the architectural characteristics of the R/C structures among architects and students of architecture based on TEC (2007). The third aim is to develop a designer guide especially for using initial part of the design stage or in the latter part for rapidly design control by architects or students of architecture.

The study presents a broad outline on structural irregularities in order to emphasize the architectural design faults which are in fact wrong as we know true. It describes basic problems in plan and structural system configuration which are frequently encountered at the initial phase of design. Any kind of failure made in the plan or the structural member’s configuration causes different structural behaviour under earthquake loads.

Both architectural design and structural configuration have the same level of importance. The interaction between both of them determines the behaviour of structures against earthquake loads. Failures in the architectural design phase can not be regulated by calculations or a detailed structural design done later by the structural engineer (Ersoy, 1999). A seismically well-arranged architectural design is necessary in order to overcome from the devastating earthquake loads.

The study mainly addresses to the architects, students of architecture and researchers who are interested in this kind of subject to improve a perception about ERD. There are many publications related to ERD, but they are generally written with an engineering understanding or perception except providing awareness among architects. When the effects of earthquake on structures are considered, the concept of ERD is generally accepted as an engineering profession consisting with various stacks of calculation, analysis, construction details, etc. As earthquake forces affect the whole building, earthquake resistance of a building should be a major issue in the responsibility of various professionals and people related to the building construction (Zacek, 2005a). Each discipline has different responsibilities about their own roles in ERD.

In this thesis, TEC (2007) is taken the basic resource and it is firstly translated and developed in a visual presentation which is for clarifying the technical dimension for architects. Then the numerical studies are performed in order to prove the illustrated structural irregularity conditions to contribute to the development of awareness and responsibility of earthquake resistant architectural design in Turkey.

## 1.3. Materials and Methodology

The study concentrates on the interaction between the architectural design and structural configuration. This is a significant issue because it has come up with the same damage picture after each earthquake, but then it has always been forgotten. The main aim is to explore the effective factors on structural irregularities. In line with the aim of the study, first of all a comprehensively survey is conducted on each structural irregularities according to the TEC (2007), and then four cases are created including each structural irregularity. Each case is designed as to have different number of sub-models. All models are analyzed by IdeCAD Static 6.0055 which is three dimensional structural analysis software. The models occupy wider space in the study because each structural irregularity condition especially in plan defined in the TEC (2007) is examined. The theoretical materials which are used for this study can be listed as follows:

1. Survey of the master and doctoral thesis from the database of the the Council of Higher Education of the Republic of Turkey.
2. Survey of the domestic and foreign publications related to the subject in the Turkish Earthquake Code, books, articles, conference proceedings,
3. Survey of the publications that appeared after the recent-past earthquakes in Turkey for a definition and analysis of common structural faults and architectural faults.
4. Drawings for illustration of each structural irregularity
5. Photographs of building damage that appeared after the recent-past earthquakes in Turkey.

Keeping the aims of the study in mind, the steps to be considered in achieving the goals of the thesis can be listed as follows:

1. Investigation of the structure of Earth and Earthquakes
2. A comprehensive research on structural irregularities based on TEC (2007) and solution suggestions
3. Examination of the earthquakes on R/C structures
4. Description of the earthquake resistant design principles and analysis methods
5. Determination of the structural analysis software, IdeCAD Static 6.0055
6. The structural analysis of the interaction of architectural design decision with R/C structural configuration under earthquake loads
    - Demonstration of earthquake effect on each type of structural irregularity through a number of cases consisting a sequence of analytical models
    - Analysis of cases consisting parametric models and their sub-models by the structural software, IdeCAD Static 6.0055
    - Discussion of the results of each cases

7. Discussion and Evaluation of the results obtained from the whole structural analysis
    - Explore the effective factors on structural irregularities

### 1.3.1. Selected Software for Analysis

IdeCAD structural software is an integrated, design and detailing software for reinforced concrete structures and especially developed for structural engineers. It covers from all stages related to reinforced concrete structures, from dynamic analyses to design of reinforced concrete cross-sections. All the necessary controls are made automatically in IdeCAD® Static 6 software which is compatible with TEC (2007) and Turkish Standard, TS 500. Moreover, reinforcement details are automatically created.

IdeCAD Structural and IdeCAD Architectural use the same static components. Object properties are compatible with each other. Thus, this characteristic provides carrying out the design process in advance of static calculations. Static calculation and reinforced-concrete measurements are carried out on the basis of the three-dimensional calculation model. 3D representation provides visual control of the model. The structural properties of all the components such as column, wall is given automatically by software. The 3D frame structure consisting of components such as columns, beams and walls can be analyzed both statically and dynamically.

In this study, IdeCAD structural software is chosen because, it presents a common platform for collaboration between the structural engineers and architects. Moreover, it is entirely compatible with Turkish Standard TS 500 and Turkish Earthquake Code, 2007. The flowchart of the analysis software is given in the Figure 1.2.

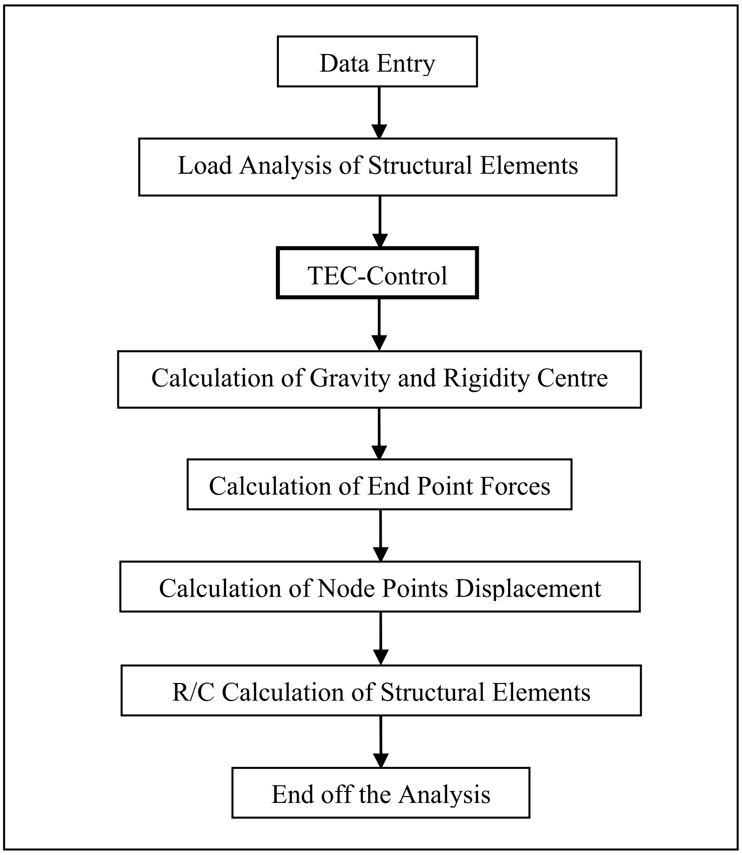


Figure 1.2. Flowchart of structural analysis software, IdeCAD

## 1.4. Disposition

General outline of the thesis is presented in six chapters. Chapter 1, the introduction, includes the main argument, the objectives of the thesis and general background information about the research field with its disposition.

Chapter 2 is the structure of Earth and earthquakes. It presents comprehensive information related to the phenomena of earthquake. A description of the seismic characteristics of the world and Turkey is compared and discussed in order to gain basic knowledge related to earthquake.

Chapter 3, a comprehensive research is made on structural irregularities in both horizontal plan and vertical direction according to the TEC (2007). All architectural and structural configuration problems are investigated. Moreover, suggestive solutions are examined for each structural irregularity.

Chapter 4 starts with the description of the material characteristics of the R/C. In the following, basic principles and analysis rules for earthquake resistant design are described. In the end of this chapter, the structural analysis software is introduced which is used in the case models.

Chapter 5 is the numerical analysis. It presents structural irregularities which is the main argument of the thesis. The study is specifically interested in the structural irregularity in plan, for each building is generally designed by the replication of the same storey plan. To examine each type of structural irregularity, a sequence of analytical models are created and analyzed with the structural software, IdeStatic 6.001. Totally, the chapter consists of four cases, and each case has a series of parametric models. The main parameters such as torsional irregularity coefficient, soft storey coefficient, effective storey drift, second order effect, etc affecting the structural irregularity conditions are discussed in the final part of each case.

Chapter 6 is the final chapter. It comprises a summary of the previous assessments and the discussion of the results of the case studies. The thesis ends with recommendations for the further studies.

## 1.5. Review of Past Studies

Earthquake behaviour of reinforced concrete structures in order to prevent structural irregularities has always been a remarkable subject and examined by many researchers. Some of the significant studies related to the subject made up to now are summarized as below:

Özmen (2004) investigated the conditions which cause torsional irregularity. In order to achieve the goal of the study, a series of eight walled and framed sample structures with different shear wall configuration is generated and their behaviour under earthquake loading is investigated. It is concluded that maximum torsional irregularity values are obtained when the both number of axes and the number of stories are low. Moreover, when the structural walls were placed closer to the gravity centre, the torsional irregularity increased.

Döndüren and Karaduman (2007) were investigated the torsional irregularities of the constructions having different plan geometry or rigidity distribution were investigated. All the models are asymmetric in terms of rigidity distribution according to the X axes due to the placement of the rigid core. Moreover, the dimensions of the frame in each model and the beam connections are not similar. To realize the aim of the study, the behaviours of multi-storeyed (15 storied) buildings having seven different forms of triangular, elliptical, square, rectangular, circular, L and T shaped geometries were considered and investigated under seismic effects. Square form shows the best seismic behaviour under earthquake loads.

Özmen (2008) made an investigation on cost analysis of earthquake resistant structures. The specific type of the thesis focused on was the reinforced concrete skeleton system. The parametric examples which were used in the thesis were chosen among applied projects in the city of Bolu. It was concluded from the study that designing earthquake resistant structures only resulted in an acceptable 4-8% rise in the overall building cost.

Mendi (2005) examines awareness about the roles and responsibilities of architects for earthquake resistance of structures for being the designers of them. It is aimed to explore architecture-based issues related to earthquake resistant design and evaluate awareness, interests or consciousness among architects about the subject. Architects working in the architectural offices of Ankara, towards earthquake and architecture-based seismic design issues is questioned and evaluated with a survey in the form of questionnaires. The evaluation of the results is presented with the help of statistical software, SPSS. It was inferred from the survey that incorporation of architecture-based seismic design issues into architectural design process should be enhanced among architects.

Dimova and Iliaalashki (2003) examined the effects of the additional torsion in symmetric buildings. They made analytical and numerical analysis and on the bases of these analyses it is concluded that even under small additional torsion the symmetric buildings show irregular behaviour and the torsional moments cannot be exactly described by the application of the static load calculation. A convenient coefficient should be calculated for the design practice to estimate accurately the accidental torsional effects on symmetric structures.

Gülay and Çalım (2003) investigated the torsional irregularity condition on ten storey shear wall framed buildings. The torsional irregularity coefficients of the modals evaluated according to the UBC 97 and TEC (97). The effects of absolute and relative displacements are examined. It is observed that UBC coefficients are rather critic with respect to the TEC (97) coefficients.

Güllü and Yerli (2004) investigated the TEC (97) and the A2 irregularity condition in shear-walled structures. The effects of shear wall arrangements in the plan are examined for improving the A2 irregularity condition.

Yulu (2003) examined the effects of floor discontinuity (A2) and Projections in plan (A3) by taking into consideration of TEC (97).

Akıncı (2003), investigated the torsional irregularity in multi-storied shear-frame system of R/C structures. The effects of axis number, plan geometry and rigidity distribution were examined. The calculations were made by a program which was created by using Visual Basic 5.0. Moreover, analyses of the models were also made by the structural software called SAP, and the results were compared. It was observed in the study that, the models which were irregular in terms of rigidity distribution showed similar sismic performance with the irregular models in terms of both plan geometry and rigidity distribution. Furthermore, the positions of shear walls were questioned, and it was gained that the torsional irregularity coefficients reached high values when the shear walls were placed at inner axis instead of at outer axis.

Evcil (2005) examined torsional irregularity (A1) in detail. The variations in torsional irregularity coefficients according to the axis number and storey number were investigated in depth.

Atımtay (2000) investigated the Turkish Earthquake Code in detail with practical examples in his book called "Instructions and examples for Specification for Buildings to be built in Seismic Zones"

Çağatay and Güzeldağ (2002) examined various parameters in TEC (97) such as seismic analysis methods, structural irregularities, etc. In the study, a sequence of models were created and evaluated in terms of structural irregularity. All models were analyzed by the structural software called SAP.

Bayülke (2001) investigated comprehensively the earthquake resistant design in his book called “Earthquake resistant reinforced and masonry structure design” Building configuration in terms of earthquake resistance evaluated into two main part: architectural design and structural element design. In the study, the characteristics of earthquake forces and the phenomena of earthquake resistant design were emphasized.

Erman (2002) searched earthquake resistant design concepts in his book called “Earthquake information and earthquake safety architectural design” The general effects of earthquakes and its effects on structures were examined. The main concepts for earthquake safety architectural design were evaluated in R/C, steel, masonry and timber structure.

Tezcan (1998), examined the structural irregularities in his book called “An architect logbook for earthquake resistant architectural design” In the book, various damage photographs in structures were given which were observed after earthquakes both in Turkey and in the world.

Tuna (2000), mentioned earthquake regulations and the effects of earthquake forces on structures i in his book called “Earthquake resistant structure design”. Moreover, the necessary things for earthquake resistant R/C skeleton system design and what the damages are in the structures took large place in the book.

Zacek (2002), researched earthquake resistant structure design principles in his book called “Earthquake resistant pre-project work”. In this book, the importance of earthquake resistant structural design and architectural aspects were emphasized. Moreover, some information was given related to what the architectural and structural features should have been in order to perform in the pre-project phase.

Sezer (2006) investigated the parameters affecting the torsional irregularity of structural systems. In this thesis, different shear wall configuration and varied number of stories were examined under earthquake loading. It is inferred from the study that if the storey number increase, the torsional irregularity coefficient decrease.

Doğan, Ünlüoğlu, and Özbaşaran (2007) examined the overhang dimension and length in terms of earthquake behaviour. Based on these parameters, analyses are made and various examples are given from existing buildings in Turkey. It was concluded from the model analysis that if the length of the overhang increases, eccentricity increases. Moreover, unit weight of materials used in overhangs affect the eccentricity value.

Livaoğlu and Doğangün (2003) evaluated the behavior of elements placed on the rigid and flexible sides. Accidental eccentricity and torsional irregularity condition are investigated with six and twelve storey buildings. Mode-combination method is used for the seismic analysis of structures. At the end of the study, it was concluded that if the design eccentricity is small, internal forces of structural elements located on rigid sides reach maximum values. Conversely, if it is high, internal forces of structural elements located on flexible sides reach maximum values.

In this thesis, unlike the above mentioned studies, all the factors which affect on structural irregularities are firstly determined for R/C structures. The commonly used R/C skeleton system types were chosen and parametric models are generated according to the determined factors which affects on structural irregularities. The study examines structural irregularity conditions with the models having both symmetric plan geometry and rigidity distribution. Approximately all of the studies, which previously have been done related to structural irregularities, focus on asymmetric plan geometries with irregular rigidity distribution. Apart from that type of studies, this thesis basically focuses on completely symmetric buildings in terms of both plan geometry and rigidity distribution. Because, the goal of the study is to determine the best one among the better designs instead of better one among the poor designs. On the other hand, the study investigates the buildings having regular plan geometry and irregular rigidity distribution and irregular plan geometry and regular rigidity distribution.

The study examines all structural irregularities defined in the TEC (2007). However, it was adopted that the structural irregularities begins in the initial part of the design phase. For that reason, the structural irregularities in plan were investigated in detail. It was deduced from the analysis that the structural irregularities can occur in completely symmetric buildings.

# CHAPTER 2

# EARTH AND EARTHQUAKES

This chapter provides the basic mechanism of earthquakes. It includes the definition of earthquake and earthquake types together with the types of seismic faults and seismic waves. It introduces the earthquake parameters such as hypocenter, epicenter, magnitude, etc. Finally, the distribution of seismicity in the world and seismicity in Turkey are investigated.

## 2.1. Anatomy of Earthquake

The Earth where we are living on has witnessed lots of stages since its formation period. The humanity has exposed to various natural disasters while the world passing on these stages. For instance, earthquake is one of the natural events. It is a suddenly released energy (Celep & Kumbasar, 1992). Earthquake is not a disaster of the nature. It is an ordinary natural event such as hurricane, drought, landslide, etc (Erman, 2002). The earthquake phenomenon has affected human life since the beginning of the planet formation that we are living on it (Karaesmen, 2002).

The earthquake can be defined as broad-banded vibratory ground motions. It occurs due to the a sudden slippage on a fault of the Earth's crust and arises from a number of causes such as tectonic ground motions, volcanism, landslides, and man-made explosions (Karaesmen, 2002). Tectonic-related earthquakes are the most common type among them. They occur by releasing of the elastic stresses (Erman, 2002). Besides, they are so hazardous, because they happen close to the Earth's crust They occurs due to the fracture and sliding of the rock along faults within the Earth's crust (Krinitzsky, 1993).

Earthquakes consist of vertical and horizontal (lateral) vibrations of the ground. These vibrations occur randomly and create a dynamic impact in character (Doğan, 2007). Düzgün (2007) states that earthquake comes out without giving any stimulus and also each type of earthquake has different features. It's time or location cannot be known before it happens.

The mechanism of an earthquake is closely related with the structure of the earth. It depends on especially inner structure of the earth (Coburn & Spence, 1992). The earth consists of three distinct parts. These are the crust at the outer part of the earth, the core at the center part and the mantle in-between. Celep and Kumbasar (1992) describe the structure of the earth with a core having a radius of 3500 km, has liquid feature; with a mantle having 2900 km in thick, has semi-molten feature. Thickness of the crust measure is approximately 5-10 km under oceanic parts and 25-70 km under continental parts. (Yılmaz & Demirtaş, 1996).

Many theories put forward to determine the causes of earthquakes. Among these theories, the plate tectonics theory is considered as the most realistic approach (Yılmaz & Demirtaş, 1996). According to this theory, the earth's crust divides into plates which consist of oceans and continents.

The crust of the earth is cracked into seven large and many other smaller plates. Their thicknesses are approximately 50 miles. Based on their movement and the direction of the movement, they collide and give shape to the deep ocean trenches, mountains, volcanoes. This event causes earthquakes.

The forces of tectonic plates have shaped the earth crust. The continents are constantly in a motion. Hundreds of millions of years ago the continents were joined together. However, they are dissipating ever slowly. The earth's crust states on a dynamic flux. This dynamic process is called as continental displacement or tectonic plate movement (Charleson, 2008). The mechanism of this movement is very complicated. The tectonic plates may go and return to each other. Moreover, one plate may go under the other plate or move along the borders of the plates. Energy is accumulated with these events. If this energy becomes stronger, it is released to the nature as a ground shake or vibration. This suddenly released energy called as the earthquake. Most earthquakes occur at the boundaries where the plates meet. However, some earthquakes occur in the middle of plates (Celep & Kumbasar, 1992).

## 2.2. Types of Earthquakes

There are many types of earthquake such as volcanic earthquake, tectonic earthquake, deep earthquake, etc. Earthquakes can be divided into four groups according to their features (Pampal & Özmen, 2002). They can be categorized according to the origin, the focal depth, the distance from recording device, and the magnitude.

### 2.2.1. According to the Origin

Earthquakes can be classified into three groups based on the origin of the earthquakes (Lindaburg & Baradar, 2001). These are tectonic earthquakes, volcanic earthquakes, and subsidence earthquakes. Among to these earthquakes, the tectonic earthquakes are widely observed in the world. They have come into being due to the movement of the plates. The hundreds of years accumulated energy release because of the stress and friction in the Earth's crust. The most destructive earthquakes in Turkey situated in this group. Volcanic and subsidence earthquakes are observed lesser than the tectonic ones. While volcanic earthquakes have come into being nearby of volcanoes due to the explosion of active volcanoes, the subsidence earthquakes have come into being due to the collapses of mines and caves.

### 2.2.2. According to the Focal Depth

Earthquakes are classified into three groups according to the size of the focal depth (Lindaburg & Baradar, 2001). These are shallow earthquake, intermediate earthquake and deep earthquake. While the focal depth is less than 70 km in shallow earthquakes, it is between 70 and 300 km deep in intermediate earthquakes. On the other hand, it is between 300 and 700 km deep in the deep earthquakes.

### 2.2.3. According to the Distance from the Recording Device

The earthquakes according to the distance from the recording device can be classified into four groups (Lindaburg & Baradar, 2001). These are local earthquakes, near earthquakes, regional earthquakes and distant earthquakes. The distance from the recording device is less than 100 km in local earthquakes. In near earthquakes that distance is between 100 and 1000 km. On the other hand, that distance is between 1000 and 5000 km in regional earthquakes. In distant earthquakes, that distance is more than 5000 km

### 2.2.4. According to the Magnitude

The earthquakes can be classified into six groups according to the their magnitude (Lindaburg & Baradar, 2001). These are very strong earthquakes, strong earthquakes, medium earthquakes, small earthquakes, micro earthquakes, and ultra micro earthquake. Very strong earthquakes have a magnitude greater than 8.0. Strong earthquakes have a magnitude between 7.0 and 8.0. Medium earthquakes have a magnitude range between 5.0 and 7.0. Small earthquakes have a magnitude range between 3.0 and 5.0. Micro earthquakes have a magnitude range between 1.0 and 3.0. If the magnitude of an earthquake is smaller than the magnitude of 1.0, this is called as ultra micro earthquakes.

## 2.3. Types of Seismic Faults

Earthquakes occur on faults. A fault is a thin zone of crushed rock that it separates blocks of the earth's crust. When an earthquake occurs on one of these faults, the rocks which are located on one side of the fault slip relative to one another parallel to the fracture (Lindeburg & Baradar, 2001). The fault surface can be vertical, horizontal or a random angle with the surface of the earth. (Lagorio, 1990). Faults extend deep into the earth and may or may not extend up to the earth's surface. Bayülke (2001a) states that faults can be accepted as the results of earthquakes rather than causes of them. The commonly encountered seismic faults are illustrated in Figure 2.1.

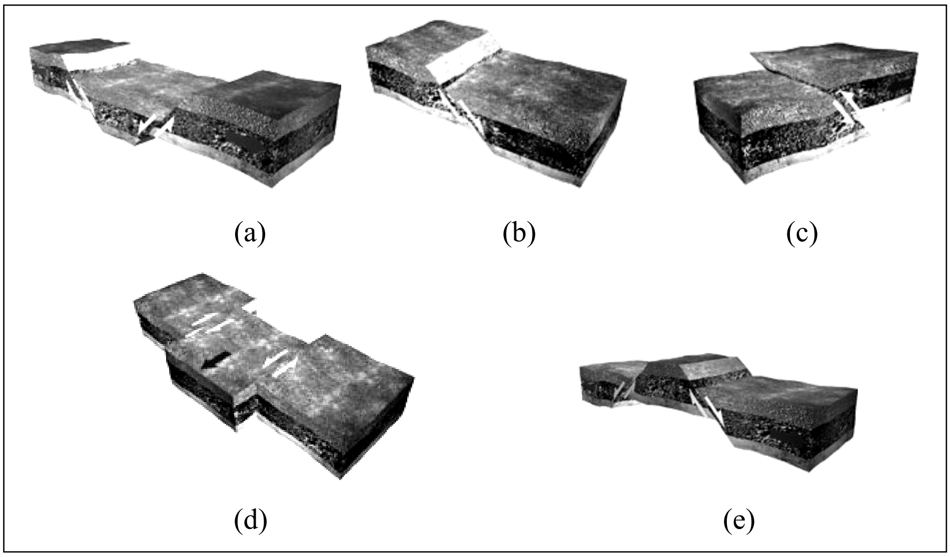


Figure 2.1. Types of fault: (a) Subsidence faults,(b) Normal Fault, (c) Reverse Fault, (d) Strike-Slip Fault, (e) Horst Fault (Source: Barka, 2000)

## 2.4. Types of Seismic Waves

Seismic energy spreads from the earth’s crust with waves. There exists two main type of elastic waves or seismic waves. These are body waves and surface waves. These waves cause shaking that is felt in the nearby region where we live, and cause dangerous and irreparable damages (Barka, 2000).

### 2.4.1. Body Waves

The body waves spread within a body of rock and strike firstly during an earthquake. Body waves travel through the earth’s interior (Lindaburg & Baradar, 2001). There are two kinds of body waves. The faster of these body waves is called Primary wave (P wave) or longitudinal wave or compressive wave. The slower one is called Secondary wave (S wave) or shear wave or transverse wave. They are illustrated in Figure 2.2 and in Figure 2.3.

P waves or Primary waves are the fastest kind among the body waves as described formerly. The P waves, which reach the surface firstly, can travel through solids, liquids and gases (Lindeburg & Baradar, 2001). Nelson states that P wave is moving with an acoustic wave in the air that people usually report this sound as a train before they feel the shake. P waves travel about 1.7 and 1.8 times faster than S waves or secondary waves and 2 to 3 times faster than the surface waves. Its velocity is changed between 1.5 and 8km/sn according to the earth’s crust.

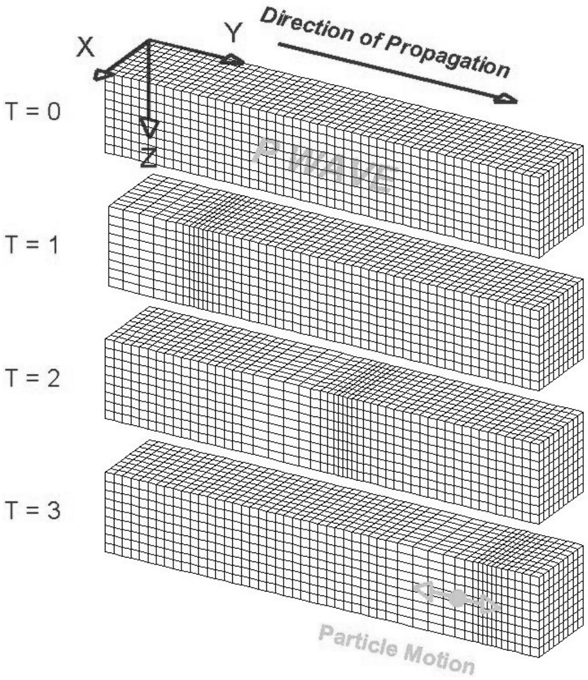


Figure 2.2. Perspective view of P-wave
(Source: Braile, 2006)

The S-waves or Secondary waves travel more slowly than the P-wave. It shears the rock sideways at right angle to the direction of propagation. This wave can only travel through solids. Therefore, it does not travel through the earth’s core.

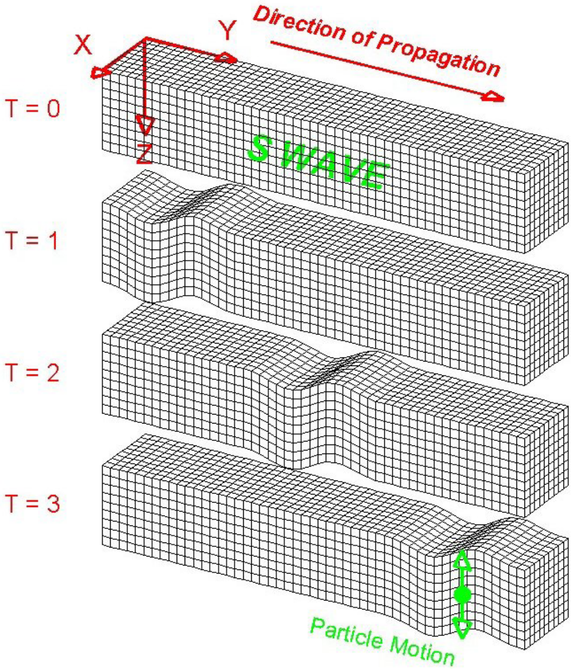


Figure 2.3. Perspective view of S-wave
(Source: Braile, 2006)

### 2.4.2. Surface Waves

The second main type of seismic wave is called body wave. It travels along the earth’s surface (Lindeburg & Baradar, 2001). Surface waves can be classified into two groups. These are Love waves and Rayleigh waves. The Love waves denoted as L, and the Rayleigh waves as R. The L wave displays vibrations which are parallel to the plane of the earth’s surface and perpendicular to the direction of wave propagation. On the other hand, the R wave displays vibrations which are perpendicular to the plane of the earth’s surface and exhibits an elliptic movement. They are illustrated in Figure 2.4 and in Figure 2.5.

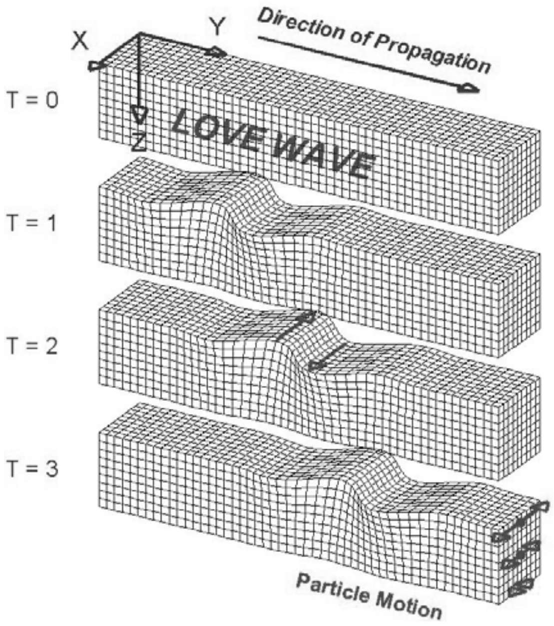


Figure 2.4. Perspective view of L-wave
(Source: Braile, 2006)

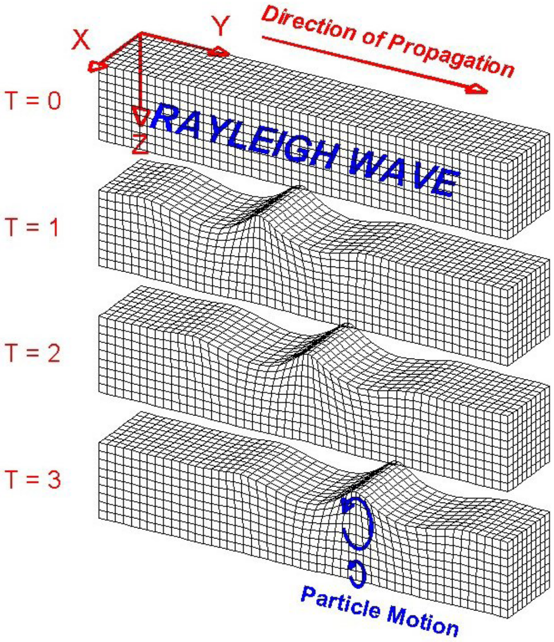


Figure 2.5. Perspective view of R-wave
(Source: Braile, 2006)

## 2.5. Basic Terms

The commonly encountered basic terms related to earthquake phenomena is explained in this part such as origin time, hypocenter, epicenter, etc. The magnitude and intensity which are the earthquake measurement parameters are comprehensively investigated. They can be described as follows:

Origin Time: The precise time that an earthquake fracture occurs that is defined according to the Greenwich hour.

Hypocenter: The hypocenter of an earthquake is the point below the earth's surface where the fault rupture begins (Figure 2.6).

Epicenter: The epicenter of an earthquake is the vertical projection of the hypocenter on the ground surface. It can be described as the location of an earthquake (Figure 2.6).

Focal depth: The distance from the focus to the point of observed ground motion is called the focal distance or depth. In other words, it is the distance between the epicenter and hypocenter.

Focal region: Seismic waves propagate from the focus through a limited region of the surrounding of the earth. It is called as focal region (Figure 2.6).

Aftershock and foreshock: Earthquakes constitute a significant part of the life due to the seismicity of the world. The largest earthquake type is called main shock. If an earthquake occurs after a main shock, this is called as aftershock. On the other hand, if earthquake occurs before the main shock, this is called as foreshock.

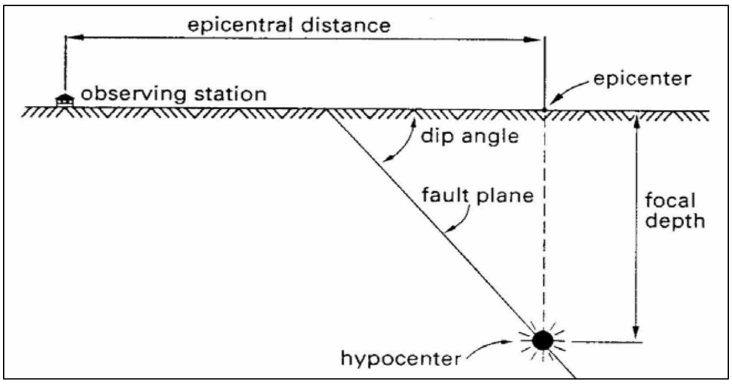


Figure 2.6. Basic Earthquake Terminology
(Source: Lindeburg & Baradar, 2001)

## 2.6. Earthquake Measurement Parameters

The origin time of an earthquake still cannot be predicted. However, human being has learned much about earthquakes as well as the Earth. They have learned how to pinpoint the locations of earthquakes and how to accurately measure their sizes.

When an earthquake occurs, the elastic energy releases and sends out vibrations that travel throughout the Earth as described formerly. These vibrations are called seismic waves which can be recorded on a sensitive instrument called seismograph. The record of ground shaking recorded by the seismograph called seismogram.

### 2.6.1. Intensity

Chen & Scawthorn (2002) describes intensity as a metric of the effect or the strength of the earthquake hazard at a specific location. Murty (2007) defines it as a qualitative measure of the the effects of an earthquake at a specific location. It is based on human behaviour and structural damage level. Numerous intensity scales has been developed. The widely used type is the Modified Mercalli Intensity Scale. It describes the level of shaking at specific sites on a scale of I to XII (Table 2.1).

Table 2.1. Modified Mercalli Intensity Scale
(Source: Lindeburg & Baradar, 2001)

| **Intensity** | **Rank** | **Observed Effects from Earthquakes** |
|---|---|---|
| I | Not felt | Nonperceptible except by a very few under especially favorable conditions. |
| II | Very Slight | Felt only by a few persons at rest in house, especially on upper floors of buildings. Hanging objects may swing. |
| III | Weak | Slightly felt by people indoors, many of those do not recognize as an earthquake. Standing vehicles may rock slightly. Vibrations like to a passing truck. Duration estimated. |
| IV | Largely Observed | Widely felt shake, Hanging objects swing. Door window and dish vibrations are detected, glasses clink, walls make creaking sound. |
| V | Strong | Felt nearly everyone. Many of them awakened. Buildings shake, glasses clink, some windows are broken. Unstable objects turned over. |
| VI | Slightly Damaging | Felt by all. Most them are frightened and run outdoors. Soil cracks, Superficial fissuring of walls and chimney fall are monitored. |
| VII | Damaging | Everybody frightened and runs outside. Damage is observed in buildings of bad design and construction. Falling of chimney and parapets, wall cracks are observed. Noticed by persons driving vehicles. |
| VIII | Heavily Damaging | Slight damage in specially designed structures, notable damage in ordinary buildings with partial collapse, great damage in poorly designed and constructed buildings. Fall of chimneys, walls columns, monuments. |
| IX | Destructive | Notable damage in specially designed structures, significant damage in ordinary buildings, great damage and partially collapse in poor designed and constructed buildings. |
| X | Very Destructive | Large soil cracks, landslides observed. Many ordinary buildings destroyed with their foundations, rails bent slightly. |
| XI | Devastating | None masonry structure remain standing. Large fissure in ground. Rails bent greately. |
| XII | Wholly Devastating | Damage total. Nearly all structures, both above and below ground, are heavily damaged and destroyed. Waves seen on ground surfaces. |

### 2.6.2. Magnitude

The size of an earthquake is measured by the strain energy which released along the fault after an earthquake (Murthy, 2007). As Wakabayashi (1986) describes magnitude is the quantitative measure of the size of an earthquake and it is about the amount of energy released from the hypocenter of the Earth. It shows the real rate of an earthquake. Various magnitude scales are in use. The most cost common magnitude scale type in used is the Richter Magnitude Scale discovered by Professor Charles Richter in 1935 and it is denoted as M or Ml (Lagorio, 1990). Richter magnitude is a logarithmic scale that one magnitude unit shows 10 times higher waveform amplitude and approximately 31 times higher energy releases. For instance, the energy released from a M 7.9 earthquake is about 31 times greater than released from a M 6.9 earthquake, and approximately 1000 (31*31) times greater than released from a M 5.9 earthquake. Doğan (2008) states that the energy released by a M 6.3 earthquake is equivalent to the released by the Atom bomb thrown into Hiroshima. The large part of the released energy converts to heat and cause fissurings in the rocks. Only a small part of it goes into the seismic waves. However, it goes far distances what cause ground shaking and damage in structures ( Lagorio, 1990).

Earthquakes which have similar Richter magnitudes may display a different impact on the built environment. Because the devastating effects of earthquakes having similar magnitudes depend on the geological features, and especially the depth of the earthquake (Lagorio, 1990). For instance, a shallow earthquake type will be more destructive than a deep earthquake type although they have similar magnitudes (Bayülke, 1989).

There are some significant differences between magnitude and intensity. As Lagorio (1990) states magnitude of an earthquake represents the measure of its size. It is shown with a single value for a given earthquake. On the other hand, intensity is a qualitative or quantitative measure of the severity of seismic ground motion at a specific site (Dowrick, 1987). Intensity is based on observed effects on people, buildings, etc. However, the intensity level of an earthquake can be changed according to the distance from its epicenter. It can be clearly guessed that the severity of vibrations is higher near the epicenter than farther away ones (Lindeburg & Baradar, 2001). Besides, intensity of an earthquake is shown with roman numerals. The relationship between intensity and magnitude is shown in Table 2.2.

Table 2.2. The connection between magnitude and the intensity of an earthquake (Source: Tuna, 2000)

| **Intensity** | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Magnitude** | 1 - 3 | 3 | 3.9 | 4 | 4.5 | 5.1 | 5.6 | 6.2 | 6.6 | 7.3 | 7.8 | 8.4 |

## 2.7. Seismicity of the World

The Earth that we are living on has witnessed lots of disasters such as mainly earthquake, floods, storms, and avalanche. Earthquake is a major problem for all human being killing thousands each year, nearly everywhere in the world is under the threat of earthquakes (Karaesmen, 2002). Its specific location, time and magnitude cannot be estimated before it occurs. Globally, earthquakes have caused considerable death and damage in built environment (Chen & Scawthorn, 2002). Several million of earthquakes occur in the world per year. While the earthquakes having high magnitudes can be recorded, the small ones cannot be detected. According to long-term records, it is expected about one very strong earthquake (M8 or above) and seventeen strong earthquake (M7-M7.9) per year. Estimated numbers of earthquakes per year are listed depending on their magnitudes below in Table 2.4. Furthermore, the numbers of earthquakes occurred each year is given in detail in Table 2.3.

Table 2.3. Frequency of earthquake occurrence
(Source: Adapted from TEC, 2007 and United State Geological Survey [USGS], 2010a)

| **Group** | **Magnitude** | **Annual Average Number** |
|---|---|---|
| Very Strong | M>8.0 | 1 |
| Strong | 7.0<M<8.0 | 17 |
| Medium | 5.0<M<7.0 | 1453 |
| Small | 3.0<M<5.0 | 143000 estimated |
| Micro | 1.0<M<3.0 | 1300000/day estimated |
| Ultra Micro | M<1.0 | |

Table 2.4. Number of worldwide earthquakes between 2001 and 2010
(Source: USGS, 2010a)

| **Magnitude** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** | **2009** | **2010** |
|---|---|---|---|---|---|---|---|---|---|---|
| 8.0-9.9 | 1 | 0 | 1 | 2 | 1 | 2 | 4 | 0 | 1 | 1 |
| 7.0-7.9 | 15 | 13 | 14 | 14 | 10 | 9 | 14 | 12 | 16 | 6 |
| 6.0-6.9 | 121 | 127 | 140 | 141 | 140 | 142 | 178 | 168 | 142 | 77 |
| 5.0-5.9 | 1224 | 1201 | 1203 | 1515 | 1693 | 1712 | 2074 | 1768 | 1725 | 849 |
| 4.0 to 4.9 | 7991 | 8541 | 8462 | 10888 | 13917 | 12838 | 12078 | 12291 | 6956 | 3713 |
| 3.0 to 3.9 | 6266 | 7068 | 7624 | 7932 | 9191 | 9990 | 9889 | 11735 | 2897 | 1379 |
| 2.0 to 2.9 | 4164 | 6419 | 7727 | 6316 | 4636 | 4027 | 3597 | 3860 | 3007 | 1074 |
| 1.0 to 1.9 | 944 | 1137 | 2506 | 1344 | 26 | 18 | 42 | 21 | 26 | 12 |
| 0.1 to 0.9 | 1 | 10 | 134 | 103 | 0 | 2 | 2 | 0 | 1 | 0 |
| No magnitude | 2807 | 2938 | 3608 | 2939 | 864 | 828 | 1807 | 1922 | 20 | 16 |
| Total | 23534 | 27454 | 31419 | 31194 | 30478 | 29568 | 29685 | 31777 | 14791 | 7127 |
| Estimated deaths | 21357 | 1685 | 33819 | 228802 | 82364 | 6605 | 712 | 88011 | 1787 | 225420 |

There are three prominent earthquake belts in the world. These are Pacific earthquake belt, mid-Atlantic belt, and the third one is Alp Himalayan earthquake belt which affects the seismicity of Turkey. Celep and Kumbasar (1992) observed that nearly 17 % of the world's major earthquakes occur at Alp Himalayan earthquake belt. The 17 August 1999 M 7.4 Kocaeli and 12 August 1999 M 7.1 Düzce earthquakes can be given as the most striking examples occurred at Alp Himalayan earthquake belt. They cause indescribable casualties. Approximately, 18000 people died and 15400 building collapsed (Parsons, Toda, Stein, Barka, & Dieterich, 2000).

The destructive earthquakes observed in the world are listed with their magnitudes in Table 2.5. China, Italy, Japon, The Soviet Union, The USA and Turkey are major countries due to the losses rate passing 100000 lives in earthquakes.

The strongest earthquake in the world is recorded with a magnitude of 9.5 on Richter scale in Valdicvia, Chile in 1960 that caused 20.000 fatalities. Second strongest earthquake was measured with a magnitude of 9.3 on Richter scale in 2004. The epicenter of this earthquake is Sumatra and Indonesia that caused 300.000 casualties. The third one of the strongest earthquake is the Alaska earthquake that measured 9.2 on Richter scale caused irreparable damage. The world's deadliest earthquake occurred in 1556 in China, killing nearly 830.000 people (Charleson, 2008).

Table 2.5. List of major earthquakes in the world
(Source: USGS, 2010b)

| DATE | LOCATION | MAGNITUDE |
|---|---|---|
| 1939 | Erzincan, Turkey | 7.9 |
| 1960 | Chile | 9.5 |
| 1964 | Alaska | 9.2 |
| 1976 | China | 7.5 |
| 1980 | S.Italy | 7.2 |
| 1985 | Mexico | 8,0 |
| 1985 | El Salvador | 8,0 |
| 1988 | Adana, Turkey | 6.2 |
| 1989 | California | 6.9 |
| 1994 | Bolivia | 7.7 |
| 1995 | Sakhalin | 7.5 |
| 1995 | Kobe | 7.2 |
| 1999 | India | 6.8 |
| 1999 | İzmit, Turkey | 7.4 |
| 1999 | Taiwan | 7.6 |
| 2001 | El Salvador | 7.7 |
| 2001 | S. Peru | 7.9 |
| 2001 | Gujarat, India | 8.1 |
| 2002 | Iran | 6.5 |
| 2002 | Afyon, Turkey | 6.5 |
| 2002 | Afganistan | 7.4 |
| 2002 | Alaska | 7.9 |
| 2003 | Bingöl, Turkey | 6.4 |
| 2003 | Algeria | 6.8 |
| 2003 | Bam, Iran | 6.6 |
| 2003 | Mexico | 7.6 |
| 2003 | Japon | 8.3 |
| 2004 | Sumatra, Indonesia | 9.3 |
| 2005 | Kashmir, India | 7.6 |
| 2005 | Tarapaca | 7.8 |
| 2005 | Sumatra, Indonesia | 8.7 |
| 2006 | New Zeland | 7.4 |
| 2006 | Russia | 8.3 |
| 2006 | Java, Indonesia | 7.7 |
| 2007 | Chinta Alta | 8.0 |
| 2007 | Soloman Islands | 8.1 |
| 2007 | Sumatra | 8.5 |
| 2008 | Sichuan, China | 7.9 |
| 2008 | Indonesia | 7.6 |
| 2009 | Russia | 7.4 |
| 2009 | New Zeland | 7.8 |
| 2009 | Japon | 7.1 |
| 2009 | Haiti | 7.0 |
| 2010 | Japon | 7.0 |
| 2010 | Chile | 8.8 |
| 2010 | Elazığ | 6.1 |
| 2010 | Sumatra | 7.8 |

## 2.8. Seismicity of Turkey

Turkey is located on Anatolian Peninsula on the Alp Himalayan earthquake belt that is seismically active region in the world. As a result of this, a great deal of destructive earthquakes has happened in Turkey. According to the seismic zone map which was come into force in 1996 by the Turkish Ministry of Public Works, approximately 96 % of its land is located on considerably risky earthquake zones and 80 % of its population is imposed upon to the large scale earthquakes (Doğan, 2007). Turkey is separated on five earthquake zones (Table 2.6).

The seismic activity is quite complicated. Turkey expose to great compression from Arabian, African and the Eurasian plate. The African and Arabian plates travel to the North and make a compression to the North Anatolian Fault. After this event, North Anatolian Fault begins to travel towards to the west of Turkey. It is shown in Figure 2.7.

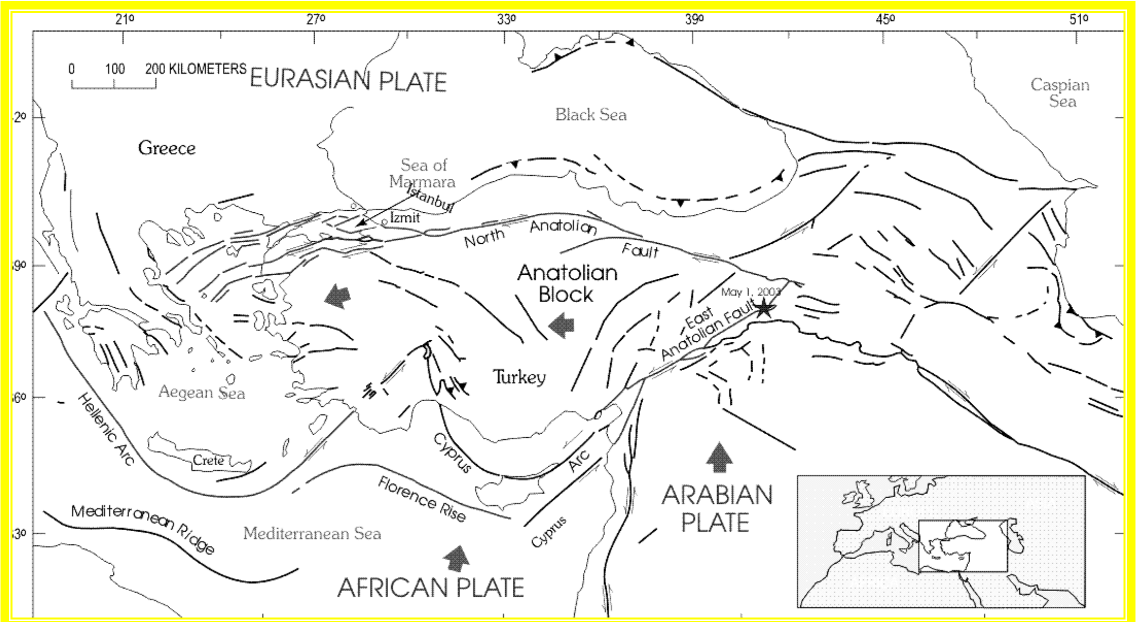


Figure 2.7. Tectonic map of Turkey
(Source: USGS, 2010c)

A large ratio of its area consists of Anatolian block. The block is surrounded by the North Anatolian Fault in the north and by the East Anatolian Fault in the south-east as shown in Figure 2.7. The North Anatolian Fault has a length of 1300 km and consists of several shorter faults (Celep & Kumbasar, 1992). Bayülke (2001b) describes that the most significant faults are North Anatolian Fault, South Anatolian Fault and West Anatolian Horst Graben System and the most risky one is the North Anatolian Fault due to the experienced earthquakes in the past.

Turkey is separated on five earthquake zones according to their risk conditions. On the 1st and 2nd earthquake zones are accepted as the most hazardous ones due to the existence of the high magnitude earthquakes in the past. However, moderate earthquakes have occurred in the 3rd and 4th earthquake zones. They are also dangerous. 5th earthquake zone is accepted as to have no risk. Only, the province of Karaman and west part of the Aksaray is in the 5th earthquake zone. Besides, the distribution of the surface area and the population to the seismic zones in Turkey are shown in Table 2.6.

Table 2.6. Seismic Zones of Turkey with surface area and population
(Source: Japan International Cooperation Agency [JICA], 2004)

| **Seismic Zones** | **Surface Area** | **Population** |
|---|---|---|
| 1st degree seismic zone | 42% | 45% |
| 2nd degree seismic zone | 24% | 26% |
| 3rd degree seismic zone | 18% | 14% |
| 4th degree seismic zone | 12% | 13% |
| 5th degree seismic zone | 4% | 2% |

Accordingly, earthquakes should be taken seriously and prepared for earthquakes in Turkey. To reduce losses in life and property, earthquake resistant buildings should be constructed. Any error in the design phase cause irreparable results with earthquakes.

# CHAPTER 3

# STRUCTURAL IRREGULARITIES AND SOLUTION SUGGESTIONS

In this chapter, structural irregularities on Reinforced Concrete (R/C) structures constituting the main subject of the thesis will be classified according to the Turkish Earthquake Code, 2007 (TEC, 2007). All structural irregularity conditions have been explained with drawings and supported with earthquake damage photographs in order to increase the intelligibility in seismic design faults. Basic architectural principles and structural issues related to earthquake resistant design (ERD) are investigated through a literature review and various solutions are shown for the different structural irregularity conditions.

Structural irregularities are described in section 2.3 of TEC (2007). They are divided into two basic groups as irregularities in plan and vertical direction defined in the TEC (2007). Irregularities in plan consist of four different type of structural irregularity. These are torsional irregularity denoted as A1, floor discontinuities denoted as A2, projections in plan denoted as A3, nonparallel structural member axes denoted as A4. Types of irregularities in plan are given in Table 3.1. Irregularities in vertical direction comprise of three type of structural irregularity. These are weak storey denoted as B1, soft storey denoted as B2, discontinuity of structural elements denoted as B3. Types of irregularities in vertical direction are given in Table 3.2.

Apart from the categorized structural irregularities in the TEC (2007), short column effect, weak column-strong beam irregularity and seismic pounding effects are investigated comprehensively under different sub-headings.

Table 3.1. Irregularities in Plan
(Source: Turkish Earthquake Code [TEC], 2007)

| **A- IRREGULARITIES IN PLAN** |
|---|
| **A-1 Torsional Irregularity:**<br>The case where Torsional Irregularity Factor $\eta bi$ which is defined for any of the two orthogonal earthquake directions as the ratio of the maximum storey drift at any storey to the average storey drift at the same storey in the same direction, is greater than 1.2<br>$[\eta bi = ( \Delta i)max / \Delta\ i)ort > 1.2]$ |
| **A-2 Floor Discontinuities:**<br>In any floor;<br>**I -** The case where the total area of the openings including those of stairs and elevator shafts exceeds 1/3 of the gross floor area,<br>**II –** The cases where local floor openings make it difficult the safe transfer of seismic loads to vertical structural elements,<br>**III –** The cases of abrupt reductions in the in-plane stiffness and strength of floors. |
| **A-3 Projections in Plan:**<br>The cases where projections beyond the re-entrant corners in both of the two principal directions in plan exceed the total plan dimensions of the building in the respective directions by more than 20%. |
| **A-4 Nonparallel Axes:**<br>The cases where the principal axes of vertical structural elements in plan are not parallel to the orthogonal earthquake directions considered. |

Table 3.2. Irregularities in Vertical Direction
(Source: TEC, 2007)

| **B- IRREGULARITIES IN VERTICAL** |
|---|
| **B1 – Interstorey Strength Irregularity (Weak Storey) :**<br>In reinforced concrete buildings, the case where in each of the orthogonal earthquake directions, Strength Irregularity Factor $\eta ci$, which is defined as the ratio of the effective shear area of any storey to the effective shear area of the storey immediately above, is less than 0.80.<br>$[\eta_{ci} = (\Sigma Ae)i / (\Sigma Ae)i+1 < 0.80]$<br>Definition of effective shear area in any storey :<br>$\Sigma Ae = \Sigma Aw + \Sigma Ag + 0.15\ \Sigma ak$ |
| **B2 – Interstorey Stiffness Irregularity (Soft Storey) :**<br>The case where in each of the two orthogonal earthquake directions, Stiffness Irregularity Factor $\eta ki$, which is defined as the ratio of the average storey drift at any storey to the average storey drift at the storey immediately above or below, is greater than 2.0.<br>$[\eta_{ki} = (\Delta_i/h_i)_{ort} / (\Delta_{i+1}/h_{i+1})_{ort} > 2.0$ or<br>$\eta_{ki} = (\Delta_i /h_i)_{ort} / (\Delta_{i-1}/h_{i-1})_{ort} > 2.0]$ |
| **B3 - Discontinuity of Vertical Structural Elements :**<br>The cases where vertical structural elements (columns or structural walls) are removed at some stories and supported by beams or gusseted columns underneath, or the structural walls of upper stories are supported by columns or beams underneath. |

## 3.1. Irregularities in Plan

Irregularities in plan consist of four different type of structural irregularity. These are torsional irregularity denoted as A1, floor discontinuities denoted as A2, projections in plan denoted as A3, nonparallel structural member axes denoted as A4. It is shown above in Table 3.1.

### 3.1.1. Torsional Irregularity (A1)

Torsional irregularity is defined in the TEC (2007) as the ratio of the maximum storey displacement to the average storey displacement at any individual storey for any of the perpendicular direction (Figure 3.1). In most of the seismic codes from different countries include torsional irregularity as a significant irregularity, because its devastating effects on buildings were realized after the earthquakes (Özmen, 2004). It is described by means of torsional irregularity coefficient which is denoted as $\eta_{bi}$ is formulated as follows:

$$\eta_{bi} = \frac{(\Delta i)\mathrm{max}}{(\Delta i)avg} > 1.2 \qquad (3.1)$$

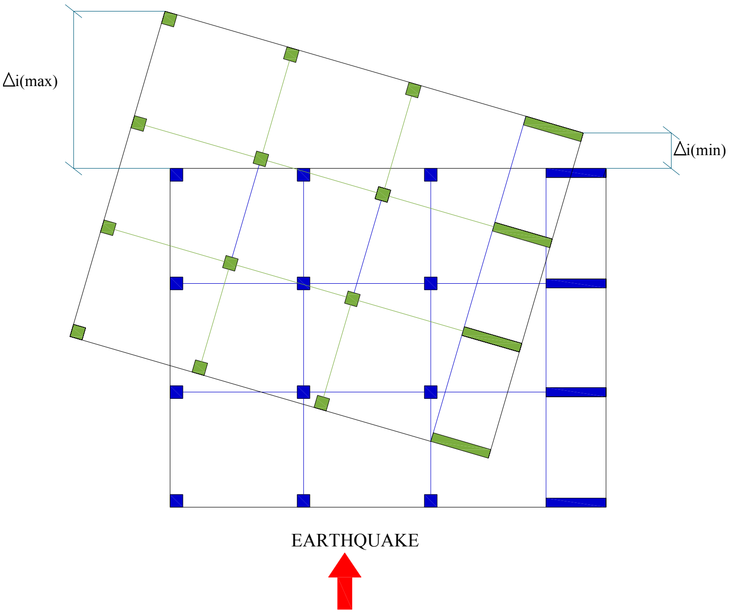
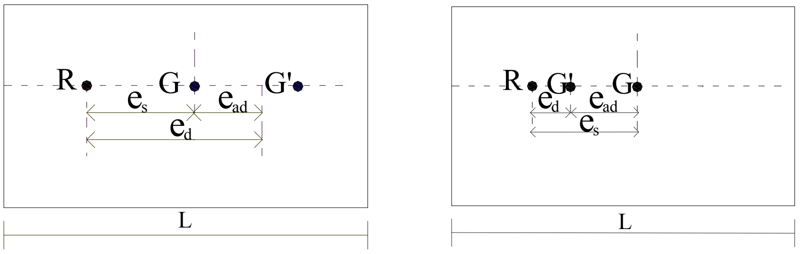


Figure 3.1. Torsional Irregularity

In the case of the torsional irregularity coefficient ($\eta_{bi}$) is greater than 1.2 at any storey of the structure, torsional irregularity occurs in that structure. The ± 5% additional eccentricity is considered in the displacement computations on both earthquake directions. The eccentricities which determine the torsional irregularity coefficients are illustrated in Figure 3.2. The existing eccentricity of the system is symbolized by $e_s$. In calculations, ± 5% additional coefficient is taken into consideration in order to calculate the additional eccentricity. It is denoted as $e_{ad}$. This additional eccentricity is firstly multiplied with the dimension of the building which is parallel to the earthquake direction. Then, the result is summed with the existing eccentricity of the system. This eccentricity is called as the design eccentricity and denoted as $e_d$. The torsional irregularity is calculated depending on this eccentricity. If the torsional irregularity coefficient of $\eta_{bi}$ is between 1.2 and 2, then the eccentricity is increased by a factor as in the following formula denoted as $D_i$ and the earthquake analysis is repeated (TEC, 2007).



(a) (b)

Figure 3.2. Design Eccentricity: (a) +5 % additional eccentricity, (b) -5 % additional eccentricity

$$D= (\eta_{bi} / 1.2)^2 \tag{3.2}$$

In any floor plan, the distance between the center of gravity and the centre of rigidity should be kept as minimum as possible. The rigidity centre is described as the centre of vertical structural elements. The gravity center is the centre of the whole building. It covers slab, beam, wall and live loads except the vertical structural elements. Doğan (2007) states that earthquake loads affect the center of gravity of the structure, but the rigidity center of the structure respond these loads (Figure 3.3). If the eccentricity between these two centers is great, a torsional moment will occur around the center of rigidity and the structure begins to rotate around the rigidity axis. This torsion moment creates additional shear forces. Because, seismic energy is largely absorbed by shear walls and the remained seismic energy is transferred to the columns (Atımtay, 2000).

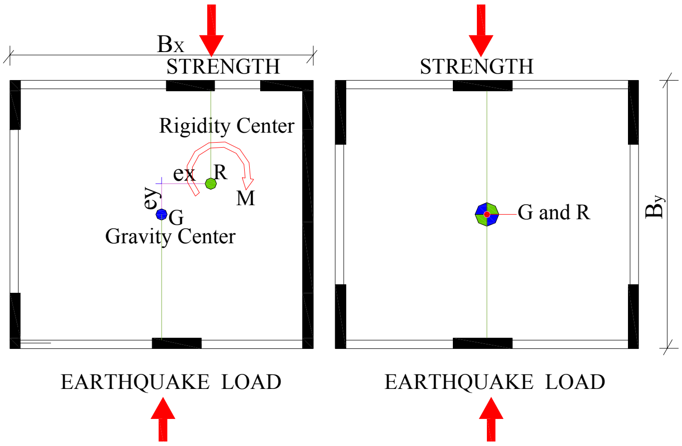


Figure 3.3. Working mechanism of the Gravity and Rigidity Centre

The centers of gravity and rigidity should be coincided through regular disposition of the vertical structural members. If the centers do not coincide, the eccentricity should not exceed 5 % of the building dimension (Tuna, 2000; TEC, 2007).

It is generally accepted that torsional irregularity exists on a structure due to the plan geometry or the structural member's rigidity distribution (Özmen, 2004; Döndüren, Karaduman, Çöğürcü, & Altın, 2007; Bayülke, 2001a). In order to prevent torsional deformation, one should design providing symmetry both in the building form and structure (Ambrose & Vergun, 1985).

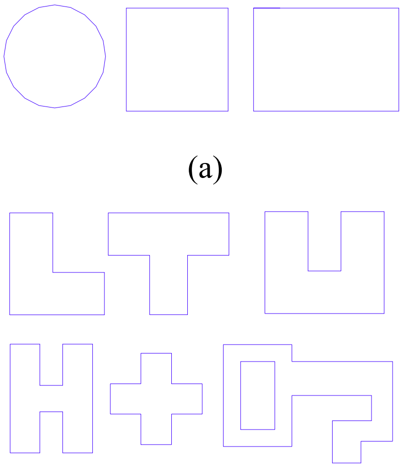
In this section, the factors causing torsional irregularity are categorized according to the widely adopted parameters which are defined as follows:

1. The Plan Geometry
2. Rigidity Distribution

### 3.1.1.1. The Plan Geometry/Form

Dowrick (1987) describes that design of a building is the geometrical arrangement of all in architecture and structure and contents. The building design should include both appropriate form and the structural arrangement.  This should be considered in the early design phase by architects.

The most appropriate form in terms of earthquake loads is circle and square due to their symmetric and simple plan geometry. Besides, the rectangular form is a suitable alternative solution owing to its simplicity and symmetry provided that the lengths of both short and long edges are close to each other (Naeim, 2001). Doğan (2007) arranges respectively the building form from better one to the worse as below in Figure 3.4:


(a)

(b)

Figure 3.4. Different building forms: (a) Simple building form, (b) Complex building form

In the event that the axis numbers of the structure increase only in the long direction, relative storey displacement which arises due to the torsion will increase as the square of its length (Naeim, 2001). This is illustrated in Figure 3.5.

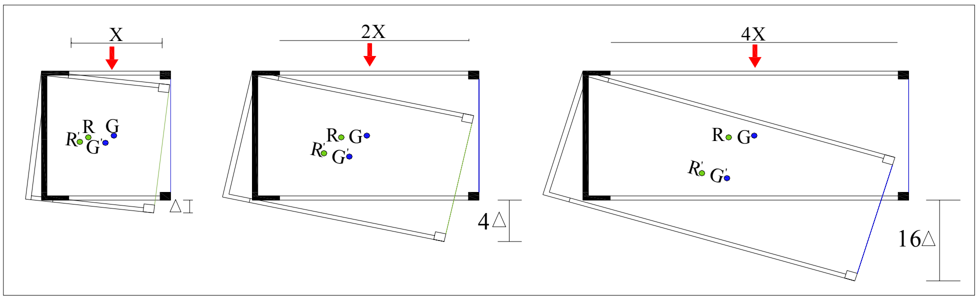


Figure 3.5. Rectangular form

Ambrose and Vergun (1985) point out that the form of a building has great deal with the determination of the effects of seismic activity on the building. It is easier to understand the overall behavior of a simple structure under earthquake loading rather than the complex one. For this reason, it should be taken into consideration in the preliminary phase of the design.

Dogan (2007) specifies that the circle is the most regular form. Because, it reacts the same inertia forces under earthquake loads coming from in every direction. On the other hand, Zacek (2002) points out that circle form may be regular and has the same bearing capacity in any direction, but it is not exactly accurate solution due to the fragmentation of the curved walls under lateral earthquake loading (Figure 3.6.). The danger of fragmentation increases directly with the open space on the building surface.

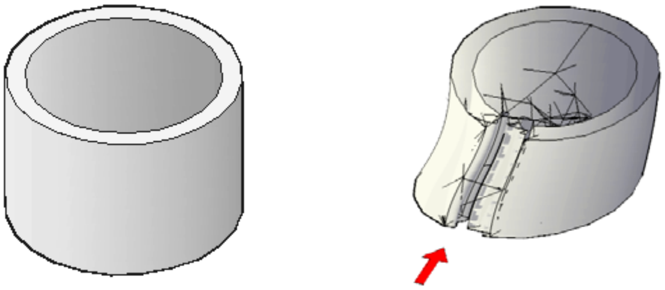


Figure 3.6. Failures in circle form

Structures which have asymmetric plan geometry have little energy absorbing capacity due to the torsional effects and stress concentrations at notch points. The energy which cannot be absorbed cause fractures in structures. On the other hand, simple forms usually provide simple details in the design stage than complex ones (Zacek, 2002). Naeim (2001) specifies that the complex shapes cause two major problem:

- Variations of rigidity
- Torsion

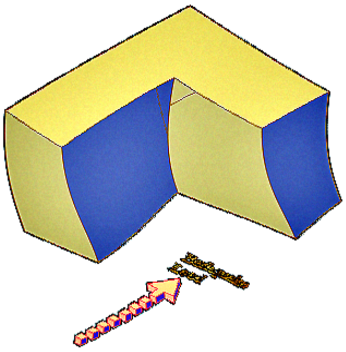


Figure 3.7. Behaviour of L-shaped structure against earthquake forces

In case the earthquake loads come from the north-south direction as shown in Figure 3.7., the wing which is located on the north-south direction incline to be stiffer than the wing which is located on the opposite direction. Both of the wings display different movements pushing and pulling each other at notch points. The buildings which have complex forms cause torsion because the centre of gravity and the centre of rigidity cannot geometrically coincide against all possible earthquake loads (Naeim, 2001; Arnold 2008).

The buildings, which have L, T, H, Y, U, and + plan geometry or a combination of these forms and designed symmetric according to one or two direction, cause torsion and stress concentration at notch points (Lagorio, 1990). This complex forms expose to unpredicted earthquake forces. Thus, it is difficult to understand the forces and analyze these types of buildings. The magnitude of the forces and severity of their results in the buildings largely depend on the features of the ground motion, the mass of the building, the structural system, the length of the wings and their ratios (length to width), and the height of the wings and their ratios (height to depth) (Arnold, 2008).

In accordance with the coming together of the different blocks in the structure, the building become susceptible against earthquake loads especially on the inside corner connection points due to the torsion and stress concentration (Zacek, 2005b).While the inside corner of a structure is called as reentrant corner, the connection point is called as notch point (Figure 3.8.).

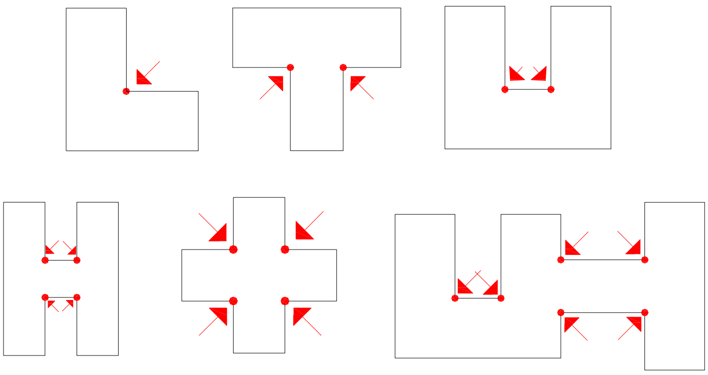


Figure 3.8. Reentrant corners and notch points

### 3.1.1.2. Rigidity Distribution

If the simplicity and regularity is not provided in the plan configuration, the earthquake will create a great range of torsional effect. Earthquake loads which come to the building during earthquake affect to the centre of gravity. Gravity centre can be taken as the geometry centre and the rigidity centre is accepted as the gravity centre of the vertical structural members such as columns and shear walls. Earthquake loads rotate buildings around a vertical axis passing through the centre of rigidity (Bayülke, 2001a).

Variations in perimeter strength and stiffness cause torsion on buildings. This problem usually occur in buildings having regular and symmetrical plan geometry. Arnold and Reitherman (2002) states that a building's seismic behavior is largely impressed by the formation of the perimeter design. If there is a great variation in strength and stiffness around the perimeter on a building, the center of gravity will not coincide with the center of rigidity, and torsional moments will incline to cause the rotation of the building around the center of rigidity.

Buildings are usually orientated towards to the scene such as beach-front apartments which are designed with open frontage facing to the beach. This orientation prevents the distribution of the strength and rigidity equally at the perimeter of the buildings due to the left large openings towards to the scene. It causes unbalanced perimeter resistance and major torsional moments. Bank halls, shops, and department stores can be exemplified for these types of buildings in which large windows are necessary for exhibition.

Atımtay (2001) specifies that it is difficult to change the centre of gravity of a structure, but the centre of rigidity can be changed by modifying the location of the structural elements or their cross sections. Infilled walls should be placed symmetrically as possible due to the effects on changing the rigidity centre except from the columns and shear walls (Ersoy, 1999). Torsion occurs around a vertical axis that can cause collapses in the farthest edge or corner columns due to the distance between rigidity and gravity centre (Aka, Keskinel, Çılı & Çelik, 2001; Bayülke, 2001b). This condition is shown in Figure 3.9.

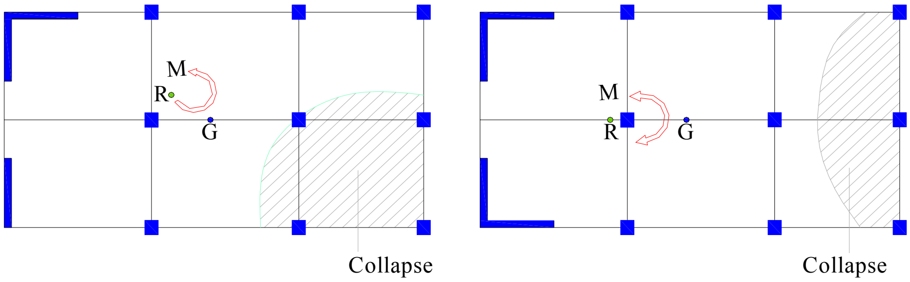


Figure 3.9. Different collapses due to the torsion

### 3.1.1.3. Solution Suggestions for Torsional Irregularity (A1)

In this part solution suggestions for the factors which cause A1 type of irregularity are examined.

- To separate the complex forms into simple and compact forms by using seismic separation joints (Figure 3.10.):

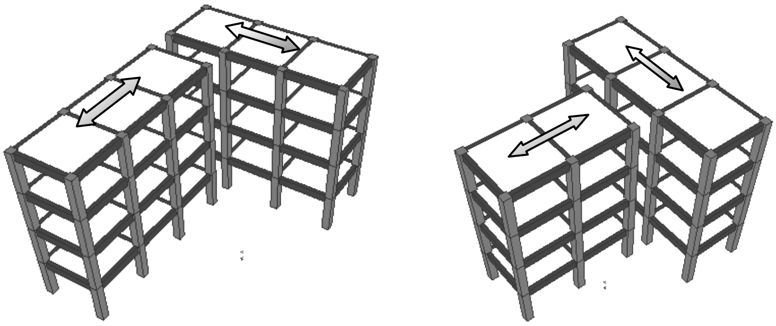


Figure 3.10. Seismic joints

It is emphasized before that simple and regular forms show better performance than complex ones under earthquake loading. In cases the complex types of planning is required due to the some architectural reasons or requirements, buildings should be divided into simple and compact pieces without impairing its function by using seismic separation joints. The rigidity center and gravity center should coincide as possible in each piece of the building which adapted with its function. Load bearing system is designed by taking into consideration of the additional torsional moments (Zacek, 2001).

- Softening of acute angle reentrant corners:

This solution suggestion involve that the wings of a building which is connected with an angle of 90° or lower than the 90° should be combined with circular lines (Figure 3.11). Thus, the wings of the building move as a whole during earthquake (Zacek, 2002).

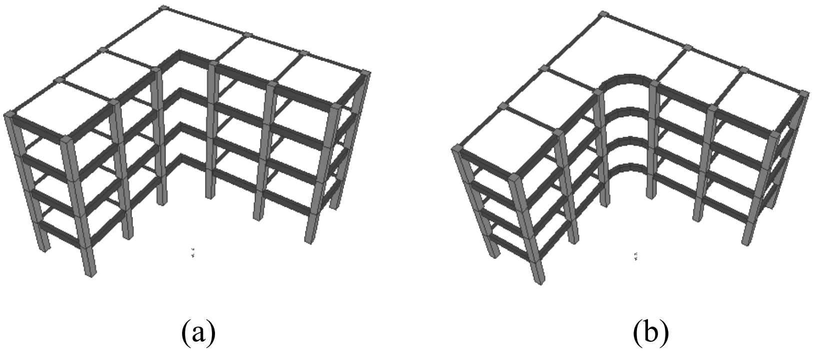

(a) (b)

Figure 3.11. Softening Reentrant corners: (a) Before softening, (b) After softening

Table 3.3. Evidence of the Figure 3.11

| | $\eta_b$ (a) | $\eta_b$ (b) |
|---|---|---|
| 3 | 1.21 | 1.19 |
| 2 | 1.19 | 1.18 |
| 1 | 1.18 | 1.17 |
| Ground | 1.17 | 1.16 |

- Strengthening of acute angle reentrant corners:

According to this solution the buildings, which have acute angle corners such as the plan geometry of L and T type, are strengthened at weak points called notch points by vertical structural members. This method is widely used in America and Japon (Zacek, 2002).

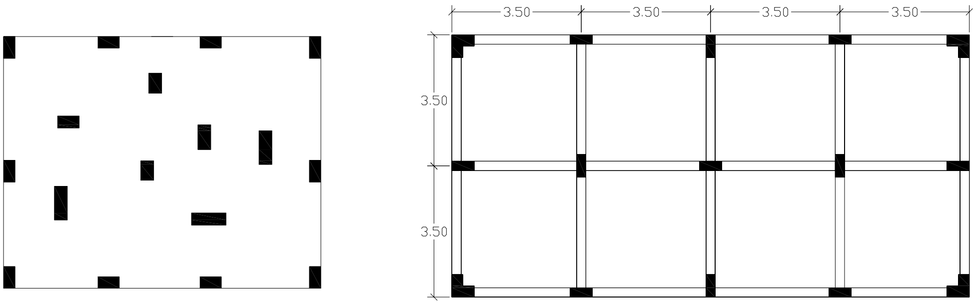
- Strengthening of flexible sides:

This solution suggests that rigid cores or stability walls can be used for preventing deformation between the wings of the building in case the rigidity center and the gravity center of the building do not coincide due to the plan geometry of the building (Zacek, 2002). For instance, open facades creates unbalanced perimeter in a building. Moreover, this causes the formation of the rigid and flexible sides in a building (Arnold, 2002). With this solution, flexible sides are made durable against earthquake forces. Besides, additional shear walls can be added to the open facades in order to reduce its flexibility (Arnold, 2002).

- Regular Configuration of Structural Elements:

Irregular arrangements of the structural elements cause torsional moments. Regular configuration of structural elements cannot be mostly achieved due to the irregular plan configuration (Bayülke, 2001a). According to Atımtay (2001) it is difficult to change the centre of gravity of a structure, but the centre of rigidity can be changed by modifying the location of the structural elements or their cross sections. Some information related to the structural configuration is given as below:

a) The Vertical structural members should be ordered regularly both in all directions. One should avoid from the irregularity in order not to meet any irregular and unexpected stresses due to the seismic forces like in Figure 3.12. (Dowrick, 1987; Tuna 2000). It is desired that structural members should be arranged as to have equal cross sections and equal or nearly to equal axis spans on similar each axis for providing equal rigidity distribution in building (Figure 3.12). Besides, structural members are placed perpendicular to the corners of the plan due to the most significant damages occur in the corners (Tuna, 2000).



(a) (b)

Figure 3.12. Regular and irregular structural system configuration: (a) Irregular structural configuration, (b) Regular structural configuration

b) Standard spans and uniform cross sections of slabs are recommended for the R/C structures. Because, any changes in the slab cross-sections makes it difficult to estimate the distribution of earthquake loads in the structural members. Moreover, construction costs will be very expensive (Dowrick, 1987; Zacek, 2005a).

c) The vertical structural members should be connected with beams to form a rectangular frame and provide the continuity in rectangular frames (Figure 3.12). Otherwise, flexible rectangular frame expose to more seismic forces than rigid frame under earthquake loading (Bayülke, 2001b). Atımtay (2001) specifies that when the beam is not continuous, lateral earthquake forces cannot be distributed evenly to the vertical structural members. If this configuration is necessary the slab thickness can be increased or a joist slab can be used. The depth of the beams should be arranged according to the span of the columns. The more shallow beams should tie the columns in order not to make any rigid area in the structure (Bayülke, 2001a). However, it is necessary that the building should be designed as to have equal spans and uniform beam sections to provide continuity and prevent unexpected earthquake deformations and excessive formwork costs (Özmen, 2008).

d) It is desired that one should avoid from the beam-to-beam connection (anchorage beam) without any vertical support (Figure 3.13). Such a configuration is quite dangerous due to the lateral earthquake forces irregular distribution on the structure. Critical moments are created in that connection points. Great rotations and cracks occur on the beams. If this type of connection is necessary, the connection point should be close to the support as possible. Because, stiffness is inversely proportional with the length of the element. For instance, when the beam spans gets shorter, the critical torsional moments gets higher (Tuna, 2000).

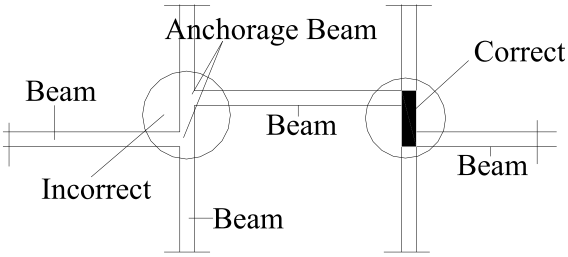


Figure 3.13. Discontinuity of beams

e) Slabs should work on both directions. Lateral forces are distributed to the beams and columns by slabs. One-way slabs cause large deformations and unexpected shear stresses on the structural members. Nevertheless, the disadvantages of discontinuity between beams have harmful effects on the structure. In Turkey, over-stretched one-way slabs are often used to generate corridors in the apartment block projects (Figure 3.13). The mains aim is to provide the rhythm of the rooms. Thus, they do not want to see a visual obstacle in the ceiling of the corridors. But, this visual problem can be resolved with the construction of the suspended ceiling (Atımtay, 2001).

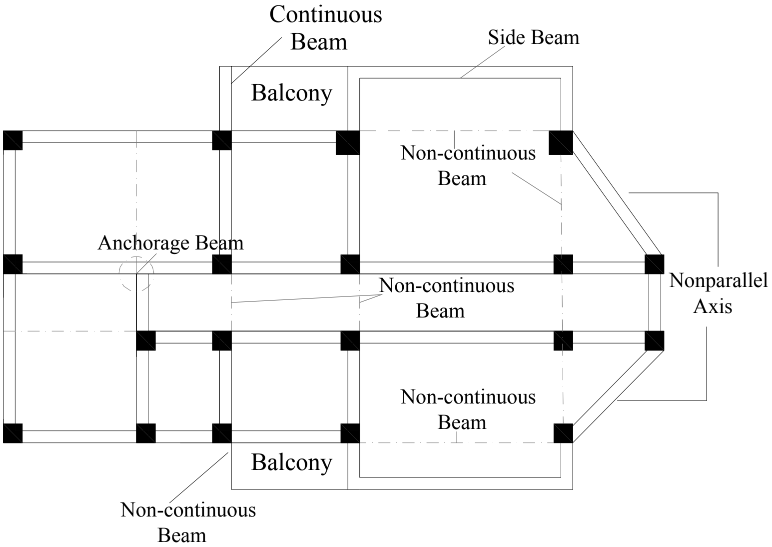


Figure 3.14. Common Structural Failures

f) Cantilever slabs cause large deflections. Both open and closed cantilever projections are widely constructed in Turkey. If it is necessary to use, the continuity between the beams is to be provided under the cantilever slabs (Figure 3.14). Moreover, a side beam should be designed to prevent critical displacement (Dowrick, 1987; Tuna, 2000; Doğan, Ünloğlu, & Özbaşaran, 2007).

g) Shear walls are the most effective method for preventing large displacements and unpredictable torsional moments, because they increase the lateral rigidity. Shear walls are more rigid members than columns. They show good seismic performance under earthquake loading owing to their higher seismic energy absorbing capacity. If lateral earthquake loads are carried by shear walls which are perpendicular to each other, relative storey displacement will decrease and thus, damage probability will decrease (Tezcan, 1998). But, the arrangement of shear walls should be made carefully to reduce the distance between the rigidity and gravity center or to coincide both of them, if it is possible. Otherwise, the rigidity of a structure is accumulated on one side that causes torsional eccentricity (Gönençen, 2000).

h) Identical with the configuration of columns, shear walls should be arranged according to an axial system in a symmetrical position. It must be considered that major lateral earthquake forces come from in a line which is parallel to the width of the structure (Bayülke, 2001a). For this reason, shear walls should be perpendicular to the building façade in this direction (Atımtay, 2001). Shear walls are commonly hidden around the staircases or elevators related to the architectural considerations. In this case, the balance between the rigidity and flexibility should be provided. Otherwise, the structure expose to the torsional effects due to the irregularity in rigidity distribution (Bayülke, 2001a).

i) Rigid core, which were designed as the main load bearing member, should be placed close to the gravity centre if it is necessary. However, at least two shear walls should be designed on the outer axis of the structure to reduce torsional effect (Tuna, 2000).

### 3.1.2. Floor Discontinuities (A2)

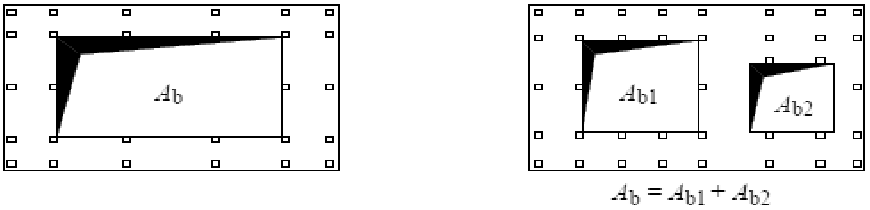
According to the TEC (2007), type A2 irregularity which is called floor discontinuities are described as follows:

In any floor;

I - The case where the total area of the openings including those of stairs and elevator shafts exceeds 1/3 of the gross floor area,

II – The cases where local floor openings make it difficult the safe transfer of seismic loads to vertical structural elements,

III – The cases of abrupt reductions in the in-plane stiffness and strength of floors.

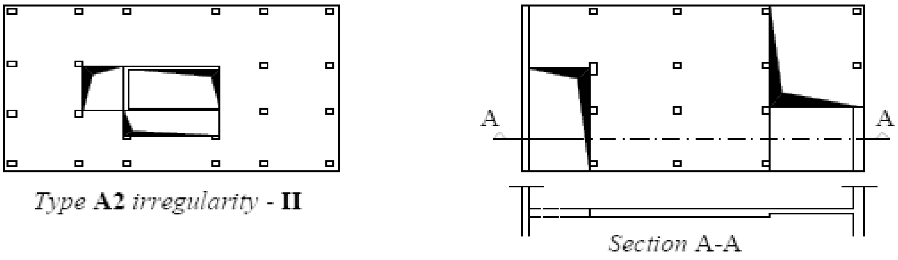


*Type* **A2** *irregularity* - **I**

$A_b / A > 1/3$

$A_b$ : *Total area of openings*

$A$ : *Gross floor area*



*Type* **A2** *irregularity* - **II**

*Type* **A2** *irregularity* - **II** and **III**

Figure 3.15. Floor discontinuity
(Source: TEC, 2007)

Some cases such as big holes in the slabs, the existence of the openings adjacent to the vertical structural members, abrupt reduction in the slabs or improper local floor holes prevent the regular distribution of the earthquake loads to the vertical structural members (Bachman, 2003).

### 3.1.2.1. Solution Suggestions for Floor Discontinuities

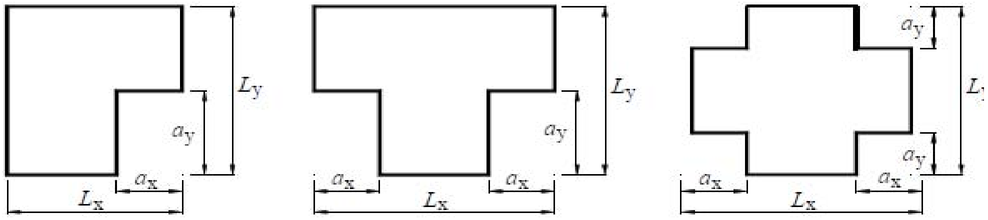
Slabs are the structural members which transfers the earthquake loads to the columns and shear walls. Therefore, it is important that slabs should be resistant against earthquake loads. If the slabs are rigid, they move like a rigid diaphragm without deformations, whereas the flexible diaphragms behave like exposed to torsional effects and show deformations. The restrictions in order to prevent the floor discontinuities (A2) are specified in the TEC (2007) (Figure 3.15).

If the ratio between the total areas of openings to the gross floor area is greater than 1/3, the diaphragm should be divided into simple and regular forms to provide the continuity in the distribution of the earthquake forces on slabs, and subsequently to the columns and shear walls (Ambrose & Vergun, 1985).

The reinforcement around the corners and edges of the openings may contribute to the continuity in floors (Arnold, 2002). Atımtay (2001) specifies that the rigidity of the columns and beams around the openings should be increased or shear walls should be placed around the openings to balance the rigidity between floors.

## 3.1.3. Projections in Plan (A3)

The projection ratio has significant role on earthquake behaviour of structures. A3 irregularity which is called projections in plan is the cases where projections beyond the re-entrant corners in both of the two principal directions in plan exceed the total plan dimensions of the building in the respective directions by more than 20 % (TEC, 2007). It is illustrated on the Figure 3.16 as below:



*Type* **A3** *irregularity :*
$a_x > 0.2\ L_x$ *and at the same time* $a_y > 0.2\ L_y$

Figure 3.16. Projections in plan

The main aim of use of projections is to animate the building. Ersoy (1999) points out that the buildings which have large projections seriously damaged from earthquakes. There are two major reasons of this condition. The first is the projections or the wings. They make different movements on different directions. This causes torsion, and naturally rotation in the building. It inclines to distort the building form. That's why, torsional forces are so difficult to analysis and predict (Arnold, 2002). The second is the stress concentration at the notch points in the reentrant corners. Therefore, critical shear forces and moments occur in the reentrant corners where the projections connect (Wakabayashi, 1986). It should not be forgotten that stress concentration has occurred in the reentrant corners of the building. Therefore, one should avoid from architectural configurations which create the reentrant corners (Ersoy, 1999).

It should be considered in the early design phase that there should not be designed large height variations between the different blocks of the same building. Because, the building, which has lower or higher block than the main building, expose more lateral forces than expected (Bakar, 2003).

#### 3.1.3.1. Solution Suggestions for Projections in Plan (A3)

There are two alternative solutions to prevent this type of irregularity. The first is to divide building blocks into simple parts. The second is to tie the building wings strongly with a linkage element to reduce torsion (Naeim, 2001). TEC (2007) described the limit of projection in plan as 20 % of the dimensions of the building.

The cantilevers in buildings create great damage in earthquakes. Dogan (2007) states that one should avoid from cantilever in buildings on earthquake zones as possible or limit the size of cantilever as possible. If it is even applied, it should not exceed 1.5 meters.

When the structure is surrounded on three sides of the cantilevers with beams, it increases the earthquake resistance in structure. Placing columns or shear walls in the end of the cantilever is another solution way for preventing this type of irregularity (Kaplan, 1999). If it is possible, the structure should be divided into several sections with seismic joints (Atımtay, 2000).

### 3.1.4. Nonparallel Axis (A4)

The TEC (2007) describes the A4 type of irregularity which is called Nonparallel Axes of Structural Elements as the cases where the principal axes of vertical structural elements in plan are not parallel to the considered orthogonal earthquake directions (Figure 3.14).

Ünay and Özmen (2007) states that a structural system can be succesful as long as the structural engineer is able to make realistic predictions on behaviour of structure under earthquake loads. If the system have non-paralel axis, it becomes increasingly difficult to estimate the loads realistically.

This type of irregularity is commonly seen as a result of the street intersections or requirements of the space organization in design. Architects, who are the designer of the buildings, generally begin planning as to abide by the parcel form. Their main goal for doing this is to take advantage of the maximum parcel area in line with owner requirements. The structures consisting of non-parallel axis will be created such as this requirements.

Favorable solutions should be developed in order to reduce the negative effects of torsion on this type of building. Beam connections with nonparallel axes are not safety in terms of lateral earthquake loads. They cause additional torsional moments. Nevertheless, one should avoid from the creation of a short and over-rigid beam, because excessive torsional irregularity occur in there (Özmen, 2002).

#### 3.1.4.1. Solution Suggestions for Nonparallel Axis

In this irregularity, the load-bearing system is not connected with right angle (Figure 3.14). This does not mean that all buildings should be composed of right angles. If it is necessary to construct a building with different angles, two different solution method can be applied described as follows:

1. To separate the buiding to the regular and simple parts by using sesimic separation joints.
2. Increasing the internal force values.

It is described before in A1 irregularity called torsional irregularity that simple and regular forms show better seismic performance than complex and irregular forms under earthquake loading. Buildings should be separated on simple and regular parts by using seismic separation joints where building direction changes to minimize the damage level and prevent the excessive damage on the axes where the building direction has changed (Erman, 2002).

Internal forces in vertical structural member can be increased as if the earthquake forces come from the both direction (Tezcan, 1998). It is defined in the 2007 Turkish Earthquake Code that under the combined effects of independently acting x and y direction earthquakes to the structural system, internal forces in element principal axes a and b shall be obtained by Eq. 3.2 such that the most unfavourable results used in design.

$$B_a = \pm B_{ax} \pm 0.30\, B_{ay} \quad \text{or} \quad B_a = \pm 0.30 B_{ax} \pm B_{ay}$$
$$B_b = \pm B_{bx} \pm 0.30\, B_{by} \quad \text{or} \quad B_b = \pm 0.30 B_{bx} \pm B_{by} \qquad (3.2)$$

## 3.2. Irregularities in Vertical Direction

Irregularities in vertical direction consist of three different type of structural irregularity. These are interstorey strength irregularity or weak storey denoted as B1, interstorey stiffness irregularity or soft storey denoted as B2, discontinuity of vertical structural elements denoted as B3. It is shown in Table 3.2. Uniformity in distribution of the masses, strength, and stiffness are demanded in the vertical direction of the building in order to provide regularity of structure.

### 3.2.1. Interstorey Strength Irregularity/Weak Storey (B1)

B1 type of irregularity is defined in the TEC (2007) that in reinforced concrete buildings, the case where in each of the orthogonal earthquake directions, Strength Irregularity Factor $\eta ci$, which is defined as the ratio of the effective shear area of any storey to the effective shear area of the storey immediately above, is less than 0.80 (Figure 3.17). If the ratio is between 0.8 and 0.6, there exists weak storey irregularity in structure. But, if it is less than 0.6, the structure must be redesigned until appropriate range of values are gained.

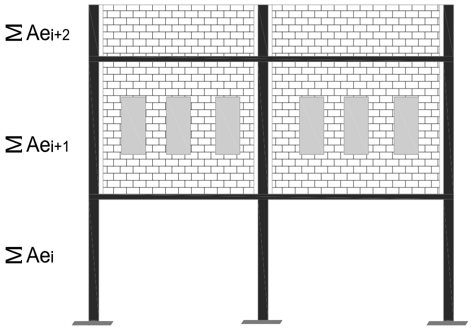


Figure 3.17. Formation mechanism of Weak Storey (B1)

$$\Sigma A_e = \Sigma A_w + \Sigma A_g + 0.15\, \Sigma A_k \qquad (3.3)$$

Definition of effective shear area in any storey:

$$\eta_{ci} = (\Sigma A_e)_i \,/\, (\Sigma A_e)_{i+1} < 0.80 \qquad (3.4)$$

Arnold (2002) describes that a weak storey is a type of vertical configuration problem in which there is a major reduction in strength when it is compared with above. Although it is so dangerous when it occurs at the first storey due to the greatest loads accumulation at this storey, it can be seen at any storey of a building. This irregularity generally occurs due to the lesser strength or major flexibility between stories. If all stories of the building are nearly equal in terms of strength or stiffness, earthquake forces can be distributed nearly equal to each storey under earthquake loading. However, architectural requirements in usage of a building restrict that type of planning. For instance, while the upper stories are used for housing, the ground floors are used as shops almost all residential buildings in Turkey. Shops are designed as to have large window openings due to the function of the space. Therefore, the ground floors have less strength than the upper floors. This problem, which is most common type of planning in Turkey, is called as interstorey strength irregularity or weak storey and denoted as B1 in TEC (2007).

Earthquake loads are directly proportional with the mass. Overturning moments will increase if the gravity center moves from ground to the upper levels (Figure 3.18). Therefore, one should especially avoid from the inverted pyramidal configuration for preventing the formation of overturning moments.

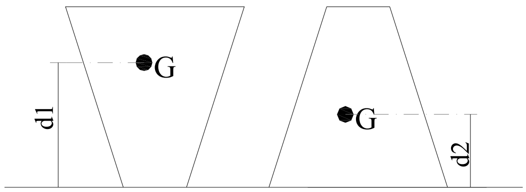


Figure 3.18. Gravity centre in pyramidal configuration

There are many factors leading to the weak storey irregularity. For instance, buildings with vertical setbacks are one of them. A setback can be defined as an abrupt and major change of strength and stiffness. For that reason, it prepares both soft and weak storey irregularity on the ground floor. It can be visualized like a building having vertical reentrant corners. The building having vertical setbacks suffers from damages in the line of the setback or notch point due to the great stress concentration. The vertical setbacks in the building start making different displacement due to the different natural period of vibration between the typical storey and the storey with setbacks (Ambrosse and Vergun, 1985). Their earthquake behaviour is quite complex to predict. That’s why Zacek (2005c) states that all storeys should have the same plan geometry. Even though setback exists in a single building block, it can also occur in adjacent buildings having different heights due to the deficiency in the amount of seismic separation joint or having no seismic separation joint.

Projections which are made in order to animate the facades of a building cause considerable damage due to the earthquake forces (Zacek, 2002). Bayülke (2001a) indicates maximum projection dimensions in vertical as below in Figure 3.19.

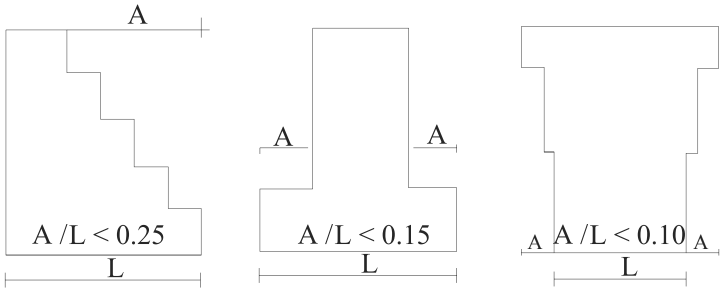


Figure 3.19. Maximum projection values

Figure 3.20.Damage due to the heavy cantilevers
(Source: Darılmaz, 1999)

The building shown above in Figure 3.20 subjected to great earthquake damage due to the insufficient cross sections of columns at ground floor. Besides, it has considerable closed overhangs. For this reason, the columns break at the ground floor level and then, fell down toward back side. When the earthquake damages are investigated, it can be easily seen that the structures having overhangs are heavily damaged that the others. In Turkey, approximately 70 or 80 % of buildings have constructed with overhangs (Doğan, Ünlüoğlu, & Özbaşaran, 2007).

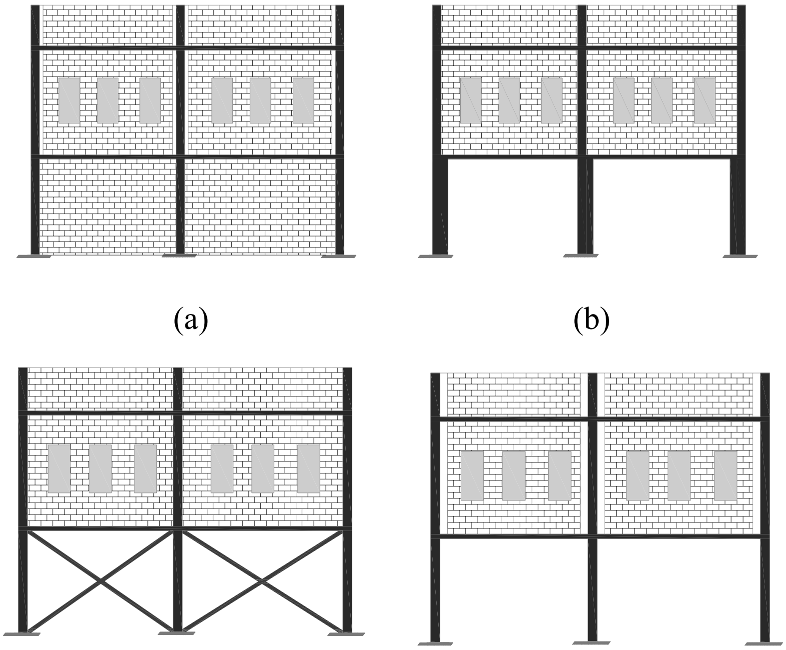
The ratio between the height and width of a building or the height and length of a building is great, which is called as the slenderness ratio, the building will create high overturning moments. It will also cause additional major forces on the corner columns. Moreover, the structure is usually designed as to have different strength on both earthquake direction of the structure which cause weak storey (Bayülke, 1998).

Dowrick (1987) specify that the slenderness ratio of a building should not exceed about 3 or 4, if it is not, it exposes to additional shear forces and overturning moments under earthquake loading. Overturning moments will increase if the gravity center of the building is away from the ground. On the other hand, Zacek (1999) states that the ratio of the sides to one to another should be greater than 3.

### 3.2.1.1. Solution Suggestions for Weak Storey (B1)

There are various alternative solutions to reduce or eliminate the negative effects of the weak storey irregularity on buildings (Figure 3.21). They can be listed as follows:

- To create partly setbacks as pyramidal configuration (Figure 3.18)
- To create seismic separation joints
- To provide equal strength between stories
- To leave joint between column and wall
- To make isolation



(a) (b)

(c) (d)

Figure 3.21. Solutions for Weak Storey: (a) Add walls, (b) Increase cross-sections of columns, (c) Add steel bars, (d) Isolation gaps

If setbacks are created, the plan area should expand towards up to down like a pyramidal configuration, it can be an alternative solution to increase the earthquake durability of buildings. Moreover, it also increases the rigidity and reduces the natural period of the building. Thus, it prevents creation of the acute angle corners.

Seismic separation joints are necessary in formed of different masses with complex geometry of the buildings so that the different blocks of the building can move independently which cause great damage due to the different behaviour of the blocks under earthquake loading.

Strengthening of the flexible stories to balance the rigidity distribution between stories can contribute to prevent the weak storey irregularity. For instance, if the ground floor of a building is designed as an opening floor, it fails under earthquake loads. To balance the strength between stories, the cross sections of the columns can be increased or diagonal steel bars can be added to the ground floor. Moreover, the wall areas can be increased in the ground floor. Besides, in each floor, same kind of material should be used to provide continuity of the material in vertical direction.

Unlike the other three suggestion, isolation method is not based on strengthen of the building against earthquake. It bases on protection of the building from earthquake loads. This method can be applied in a very few building in our country due to the high building cost. These buildings are determined according to the building importance factor which is defined in the TEC (2007).

## 3.2.2. Interstorey Stiffness Irregularity (Soft Storey) (B2)

B2 type of irregularity is defined in the TEC (2007) as the case where in each of the two orthogonal earthquake directions, Stiffness Irregularity Factor $\eta ki$ , which is defined as the ratio of the average storey drift at any storey to the average storey drift at the storey immediately above or below, is greater than 2.0 (Figure 3.22). Moreover, storey drifts should be calculated by considering the effects of ± %5 additional eccentricities.

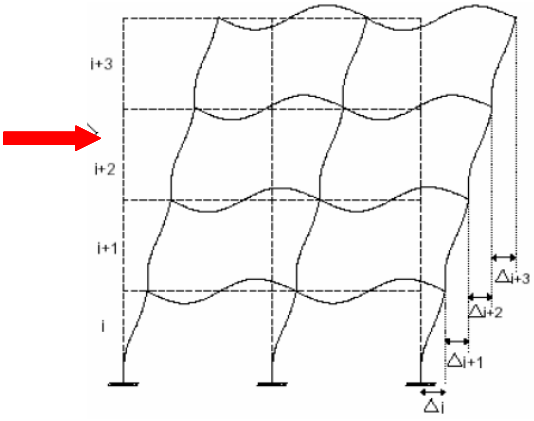
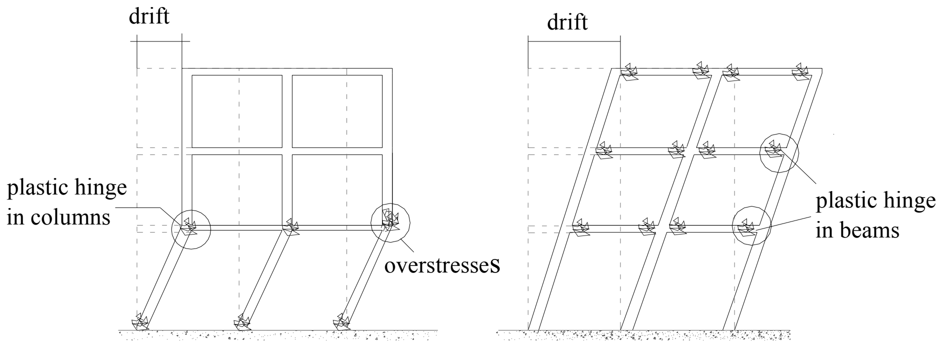


Figure 3.22. Storey Drifts

$$[\eta ki = (\Delta i/hi)ort / (\Delta i+1/hi+1)ort > 2.0 \text{ or } \eta ki = (\Delta i /hi)ort / (\Delta i-1/hi-1)ort > 2.0] \tag{3.5}$$

The building codes distinguish between “soft” and “weak” stories. Soft stories are less stiff, or more flexible, than the story above; weak stories have less strength. Soft storey causes a significant decrease in lateral stiffness (Naeim, 1998).

There are various parameters that cause soft storey irregularity. For instance, a discontinuity between the ground and first floor cause critical conditions on earthquake behaviour of building (Arnold, 2002). The height difference between the floors is a remarkable one among them (Figure 3.23). The ground floor of a building is generally designed as higher than the upper floors due to the user requirements. This causes stiffness losses and more displacement in the ground storey. Because, the cross sections of the columns are kept in same size in the ground floor even though there is a height difference is created between the two floors. Therefore, it causes a difference in rigidity or stiffness between the floors. This type of floors is called as the soft storey. It usually occurs due to the architectural requirements. For instance, using open ground storey such as shops, meeting rooms, banking halls create severe damage. Because, while a great storey drift occurs in the ground floor, the upper floors move like a diaphragm. High stress concentration occurs along the connection line between the ground and first floor that leads to distortion or collapse in structures (Arnold, 2002).



(a) (b)

Figure 3.23. The soft first storey failure mechanism: (a) Plastic hinge in columns, (b) Plastic hinge in beams

Soft storey irregularity does not only depend on the difference between the storey height, but also an abrupt change in stiffness or rigidity between stories cause soft storey irregularity despite the same storey height among the stories of the building. For instance, excessive usage of infilled walls in upper floors increases the stiffness in those floors. They are not usually used in the ground floors due to the commercial purposes. The reason is to provide visual perception with large window openings. Thus, soft storey irregularity has been created again.

The soft storey irregularity may be created by an open ground floor. It carries heavy structural or nonstructural walls which is located on upper floors. This turns into quite critical condition if the continuity in the vertical structural elements is not provided. For instance, the columns in upper floors sometimes have not been continued to the ground floor due to the requirements of large spans. Thus, this condition will also create the soft storey irregularity (Figure 3.24).

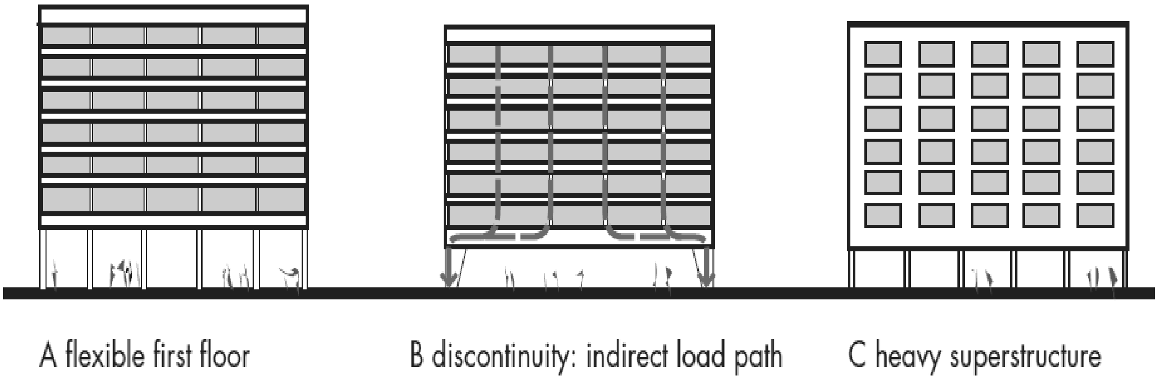
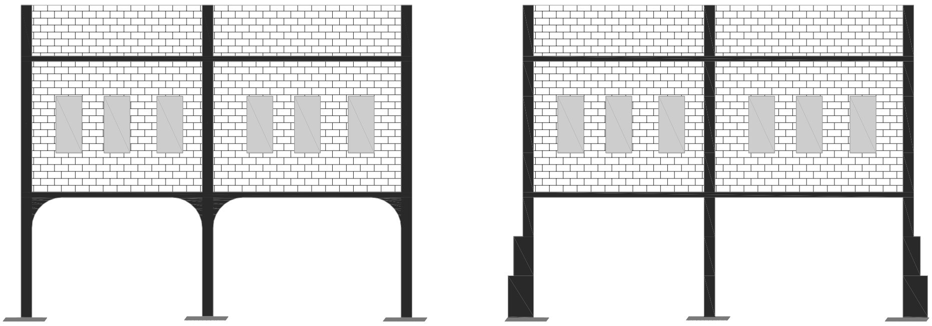


Figure 3.24. Common types of soft storey irregularity
(Source: Arnold, 2002)

### 3.2.2.1. Solution Suggestions for Soft Storey (B2)

The conditions causing soft storey irregularities are described in previous part. To prevent this irregularity, the solution suggestions can be listed as follows:

a) Add bracing elements which stiffen the columns up to a level
b) Add additional columns at ground storey to increase the stiffness
c) Increase the cross-sections of the columns at first storey.
d) Add external buttresses (Figure 3.25)
e) Create vaults on the ground floor (Figure 3.25)



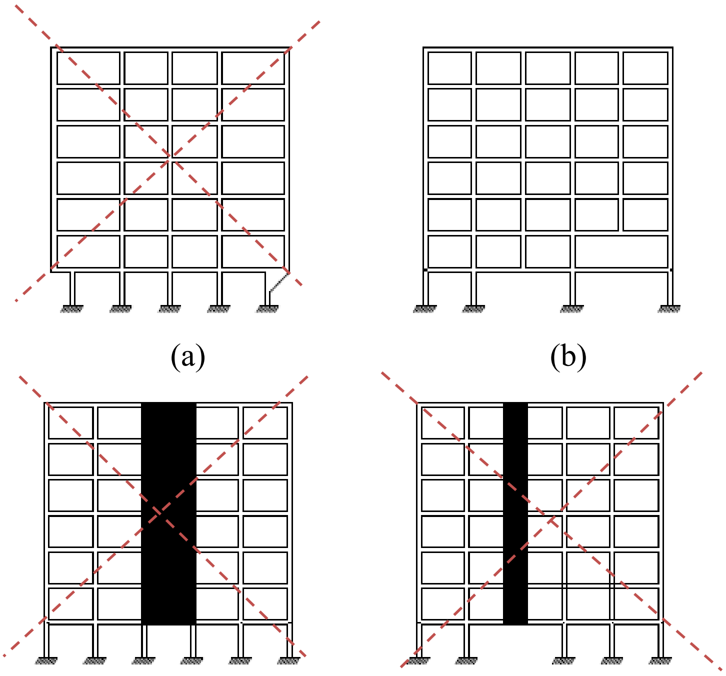
(a) (b)

Figure 3.25. Solutions for Soft Storey irregularity: (a) Vaults, (b) External buttresses

### 3.2.3. Discontinuity of Vertical Structural Elements (B3)

B3 type of irregularity is described as the case where vertical structural elements are positioned wrongly. The factors causing B3 type of irregularity are visualized in Figure 3.15. Conditions related to the irregular buildings with type B3 irregularity are given as follows:

a) Gusseted columns or the columns which rest on cantilever beams are prohibited as illustrated in Figure 3.26 and Figure 3.27.
b) In the case where a column rest on a beam supported with columns at both ends, all internal forces consisting vertical loads and seismic loads from the earthquake direction shall be increased by 50 % at all sections of the all beams and the columns which are adjacent to the beam (Figure 3.26).
c) In no case the shear walls should be allowed to rest under the columns (Figure 3.26).
d) In no case the shear walls should be allowed to rest on the beams (Figure 3.26).



(a) (b)

(c) (d)

Figure 3.26. Types and solutions of B3 irregularity
(Source: TEC, 2007)

Figure 3.27. Damage due to the gusset on columns
(Source: Çiftçi, 1999)

The gusset on the ground floor column, which is made for ornamentation, cause damages where connects with column. It is prohibited in TEC (2007).

### 3.2.4. Short Column Effect

When a building has both long and short columns in the same storey, the columns expose to different shear forces due to their height differences. The lateral loads firstly come to the long and flexible columns, and then go towards to the short column and accumulate in there (Figure 3.28). Due to the excessive accumulation of the seismic energy, shear cracks occurs at both ends of the columns (Doğan, 2002). Murthy (2004) states that the long and short column having the same cross section show the same displacement (Δ) under earthquake loads. However, the short columns are more stiff or rigid as it compared with the long column and expose greater earthquake forces than short columns. If they are not adequately designed for such a large force, it can suffer from significant damages during an earthquake. This behaviour is called short column effect and it must be accounted in the initial design phase (Murthy, 2004). The damage in these short columns is often in the form of X-shaped cracking that occurs due to shear failures.

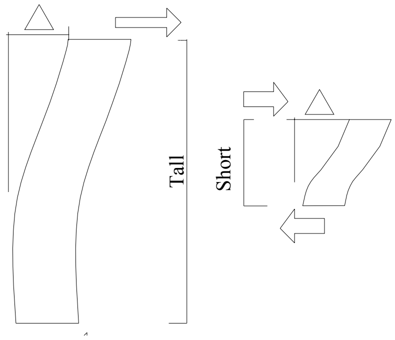


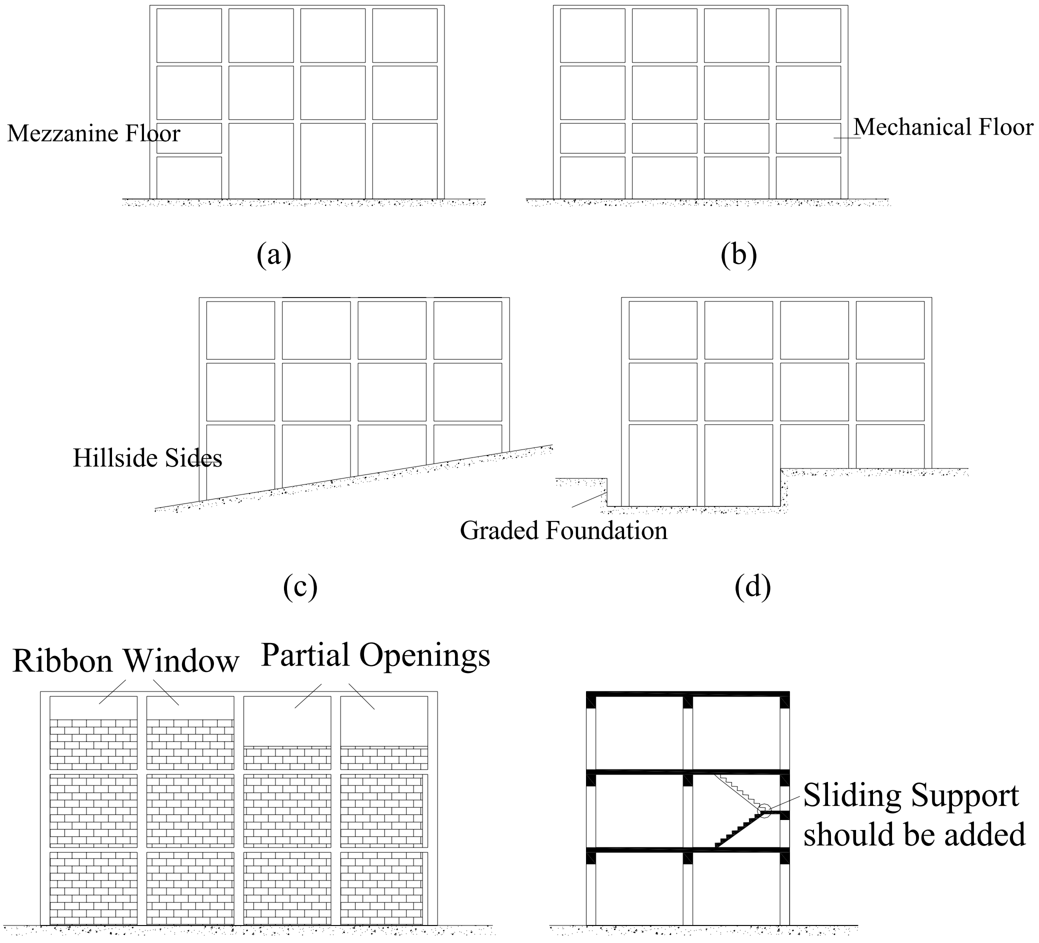
Figure 3.28. Tall and Short Columns Behaviour

The conditions causing short column can be listed as follows and illustrated in Figure 3.29:

a) Mezzanine floors
b) Mechanical floors
c) Hillside sides
d) Graded foundation
e) Adjacent columns to the openings
f) Stair landing

Two explicit examples of short column effects are the formation of the mezzanine floors and the design of the columns with different heights in the sloped areas (Figure 3.29). There are some other conditions in buildings which cause short column effect. For instance, if a masonry or RC wall have a partial height which was built to fit a window over the remaining height, the adjoined columns behave as short columns due to the existence of these walls.

The stiff walls restrain horizontal movement of the column part which is adjacent to the wall. However, the openings which are adjacent to the column and above the wall cause short column effect. X-cracking are observed in that column along the opening and expose to the great force. On the other hand, the regular building which does not have short column expose to X-cracking along the whole height of the column (Murthy, 2004).



(a) (b)

(c) (d)

(e) (f)

Figure 3.29. Formation of short columns

### 3.2.4.1. Solution Suggestions for Short Column

As it is required for all other irregularities, short column effect should be prevented as possible during architectural design phase. Although it is difficult to change short columns in the architectural design phase, this effect must be arranged in structural design (Murty, 2004).

Horizontal bracing throughout the height and into column above can be accepted as an alternative solution for preventing or reducing the short column effect. This solution provides regular distribution in stiffness among the columns. It can be used short column due to the mechanical floors, adjacent openings to the columns and in stair landing. Heavy non-structural walls play a major role on short column. For that reason, heavy non-structural walls must be isolated from the columns to prevent the formation of the short column (Naeim, 2001).

The foundation of a structure should be located on the same plane surface. This is taken into consideration in hillside sides and one should avoid from designing graded foundations. To prevent short column due to the stair landing, sliding support should be placed between the steps on the intermediate landing.

### 3.2.5. Strong Beam-Weak Column

In a structure, it is desired that beams should begin deforming before columns. Failure in a column can affect the stability of the overall building. However, beams deformation partly affects the building (Bayülke, 1998). For that reason, beams need to be made ductile rather than the columns. Sufficient ductility is ensured in the structural members where the damage is estimated to happen under earthquake loads.

Plastic hinging at both ends of the columns may initiate a storey displacement or even leading to the overall collapse of the building (Bayülke, 1999). The beams should have weakest links instead of columns to prevent plastic hinging in columns. This condition can be provided by correctly sizing the structural members and using sufficient amount of steel in them (Murthy, 2004).

Figure 3.30. Damage due to the hollow-tile floor slab
(Source: Çiftçi, 1999)

The building shown above in Figure 3.30 exposes to great damage in earthquake due to the hallow-tile slab. Hollow-tile slab is usually used in projects to prevent visibility of beams. But, it increases the building weight. Thus, it increases the earthquake forces simultaneously due to the direct proportion between the building mass and earthquake forces.

### 3.2.6. Seismic Pounding Effect

Pounding is a damage type in two buildings or different parts of the same building under earthquake loads. It causes hitting the buildings one another (Naeim, 2001). It commonly occurs due to the insufficient seismic gap or no gap between two adjacent buildings (Doğan, 2002). A seismic gap is a seismic separation which is left depending on predicted seismic drifts of stories. If the size of the seismic gap is insufficient based on the expected storey drifts, pounding between adjacent structures may occur.

There are various parameters causing irregularity of pounding in structures. They can be listed as follows:

a) Soft ground floors
b) Irregular plan geometry
c) Setbacks
d) Liquefaction

The soft ground floors lead to extreme displacement or even collapse in structures. Adjacent buildings with irregular plan geometry expose to torsional effects under earthquake loads and pounding is observed due to the less seismic joint gaps (Figure 3.31). Moreover, the setbacks cause stress concentration and the blocks hit each other due to the different vibrations of blocks in structure. The soil type where the structure is constructed affects the seismic behaviour of the structure. In poor quality soil, the liquefaction can occur and the structures usually overturn to one side without big damages in upper floors. If there is a structure next to that, the event of pounding happens. In Turkey, the pounding widely occurs due to the insufficient seismic joint between the adjacent structures. Moreover, in adjacent structures if the floors are not in the same level, the amount of damage increases in structures which are constructed like that type.

Figure 3.31. Pounding due to the torsion between adjacent buildings
(Source: İstanbul Büyüksehir Belediyesi Devlet Arsivi, 1999)

The building shown in above Figure 3.31 expose to damage in earthquake due to the inadequate seismic joints. This condition causes of torsion in the building which is located in the middle among three of them. Besides, shop storey in the ground floor is completely collapsed due to the weak storey condition. Therefore, the building is heavily damaged under earthquake forces.

3.34). If the floors are not in the same level between two adjacent building, hammering occur at pounding point as shown in Figure 3.34.

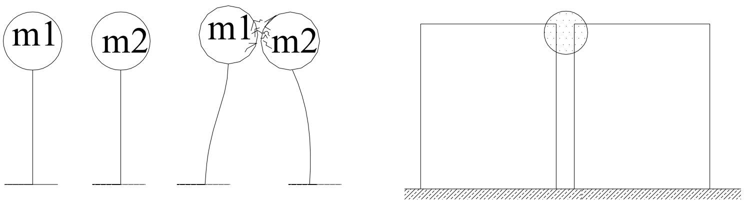


Figure 3.33. Dynamic pounding model for one-storey building

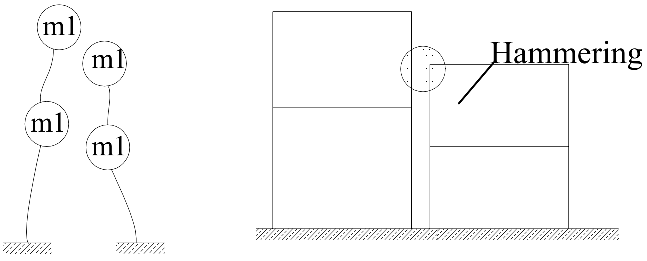


Figure 3.34. Dynamic pounding model for different floors

Minimum size of the seismic gaps should be 30 mm up to 6 m height. From thereon a minimum 10 mm shall be added for every 3 m height increment. The construction of dilatation joints is not easy in terms of protecting the gaps from any objects. Gaps should be protected against filling with any objects by flexible materials such as twisted metal plate or rubber accordion. Removable moulds or simple concrete moulds can be used in the construction of the dilatation joints (Zacek, 2002).

The sizes of gaps to be left in the seismic joints between building blocks or between the old and newly constructed buildings should be determined with respect to the following conditions. Sizes of gaps should not be less than the square root of sum of squares of average storey displacements multiplied by the coefficient α specified below:

a) $\alpha = R / 4$ should be taken if all floor levels of adjacent buildings or building blocks are the same.

b) $\alpha = R / 2$ should be taken if any of the floor levels of adjacent buildings or building blocks are not the same.

Figure 3.32. Pounding from Marmara earthquake due to the liquefaction (Source: Çiftçi, 1999)

Major energy revealed with pounding and some amount of this energy is absorbed by the structural elements. The remained energy which can not be absorbed causes collapses of structural elements. The building shown in Figure 3.32 subjected to earthquake forces on August 17, 1999. It is greatly damaged depending on many factors. The first reason of this condition is that the building is constructed in the corner parcel. For that reason, it is directly vulnerable to external forces. Secondly, the rate between the width and height of the building is quite high. These types of buildings are called as slender buildings. The most significant one, there is not a basement floor in the building. Moreover, the ground floors are used as shops having large window openings. This causes soft storey irregularity. Besides, short columns occur due to the mezzanine floor in the first storey. It is observed in the Figure that liquefaction is occurred on the ground and the building overthrown on one side. The building, which is constructed near to this damaged building, expose to pounding effect. Seismic joint between two adjacent buildings must be equal to the highest one in order to prevent the pounding between two buildings which occurred due to the liquefaction. According to Çiftçi (1999) the rate between the foundation depth and height of a building is to be 1/6, and also one should stay away from designing slender building. Therefore, the building collapses on one side.

While dynamic behaviour of buildings is investigated, it is accepted that the mass of the building is accumulated at a point. This point is accepted as the floor level. Thus, a mass accumulation is defined for each storey of the building. And, surely each storey has rigidity and damping coefficient (TDY, 2007). The degree of the pounding shows differences for the pounding conditions in different floor levels (Figure 3.33 &

# CHAPTER 4

# EARTHQUAKES ON REINFORCED CONCRETE STRUCTURES

This chapter consists of three main parts. In the first part, a review of the material properties of reinforced concrete (R/C) is practiced by taking into consideration of the Turkish Standard TS 500, the earthquake load and its mechanism are described in order to understand the seismic behavior of buildings. In the second part, basic principles of earthquake resistant design criterions are described. Finally, in the third part, earthquake load calculation methods are described according to the Turkish Earthquake Code, 2007 (TEC, 2007).

## 4.1. Characteristics of Reinforced Concrete (R/C) and its Earthquake Behaviour

Turkey is located on a highly seismic region and approximately whole of its area located on the first earthquake zone as previously mentioned. For that reason, it suffers from earthquakes frequently and expose to many life and property loses. Most of the buildings in Turkey have been constructed with reinforced concrete (R/C) material and the buildings which expose to more damage in earthquakes are even so the R/C buildings. For this reason, it is quite important that characteristics of the concrete material and earthquake behaviour of R/C should be known.

R/C material is the preeminent building material in Turkey. This condition depends on the economic reasons (Atımtay, 2000). The raw of the concrete material which comprised of carbonate, calcium, aggregates and water, is abundant in the nature. Moreover, it is cheaper to gain than the other materials such as steel. The percentage of steel which is used in R/C is approximately 1 % (Bayülke, 2001b). Besides, lacking of the experienced workforce in other materials cause commonly usage of the concrete material.

Some basic knowledge related to the material properties of R/C should be known in order to have an understanding of R/C buildings behaviour under earthquake loads. R/C is a composite material. It constitutes a structural system type. R/C is formed by adding the steel bars with circular cross sections in concrete material (Figure 4.1). These bars are called as reinforcing bars. While concrete material can resist to the compression forces, steel can resist tension forces rather than compression forces. In the result of caracteristics of these two materials, they can support to each other in order to withstand to the earthquake loads.

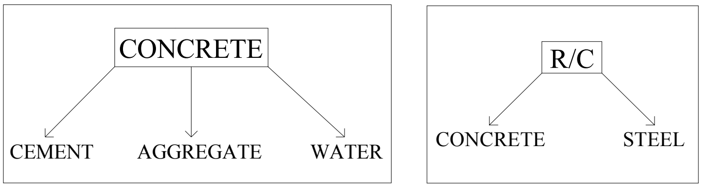


Figure 4.1. Components of concrete and Reinforced Concrete

The rules for providing the earthquake resistance of buildings are given in the TEC (2007). Furthermore, the requirements for the production of R/C are subjected to the Turkish Standard, TS 500 called Requirements for design and construction of Reinforced Concrete Structures. This code and standard determine the minimum requirements of the materials. The aim is to reduce the life and property losses as minimum as possible.

There are various concrete class and reinforcing steel types defined in the Turkish Standard TS 500. According to TS 500 concrete quality must be a certain level in order to provide the required earthquake durability in buildings. Concrete classes are categorized based on their characteristic strength ($f_{ck}$) and denoted by C (XX). On the other hand, steel types are categorized based on their characteristic yielding stress ($f_{yk}$) and denoted by S (XXX). For instance, C (20) means that characteristic strength of that structure is 20 Mpa N/mm$^2$) and S420 means that characteristic yielding stress of that steel is 420 Mpa (N/mm$^2$). Furthermore, it is defined in the TEC (2007) that merely C20 or higher concrete class and S420 or lower steel class can be used in all R/C buildings in Turkey (Özmen, 2008).

R/C buildings are constituted by a carcass skeleton system which can change its form before collapsing. This carcass skeleton system comprise of structural elements such as column, beam and slab which are carrying elements in R/C structures. Walls are later placed above these elements. They are carried by columns, beams and slabs (Büyükyıldırım, 2006).

Earthquake behaviour of a structure is too complex to estimate, especially in large-scale structures. It is assumed during the analyzing process of the small- scale structures that earthquake forces act on every floor level of the structure. One must understand the earthquake behaviour of a building in order to guess structural behaviour when it occurs.

Along the seismic calculations, it is assumed that the earthquake loads act on every floor level of a structure that are called as storey forces. They are equal to storey weight ($w_{i)}$ times the storey height from the ground ($H_i$). For instance, based on the Figure 4.2, the forces on first storey which denoted as $F_i$ equals to the fist storey weight times its height from ground ($F_i$ = w1 x h1). Besides, $F_{(i+1)}$ which is the second storey forces, equals to the weight of second storey times its height from the ground level ($F_{(i+1)}$ = w2 x h2). Additionally, the storey force in third storey equals to weight of the third floor times its height from ground level ($F_{(i+2)}$ = w3 x h3). Therefore, the storey forces are directly proportional with the buildings own mass. The structures are accepted as a single freedom degree of system, but real structures are not. Moreover, the levels of acceleration are not stable throughout the structure. The base shear forces which are denoted as V are accumulated in the ground floor. The total design earthquake loads or total base shears is the sum of the all storey loads and these loads are totally accumulated on the ground floor. This condition is visualized in Figure 4.2.

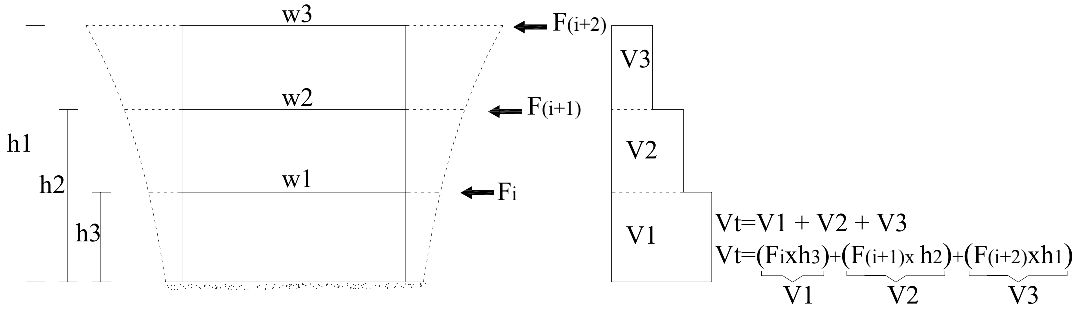


Figure 4.2. Equivalent earthquake forces and base shear forces

Seismic waves cause a three dimensional motion on the ground due to the characteristics of the ground (Mertol, 2002). However, safety factors in vertical direction are kept high level in R/C structures. Therefore, the earthquake forces in z direction can be neglected (Atımtay, 2000).

Earthquake is a release of the accumulated energy. This energy firstly reaches to the foundation of the structure and causes movement in all directions. When the seismic waves reach the foundation of the building, it causes a vibration. But, the structure tries to respond the vibration. This is called the dynamic behaviour of the structure. It depends on many factors such as plan geometry, rigidity distribution or configuration of structural members, the total building mass and its distribution in horizontal and vertical direction. Heavier buildings expose to larger earthquake forces than lighter buildings under the same earthquake loads (Özmen & Ünay, 2007). For instance, R/C structures are heavier than steel and timber buildings and subjected to great forces when earthquake happens.

Inertia forces occur as a result of dynamic behaviour. Inertia can be described as a tendency for an object at rest to remain at rest, or in motion to remain in motion. This is a general physical property of matter. It maintains its existing condition of rest or motion unless an external force is applied (Bayülke, 2001a). Inertia forces stand against those external forces. For instance, when a car is accelerating, the passenger feel himself pushed backward, for the inertial force on the body acts opposite direction of the acceleration. If the vehicle is decelerating or breaking, the passenger may be thrown forward in his location points (Figure 4.3). The buildings behaviour against earthquake loads is similar with this behaviour.

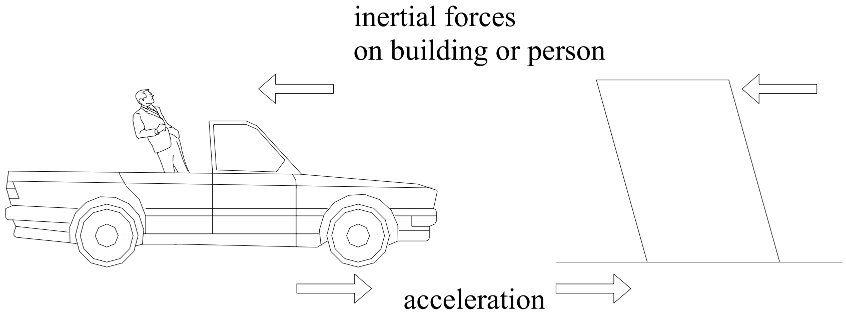


Figure 4.3. Inertia forces

Magnitude of the inertia forces of a building against earthquake loads depend on various factors as follows (Mertol, 2002):

1. Dynamic properties of the building (Period, absorbing capacity)

2. Characteristics of the seismic waves
3. Total mass of the building
4. The distribution of the mass between floors
5. Plan geometry of the building
6. Arrangements of the structural elements
7. The type of load-bearing system
8. The characteristics of the soil where the building is constructed
9. Epicentral distance

Earthquakes send out seismic waves that travel in every direction of the earth. These waves accord horizontal and vertical forces on buildings. The vertical forces generally cause to move up and down safely with the ground. However, horizontal forces vibrate the building back and forth during an earthquake, and cause lateral displacements in buildings. The period of vibration is one of the most significant factors determining how a structure will respond to ground shaking. The time which takes to vibrate back and forth one complete cycle is known as its period of vibration. Besides, periods of vibration depend on weight and height of the building.

Turkey has a great number of building stocks consisting of R/C structures due to the economical circumstances. However, reinforced concrete buildings subjected to major damages due to the various failures. The most significant damage level was observed in middle-storied structures which are constructed at last twenty year (Gülkan, 2000). When the damages in R/C buildings are investigated, the same failures can be observed as follows:

1. Slender buildings
2. No basement floor
3. The difference in the storey height between the ground and upper floors (Soft storey)
4. The difference in strength between the floors (Weak storey)
5. Columns with gusset (prohibited in TEC, 2007)
6. Arrangement of structural elements only on one direction along the all axis.
7. Adjacent buildings with different storey height connections
8. Usage of hollow-tile floor slab
9. Projections in plan (A3)
10. Heavy projection in vertical direction

Earthquake damage of R/C buildings firstly begin with plaster cracks. Later, cracks occur between the columns or shear wall which create R/C skeleton system and separation wall. After, it occurs along the line of the connection between the wall and column or/ and shear wall. With this degree of damage type, structural elements in R/C skeleton system usually do not have a considerable damage. When the walls cannot absorb the seismic energy, they demolish under earthquake loading. After, the left-over seismic energy is transferred to the columns and shear walls. The damage in R/C buildings due to the earthquake forces generally starts at columns due to their seismic energy absorbing capacity. On the other hand, shear walls absorb the seismic energy in a high level. Their seismic energy absorbing capacity level is higher than the columns. When they cannot sufficiently resist to the earthquake loads, the building is highly damaged or collapsed.

## 4.2. Basic Principles of Earthquake Resistant Design

The main principle of earthquake resistant design (ERD) is to prevent the damage formation in structural or non-structural elements of buildings under low intensity earthquake; to limit the damage or left a level that can be repaired in structural and non-structural elements under medium-intensity earthquake and prevent partial or overall collapse of building under high-intensity earthquake in order to provide life safety. The probability of exceed in design earthquake within a process of 50 years is 10 % (TEC, 2007). Each structural system should have sufficient rigidity, strength and stability and can transfer the seismic loads to the ground (TEC, 2007).

Architecture and engineering are interdependent disciplines. Therefore, seismic design faults do not only depend on engineering calculation, but also architectural design failures (Arbabian, 2000). A fault resembles a ring of a chain. If one ring spoils, the chain badly damages from this condition. ERD can be seen as a complex chain consisting of various rings. Each of these rings has a great importance for the earthquake resistance. Moreover, the damages on buildings observed after earthquakes depend on various faults. Architectural faults, structural faults, construction faults, the usage of poor materials, poor workmanship, etc. can be given for the most common faults observed after earthquakes. Accordingly, the main parameters affecting the earthquake resistance of buildings can be ordered as follows:

- Building geometry
- Continuity in structural members
- Building weight
- Strength
- Ductility
- Fragility
- Stiffness

Building geometry affects the earthquake behaviour. An important feature is regularity and symmetry in the overall plan geometry of the building. The type of plan geometry is investigated comprehensively in Chapter 3 with its size, proportion and the other characteristics. The more suitable plan geometry in terms of earthquake resistance is determined with comparing the worse ones.

Continuity in structural members is described in Chapter 3. Discontinuity in a structural member cause the irregularity type of B3 which is a sub-category of structural irregularity defined in the TEC (2007). Continuity in structural elements provides stability in building.

Building weight is proportional with the earthquake forces. Therefore, the vibration effects get greater if the mass of the building increase. It is verified in the equation below, the forces of earthquake (F) is calculated by the multiplication of the building mass with acceleration created by the earthquake (Eq 4.1).

$$F = m \times a \tag{4.1}$$

There are two methods in order to decrease the building mass. One is to use light materials, and the other is to design according to earthquake resistant design criteria. Unbalanced mass distribution cause irreparable damage on buildings. One should abstain from that condition.

Strength is a resistance condition to the internal forces which occurred due to the earthquake loading. Structural elements should have a certain level of resistance. Moreover, it is identical with the load carrying capacity of the structure which is the limit value of load bearing capacity. Strength is the ability of a material to withstand an applied force without damage (Özmen & Ünay, 2008).

Ductility is a kind of structural elements behaviour against loads. Ductility is the ability of the building to bend, sway, and deform by large amounts without collapse. In ductile buildings, deformations occur without any great decrease in the load bearing capacity or strength of structural elements (Bachman, 2003). Seismic energy is consumed in ductile buildings as deformation which exceeds the elastic limit. With this deformation, the building changes its condition from ductile condition to the fragile condition (Erman, 2002). Beam deflection under a load can be given as an example of this condition. Maximum deflection occurs in the middle of the beam.

Fragility is the opposite condition of ductile behavior**.** In ductile buildings, the deformations are made without any decrease in the load carrying capacity of the structural elements. On the other hand, in fragile buildings, major shear cracks occur which creates stiffness changes suddenly. Ductile buildings usually provide substantial advantages when it is compared with fragile buildings. Ductile material gets great longer or shorter before buckling or crushing (Bachman, 2003).

Rigidity or stiffness can be described as the resistance of structural elements against torsional moments and excessive displacements (Özmen & Ünay, 2008). The rigidity of a building along the vertical direction should be distributed uniformly. Previously, low stiffness and more flexibility are preferred for a good seismic performance in buildings. However, later from the lived earthquakes it is witnessed that buildings expose to more damage due to the less stiffness in buildings. Mertol (2002) states that rigid buildings should be made without any neglect in the ductility conditions. Because, the building should show flexible behavior under earthquake forces during the vibration occurs. These vibrations prevent collapses in buildings.

The structural members of a building should be designed as to have sufficient strength, rigidity and stability. The seismic loads should be transferred uninterrupted and safely (TEC, 2007).

Elasticity is non-rigid condition of the building which resist to the deformation of the earthquake loads. The important quality of various structural materials is their ability to reacquire their original form after a force affects. These types of materials are called elastic. For instance, the material of reinforced concrete is not as elastic as steel.

## 4.3. Analysis Rules of Earthquake Resistant Design

In this part, the parameters which are necessary for earthquake analysis of buildings are described in accordance with TEC (2007). Moreover, calculation methods which are used in earthquake analysis of buildings are given.

### 4.3.1. Definition of Elastic Seismic Loads: Spectral Acceleration Coefficient A(T)

The Spectral Acceleration Coefficient which is denoted as A(T) is considered as the main parameter for determination of the earthquake loads (Eq 4.2). The elastic spectral acceleration, Sae(T), which is defined as the ordinate of the 5 % damped elastic acceleration spectrum, equals spectral acceleration coefficient times acceleration of gravity, g (TEC, 2007).

$$A(T) = A_o \, I \, S(T) \qquad S_{ae}(T) = A(T) \, g \tag{4.2}$$

### 4.3.2. Effective Ground Acceleration Coefficient ($A_o$)

The effective ground acceleration coefficient, which is denoted as $A_{o,}$ is shown in equation 4.2. This coefficient shows the condition of earthquake hazard in different region. Turkey is divided into five earthquake zones as $1^o$, $2^o$, $3^o$, $4^o$ and $5^o$, earthquake zone (Table 4.1). The $5^o$ earthquake zone does not rest under the influence of earthquake hazard. For why, effective ground acceleration coefficient is classified for the first four zone except $5^o$ earthquake zone.

Table 4.1.Effective ground acceleration coefficient

| **Seismic Zone** | **$A_o$** |
|---|---|
| 1 | 0.4 |
| 2 | 0.3 |
| 3 | 0.2 |
| 4 | 0.1 |

### 4.3.3. Building Importance Factor (I)

The building importance factor, I, which is given in equation 4.2, varies between 1.0 and 1.5. The maximum building importance factor of 1.5 is taken in buildings which are required to be utilized immediately after an earthquake. For instance, hospitals, health wards, fire fighting buildings, telecommunication facilities, transportation stations, governmental buildings and the buildings containing explosive materials are situated in this category. The building importance factor of 1.4 is taken in buildings which are intensively and long term occupied. Educational buildings, museums, prisons and military barracks can be given as examples of this group. The building importance factor of 1.2 is taken in buildings which are intensively but short-term occupied buildings such as cinemas, theatre, sport facilities, concert halls, etc. The minimum building importance factor of 1.0 is taken in hotels, residential and office buildings (TEC, 2007).

### 4.3.4. Spectrum Coefficient S(T)

Spectrum Coefficient, S(T) which is given in Equation 4.3 will be calculated by depending on local site conditions and natural period of the building, T (Figure 4.4).

$$\begin{aligned} S(T) &= 1+1.5\frac{T}{T_A} && (0 \leq T \leq T_A) \\ S(T) &= 2.5 && (T_A < T \leq T_B) \\ S(T) &= 2.5\left(\frac{TB}{T}\right)^{0.8} && (T_B < T) \end{aligned} \qquad 4.3$$

Spectrum Characteristic Periods, $T_A$ and $T_B$, described in Eq. (4.3) are shown in Table 4.3, depending on local site classes which are divided into four types (Table 4.2).

Table 4.2. Spectrum Characteristic Periods ($T_{A,}$ $T_B$)

| Local Site Class | TA (second) | TB(second) |
|---|---|---|
| Z1 | 0.10 | 0.30 |
| Z2 | 0.15 | 0.40 |
| Z3 | 0.15 | 0.60 |
| Z4 | 0.20 | 0.90 |

These periods ($T_{A,}$ $T_B$) include the interaction between the characteristics of local soil and characteristics of building vibration. Earthquakes cause ground motions under the buildings. These motions should be defined numerically in order to design the building. It is shown in Figure 4.4.

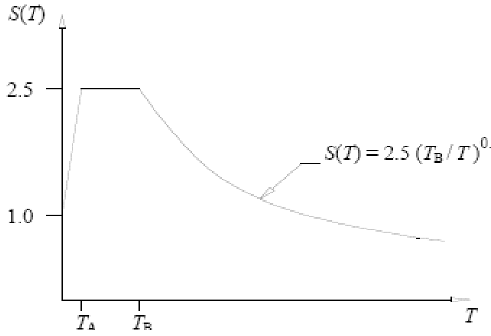


Figure 4.4. Design acceleration spectrum

Soil types are divided into four main groups (Table 4.3). These are denoted as A, B, C and D (TEC, 2007). The soil group, A, consists of firm massive volcanic rocks, strong metamorphic rocks, firm sedimentary rock with cement, more dense sand, aggregate, and hard and silty clay. The soil group, B, consists of crumbly rock, dense sand and aggregate, and more hard and silty clay. The soil group, C, consists of soft metamorphic rocks, medium level of dense sand and aggregate, and hard and silty clay. The soil group, D, consists of soft and thick alluvium layer, loose sand, and soft and silty sand.

Table 4.3. Local site classes and groups

| **Local Site Class** | **Site Group and Thickness of Top Layer (h1)** |
|---|---|
| Z1 | (A) Site group,<br>h ≤ 15m (B) Site group |
| Z2 | h1 > 15 m (B) Sitel group<br>h1≤ 15 m (C) Site group |
| Z3 | 15m < h1≤ 50m (C) Site group<br>h1≤ 10m (D) Site group |
| Z4 | h1 >50 m (C) Site group<br>h1> 10 m (D) Site group |

## 4.4. Analysis Methods

There are three methods for the linear seismic analysis of buildings and building-like structures defined in the TEC (2007). These are described as follows:

1. Equivalent Seismic Load Method (Static)
2. Mode-Combination Method (Dynamic)
3. Time Domain Method (Dynamic)

### 4.4.1. Equivalent Seismic Load Method

Equivalent seismic load method is a kind of static analyses method. It can be used when the conditions described in Figure 4.6 are provided. Earthquake loads are accepted as the lateral loads which affect buildings on floor levels and on both earthquake directions. The cross section impacts are calculated (TEC, 2007).

### 4.4.2. Mode-Combination Method

Mode-Combination method is a kind of dynamic analyses method that the building mass is considered to have collected in the floors. In this method, maximum internal forces and displacements are defined by the statistical combination of maximum contributions obtained from each of the adequate number of natural vibration modes which is considered (TEC, 2007). A sample for the different modes of the building is displayed on Figure 4.5.

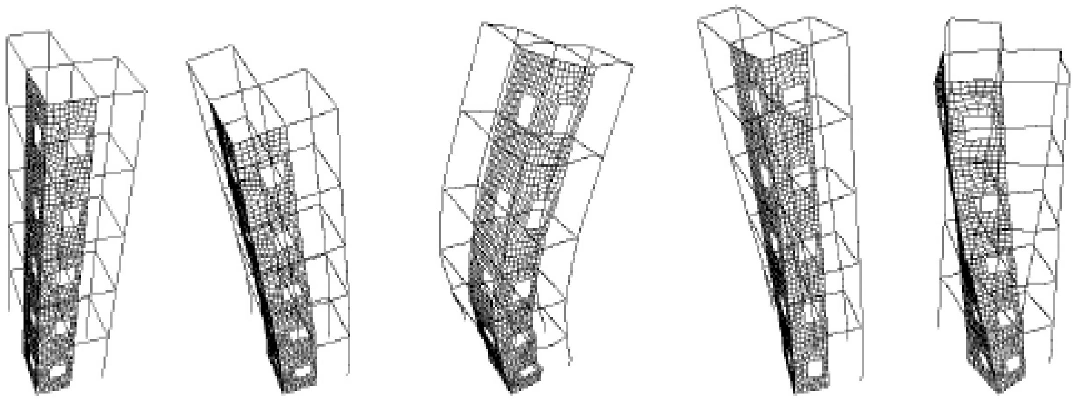


Figure 4.5. A sample for the different modes of the structure (IdeCAD Analysis Report)

### 4.4.3. Analysis Methods in Time Domain

Analysis method in time domain is a kind of dynamic analyses method used in various research. The inelastic effect of the building is considered in this method to understand the general behavior of the building. Turkish Earthquake Code (2007) suggests this method only for so important building because this analysis method is too time-consuming. Artificially generated, previously recorded or simulated earthquake ground motions can be used in this method for seismic analysis of buildings.

### 4.4.4. Selection of Analysis Method

Earthqauke calculation method of the building depends on three main factors. The first one is the earthquake zones. The second one is building height, and finally the third one is the structural irregularity types, A1 and B2. Earthquake calculation can be made with two different method by taking into consideration these factors. Each structure's earthquake calculation can be made with one of the dynamic method.

In the first and second earthquake zones, if the storey height is higher than 40 meter, dynamic earthquake analysis is compulsory to be applied. If it is lower than 25 meter, torsional irregularity check must be made. In the event that the torsional irregularity coefficient is higher than 2.0, dynamic analysis must be made. On the other hand, if the building height is between 25 and 40meter, firstly soft storey (B2) irregularity check must be applied, and then the torsional irregularity (A1) check must be examined. If the B2 coefficient is greater than 2.0, dynamic analysis is compulsory. However, the B2 coefficient is lower than 2.0, at this time torsional irregularity checks are applied. If the A1 coefficient is greater than 2.0, dynamic analysis must be made. On the other conditions, static methods are applied. Moreover, in the third and fourth degree earthquake zones, if the building height is greater than 40 meter, dynamic analysis is compulsory without A1 or B2 irregularity check. Besides, static analysis is applied without B2 irregularity check if the building height is lower than 40 meter (TEC, 2007). Moreover, if the value of $\eta bi \leq 2$, then equivalent static method for the seismic analysis can be applied for buildings up to 40 m in height provided that there is no B2 type of structural irregularity. A1 and B2 type of irregularities are approved as the determinative irregularities in the selection of the seismic analysis method.

Methods to be used for the earthquake analysis of the existing structures or the newly designed structures are determined according to the application limits of the factors. The choice of the earthquake analysis method between the static or dynamic method is represented in Figure 4.6.

Mode-combination method is used in all the cases of Chapter 5. Although mode-combination method is not compulsory, it is chosen for the earthquake analysis of the models due to its reliable results.

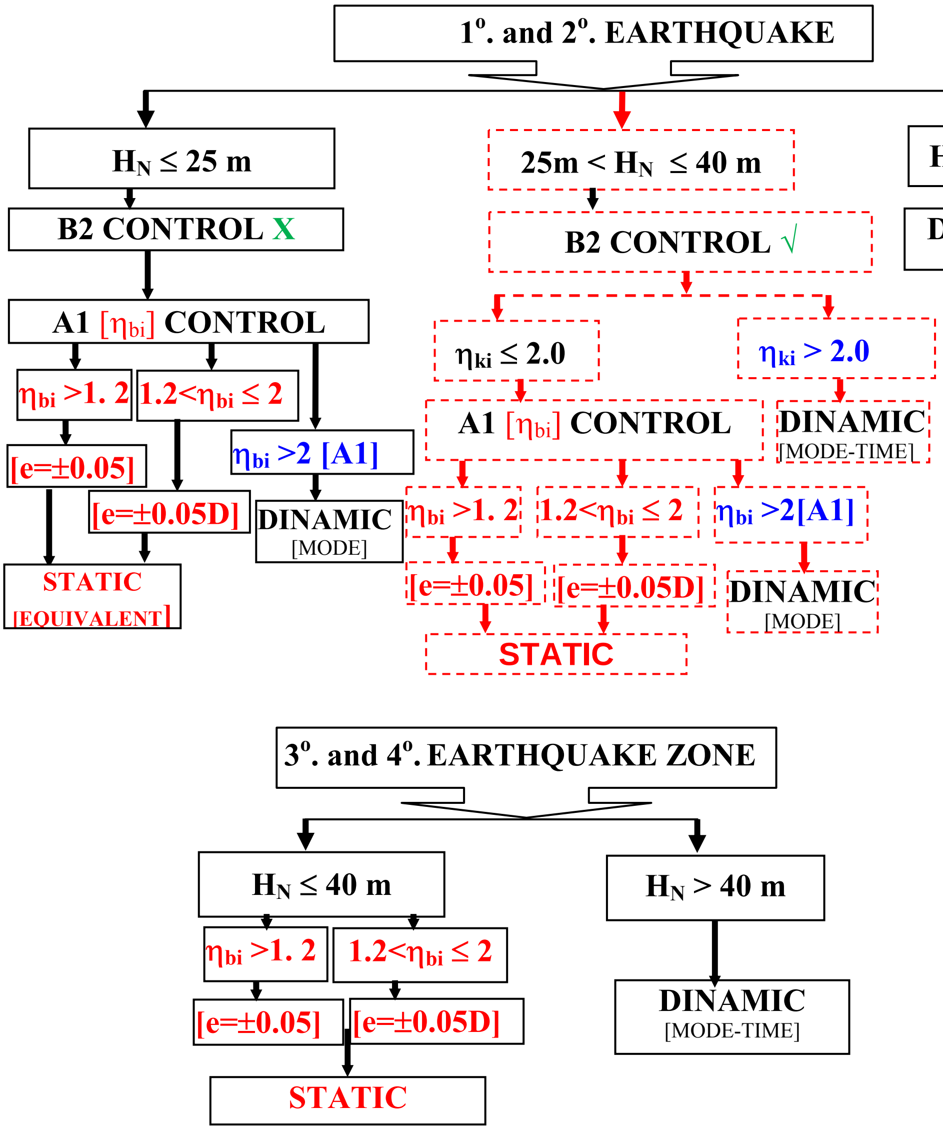


Figure 4.6. Selection of the method for seismic analysis

## 4.5. Effective Storey Drifts $(\delta i)_{max}$

The reduced storey drift, $\Delta i$, of any column or structural wall shall be determined by Eq.(4.4) as the difference of displacements between the two consecutive stories. In Eq.(4.4) di and di−1 represent lateral displacements obtained from the analysis at the ends of any column or structural wall at stories i and (i - 1) under reduced seismic loads (Figure 4.7). Effective storey drift , $\delta i$ , of columns or structural walls at the i'th storey of a building shall be obtained for each earthquake direction by Eq.(4.5). The maximum value of effective storey drifts, $(\delta i)$max, obtained for each earthquake direction by Eq.(4.5) at columns or structural walls of a given i'th storey of a building shall satisfy the condition given by Eq.(4.6). In the case where the condition given by Eq.(4.6) is not satisfied at any storey of the building, the seismic analysis shall be repeated with increased stiffness of the structural system.

$$\Delta = d_i - d_{i-1} \tag{4.4}$$

$$\delta_i = R\,\Delta_i \tag{4.5}$$

$$\frac{(\delta i)_{\max}}{h_i} \leq 0.02 \tag{4.6}$$

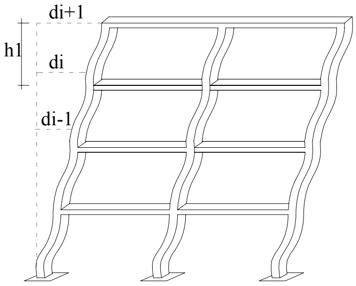


Figure 4.7. Effective storey drifts

## 4.6. Second Order Effects ($\theta_i$)

The second order effect indicates the nonlinear behaviour of the structural elements. Its limit coefficient, which is denoted as $\theta_i$ is formulized in Eq. (4.7). Less stiffness causes augmentation in the second order effects in buildings. Second order effects occur due to the excessive displacement in buildings which can cause the total collapses in buildings (Doğan, 2007). In the case the condition is not satisfied, the rigidity of the structural elements should be increased and the seismic analysis should be repeated.

$$\theta_i = \frac{(\Delta_i)_{ort} \sum_{j=i}^{N} wj}{V_i h_i} \leq 0.12 \tag{4.7}$$

# CHAPTER 5

# NUMERICAL ANALYSIS

The theoretical information related to the earthquake resistant design (ERD) of reinforced concrete (R/C) buildings in terms of structural irregularities was described in Chapter 3. As previously mentioned, the main objective of this thesis is to determine the effective factors on structural irregularities to develop a substantial guide for architects and students of architecture. This can be succeeded with proving the failures which are commonly recurring by architects. Therefore, previously mentioned rules related to structural irregularities are tested in a simple visual and analytical style to demonstrate the earthquake effects on structures.

This chapter comprises of 4 cases. Case I consists of six main parametric models. Additionally, it totally consists of 144 models with various R/C structural system type, the number of storey and the number of structural axis options. The R/C system types which are commonly used in Turkey are compared. Case II totally consists of 9 parametric models having twenty stories. The effects of irregular rigidity distribution despite the symmetric plan geometry are investigated. Additionally, the effects of overhang direction on earthquake behaviour of structure are examined. Case III comprises of 9 main models, and totally 72 models with various numbers of stories and structural configuration. The floor opening rate, its location in the plan and its interaction with structural configuration are investigated. Case IV consists of 5 main models and in total with sub models it has 40 models. Square plan geometry is chosen to analyze the earthquake behaviour of structures in all cases except case IV due to its regularity in plan geometry and symmetry condition. The earthquake behaviours of different plan geometries are investigated in case IV by holding constant of the floor area of the models.

The square model has 5 axis or 4 bays with 5 m beam span in both X and Y direction. Thus, the dimension of square model is 20 m × 20 m. Floors consist of R/C slabs of 15 cm in thickness except the void floors in case III. Floor heights are taken as 2.80 m in every storey. The models are assumed to be in the first degree earthquake zone. Besides, they are designed by using C30 class concrete and S420 class steel.

Project and TEC (2007) parameters which are used in the cases are described in the Table 5.1 as follows:

Table 5.1 Project and TEC parameters

| **Project Parameters of the models** | **2007 Turkish Earthquake Code Parameters** |
|---|---|
| Maximum Storey Number: 20 | Earthquake Zone:1 |
| Storey Height: 2.80 m | Soil Class: Z2 |
| Maximum Building Height (Hn): 56 m | Earthquake Zone Factor: 0.4 |
| Beam Span: 5 m | Building Importance Factor: 1 |
| Beams: 30/60 cm | Concrete Class: C30 |
| Columns: 60/60 cm | Steel Class: S420 |
| Shear Wall: 25/500 cm | Ductility Level: High, R: 6.00 |
| Slab thickness: 15 cm | Live Load Factor : 0.3 |

In this chapter, structural irregularities constituting the main subject of the thesis will be evaluated according to the TEC (2007). With this aim, many parametric studies are developed. A series of model is generated for each defined structural irregularity. The changes in the parameters such as torsional irregularity coefficient, stiffness irregularity coefficient, maximum effective storey drift, interstorey drift and second order effect will be compared in each parametric model.

## 5.1. Case I: R/C Structural Systems: Symmetric Configuration (A1)

The case consists of 6 main models and totally consists of 144 models with sub models. All models are designed to have both symmetrical and regular plan geometry and rigidity distribution. It is aimed to explore that despite the symmetrical plan geometry and rigidity distribution, structural elements type, their location in the plan and their sufficiency in terms of rigidity, strength and stability according to the each system defined above play the most effective role in determining the earthquake behaviour of structures. All models are generated based on defined variables and their earthquake behaviour is compared on the basis of structural irregularities. Then, obtained results are discussed.

In this case, various certain R/C structures are chosen to examine the earthquake behaviour of structures on basis structural irregularities in detail. Therefore, the R/C structural system types, which are commonly used in Turkey, are grouped based on R/C structural systems as follows:

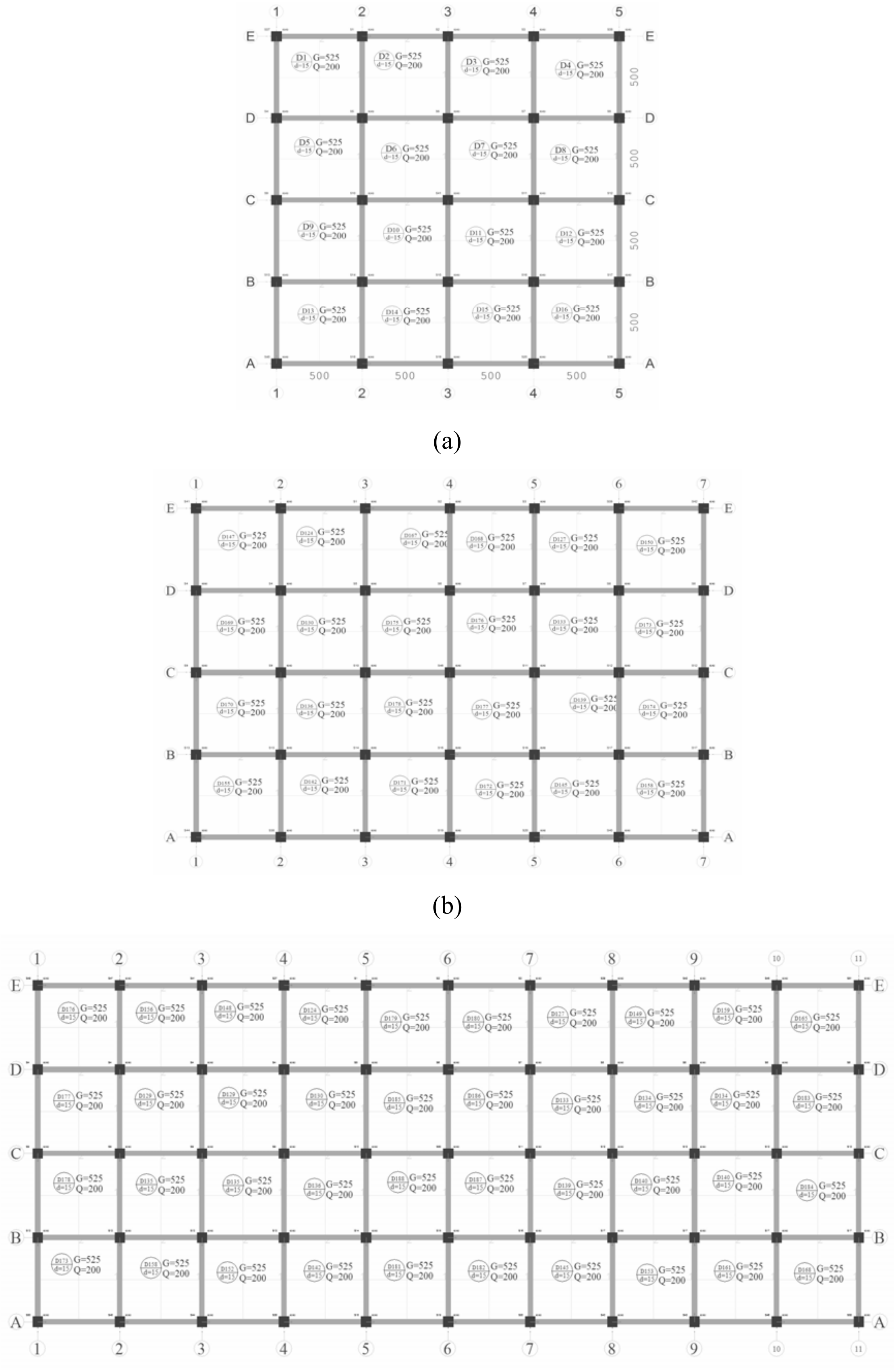
1. Frame System
2. Frame System + Rigid Core
3. Shear-Frame System
4. Shear-Frame System + Rigid Core

For each selected R/C structural system type, three models which have a dimension of 20 m x 20 m, 20 m x 30 m, and 20 m x 50 m are generated by increasing the number of axis along the X direction. These main models are coded differently in each parametric model without changing dimensions. The main variables can be listed as follows:

- R/C structural system type
- The number of axis
- The number of storey (1S, 3S, 5S, 8S, 10S, 12S, 15S, 20S)

### 5.1.1. Parametric Model Ia: Frame Systems

In this model, the structure has been designed as a frame system. Each beam span has a length of 5 meter. The model has both a symmetrical and regular plan geometry and also rigidity distribution. There is no A3 irregularity (projections in plan). The parametric models of Ia are shown in Figure 5.1 and it consists of three sub models as Ia 20x20, Ia 20x30, and Ia 20x50. Earthquake behaviour of frame systems is investigated by changing the number of storey and axis. The analysis results which are shown in Table 5.2 are discussed by comparing each result of Ia 20x20, Ia 20x30 and Ia 20x50.



(a)

(b)

(c)

Figure 5.1. Structural plans of parametric model Ia a) Ia 20x20, b) Ia 20x30, c) Ia 20x50.

Table 5.2. Analysis results of parametric model Ia

| | **Storey** | (δi)max | δ max/hi≤0.02 | θ≤0.12 | ηbi<1.2 | ηki<2.00 |
|---|---|---|---|---|---|---|
| Ia 20x20 | 1S | 1.38 | 0.0005 | 0.0004 | 1.11 | - |
| | 3S | 4.90 | 0.0018 | 0.0015 | 1.11 | 1.52 |
| | 5S | 9.27 | 0.0034 | 0.0032 | 1.11 | 1.67 |
| | 8S | 13.02 | 0.0048 | 0.0057 | 1.11 | 1.64 |
| | 10S | 14.07 | 0.0052 | 0.0073 | 1.11 | 1.57 |
| | 12S | 14.88 | 0.0055 | 0.0090 | 1.11 | 1.53 |
| | 15S | 15.84 | 0.0059 | 0.0116 | 1.11 | 1.54 |
| | 20S | 17.38 | 0.0064 | 0.0162 | 1.10 | 1.56 |
| Ia 20x30 | 1S | 1.50 | 0.0006 | 0.0004 | 1.16 | - |
| | 3S | 5.33 | 0.0020 | 0.0016 | 1.16 | 1.53 |
| | 5S | 10.07 | 0.0037 | 0.0033 | 1.16 | 1.70 |
| | 8S | 13.93 | 0.0052 | 0.0059 | 1.16 | 1.69 |
| | 10S | 15.04 | 0.0056 | 0.0076 | 1.16 | 1.64 |
| | 12S | 15.91 | 0.0059 | 0.0094 | 1.16 | 1.58 |
| | 15S | 16.95 | 0.0063 | 0.0121 | 1.15 | 1.54 |
| | 20S | 18.55 | 0.0069 | 0.0169 | 1.15 | 1.55 |
| Ia 20x50 | 1S | 1.63 | 0.0006 | 0.0004 | 1.21 | - |
| | 3S | 5.79 | 0.0021 | 0.0016 | 1.21 | 1.55 |
| | 5S | 10.94 | 0.0041 | 0.0034 | 1.21 | 1.72 |
| | 8S | 14.94 | 0.0055 | 0.0061 | 1.21 | 1.73 |
| | 10S | 16.13 | 0.0060 | 0.0079 | 1.21 | 1.71 |
| | 12S | 17.06 | 0.0063 | 0.0097 | 1.21 | 1.67 |
| | 15S | 18.19 | 0.0067 | 0.0125 | 1.21 | 1.59 |
| | 20S | 19.91 | 0.0074 | 0.0174 | 1.21 | 1.55 |

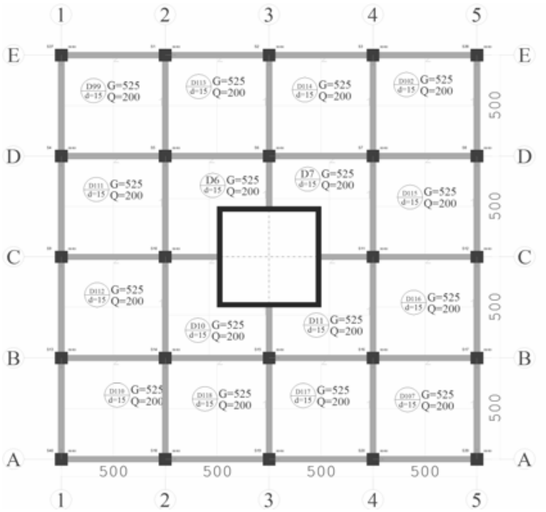
Based on the structural irregularities report, the maximum value of effective storey drift is changing depending on parametric models. While the maximum values of effective storey drift in model Ia 20x20 is17.38 mm, it is 19.91 mm in Ia 20x50. The limit values of interstorey drifts and second order effect in above models have not been exceeded. These values also gradually increase from one storey model up to twenty storey model. Besides, they are gradually increase from the ground floors to the upper floors of model Ia 20x20, Ia 20x30, and Ia 20x50.

The maximum torsional irregularity coefficient ($\eta bi$) is obtained 1.11 in Ia 20x20, 1.16 in Ia 20x30, and 1.21 in Ia 20x50. It is observed that if the number of storey of the parametric models in Ia increase, the maximum torsional irregularity coefficient will decrease. Furthermore, it is noticed that the torsional irregularity coefficients gradually decrease from the ground floor to upper floors within the own stories of each different storied parametric models of Ia. Besides, torsional irregularity coefficients increase from parametric model Ia 20x20 to Ia 20x50. It can be concluded that if the number of axis increase in parametric model Ia, the torsional irregularity coefficients will increase. Though there is not torsional irregularity in Ia 20x20 and Ia 20x30, there is torsional irregularity in Ia 20x50. The maximum torsional irregularity coefficient is obtained as 1.21 in Ia 20x50.

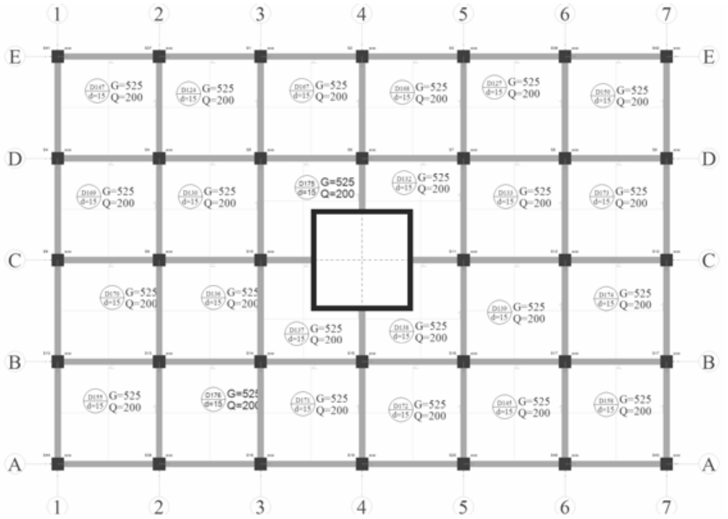
Stiffness irregularity coefficient ($\eta ki$) is between normal ranges in parametric model Ia. It changes between 1.52 and 1.67 in Ia 20x20, 1.53 and 1.70 in Ia 20x30, 1.55 and 1.73 in Ia20x50. There is an increase in the stiffness irregularity coefficient from Ia 20x20 to Ia 20x50. There is not stiffness irregularity in parametric models of Ia. The maximum stiffness irregularity coefficient is found as 1.73 in eight storey sub model of Ia 20x50. Furthermore, it is observed that if the number of storey in the parametric model Ia increases, it does not create a regular increase or reduction in the maximum soft storey coefficients. On the other hand, it is observed that stiffness irregularity coefficient is higher when this coefficient is calculated based on below storey.

### 5.1.2. Parametric Model Ib: Frame System+ Rigid Core

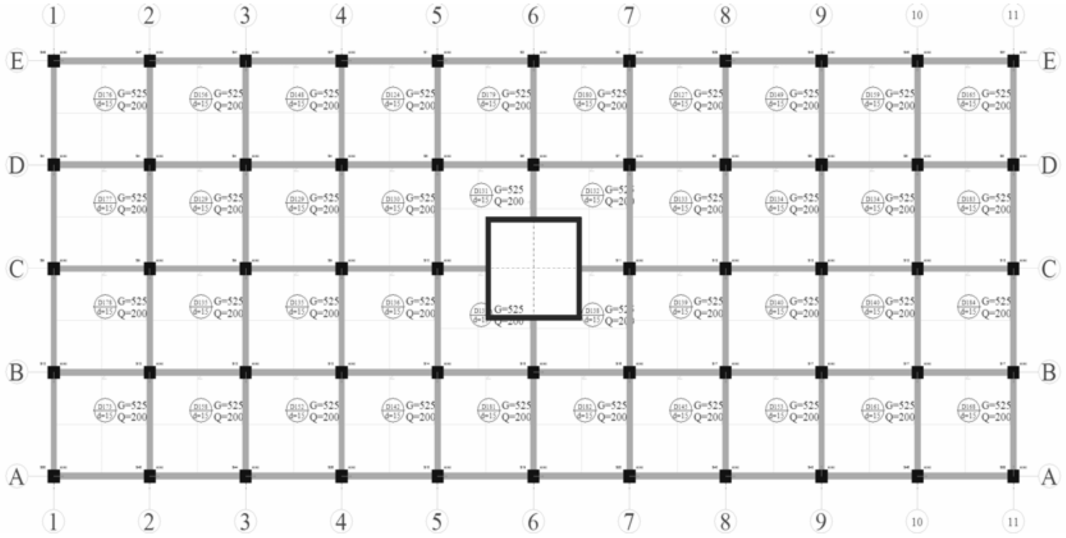
In this model, the structure has been designed as a frame system. Apart from the parametric model Ia, a rigid core placed in the centre of the structure to maintain the symmetry. The model has both a regular plan geometry and rigidity distribution. There is not any projection in plan. The parametric models of Ib, which have three sub models as Ib 20x20, Ib 20x30 and Ib 20x50, are drawn in Figure 5.2. The effects of the central rigid core in terms of earthquake behaviour of a structure are investigated by changing the number stories and axis. The analysis results shown in Table 5.3 will be evaluated by comparing each results obtained from Ib 20x20, Ib 20x30 and Ib 20x50.



(a)



(b)



(c)

Figure 5.2. Structural plans of parametric model Ib
a) Ib 20x20, b) Ib 20x30, c) Ib 20x50

Table 5.3. Analysis results of parametric model Ib

| | **Storey** | (δi)max | δ max/hi≤0.02 | θ≤0.12 | ηbi<1.2 | ηki<2.00 |
|---|---|---|---|---|---|---|
| Ib 20x20 | 1S | 0.58 | 0.0002 | 0.0001 | 1.27 | - |
| | 3S | 2.37 | 0.0009 | 0.0007 | 1.24 | 1.51 |
| | 5S | 4.97 | 0.0018 | 0.0015 | 1.23 | 1.71 |
| | 8S | 9.78 | 0.0036 | 0.0033 | 1.22 | 1.83 |
| | 10S | 11.07 | 0.0041 | 0.0046 | 1.21 | 1.87 |
| | 12S | 12.35 | 0.0046 | 0.0062 | 1.21 | 1.90 |
| | 15S | 14.08 | 0.0052 | 0.0087 | 1.20 | 1.93 |
| | 20S | 16.82 | 0.0062 | 0.0136 | 1.20 | 1.96 |
| Ib 20x30 | 1S | 0.78 | 0.0003 | 0.0002 | 1.35 | - |
| | 3S | 1.01 | 0.0005 | 0.0022 | 1.32 | 1.46 |
| | 5S | 6.11 | 0.0023 | 0.0018 | 1.31 | 1.66 |
| | 8S | 11.12 | 0.0041 | 0.0037 | 1.29 | 1.76 |
| | 10S | 12.50 | 0.0046 | 0.0052 | 1.29 | 1.80 |
| | 12S | 13.78 | 0.0051 | 0.0069 | 1.28 | 1.83 |
| | 15S | 15.47 | 0.0057 | 0.0095 | 1.28 | 1.86 |
| | 20S | 18.18 | 0.0067 | 0.0145 | 1.27 | 1.89 |
| Ib 20x50 | 1S | 1.04 | 0.0004 | 0.0002 | 1.40 | - |
| | 3S | 3.90 | 0.0014 | 0.0010 | 1.38 | 1.42 |
| | 5S | 7.52 | 0.0028 | 0.0022 | 1.37 | 1.59 |
| | 8S | 12.71 | 0.0047 | 0.0043 | 1.35 | 1.69 |
| | 10S | 14.21 | 0.0053 | 0.0059 | 1.35 | 1.73 |
| | 12S | 15.39 | 0.0057 | 0.0076 | 1.35 | 1.75 |
| | 15S | 17.12 | 0.0063 | 0.0104 | 1.34 | 1.77 |
| | 20S | 19.67 | 0.0073 | 0.0156 | 1.34 | 1.79 |

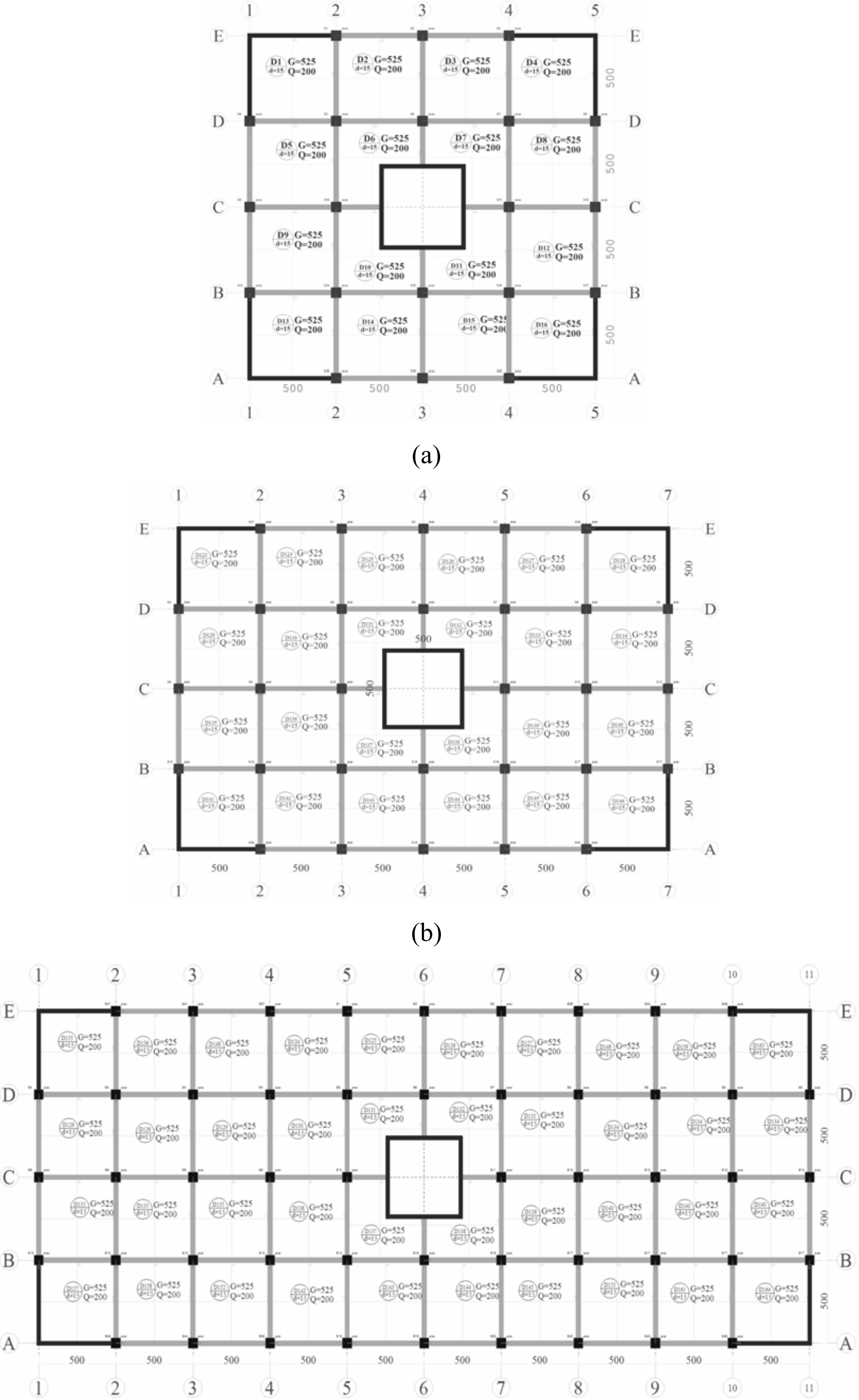
Based on the earthquake analysis report of structural irregularities, while the maximum value of effective storey drift in parametric model Ib 20x20 is obtained as 16.82 mm, it is 18.18 mm in parametric model Ib 20x30 and 19.67 mm in Ib 20x50. The limit irregularity values of interstorey drifts and second order effect have not been exceeded in parametric model Ib. All that values gradually increase from one storey model to twenty storey model of Ib. Moreover, they are all increase toward upper floor within the own stories of each different storied parametric model Ib.

The maximum torsional irregularity coefficient ($\eta_{bi}$) is 1.27 in Ib 20x20, 1.35 in Ib 20x30 and 1.40 in Ib 20x50. It is noticed that if the number of storey in parametric model Ib increase, the maximum torsional irregularity coefficient will decrease. Moreover, the torsional irregularity coefficients gradually decrease toward upper floors within the own stories of each different storied parametric models of Ib 20x20, Ib20x30 and Ib 20x50. Additionally, the torsional irregularity coefficients increase gradually from parametric model Ib 20x20 to Ib 20x50. It can be said that if the number of axis increase in parametric model Ib, the torsional irregularity coefficients will gradually increase. There is torsional irregularity in each sub models of Ib. Rigid core cause a considerable increase in the torsional irregularity coefficients because it is near to the gravity centre.

Stiffness irregularity coefficient ($\eta_{ki}$) is under the limit value in parametric models of Ib. The range varies between 1.51 and 1.96 in Ib 20x20, 1.46 and 1.89 in Ib 20x30 and 1.42 and 1.79 in Ib 20x50. There is a decrease in the maximum stiffness irregularity coefficient from Ib 20x20 to Ib 20x50. There is no stiffness irregularity in parametric model Ib. However, there are high stiffness irregularity coefficients which close to the limit coefficient for the stiffness irregularity. The maximum stiffness irregularity coefficient is obtained as 1.96 in twenty storey parametric model of Ib 20x20. Furthermore, it is concluded that if the number of storey in parametric model Ib increase, the maximum soft storey coefficient will gradually increase in each parametric model of Ib. On the other hand, it is realized that the stiffness irregularity coefficient calculated according to the below storey shows higher values than the values calculated based on above storey.

### 5.1.3. Parametric Model Ic: Shear-Frame System (1)

The parametric model Ic has been designed as a shear-frame system. Apart from the parametric model Ib, four shear walls having L-shape are placed on the corners of the structure (Figure 5.3). The rigid core is not removed. The effects of shear walls located on the corner of the structure are examined with its rigid core in terms of earthquake behaviour.



(a)

(b)

(c)

Figure 5.3. Structural plans of parametric model Ic
a) Ic 20x20, b) Ic 20x30, c) Ic 20x50

Table 5.4. Analysis results of parametric model Ic

| | **Storey** | (δi)max | δ max/hi≤0.02 | θ≤0.12 | ηbi<1.2 | ηki<2.00 |
|---|---|---|---|---|---|---|
| Ic 20x20 | 1S | 0.25 | 0.0001 | 0.0001 | 1.08 | - |
| | 3S | 1.32 | 0.0005 | 0.0004 | 1.09 | 1.64 |
| | 5S | 3.47 | 0.0013 | 0.0011 | 1.09 | 1.92 |
| | 8S | 8.23 | 0.0030 | 0.0027 | 1.10 | 2.08 |
| | 10S | 10.19 | 0.0038 | 0.0040 | 1.10 | 2.14 |
| | 12S | 11.78 | 0.0044 | 0.0057 | 1.10 | 2.18 |
| | 15S | 14.21 | 0.0053 | 0.0086 | 1.09 | 2.23 |
| | 20S | 18.51 | 0.0069 | 0.0147 | 1.09 | 2.28 |
| Ic 20x30 | 1S | 0.34 | 0.0001 | 0.0001 | 1.11 | - |
| | 3S | 1.68 | 0.0006 | 0.0005 | 1.13 | 1.61 |
| | 5S | 4.23 | 0.0016 | 0.0013 | 1.14 | 1.86 |
| | 8S | 9.48 | 0.0035 | 0.0030 | 1.15 | 2.00 |
| | 10S | 11.10 | 0.0041 | 0.0044 | 1.15 | 2.06 |
| | 12S | 12.67 | 0.0047 | 0.0061 | 1.15 | 2.09 |
| | 15S | 15.04 | 0.0056 | 0.0090 | 1.14 | 2.13 |
| | 20S | 19.08 | 0.0071 | 0.0150 | 1.13 | 2.18 |
| Ic 20x50 | 1S | 0.49 | 0.0002 | 0.0001 | 1.15 | - |
| | 3S | 2.22 | 0.0008 | 0.0007 | 1.17 | 1.56 |
| | 5S | 5.24 | 0.0019 | 0.0016 | 1.20 | 1.78 |
| | 8S | 10.65 | 0.0039 | 0.0034 | 1.22 | 1.90 |
| | 10S | 12.40 | 0.0046 | 0.0050 | 1.23 | 1.95 |
| | 12S | 12.67 | 0.0047 | 0.0061 | 1.15 | 2.09 |
| | 15S | 16.37 | 0.0061 | 0.0097 | 1.22 | 2.02 |
| | 20S | 20.16 | 0.0075 | 0.0154 | 1.19 | 2.05 |

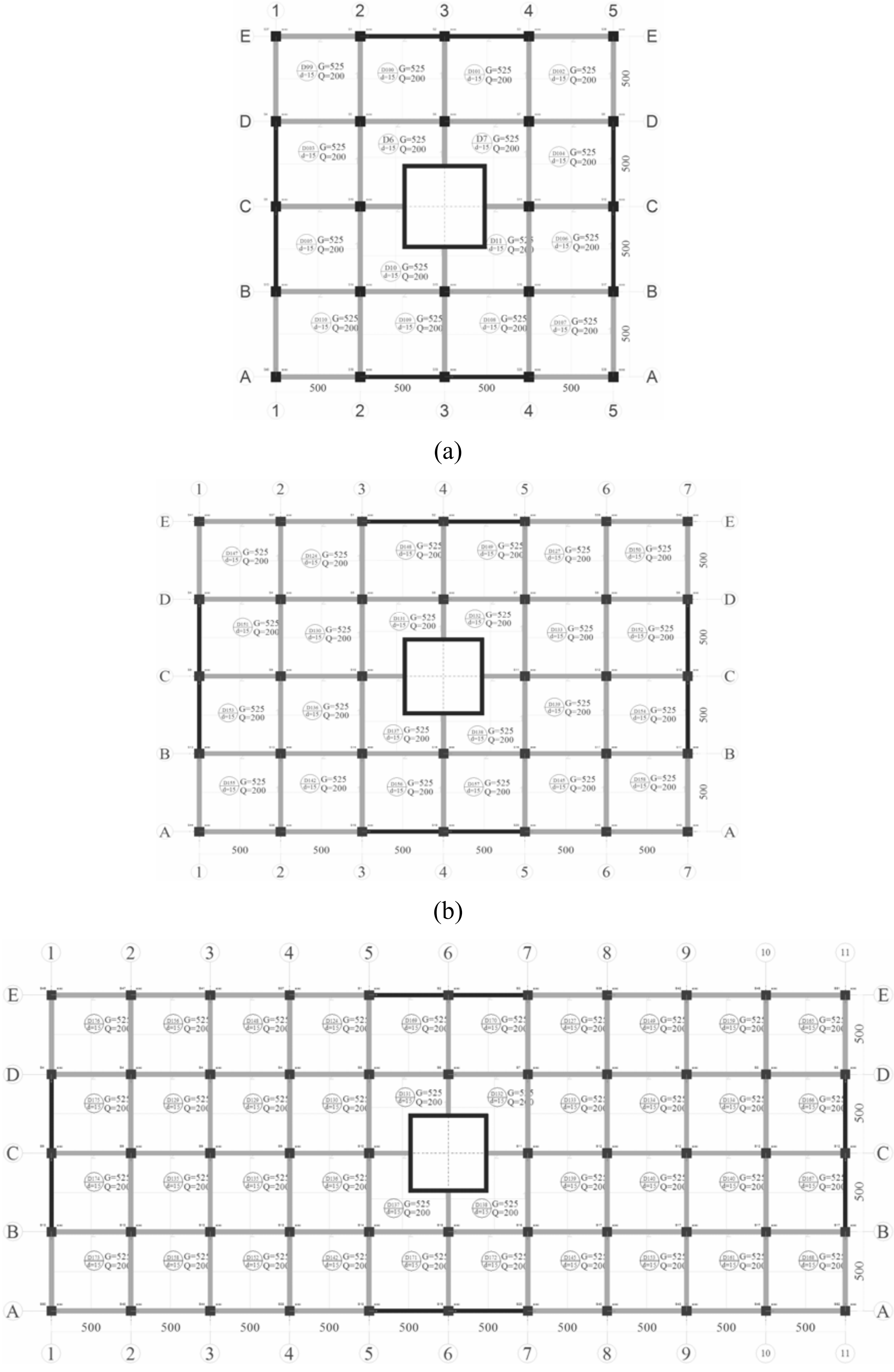
Obtained from the earthquake analysis report of structural irregularities, while the maximum value of effective storey drift in parametric model Ic 20x20 is 18.51 mm, it is 19.08 mm in Ic 20x30 and 20.16 mm in Ic 20x50. Interstorey drifts and second order effect coefficients defined in the TEC (2007) have not been exceeded. These values gradually increase from one storey structure to twenty storey structure (Table 5.4).

The maximum torsional irregularity coefficient ($\eta bi$) is obtained as 1.10 in parametric model Ic 20x20, 1.15 in Ic 20x30 and 1.23 in Ic 20x50. Moreover, an increase in the number of storey does not create a regular change in the maximum torsional irregularity coefficients between stories. It is noticed that the torsional irregularity coefficients increase gradually from ground floor to the upper floors within the own stories of each different storied sub models of Ic. Besides, torsional irregularity coefficients increase from parametric model Ic 20x20 to Ic 20x50. It can be concluded that if the number of axis increase in parametric model Ic, the torsional irregularity coefficients will increase. While there is no torsional irregularity in Ic 20x20 and Ic 20x30, there is torsional irregularity in Ic 20x50. The torsional irregularity is started to exceed the limit coefficient in five storey sub model of Ic 20x50.

Stiffness irregularity coefficient ($\eta ki$) shows great values in the parametric models of Ic. The range varies between 1.64 and 2.28 in Ic 20x20, 1.61 and 2.18 in Ic 20x30 and 1.56 and 2.05 in Ic 20x50. There is a decrease in the maximum stiffness irregularity coefficient from Ic 20x20 to Ic 20x50. There is stiffness irregularity in all parametric models of Ic. The maximum stiffness irregularity coefficient is obtained as 2.28 in twenty storey sub model of Ic 20x20. Furthermore, it is realized that if the number of storey in parametric model Ic increases, the maximum soft storey coefficient will gradually increase from one storey model to twenty storey model. Also, the stiffness irregularity coefficient calculated based on storey above or below are compared, it is observed that stiffness irregularity coefficient has higher values for the ratio below than the ratio above. Besides, it is noticed that stiffness irregularity or soft storey irregularity was observed on the first storey of each parametric models of Ic which have different number of storey and axis.

### 5.1.4. Parametric Model Id: Shear-Frame System (2)

In this model, the structure has been designed as a shear-frame system like in the parametric model Ic. Apart from the parametric model Ic, four I-shaped shear walls are placed in the middle of the outer axis of the structures as illustrated in Figure 5.4. Besides, the rigid core is not removed. The contributions of shear walls located in the middle of the outer axis are examined in terms of earthquake behaviour with its rigid core.



(a)

(b)

(c)

Figure 5.4. Structural plans of parametric model Id
a) Id 20x20, b) Id 20x30, c) Id 20x50

Table 5.5. Analysis results of parametric model Id

| | **Storey** | (δi)max | δ max/hi≤0.02 | θ≤0.12 | ηbi<1.2 | ηki<2.00 |
|---|---|---|---|---|---|---|
| Id 20x20 | 1S | 0.27 | 0.0001 | 0.0001 | 1.08 | - |
| | 3S | 1.44 | 0.0005 | 0.0004 | 1.09 | 1.66 |
| | 5S | 3.74 | 0.0014 | 0.0012 | 1.10 | 1.93 |
| | 8S | 8.79 | 0.0033 | 0.0029 | 1.11 | 2.09 |
| | 10S | 10.70 | 0.0040 | 0.0043 | 1.12 | 2.15 |
| | 12S | 12.43 | 0.0046 | 0.0061 | 1.12 | 2.19 |
| | 15S | 15.07 | 0.0056 | 0.0092 | 1.12 | 2.24 |
| | 20S | 19.70 | 0.0073 | 0.0155 | 1.12 | 2.28 |
| Id 20x30 | 1S | 0.36 | 0.0001 | 0.0001 | 1.12 | - |
| | 3S | 1.81 | 0.0007 | 0.0005 | 1.13 | 1.63 |
| | 5S | 4.50 | 0.0017 | 0.0014 | 1.15 | 1.87 |
| | 8S | 9.87 | 0.0037 | 0.0032 | 1.16 | 2.01 |
| | 10S | 11.57 | 0.0043 | 0.0047 | 1.17 | 2.06 |
| | 12S | 13.27 | 0.0049 | 0.0065 | 1.18 | 2.10 |
| | 15S | 15.79 | 0.0058 | 0.0095 | 1.18 | 2.14 |
| | 20S | 20.06 | 0.0074 | 0.0156 | 1.17 | 2.18 |
| Id 20x50 | 1S | 0.51 | 0.0002 | 0.0001 | 1.15 | - |
| | 3S | 2.36 | 0.0009 | 0.0007 | 1.18 | 1.57 |
| | 5S | 5.51 | 0.0020 | 0.0016 | 1.21 | 1.79 |
| | 8S | 10.99 | 0.0041 | 0.0036 | 1.23 | 1.91 |
| | 10S | 12.84 | 0.0048 | 0.0052 | 1.24 | 1.95 |
| | 12S | 14.52 | 0.0054 | 0.0070 | 1.25 | 1.99 |
| | 15S | 16.94 | 0.0063 | 0.0101 | 1.25 | 2.02 |
| | 20S | 20.82 | 0.0077 | 0.0159 | 1.23 | 2.05 |

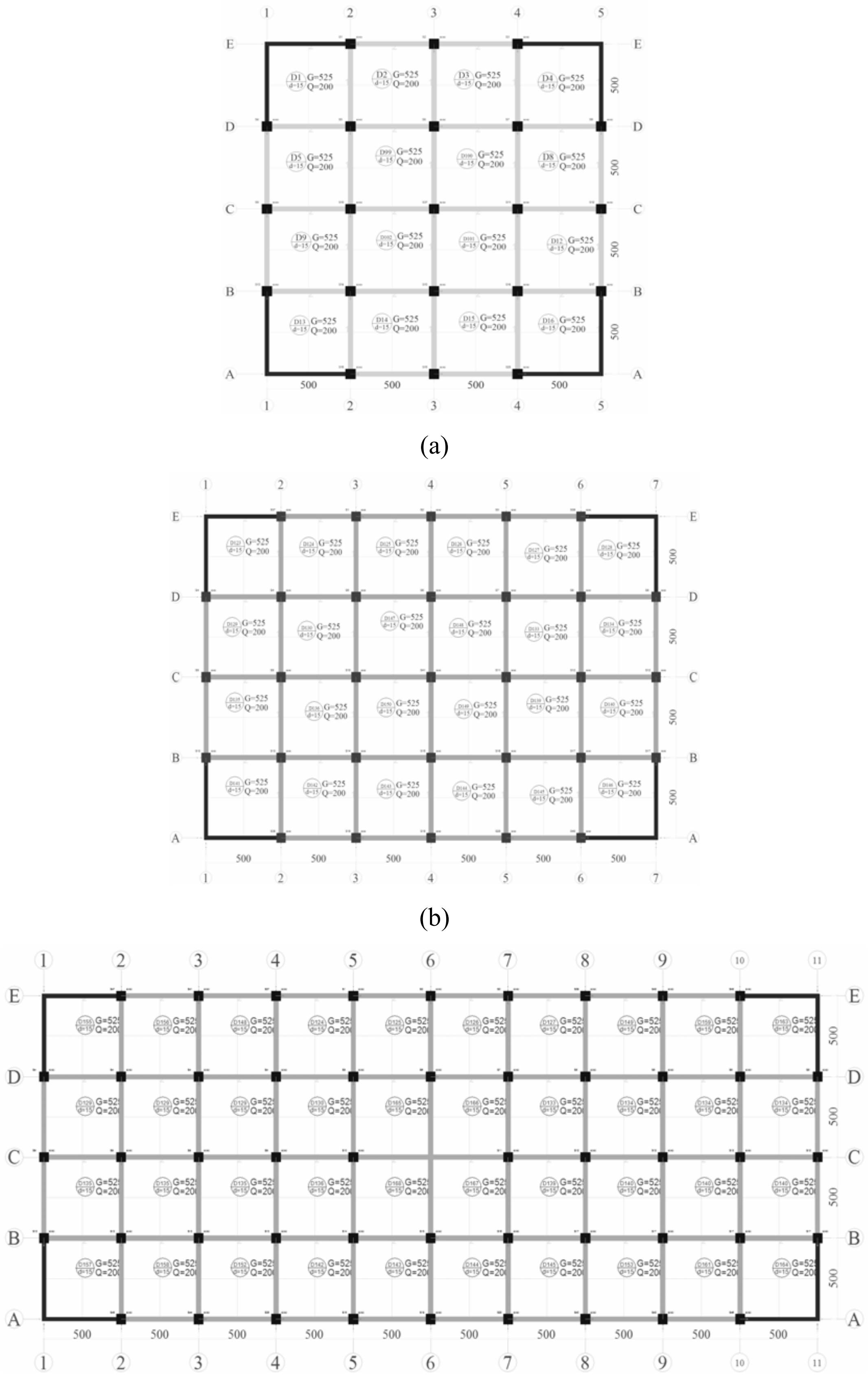
According to the earthquake analysis report of structural irregularities shown in Table 5.5, it is observed that the maximum coefficient of effective storey drift in parametric model Id 20x20 is 19.70 mm, 20.06 mm in Id 20x30 and 20.82 mm in Id 20x50. The interstorey drifts coefficients and second order effect coefficients have not been exceeded. All that values gradually increase from one storey structure to twenty storey structure. Furthermore, they are all increase towards upper floors within the own stories of each different storied parametric models of Id 20x20, Id 20x30 and Id 20x50.

The maximum torsional irregularity coefficient ($\eta bi$) is 1.12 in Id 20x20, 1.18 in Id 20x30 and 1.25 in Id 20x50. Besides, it is noticed that if the number of storey in parametric models of Id increases, the maximum torsional irregularity coefficients and the coefficients within each different storied sub models of Id gradually increase from ground floor to upper floor. Besides, torsional irregularity coefficients increase from parametric model Id 20x20 to Id 20x50. Therefore, it can be concluded that if the number of axis increase in parametric model Id, the torsional irregularity coefficients will increase. While there is not torsional irregularity in Id 20x20 and Id 20x30, the parametric model Id 20x50 has torsional irregularity. The torsional irregularity started to exceed the limit coefficient in five storey sub model of Id 20x50.

Stiffness irregularity coefficient ($\eta ki$) shows large ranges in the parametric models of Id. The range varies between 1.66 and 2.28 in Id 20x20, 1.63 and 2.18 in Id 20x30 and 1.57 and 2.05 in Id 20x50. There is a decrease in the maximum stiffness irregularity coefficient from Id 20x20 to Id 20x50. There is stiffness irregularity in all parametric models of Id. The maximum stiffness irregularity coefficient is gained as 2.28 in twenty storey parametric model of Id 20x20. As a result, if the number of storey in parametric model Id increases, the maximum soft storey coefficient will gradually increase in each parametric model of Id. In addition, when the stiffness irregularity coefficient calculated by the storey above or below is compared, it is observed that stiffness irregularity coefficient has higher values for the ratio below than the ratio above. Besides, it is found that this irregularity was seen on the first storey of each sub models of Id.

### 5.1.5. Parametric Model Ie: Shear-Frame System (3)

In this model, the structure has been designed as a shear-frame system like the parametric models Ic and Id. Apart from the parametric model Ic, the rigid core is removed in parametric model Ie. Shear walls having L-shape are located on the corners of the structure (Figure 5.5). The effects of shear walls which are located on the corners of the structure are investigated without a central rigid core. The behaviour of the structure against earthquake loads are evaluated on basis of the structural irregularity coefficients.



(a)

(b)

(c)

Figure 5.5. Structural plans of parametric model Ie
a) Ie 20x20, b) Ie 20x30, c) Ie 20x50

Table 5.6. Analysis results of parametric model Ie

| | **Storey** | (δi)max | δ max/hi≤0.02 | θ≤0.12 | ηbi<1.20 | ηki<2.00 |
|---|---|---|---|---|---|---|
| Ie 20x20 | 1S | 0.33 | 0.0001 | 0.0001 | 1.06 | - |
| | 3S | 1.65 | 0.0006 | 0.0005 | 1.07 | 1.62 |
| | 5S | 4.17 | 0.0015 | 0.0013 | 1.08 | 1.87 |
| | 8S | 9.21 | 0.0034 | 0.0031 | 1.09 | 2.01 |
| | 10S | 10.78 | 0.0040 | 0.0046 | 1.10 | 2.06 |
| | 12S | 12.31 | 0.0046 | 0.0063 | 1.10 | 2.10 |
| | 15S | 14.60 | 0.0054 | 0.0093 | 1.10 | 2.14 |
| | 20S | 18.46 | 0.0068 | 0.0152 | 1.09 | 2.18 |
| Ie 20x30 | 1S | 0.44 | 0.0002 | 0.0001 | 1.08 | - |
| | 3S | 2.03 | 0.0008 | 0.0006 | 1.10 | 1.58 |
| | 5S | 4.91 | 0.0018 | 0.0016 | 1.12 | 1.80 |
| | 8S | 10.06 | 0.0037 | 0.0034 | 1.15 | 1.93 |
| | 10S | 11.69 | 0.0043 | 0.0050 | 1.16 | 1.98 |
| | 12S | 13.29 | 0.0049 | 0.0067 | 1.16 | 2.01 |
| | 15S | 15.53 | 0.0058 | 0.0098 | 1.16 | 2.04 |
| | 20S | 19.17 | 0.0071 | 0.0156 | 1.13 | 2.08 |
| Ie 20x50 | 1S | 0.61 | 0.0002 | 0.0002 | 1.11 | - |
| | 3S | 2.68 | 0.0010 | 0.0008 | 1.14 | 1.52 |
| | 5S | 6.05 | 0.0022 | 0.0019 | 1.17 | 1.72 |
| | 8S | 11.37 | 0.0042 | 0.0040 | 1.22 | 1.84 |
| | 10S | 13.14 | 0.0049 | 0.0057 | 1.23 | 1.88 |
| | 12S | 14.71 | 0.0054 | 0.0076 | 1.24 | 1.91 |
| | 15S | 17.01 | 0.0063 | 0.0106 | 1.23 | 1.94 |
| | 20S | 20.51 | 0.0076 | 0.0165 | 1.20 | 1.97 |

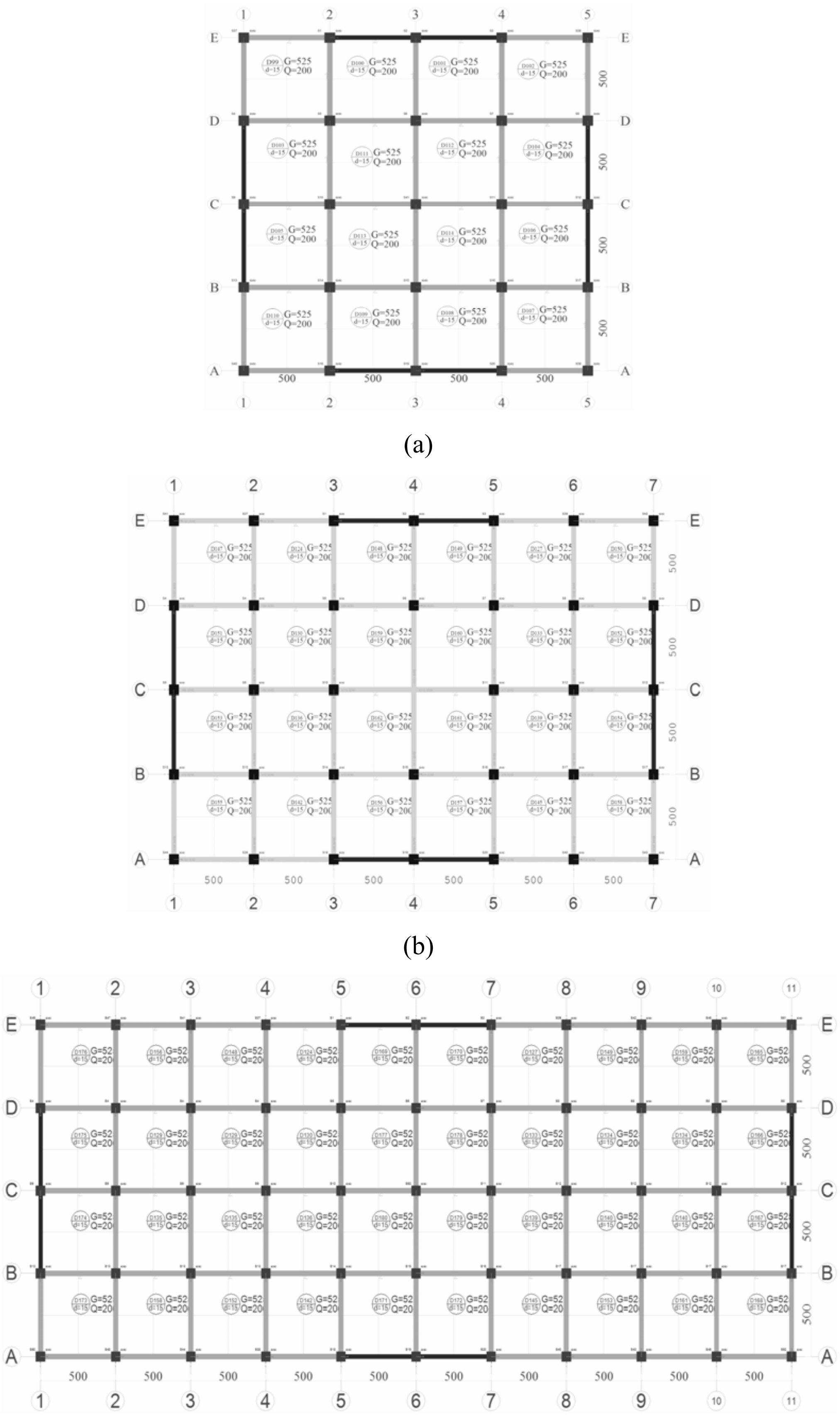
According to the structural irregularities report, while the maximum value of effective storey drift in parametric model Ie 20x20 is 18.46 mm, it is 19.17 mm in Ie 20x30 and 20.51 mm in Ie 20x50. The limit values in terms of interstorey drifts and second order effect have not been exceeded. All that values gradually increase from one storey structure up to twenty storey structure.

The maximum torsional irregularity coefficient (ηbi) obtained as 1.10 in Ie 20x20, 1.16 in Ie 20x30 and 1.24 in Ie 20x50. It is observed that if the number of storey in parametric models Ie increases, the maximum torsional irregularity coefficients and the coefficients in each storey for different storied parametric models of Ie gradually increase from ground floor to upper floors. Besides, torsional irregularity coefficients increase from parametric model Ie 20x20 to Ie 20x50. Accordingly, it can be deduced from the analysis that if the number of axis increases in parametric model Ie, the torsional irregularity coefficients will increase. While there is not torsional irregularity in Ie 20x20 and Ie 20x30, it is observed in Ie 20x50.

Stiffness irregularity coefficient ($\eta_{ki}$) shows large value range in the parametric models of Ie. The range varies between 1.62 and 2.18 in Ie 20x20, 1.58 and 2.08 in Ie 20x30 and 1.52 and 1.97 in Ie 20x50. There is a decrease in the maximum stiffness irregularity coefficient from Ie20 to Ie50. As evidence, while there is stiffness irregularity in Ie 20x20 and Ie 20x30, there is not stiffness irregularity in any parametric model of Ie 20x50. The maximum stiffness irregularity coefficient obtained as2.18 in twenty storey parametric model of Ie 20x20. As results, if the number of storey in parametric model Ie increases, the maximum soft storey coefficient will gradually increase in each parametric model of Ie. On the other hand, the stiffness irregularity coefficient based on the calculation with above storey shows lesser soft storey irregularity coefficients than the calculation with below storey. At the same time, it is realized that this irregularity was seen on the first storey of each parametric model of Ie. The value ranges depending on the comparison parameters are given comprehensively in Table 5.6.

### 5.1.6. Parametric Model of If: Shear-Frame System (4)

The parametric model If has been designed as a shear-frame system like parametric model Id. The only difference between the parametric model Id and If is the central rigid core. It is removed from the parametric model If (Figure 5.6). I-shaped shear walls are located in the middle of the outer axis of the structure. Earthquake behaviour of these kinds of systems is investigated by changing the number of stories and the number of axis in X direction. Analysis results which are shown in Table 5.7 are discussed by reviewing each result of If 20x20, If 20x30 and If 20x50.



(a)

(b)

(c)

Figure 5.6. Structural plans of parametric model If
a) If 20x20, b) If 20x30, c) If 20x50

Table 5.7. Analysis results of parametric model If

| | **Storey** | (δi)max | δ max/hi≤0.02 | θ≤0.12 | ηbi<1.20 | ηki<2.00 |
|---|---|---|---|---|---|---|
| If 20x20 | 1S | 0.36 | 0.0001 | 0.0001 | 1.06 | - |
| | 3S | 1.84 | 0.0007 | 0.0006 | 1.07 | 1.65 |
| | 5S | 4.56 | 0.0017 | 0.0015 | 1.08 | 1.89 |
| | 8S | 9.72 | 0.0036 | 0.0034 | 1.10 | 2.02 |
| | 10S | 11.39 | 0.0042 | 0.0050 | 1.12 | 2.07 |
| | 12S | 13.09 | 0.0048 | 0.0068 | 1.13 | 2.11 |
| | 15S | 15.55 | 0.0058 | 0.0100 | 1.14 | 2.15 |
| | 20S | 19.65 | 0.0073 | 0.0162 | 1.15 | 2.19 |
| If 20x30 | 1S | 0.47 | 0.0002 | 0.0001 | 1.08 | - |
| | 3S | 2.26 | 0.0008 | 0.0007 | 1.10 | 1.61 |
| | 5S | 5.41 | 0.0020 | 0.0017 | 1.12 | 1.83 |
| | 8S | 10.70 | 0.0040 | 0.0038 | 1.15 | 1.95 |
| | 10S | 12.51 | 0.0046 | 0.0056 | 1.17 | 2.00 |
| | 12S | 14.25 | 0.0053 | 0.0075 | 1.18 | 2.03 |
| | 15S | 16.71 | 0.0062 | 0.0108 | 1.19 | 2.07 |
| | 20S | 20.58 | 0.0076 | 0.0170 | 1.19 | 2.10 |
| If 20x50 | 1S | 0.64 | 0.0002 | 0.0002 | 1.11 | - |
| | 3S | 2.87 | 0.0011 | 0.0009 | 1.15 | 1.54 |
| | 5S | 6.37 | 0.0024 | 0.0020 | 1.19 | 1.73 |
| | 8S | 11.75 | 0.0044 | 0.0042 | 1.24 | 1.84 |
| | 10S | 13.50 | 0.0050 | 0.0058 | 1.26 | 1.88 |
| | 12S | 15.14 | 0.0056 | 0.0078 | 1.27 | 1.90 |
| | 15S | 17.42 | 0.0065 | 0.0108 | 1.28 | 1.93 |
| | 20S | 20.87 | 0.0077 | 0.0165 | 1.26 | 1.96 |

Depending on the obtained coefficients from the earthquake analysis report of structural irregularities, though the maximum value of effective storey drift in parametric model If 20x20 varies between 0.36 and 19.65 mm, it varies between 0.47 and 27.58 mm in If 20x30 and 0.64 and 20.87 mm in If 20x50. The limit values of interstorey drifts and second order effect have not been exceeded. These values also gradually increase from one storey structure to twenty storey structure. Moreover, they are all increase from ground floor to upper floors in parametric models of If 20x20, If 20x30 and If 20x50 (Table 5.7).

The maximum torsional irregularity coefficient ($\eta_{bi}$) is 1.15 in If 20x20, 1.19 in If 20x30 and 1.28 in If 20x50. It is observed that if the number of storey of the parametric models in If increases, the maximum torsional irregularity coefficients will increase. Besides, it increases from parametric model If 20x20 to If 20x50. As results, it can be concluded that if the number of axis increase in parametric model of If, the torsional irregularity coefficients will increase. While there is not torsional irregularity in If 20x20 and If 20x30, there is torsional irregularity in If 20x50.

Stiffness irregularity coefficient ($\eta_{ki}$) has considerable coefficients in parametric models of If. The coefficients vary between 1.65 and 2.19 in If 20x20, 1.61 and 2.10 in If 20x30 and 1.54 and 1.96 in If 20x50. There is a decrease in the maximum stiffness irregularity coefficient from If 20x20 to If 20x50. While there is stiffness irregularity in If 20x20 and If 20x30, there is not observed stiffness irregularity in If 20x50. The maximum stiffness irregularity coefficient is obtained as 2.19 in twenty storey sub model of If 20x20. Furthermore, it is noticed that if the number of storey in parametric model of If increase, the maximum soft storey coefficient will gradually increase in each parametric model of If. On the other hand, it is observed that the stiffness irregularity coefficient has higher values for the ratio below than the ratio above. Besides, it is realized that the stiffness irregularity was occurred on the first storey in sub models if having soft storey irregularity.

### 5.1.7. Discussion and Results of Case I

In this case, a set of 6 main models and their sub-models which were generated by changing the number of axis number, storey and the RC structural system type were analyzed in terms of earthquake behaviour on bases of the structural irregularities. All models were created as to have both symmetric plan geometry and rigidity distribution. The aim of this case was to investigate the seismic behaviour of completely symmetrical structures in terms of plan geometry and rigidity distribution. R/C structural system types which are commonly constructed in Turkey are grouped and the models are created for each type. The results were discussed according to the several criteria containing torsional irregularity coefficient, soft storey coefficient, effective storey drifts, interstorey drifts and second order effects. On the basis of the carried out numerical analysis in case I for the different type of R/C models the following conclusions could be drawn up:

- If the number of axis increases, the torsional irregularity coefficients increase in all parametric models and their sub models in case I. On the other hand, it is observed that while the torsional irregularity shows a regular increase between the own stories of each different storied parametric models, in contrast in some models it shows a regular decrease or an unbalanced increase or decrease under earthquake loading.
- The parametric model Ic which consists of a central rigid core and L-shaped shear walls on the corners of the building show similar seismic performance with the parametric model Id which have I-shaped shear walls in the middle of the outer axis of the structure. While the maximum torsional irregularity coefficient is obtained 1.23 in parametric model Ic, it is 1.25 in parametric model Id. On the other hand, both of the models have the same maximum soft storey irregularity coefficient, 2.28. Moreover, the parametric model Ie which consists of L-shaped parametric model without a central rigid core behaves similarly against earthquake loads with the parametric model If which consists of I-shaped shear walls in the middle of the outer axis of the structure without a central rigid core.
- The direction of the vertical structural member's has a significant effect on the earthquake behaviour of the structures. There is no doubt if the rigidity distributions in the system arranged randomly in both of the earthquake direction, the structure will failure on the flexible side. Distributions of the structural member's regularly in both earthquake directions improve the seismic behaviour of the structure (Case II).
- It can be deduced from the analysis that shear-frame systems with a central rigid core show better seismic performance than the shear-frame systems without a central rigid core.
- It is observed that the models designed as frame systems (parametric model Ia) shows acceptable torsional irregularity coefficients. However, a central rigid core added to the system, the structures expose to high torsional irregularity coefficients like in sub models of Ib.

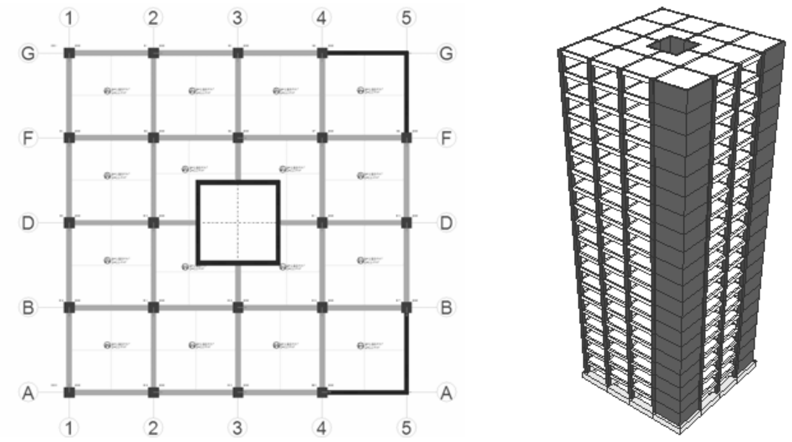
- The models which have shear walls on the corner of the structure shows better seismic performance rather than the models which have shear walls in the middle of the outer axis.
- It is gained that except the models consisting only frame systems, the soft storey irregularity coefficient will increase if the number of axis in models increases.
- While the lowest soft storey irregularity coefficient is observed in sub models of parametric model Ia, the critical ones are observed in Ic and Id. On the other hand, the parametric model Ie and If show similar earthquake behaviour in terms of soft storey irregularity. While the sub models of Ie 20x20, Ie 20x30, If 20x20 and If 20x30 have soft storey irregularity, there is not observed soft storey irregularity in sub models of Ie 20x50 and If 20x50.
- The limit values for effective storey drifts and second order effects have not been exceeded in all the models of case I.
- Increasing rigidity in the structure is not enough by itself to provide earthquake resistance in structures. The usage of shear walls significantly support the earthquake behaviour of structures provided that they are correctly placed in the structure even placed symmetrical. For instance, although the parametric model Ia has not torsional irregularity, the model Ib expose to the torsion due to the incorrectly placed shear walls. The rigid core is located in the centre of the structure in symmetrical structure close to the gravity centre. Therefore, it causes the torsional irregularity. Shear walls should be located on the outer axis of the structures or distant from the gravity centre as possible.
- Sufficiency in rigidity of a structure can change according to the number of storey and axis of the structure. Therefore, excessive usage of shear walls does not an indicator of excessive resistant structure against earthquake loads in other words it does not mean the best earthquake resistant building.
- Despite the symmetrical plan geometry and rigidity distribution, structural elements type, their location in the plan and their sufficiency in terms of rigidity, strength and stability according to the each system created in Case I play the most effective role in earthquake behaviour of structures.

## 5.2. Case II: R/C Structural Systems: Asymmetric Configuration (A1)

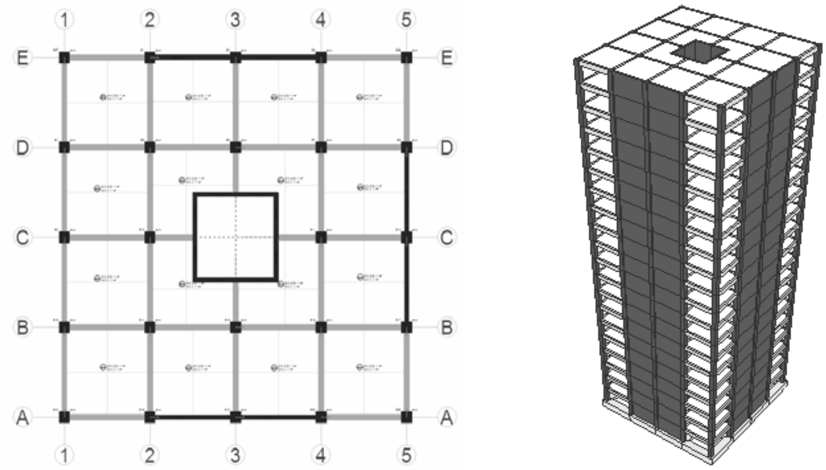
In this case, the effects of asymmetric rigidity distribution on torsional irregularity coefficients were examined. It was questioned that how they affect the torsional irregularity coefficients despite the regular plan geometry. Besides, the effects of overhangs on earthquake behaviour of structures were investigated depending on their direction.

The models were chosen from the case I which has regular rigidity distribution and plan geometry. Among the parametric models of case I, only the square plan geometry consisting shear-frame systems (Ic 20x20, Id 20x20, Ie 20x20 and If 20x20) was chosen in order to discuss the effects of torsional irregularity. All models are accepted as having 20 stories with 2.80 m in height. The dimension of the overhang is 1.50 m. Square plan geometry was chosen due to its better seismic performance under earthquake loads than rectangular plan geometry. It shows the same inertia forces against the earthquake loads that come from any earthquake direction. In these models, the shear walls which are placed at the 1 axis are removed.

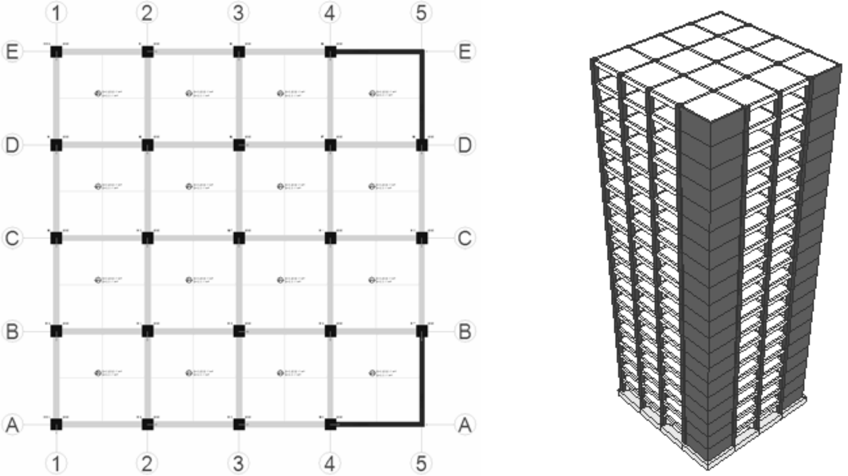
Apart from the mentioned models above, the model Ic 20x20 was chosen and designed as having closed one-sided overhang denoted as IIe, asymmetric two-sided overhang denoted as IIf, symmetric two sided overhang denoted as IIg, three-sided overhang denoted as IIh, and four-sided overhang denoted as IIi (Figure 5.7). In this way, the effects of overhangs were taken into consideration in the earthquake analysis. The parametric model Ic 20x 20 was chosen due to the its best earthquake behaviour. It was investigated that how overhangs can change the earthquake behaviour.



a) IIa



b) IIb



c) IIc

Figure 5.7. Structural plans of parametric models in case II

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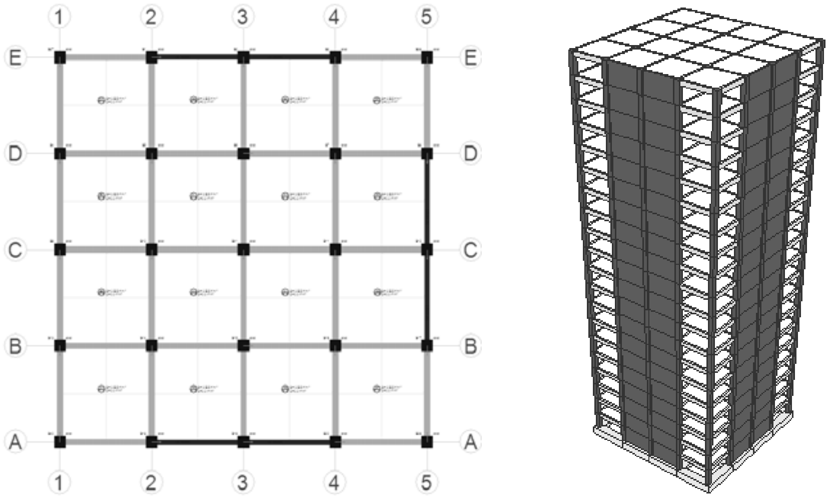
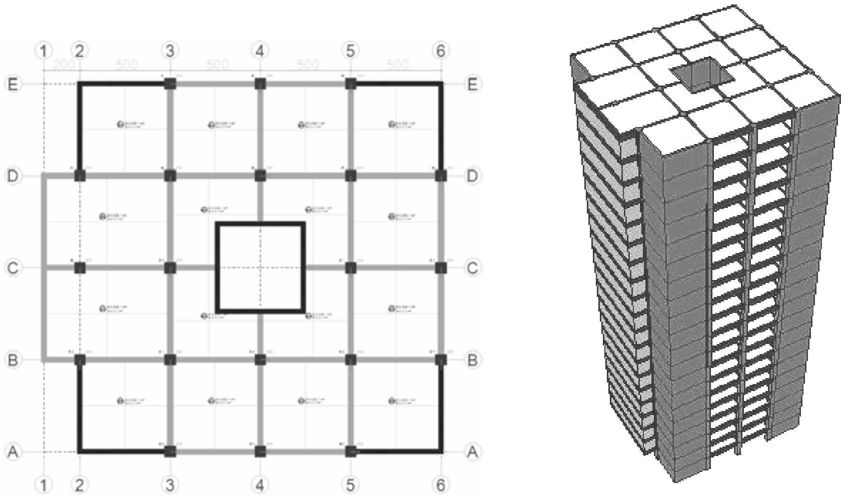
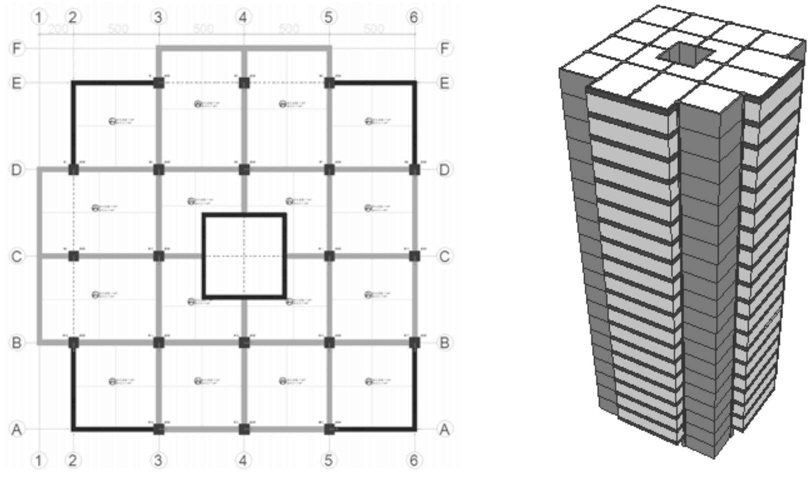


d) IId



e) IIe



f) IIf

Figure 5.7. (cont.)

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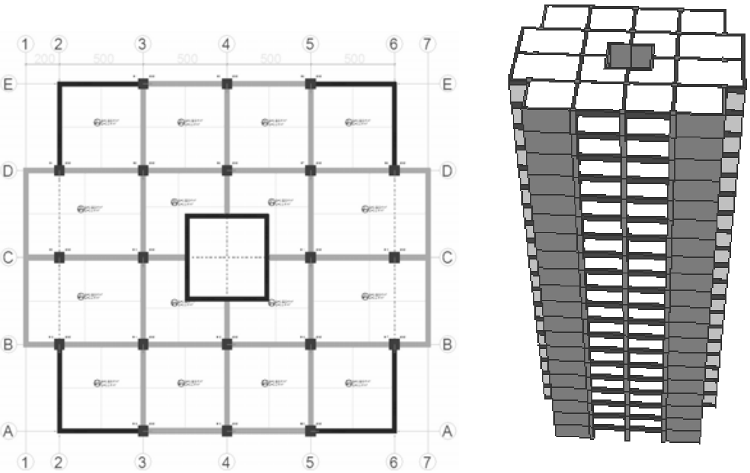
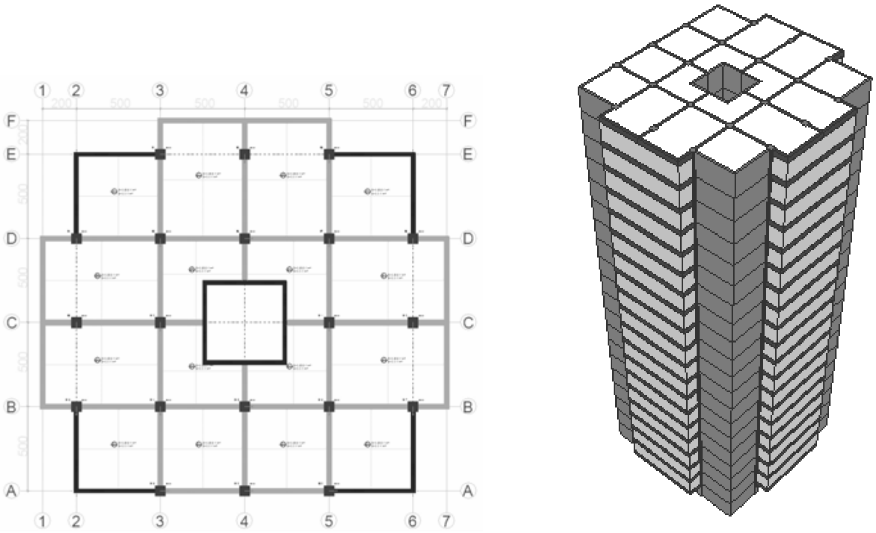
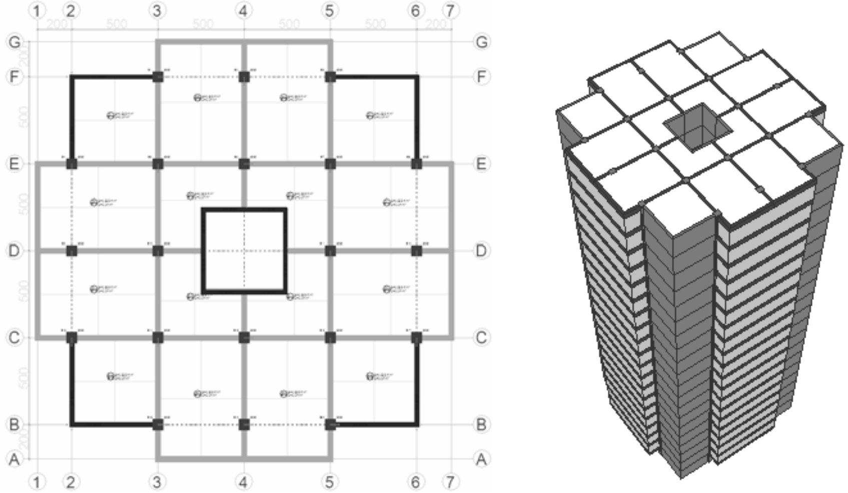


g) IIg



h) IIh



i) IIi

Figure 5.7. (Cont.)

### 5.2.1. Discussion and Results of Case II

A set of 9 models, 4 of which had irregular rigidity distribution and 5 of which had different sided overhangs were analyzed during the case II. The case focused on two main aims. The first one was to research the effects of irregular rigidity distribution on torsional irregularity coefficient despite the simple and symmetric plan geometry. The second one was to evaluate the effects of overhangs on torsional irregularity. The changes in the torsional irregularity coefficient were examined for the same plan geometry and different R/C structural configuration. On the basis of the attained results of numerical analysis in case II the following conclusions could be drawn up: (Table 5.8)

- The models which have regular rigidity distribution show lower torsional coefficients than the models which have irregular rigidity distribution.
- Torsional irregularity coefficients get very high level on irregular structures in terms of rigidity distribution.
- While there is not observed any torsional irregularity in all models which have regular rigidity distribution, On the other hand, there is torsional irregularity in all models which have irregular rigidity distribution.
- The structure shows favorable results against earthquake loads coming from symmetry direction of the structure rather than the earthquake loads coming from asymmetry direction. For instance, the earthquake direction of Y is the unfavorable direction for the models of IIa, IIb, IIc, and IId.
- Shear walls should be positioned symmetrically in order to provide similar rigidity distribution on both earthquake directions.
- The locations of shear walls affect the torsional irregularity coefficient although both of the structure have similar rigidity rate. For instance, while the model of IIa has a value of 1.61 torsional irregularity coefficients, the model of IId has a value of 2.65 torsional irregularity coefficients. There is a great difference between the two models in the torsional irregularity coefficients although they have similar rigidity rate.
- The lowest torsional coefficient was observed in model Ic 20x20 which have regular rigidity distribution. On the other hand, the highest torsional

irregularity coefficient was observed in model IId. Because, it has lower and irregular rigidity rate due to the asymmetrical distribution.

- It is attained from the analysis that regular rigidity distribution has a significant role on the torsional irregularity coefficient rather than the simple plan geometry.
- The building mass is proportional with earthquake loads. If overhangs added to the structure, the buildings mass increase. Therefore, it can be asserted that heavier buildings are exposed to greater earthquake loads than lighter buildings during the same earthquake.
- Overhang direction is quite important in terms of torsional irregularity coefficient. The minimum torsional irregularity coefficient among the models having overhangs was observed in model IIg which have two-sided symmetrical overhangs.
- The model IIe has lower building mass than IIg. However, it is symmetric according to only one axis. For this reason, it has higher torsional irregularity coefficient than the model IIg.
- The model IIf expose to higher torsional irregularity coefficient than the model IIg although they both have two-sided overhangs. Because, the model IIf has asymmetrical overhangs.
- The model IIi has four-sided overhangs. It is symmetrical according to the both earthquake direction. Therefore, it has lower torsional irregularity coefficients than the models having asymmetrical overhangs.
- The maximum torsional irregularity was observed in model IIh. Because it has both high building mass and asymmetrical three-sided overhangs.
- It is noticed from the analysis that there is no torsional irregularity in models of IIg and IIi which are symmetrical according to the both X and Y earthquake direction. On the other hand, there exists torsional irregularity in the models which have asymmetrical overhangs. The interaction between the direction of overhangs in terms of symmetry and building mass has a significant role on the torsional irregularity.

Table 5.8. Analysis results of case II

| | Irregular rigidity distribution | | | | Regular rigidity distribution | | | | Overhangs | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Storey** | IIa | IIb | IIc | IId | Ic 20x20 | Id 20x20 | Ie 20x20 | If 20x20 | IIe | IIf | IIg | IIh | IIi |
| 19 | 1.61 | 2.33 | 2.43 | 2.65 | 1.07 | 1.12 | 1.09 | 1.15 | 1.22 | 1.26 | 1.12 | 1.30 | 1.17 |
| 18 | 1.43 | 1.71 | 1.96 | 2.43 | 1.07 | 1.12 | 1.09 | 1.15 | 1.21 | 1.25 | 1.12 | 1.28 | 1.17 |
| 17 | 1.40 | 1.62 | 1.82 | 2.32 | 1.08 | 1.12 | 1.09 | 1.14 | 1.21 | 1.25 | 1.12 | 1.28 | 1.17 |
| 16 | 1.35 | 1.46 | 1.49 | 1.57 | 1.08 | 1.12 | 1.09 | 1.14 | 1.20 | 1.23 | 1.12 | 1.26 | 1.17 |
| 15 | 1.26 | 1.37 | 1.31 | 1.43 | 1.08 | 1.12 | 1.09 | 1.13 | 1.20 | 1.23 | 1.12 | 1.26 | 1.17 |
| 14 | 1.26 | 1.36 | 1.31 | 1.41 | 1.08 | 1.12 | 1.09 | 1.13 | 1.20 | 1.22 | 1.12 | 1.25 | 1.17 |
| 13 | 1.27 | 1.35 | 1.31 | 1.39 | 1.08 | 1.12 | 1.09 | 1.13 | 1.20 | 1.22 | 1.12 | 1.25 | 1.17 |
| 12 | 1.27 | 1.34 | 1.30 | 1.38 | 1.08 | 1.12 | 1.09 | 1.12 | 1.19 | 1.22 | 1.12 | 1.25 | 1.17 |
| 11 | 1.27 | 1.33 | 1.30 | 1.36 | 1.08 | 1.12 | 1.09 | 1.12 | 1.19 | 1.22 | 1.13 | 1.24 | 1.16 |
| 10 | 1.27 | 1.32 | 1.30 | 1.34 | 1.08 | 1.11 | 1.09 | 1.12 | 1.19 | 1.21 | 1.13 | 1.24 | 1.16 |
| 9 | 1.27 | 1.30 | 1.30 | 1.32 | 1.09 | 1.11 | 1.09 | 1.11 | 1.19 | 1.21 | 1.13 | 1.23 | 1.16 |
| 8 | 1.26 | 1.29 | 1.29 | 1.30 | 1.09 | 1.11 | 1.08 | 1.11 | 1.19 | 1.21 | 1.13 | 1.23 | 1.16 |
| 7 | 1.26 | 1.28 | 1.28 | 1.28 | 1.09 | 1.11 | 1.08 | 1.11 | 1.19 | 1.21 | 1.13 | 1.23 | 1.16 |
| 6 | 1.25 | 1.26 | 1.27 | 1.26 | 1.09 | 1.11 | 1.08 | 1.11 | 1.18 | 1.20 | 1.13 | 1.22 | 1.16 |
| 5 | 1.25 | 1.24 | 1.25 | 1.23 | 1.09 | 1.11 | 1.08 | 1.10 | 1.18 | 1.20 | 1.13 | 1.22 | 1.16 |
| 4 | 1.23 | 1.22 | 1.22 | 1.20 | 1.09 | 1.11 | 1.08 | 1.10 | 1.18 | 1.19 | 1.13 | 1.21 | 1.15 |
| 3 | 1.22 | 1.20 | 1.19 | 1.16 | 1.09 | 1.11 | 1.08 | 1.10 | 1.17 | 1.19 | 1.13 | 1.20 | 1.15 |
| 2 | 1.19 | 1.17 | 1.14 | 1.11 | 1.09 | 1.10 | 1.08 | 1.09 | 1.17 | 1.18 | 1.13 | 1.20 | 1.15 |
| 1 | 1.16 | 1.13 | 1.07 | 1.05 | 1.09 | 1.10 | 1.08 | 1.09 | 1.16 | 1.17 | 1.13 | 1.19 | 1.15 |
| Ground | 1.09 | 1.06 | 1.04 | 1.03 | 1.09 | 1.10 | 1.07 | 1.08 | 1.15 | 1.16 | 1.12 | 1.17 | 1.14 |

## 5.3. Case III: Floor Discontinuity (A2)

In this case, TEC (2007) has been studied in terms of floor discontinuity (A2). The effect of A2 irregularity condition is examined according to the variety in the floor space rate and different location of shear walls. It is essential to understand the simple idealized mathematical model for understanding the behavior of a real complex building against earthquake loads.

The case consists of 9 main models and with sub-models it totally composes of 72 models. The parametric models comprise of both low-storied R/C structure such as three-storied, five- storied, eight-storied and multi-storied R/C structure such as ten-storied, twelve-storied, fifteen-storied and twenty-storied buildings.

The plan has 4 bays with 5 m span in both directions. Floors consist of R/C slabs of 0.15 m in thickness, except the floor openings which are differently placed to the floors to represent the effect of the gallery space, stairs and elevator in the building. Floor heights are taken as 2.8 m at all floors although in Turkey the bottom floors are typically used as shops having high storey height. In this way, it is aimed to only compare the effects of A2 floor discontinuity by holding constant the other variables as possible. The building is assumed to be in the first degree earthquake zone and located in the Z2 soil class defined in the TEC (2007) (Table 4.2 & Table 4.3). The structural elements in parametric models of case 3 are designed by using C25 class concrete and S420 class steel described in the TS-500 standard. The project and TEC (2007) parameters of the models are given in detail at the beginning of Chapter 5 (Table 5.1).

All models were examined according to the comparison criteria of structural irregularities described in Chapter 3 and 4. These are listed as structural irregularity coefficients such as torsional irregularity coefficient and soft storey coefficient, effective storey drifts, interstorey drifts and second order effects.

### 5.3.1. Parametric Model IIIa

In this model, storey gross area is A=$20\times20$= 400m$^2$ and floor opening area is A$_{fo}$=$4\times5\times5$=100m$^2$. Floor opening ratio is $A_{fo}/A=0.25$. Floor discontinuity does not exist for the floor discontinuity ratio is defined as 0.333 in the TEC (2007) and the parametric model IIIa did not exceed that ratio. In this model, shear walls were placed to the middle of the outer axes. The model has four floor openings which are left on the corners of the parametric model IIIa (Figure 5.8).

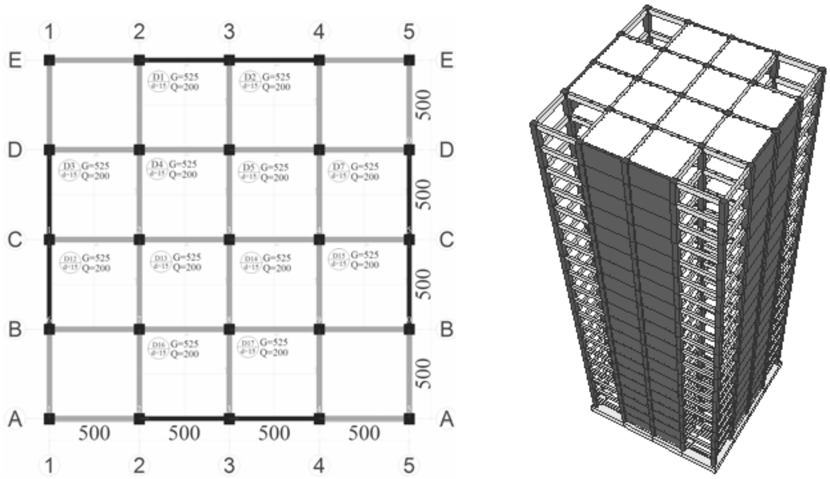


Figure 5.8.Structural plan and 3D view of parametric model IIIa

Table 5.9 Analysis results of parametric model IIIa

| **Storey** | (δi)max | δ max/hi≤0.02 | θ≤0.12 | ηbi<1.20 | ηki<2.00 |
|---|---|---|---|---|---|
| 1S | 0.32 | 0.0001 | 0.0001 | 1.06 | - |
| 3S | 1.66 | 0.0006 | 0.0005 | 1.07 | 1.66 |
| 5S | 4.16 | 0.0015 | 0.0013 | 1.08 | 1.91 |
| 8S | 9.20 | 0.0034 | 0.0031 | 1.11 | 2.05 |
| 10S | 10.78 | 0.0040 | 0.0045 | 1.12 | 2.09 |
| 12S | 12.35 | 0.0046 | 0.0062 | 1.13 | 2.13 |
| 15S | 14.65 | 0.0054 | 0.0091 | 1.15 | 2.17 |
| 20S | 18.43 | 0.0068 | 0.0147 | 1.16 | 2.21 |

Based on the earthquake analysis report, maximum value of effective storey drift in parametric model IIIa is obtained between 0.32 and 18.43mm. The limit values in terms of interstorey drifts and second order effect have not been exceeded. All that coefficients gradually increase from one storey structure to twenty storey structure. Moreover, they evenly increase for each storey of the parametric models of IIIa (Table 5.9).

Following the analysis, it is observed that the most negative torsional irregularity coefficient ($\eta bi$) is 1.16 in twenty storey sub model of IIIa. Therefore, the torsional irregularity coefficient is under the limit value of 1.20. For this reason, there is no torsional irregularity in sub models of parametric model IIIa. It is inferred from the analysis that the maximum torsional irregularity coefficient will gradually increase from one storey model to twenty storey model. Besides, it takes greater coefficients toward upper floors within the own stories of each sub models of IIIa.

Stiffness irregularity coefficient or soft storey irregularity coefficient ($\eta ki$) shows considerable value range in parametric models of IIIa. The range varies between 1.66 and 2.21 from three storey building to twenty storey building. There is an available soft storey coefficient in the three storey and five storey sub models of IIIa because the limit value for soft storey irregularity coefficient, 2.0 defined in the TEC (2007) has not been exceeded. It began to be exceeded in eight storey parametric model of IIIa and gradually increase toward twenty storey sub model of IIIa. The most critical soft storey coefficient is calculated as 2.21 in twenty storey sub model of IIIa. Moreover, it was usually observed on the first and second storey of each parametric model of IIIa.

Stiffness irregularity coefficient is the ratio of average storey drifts to the average storey drift at the storey above or below. When this two ratio is compared it is observed that stiffness irregularity coefficient has higher values based on the calculation with below than the ratio above storey. For instance, although the most critical soft storey coefficient created by the ratio with below storey is calculated as 2.21, the soft storey coefficient created by the ratio with above is calculated under the limit value of 2.00.

## 5.3.2. Parametric Model IIIb

In this model, storey gross area, floor opening area and the location of the floor opening area are kept as the same size with the parametric model of IIIa. Floor opening area is preserved as 25%. The only difference created in the model is to change the location of the shear walls. The shear walls are removed from the middle of the A-A, E-E, 1-1 and 5-5 axes to the corners of the structure where the floor openings are placed (Figure 5.9). Floor discontinuity (A2) does not exist in the model because floor discontinuity ratio did not exceed the coefficient of 0.333 defined in the TEC (2007).

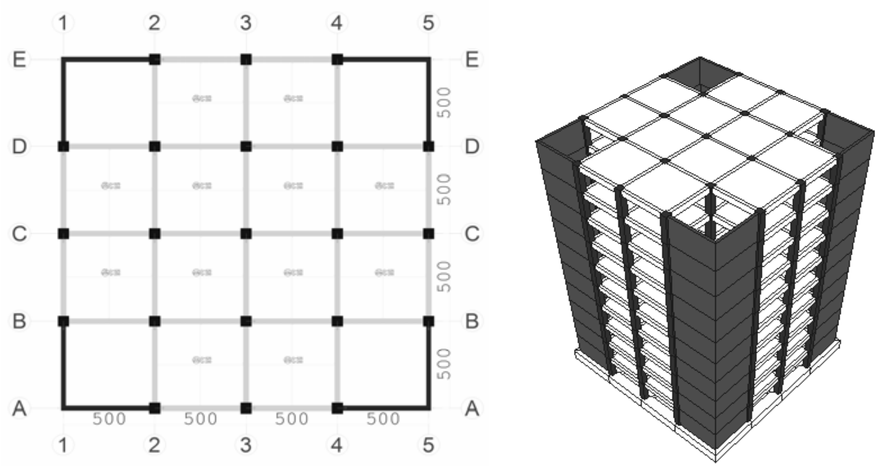


Figure 5.9 Structural plan and 3D view of parametric model IIIb

Table 5.10 Analysis result of parametric model IIIb

| **Storey** | (δi)max | δ max/hi≤0.02 | θ≤0.12 | ηbi<1.20 | ηki<2.00 |
|---|---|---|---|---|---|
| 1S | 1.63 | 0.0006 | 0.0005 | 1.13 | - |
| 3S | 5.97 | 0.0022 | 0.0018 | 1.14 | 1.50 |
| 5S | 11.31 | 0.0042 | 0.0038 | 1.13 | 1.66 |
| 8S | 14.90 | 0.0055 | 0.0068 | 1.13 | 1.62 |
| 10S | 16.13 | 0.0060 | 0.0088 | 1.13 | 1.54 |
| 12S | 17.07 | 0.0063 | 0.0108 | 1.13 | 1.55 |
| 15S | 18.24 | 0.0068 | 0.0139 | 1.13 | 1.57 |
| 20S | 19.97 | 0.0074 | 0.0196 | 1.13 | 1.58 |

Depending on the earthquake analysis report, the maximum value of effective storey drift in parametric model IIIb is obtained a value range between 1.63 and 19.97 mm. The limit values in terms of interstorey drifts and second order effect have not been exceeded defined in the TEC (2007). These values gradually increase from one storey structure up to twenty storey structure.

The maximum torsional irregularity coefficients ($\eta bi$) in parametric model IIIb is obtained as 1.14. It is less than the limit value of 1.20. For that reason, there is no torsional irregularity in sub models of IIIb. Additionally, it is realized that if the storey number of the parametric model of IIIb increase, the maximum torsional irregularity coefficient will increase in each different storied sub models of IIIb (Table 5.10).

Stiffness irregularity coefficient or soft storey irregularity coefficient ($\eta ki$) shows normal ranges in parametric models of IIIb. The range varies between 1.50 and 1.62 from three storey building to twenty storey building. There is a favorable soft storey coefficient in all sub models of IIIb, for the limit value of 2.00 defined in the TEC (2007) has not been exceeded. The highest soft storey coefficient is calculated as 1.66 in five storeyed parametric model of IIIb. There is not a balanced increase or decrease in the maximum soft storey coefficient among sub models of IIIb.

The stiffness irregularity coefficient takes higher values for the calculation by above storey than the below storey. The maximum soft storey coefficient calculated with below storey is 1.45 in five storey parametric model of IIIb. The highest coefficient is 1.66. It is under the limit coefficient of 2.00.Consequently, there is no soft storey irregularity.

### 5.3.3. Parametric Model IIIc

In this model, the location of the shear walls is designed as similar with the parametric model IIIa. Different from the parametric model IIIa, a rigid core is joined to the center of the structure in parametric model IIIc (Figure 5.10). This naturally leads to an increase in the floor opening area. Storey gross area is kept as the same size with other models. Floor opening area increases from 25% to 31%. Because, the floor opening ratio is $A_{f0} / A = 125 / 400 = 0.31$. However, this increase does not cause floor discontinuity (A2), for floor discontinuity ratio did not exceed the coefficient of 0.333 defined in the TEC (2007).

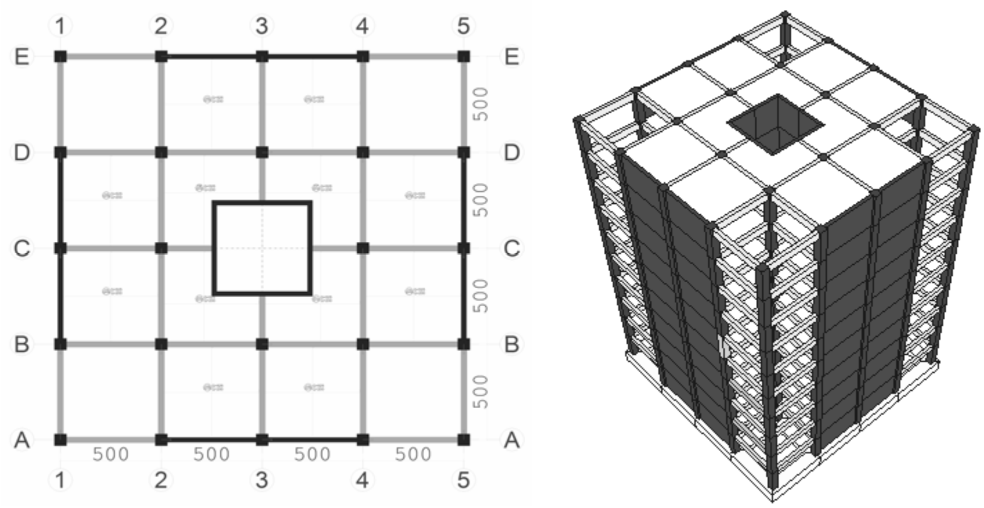


Figure 5.10.Structural plan and 3D view of parametric model IIIc

Table 5.11. Analysis results of parametric model IIIc

| **Storey** | (δi)max | δ max/hi≤0.02 | θ≤0.12 | ηbi<1.20 | ηki<2.00 |
|---|---|---|---|---|---|
| 1S | 0.24 | 0.0001 | 0.0001 | 1.08 | - |
| 3S | 0.49 | 0.0005 | 0.0004 | 1.09 | 1.67 |
| 5S | 3.39 | 0.0013 | 0.0010 | 1.10 | 1.95 |
| 8S | 8.07 | 0.0030 | 0.0026 | 1.11 | 2.11 |
| 10S | 10.13 | 0.0038 | 0.0039 | 1.12 | 2.17 |
| 12S | 11.75 | 0.0044 | 0.0055 | 1.13 | 2.21 |
| 15S | 14.20 | 0.0053 | 0.0083 | 1.13 | 2.25 |
| 20S | 18.46 | 0.0068 | 0.0141 | 1.13 | 2.30 |

Following the analysis, the maximum value of effective storey drift in parametric model IIIc is obtained between 0.24 and 18.46 mm. The limit values in terms of interstorey drifts and second order effect have not been exceeded. All that values gradually increase from one storey structure to twenty storey structure (Table 5.11).

The unfavorable torsional irregularity coefficient is noticed as 1.13 in parametric model IIIc. It is under the limit value of 1.20. As a result, there is no torsional irregularity in parametric model IIIc. Furthermore, it is realized that if the number of storey in parametric model IIIc increase, the maximum torsional irregularity coefficient will gradually increase in each different storied sub models of IIIc. Besides, it increases from ground floor to upper floors within the own stories of each different storied sub models of parametric model IIIc.

Stiffness irregularity coefficient or soft storey irregularity coefficient ($\eta_{ki}$) shows considerable coefficients in parametric model IIIc. There is a value range between 1.67 and 2.30 from three storey building to twenty storey building. There is an agreeable soft storey coefficient in three storey and five storey sub models of IIIc since the limit value for soft storey irregularity, 2.00 defined in the TEC (2007) has not been transcended. It begins to be exceeded in eight storey sub model of IIIc and gradually increase towards twenty storey sub model of IIIc. The most critical soft storey coefficient is calculated as 2.30 in twenty storey sub model of IIIc.

The stiffness irregularity coefficients depending on the below storey take higher values as compared with above storey. Based on the soft storey checks, it is noticed that while the parametric model IIIc have soft storey according to the calculation with below storey, there is no soft storey calculated with above storey. Moreover, the soft storey irregularity is discovered on the first storey in sub models of IIIc which have soft storey irregularity. Additionally, it is realized that if the storey number of the parametric model of IIIc increase, the maximum soft storey coefficient will gradually increase in each different storied sub models of IIIc.

### 5.3.4. Parametric Model IIId

In parametric model IIId, the shear walls are placed on the corners of the model as in parametric model IIIb. As distinct from the parametric model IIIb, a rigid core is added to the center of the structure (Figure 5.11). This application does not naturally cause any change in the floor opening area as it is compared with the model IIIc. It has a value of 31 % floor opening area which does not cause floor discontinuity. Storey gross area has same size with other models.

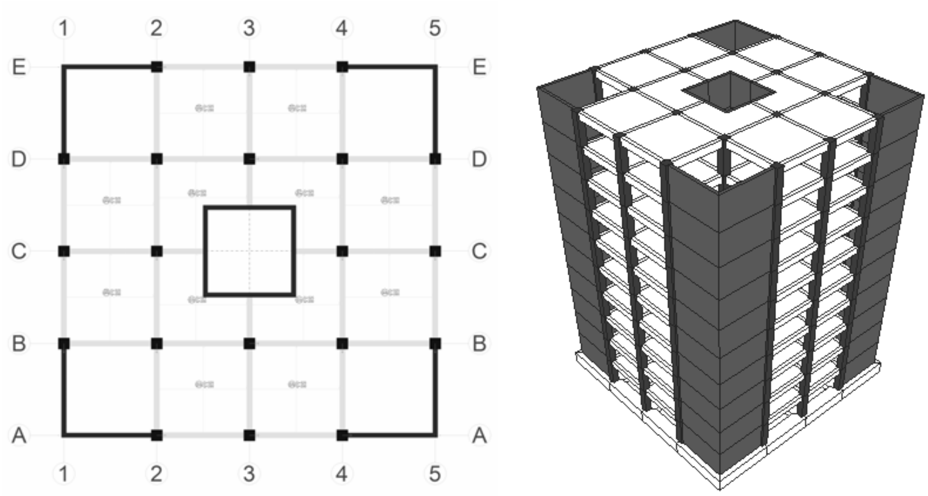


Figure 5.11.Structural plan and 3D view of parametric model IIId

Tablo 5.12. Analysis results of parametric model IIId

| **Storey** | (δi)max | δ max/hi≤0.02 | θ≤0.12 | ηbi<1.20 | ηki<2.00 |
|---|---|---|---|---|---|
| 1S | 0.63 | 0.0002 | 0.0001 | 1.35 | - |
| 3S | 2.62 | 0.0010 | 0.0007 | 1.31 | 1.54 |
| 5S | 5.66 | 0.0021 | 0.0017 | 1.29 | 1.75 |
| 8S | 10.83 | 0.0040 | 0.0036 | 1.28 | 1.87 |
| 10S | 12.38 | 0.0046 | 0.0053 | 1.27 | 1.92 |
| 12S | 13.83 | 0.0051 | 0.0071 | 1.26 | 1.95 |
| 15S | 15.96 | 0.0059 | 0.0102 | 1.26 | 1.99 |
| 20S | 19.50 | 0.0072 | 0.0162 | 1.25 | 2.03 |

Concerning on the earthquake analysis, the maximum value of effective storey drift in parametric model IIId is obtained between 0.63 and 19.50 mm. The limit values in terms of interstorey drifts and second order effect have not been exceeded. These values gradually increase from one storey structure to twenty storey structure.

The most critic torsional irregularity coefficient is found as 1.35 in one storey sub model of IIId. It transcends the limit value of 1.20. Therefore, there is torsional irregularity in parametric model IIId. Moreover, it is observed that if the number of storey in parametric model IIId increase, the maximum torsional irregularity coefficient will gradually decrease from one storey sub model IIId to twenty storey sub model of IIId

Stiffness irregularity coefficient ($\eta_{ki}$) shows significant value ranges in parametric model IIId. The range varies between 1.54 and 2.03 from three storey sub models to twenty storey sub models. The soft storey coefficient is not exceeded the limit value of 2.00 except twenty storey sub model of IIId. It is calculated as 2.03 in twenty storey sub model of IIId. Moreover, it is noticed that the soft storey irregularity observed in the first storey of twenty storey sub model of IIId. Besides, it gradually increases towards twenty storey sub models of IIId.

The calculations for the stiffness irregularity made with above storey show lower soft storey coefficients than the calculations with below storey. They take values which are under the limit value of 2.00. The highest soft storey coefficient calculated with above storey is 1.14. Besides, it is observed that if the number of storey in parametric model IIId increase, the maximum soft storey coefficient will gradually increase towards upper floors. On the other hand, it gradually decreases toward upper floors within the own stories of each different storied sub models of IIId (Table 5.12).

### 5.3.5 Parametric Model IIIe

In this model, the locations of shear walls are designed as parametric model IIIa. Apart from parametric model IIIa, floor openings are placed in front of the shear walls which are located in the middle of the outer axes of the structure in parametric model IIIe. It is shown in Figure 5.12. The rate of floor opening area is increased from 25 % to 50 %. This condition creates floor discontinuity in the parametric model because the limit value for floor discontinuity defined in the TEC (2007) as 33% is exceeded. Excessive openings in the floors are left in this model. Through this model, the effects of floor openings rate to the A2 irregularity are investigated. Storey gross area is kept as same size with other models.

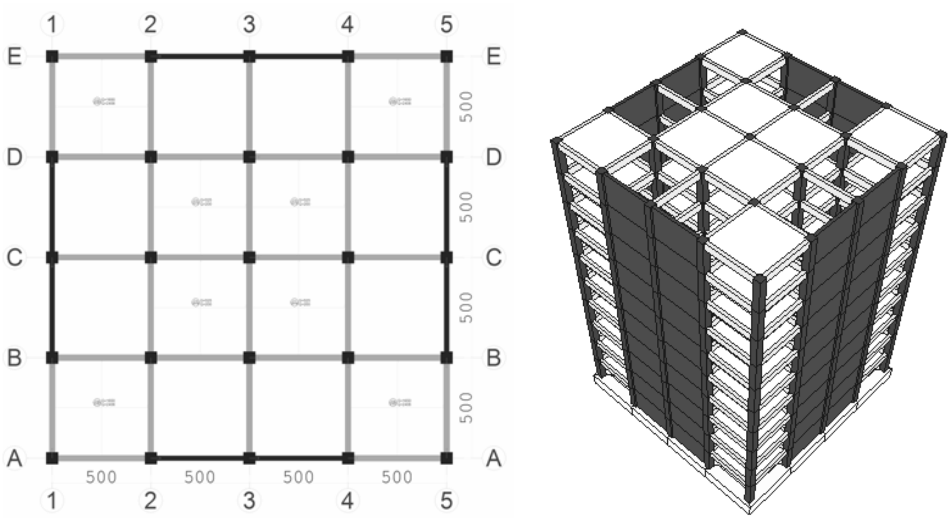


Figure 5.12.Structural plan and 3D view of parametric model IIIe

Table 5.13. Analysis results of parametric model IIIe

| **Storey** | (δi)max | δ max/hi≤0.02 | θ≤0.12 | ηbi<1.20 | ηki<2.00 |
|---|---|---|---|---|---|
| 1S | 0.32 | 0.0001 | 0.0001 | 1.06 | - |
| 3S | 1.68 | 0.0006 | 0.0005 | 1.07 | 1.66 |
| 5S | 4.22 | 0.0016 | 0.0014 | 1.08 | 1.91 |
| 8S | 9.29 | 0.0034 | 0.0032 | 1.10 | 2.05 |
| 10S | 10.91 | 0.0040 | 0.0047 | 1.11 | 2.10 |
| 12S | 12.51 | 0.0046 | 0.0064 | 1.12 | 2.13 |
| 15S | 14.89 | 0.0055 | 0.0094 | 1.13 | 2.17 |
| 20S | 18.83 | 0.0070 | 0.0153 | 1.15 | 2.21 |

The maximum value of effective storey drift in parametric model IIIe is obtained as a value range between 0.32 and 18.83 mm. The limit values in terms of interstorey drifts and second order effect have not been exceeded. All that values gradually increase from one storey structure to twenty storey structures.

Following the earthquake analysis, the maximum torsional irregularity coefficient (ηbi) in parametric model IIIe is 1.15. It can decrease up to 1.06 within the different storied sub models of IIIe. The torsional irregularity coefficient is under the limit value of 1.20. As a result of that condition, there is no torsional irregularity in parametric model IIIe. Moreover, it is observed that if the number storey in parametric model of IIIe increases, the maximum torsional irregularity coefficient will gradually increase in each different storied sub models of IIIe. Besides, it increases toward upper floors within the own stories of each different storied parametric models of IIIe. It is listed in Table 5.13.

Soft storey irregularity coefficient ($\eta_{ki}$) shows large ranges in parametric model IIIe. The range varies between 1.66 and 2.21 from three storey models to twenty storey models. There is a favorable soft storey coefficient in three storey and five storey sub models of IIIe. However, it starts taking high soft storey irregularity coefficients in eight storeyed sub model of IIIe, which exceeds the limit value of 2.00 for the soft storey irregularity. The most crucial coefficient for the soft storey irregularity is calculated as 2.21 in twenty storey sub model of IIIe.

Based on the analysis, the stiffness irregularity coefficient takes higher values with the calculation made by above storey than the below storey. The soft storey coefficient created by the ratio with above is calculated under the limit value of 2.00. The maximum soft storey coefficient calculated with above storey is 1.08. However, there is soft storey irregularity in the model due to the significant coefficients taken from the calculations with below storey. It supports the view that, while the parametric model IIIe have soft storey calculated by the ratio with below storey, there is no soft storey calculated with above storey. Moreover, the soft storey irregularity is observed on the first storey in models having soft storey irregularity. Additionally, it is concluded that if the number of storey in parametric model IIIe increase, the maximum soft storey irregularity coefficient will gradually increase from one storey model to twenty storey model. On the other hand, it gradually decreases from ground floor to upper floor within the own stories of each different storied sub models of IIIe.

### 5.3.6. Parametric Model IIIf

In this model, the locations of shear walls are placed on the corners of the model as in parametric model IIIb. Apart from the parametric model IIIb, the floor opening area is placed on the center of the model with the same floor opening ratio of 25% (Figure 5.13). It is under the limited value of 0.33. Therefore, the parametric model IIIf does not include the irregularity of floor discontinuity defined in the TEC (2007). The aim of this parametric model is to examine the effects of a central floor opening to the floor discontinuity. Therefore, the floor opening rate is preserved as 25%. Storey gross area is kept as the same size with other models.

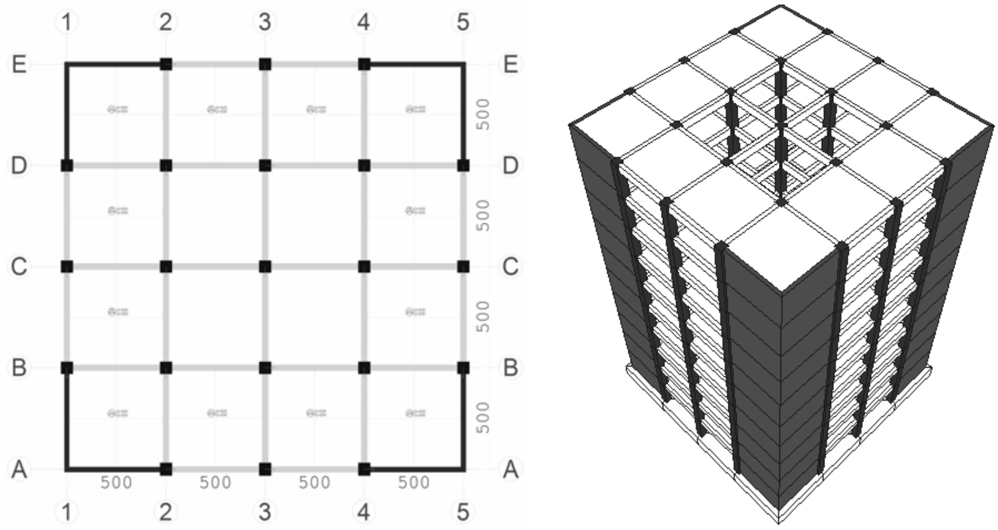


Figure 5.13.Structural plan and 3D view of parametric model IIIf

Tablo 5.14. Analysis results of parametric model IIIf

| **Storey** | (δi)max | δ max/hi≤0.02 | θ≤0.12 | ηbi<1.20 | ηki<2.00 |
|---|---|---|---|---|---|
| 1S | 0.29 | 0.0001 | 0.0001 | 1.06 | - |
| 3S | 1.46 | 0.0005 | 0.0005 | 1.07 | 1.62 |
| 5S | 3.70 | 0.0014 | 0.0012 | 1.08 | 1.88 |
| 8S | 8.35 | 0.0031 | 0.0028 | 1.09 | 2.02 |
| 10S | 10.06 | 0.0037 | 0.0041 | 1.10 | 2.08 |
| 12S | 11.46 | 0.0042 | 0.0057 | 1.10 | 2.11 |
| 15S | 13.60 | 0.0050 | 0.0084 | 1.10 | 2.15 |
| 20S | 17.19 | 0.0064 | 0.0138 | 1.08 | 2.20 |

According to the analysis report shown in Table 5.14, the maximum value of effective storey drift in parametric model IIIf is obtained between 0.29 and 17.19 mm. The limit values in terms of interstorey drifts and second order effect have not been exceeded. All that values gradually increase from one storey structure up to twenty storey structures.

The highest torsional irregularity value is 1.10 in parametric model IIIf. It is under the limit value of 1.20. Therefore, there is no torsional irregularity in parametric model IIIf. Moreover, it is realized that an increase in the number of storey of parametric model IIIf affects negatively the torsional irregularity coefficients. It increases from one storey model to twenty storey model. On the other hand, the torsional irregularity coefficients gradually increase towards upper floors within each different storied sub models of parametric model IIIf (Table 5.14).

Stiffness irregularity coefficient ($\eta ki$) shows large value ranges in parametric model IIIf. The range varies between 1.62 and 2.20 from three storey building to twenty storey building. There is a favorable soft storey irregularity coefficient in three storey and five storey parametric models of IIIf because the limit value of 2.00 has not been transcended. It begins passing the limit value in eight storey sub model IIIf and gradually increase up to twenty storey sub models of IIIf. The most critical soft storey coefficient is calculated as 2.20 on the first storey of a twenty storey sub model of IIIf.

Based on the analysis report shown in Table 5.14, the stiffness irregularity coefficient takes higher values for the calculation by below storey than the above storey. The maximum soft storey irregularity coefficient calculated with above storey is 1.08. Moreover, the soft storey irregularity is observed on the first storey of twenty storey sub model of IIIf. It can be concluded that if the number of storey in parametric model IIIf increase, the maximum soft storey irregularity coefficient will gradually increase in each different storied sub models of IIIf. On the other hand, it gradually decreases toward upper floors in each different storied sub models of IIIf.

### 5.3.7. Parametric Model IIIg

In this model, shear walls are placed in the middle of the outer axes of the model as in parametric model IIIa. Apart from the parametric model IIIa, floor opening area is placed on the center of the model with the same floor opening ratio of 25%. It is illustrated in Figure 5.14. Hence, the parametric model IIIg does not involve the irregularity of floor discontinuity defined in the TEC (2007). Storey gross area is kept as the same size with other models.

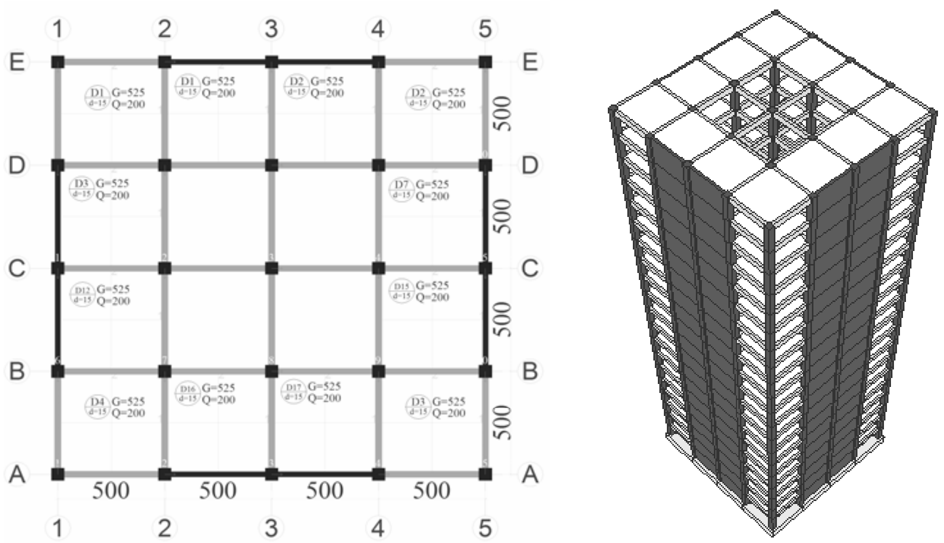


Figure 5.14.Structural plan and 3D view of parametric model IIIg

Table 5.15. Analysis results of parametric model IIIg

| **Storey** | (δi)max | δ max/hi≤0.02 | θ≤0.12 | ηbi<1.20 | ηki<2.00 |
|---|---|---|---|---|---|
| 1S | 0.32 | 0.0001 | 0.0001 | 1.06 | - |
| 3S | 1.63 | 0.0006 | 0.0005 | 1.07 | 1.65 |
| 5S | 4.06 | 0.0015 | 0.0013 | 1.08 | 1.90 |
| 8S | 9.08 | 0.0034 | 0.0030 | 1.10 | 2.04 |
| 10S | 10.67 | 0.0040 | 0.0045 | 1.11 | 2.09 |
| 12S | 12.24 | 0.0045 | 0.0062 | 1.12 | 2.13 |
| 15S | 14.57 | 0.0054 | 0.0091 | 1.13 | 2.17 |
| 20S | 18.45 | 0.0068 | 0.0148 | 1.14 | 2.21 |

The maximum value of effective storey drift in parametric model IIIg is obtained as a range between 0.32 and 18.45 mm. The limit values in terms of interstorey drifts and second order effect have not been exceeded. These values gradually increase from one storey model up to twenty storey models.

Following the earthquake analysis, the maximum torsional irregularity coefficient ($\eta$bi) is noticed as 1.14 in twenty storey sub model of IIIg. It is under the limit value of 1.20. Therefore, there is no torsional irregularity in the parametric model IIIg. Moreover, it is realized that if the number of storey in parametric model IIIg increase, the maximum torsional irregularity coefficient will gradually increase towards twenty storey sub model of IIIg. Besides, the torsional irregularity coefficient gradually increase from the ground floor to upper floors within the own stories of each different storied sub models of IIIg (Table 5.15).

Soft storey irregularity coefficients ($\eta$ki) show a large value range between 1.65 and 2.21 from three storey building to twenty storey building. There is an available soft storey irregularity coefficient in the three storey and five storey sub models of IIIg because the limit value of 2.00 has not been exceeded. It starts passing the limit coefficient in eight storey sub model of IIIg and gradually increase up to twenty storey sub models of IIIg. The most critical soft storey irregularity coefficient is calculated as 2.21 in twenty storey sub model of IIIg.

The soft storey calculations which depend on below storey show higher irregularity coefficients than the calculations depending on above storey. The maximum soft storey coefficient calculated with above storey is 1.08. As a result of soft storey irregularity checks, it is realized that while the parametric model IIIg has soft storey irregularity calculated by the ratio with below storey, there is no soft storey calculated with above storey. Moreover, the soft storey irregularity is noticed on the first storey in sub models of IIIg which have soft storey irregularity.

### 5.3.8. Parametric Model IIIh

In this model, the shear walls are located on similar parts of the model with parametric model IIIa and IIIe. Floor opening area is same with IIIa as 0.25 %. Apart from the parametric model IIIa and IIIe, floor openings are placed asymmetrically to the model (Figure 5.15). However, the model does not have floor discontinuity because the limit floor discontinuity coefficient is under the defined coefficient. The aim of this model is to explore the effects of asymmetric floor openings to the earthquake behaviour of structure. It is examined that despite the symmetric plan geometry, how asymmetrical configuration of floor openings affects the earthquake behaviour of structure. Storey gross area is kept as same size with other models.

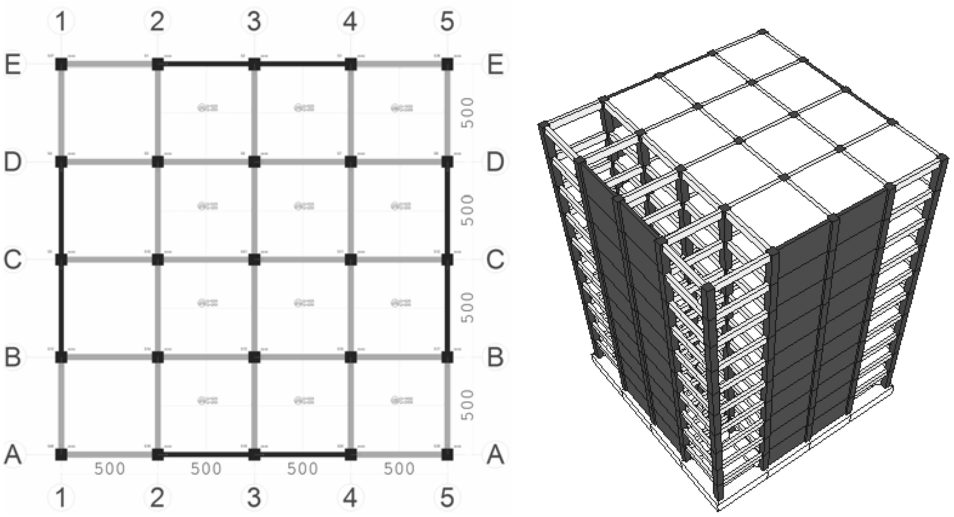


Figure 5.15.Structural plan and 3D view of parametric model IIIh

Table 5.16. Analysis results of parametric model IIIh

| **Storey** | (δi)max | δ max/hi≤0.02 | θ≤0.12 | ηbi<1.20 | ηki<2.00 |
|---|---|---|---|---|---|
| 1S | 0.71 | 0.0003 | 0.0002 | 1.19 | - |
| 3S | 2.98 | 0.0011 | 0.0009 | 1.17 | 1.66 |
| 5S | 5.91 | 0.0022 | 0.0020 | 1.15 | 1.90 |
| 8S | 10.25 | 0.0038 | 0.0040 | 1.28 | 2.04 |
| 10S | 12.17 | 0.0045 | 0.0057 | 1.53 | 2.09 |
| 12S | 13.97 | 0.0052 | 0.0076 | 1.99 | 2.14 |
| 15S | 16.47 | 0.0061 | 0.0109 | 2.10 | 2.21 |
| 20S | 20.49 | 0.0076 | 0.0171 | 2.24 | 2.28 |

According to the earthquake analysis report, the maximum value of effective storey drift in parametric model IIIh varies between 0.71 and 20.49 mm. The limit values in terms of interstorey drifts and second order effect have not been exceeded. All that values gradually increase from one storey model up to twenty storey model.

Based on the earthquake analysis report, the maximum torsional irregularity coefficient ($\eta_{bi}$) is obtained as 2.24 in twenty storey sub model of IIIh. The limit value of 1.20 is exceeded. Therefore, there is torsional irregularity in parametric model IIIh. Furthermore, it is observed that if the number of storey in parametric model IIIh increase, the maximum torsional irregularity coefficient will gradually increase in each different storied sub models of IIIh.

Stiffness irregularity coefficient or soft storey irregularity coefficient ($\eta_{ki}$) has a large value ranges in sub models of IIIh. The range varies between 1.66 and 2.28 from three storey structure to twenty storey structure. There is a favorable soft storey irregularity coefficient in the three storey and five storey sub models of IIIh because the limit value of 2.00 has not been exceeded. The most critical soft storey irregularity coefficient is calculated as 2.28 in twenty storey sub model of IIIh (Table 5.16).

When the stiffness irregularity coefficients calculated by the storey above or below are compared it is observed that stiffness irregularity coefficient has higher values for the ratio below than the ratio above. The maximum soft storey coefficient calculated with above storey is 1.08. Moreover, the soft storey irregularity is observed on the first storey of each sub models of IIIh except one, three and five storey structure. An increase in the number of stories cause increase in the soft storey irregularity coefficients. Besides, soft storey irregularity coefficient gradually decreases towards upper floors within the own stories of each different storied sub models of IIIh.

### 5.3.9. Parametric Model IIIi

In this model, the shear walls are designed on the corners of the structure as in the parametric model IIIb and IIIf. Therefore, the floor opening area is 0.25 %. The model does not have floor discontinuity because it is under the defined limit value. The only difference between parametric model IIIh and IIIi is the positions of the shear walls. (Figure 5.16). The interaction between the locations of floor openings and structural elements are examined. Storey gross area is kept as same size with the others.

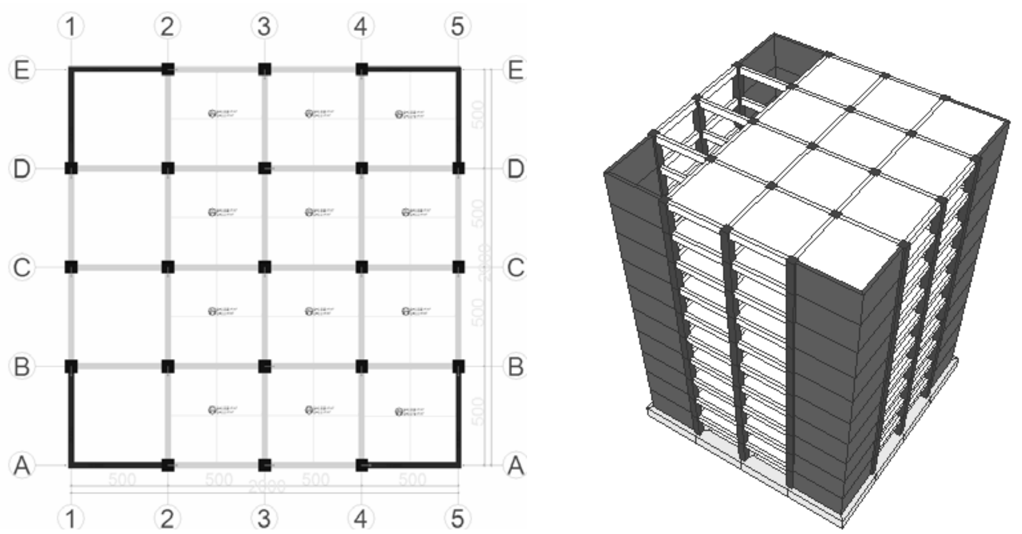


Figure 5.16. Structural plan and 3D view of parametric model IIIi

Tablo 5.17. Analysis result of parametric model IIIi

| **Storey** | (δi)max | δ max/hi≤0.02 | θ≤0.12 | ηbi<1.20 | ηki<2.00 |
|---|---|---|---|---|---|
| 1S | 0.66 | 0.0002 | 0.0002 | 1.22 | - |
| 3S | 2.67 | 0.0010 | 0.0008 | 1.19 | 1.56 |
| 5S | 5.18 | 0.0019 | 0.0018 | 1.16 | 1.77 |
| 8S | 11.02 | 0.0041 | 0.0037 | 1.63 | 1.82 |
| 10S | 12.37 | 0.0046 | 0.0054 | 1.79 | 2.10 |
| 12S | 14.02 | 0.0052 | 0.0072 | 2.00 | 2.18 |
| 15S | 16.49 | 0.0061 | 0.0104 | 2.17 | 2.24 |
| 20S | 20.69 | 0.0077 | 0.0167 | 2.28 | 2.31 |

Following the analysis, it is obtained that the maximum value of effective storey drift in parametric model IIIi shows variety between 0.66 and 20.69 mm. The limit values in terms of interstorey drifts and second order effect have not been transcended. They gradually increase from one storey structure up to twenty storey structure.

Based on the analysis report shown in Table 5.17, it is realized that the maximum torsional irregularity coefficient (ηbi) is obtained as 2.28 in twenty storey sub model of IIIi. The limit value of 1.20 is exceeded. Excessive torsional irregularity is noticed in parametric model IIIi. Moreover, it is realized that there is not a balanced decrease or increase within the all sub models of IIIi. (Table 5.17).

Stiffness irregularity coefficient or soft storey irregularity coefficient ($\eta ki$) takes a large value ranges in the sub models of IIIi. The range varies between 1.56 and 2.31 from three storey model to twenty storey model. There is a favorable soft storey irregularity coefficient in three storey and five storey sub models of IIIi, for the limit value of 2.00 has not been exceeded. It began to be exceeded in eight storey sub model of IIIi. The most critical soft storey irregularity coefficient is calculated as 2.31 in twenty storey sub model of IIIi.

When the stiffness irregularity coefficient calculated by the storey above or below is compared it is observed that stiffness irregularity coefficient has higher values for the ratio below than the ratio above. The maximum soft storey coefficient calculated with above storey is gained as 1.14. For that reason, it is realized from the soft storey checks that while the parametric model IIIi has soft storey irregularity calculated by the ratio with below storey, there is no soft storey irregularity calculated with above storey. Moreover, the soft storey irregularity is observed on the first and second storey of the sub models of IIIi except three storey and five storey sub models of IIIi. Furthermore, it is observed that the maximum soft storey irregularity coefficient gradually increase from one storey structure to twenty storey structure.

With this type of configuration, the structure behaves like a complex structure against earthquake loads despite the symmetrical plan geometry and symmetrical configuration of columns and shear walls. Consequently it can be said that asymmetrical configurations of floor openings cause excessive changes in coefficients which describes the earthquake behaviour of structures. When the last two models (IIIh and IIIi) which have asymmetrical floor openings are compared with the other models in case III, it is noticed that these two models expose to higher earthquake forces and shows significant irregularity coefficients than the other models. This demonstrates that symmetry in both horizontal and vertical direction supports to regularity in earthquake behaviour of structures.

### 5.3.10. Discussion and Results of Case III

A set of 9 models, 8 of which had no A2 floor discontinuity and 1 of which had floor discontinuity were analyzed during the case III. The aim of this case was to verify that location of the floor openings in the floors has primary importance rather than the amount of the floor openings. In the TEC (2007), a limit value of 0.33 was given for the floor discontinuity irregularity. The models were created according to the basis specified in Chapter 3 and 4. The results were evaluated according to the several criteria containing torsional irregularity coefficient, soft storey coefficient, effective storey drifts, interstorey drifts and second order effects. On the bases of the carried out numerical analysis in Case III for the floor discontinuity, the following conclusions could be drawn up:

- In the case of A2 irregularity exists in the structure, the structure shows favorable results under earthquake loads coming from symmetry direction of the structure rather than the earthquake loads coming from asymmetry direction.
- The locations of shear walls and floor openings within the structure are significant factors affecting the earthquake behavior of overall structure rather than the amount of floor openings. The distribution of rigidity according to the location of floor openings should be arranged properly.
- Despite the regular plan geometry, it is noticed that when the floor openings were placed asymmetrically on the floors, the structure would fail under the earthquake loads arrived from the weakest direction. Moreover, it leads to a significant increase in the torsional irregularity coefficient. On the other hand, a central floor opening in the structure provides better earthquake behavior than the structures which are asymmetrically or improperly arranged with shear walls.
- The location of shear walls and its interaction with floor openings have a significant effect in terms of the earthquake behavior of the structure. For instance, if the floor openings are placed symmetrically on the corners of the structure, shear walls should be placed in the middle of the outer axis of the structure (IIIa) instead of on the corners of the structure (IIIb) in order to balance of the rigidity and support load distributions.

- Buildings having shear walls and buildings having shear walls and additionally a central rigid core are evaluated in terms of A2 irregularity. It is observed that shear walls should be placed distant from the centre of gravity as far as if possible, towards to the exterior of the structure. For instance, when the parametric model IIIb and IIId are compared, it is observed that parametric model IIIb shows better earthquake behaviour than the parametric model IIId. Because rigidity core cause increase in the structural irregularity coefficient in parametric model IIId like in parametric model IIIc.
- The changes in the location of shear walls are particularly effective on the torsional irregularity coefficients. Therefore, it is inevitable that if the shear walls are located asymmetrically, structure exposes to large earthquake loads on the weakest direction. They should be positioned symmetrically to provide similar rigidity on both earthquake directions.
- It is observed that if a structure has a central rigid core, additional shear walls should be designed in the middle of the outer axes instead of the corner of the structure to balance the rigidity.
- It is noticed that if the structure has a central floor opening, shear walls should be positioned on the corners of the structure instead of in the middle of the outer axis of the structure as in model IIIf.
- It is gained from the analysis that when the floor openings are placed asymmetrically, the soft storey coefficients directly increase.
- If the floor openings area increases, the building mass decreases. However, the floor openings placed asymmetrically in the structure, the building mass accumulated in one side of the structure. Although building mass decrease, the torsional irregularity occurs again in those structures.
- It is concluded from the case that location of the floor openings have a significant role rather than the floor opening ratio. For this reason, there should be made a sanction in the TEC (2007) where floor openings should be left. Alternative solutions for different plan geometries and with different arrangements of floor openings should be considered.

## 5.4. Case IV: Projection in Plan (A3)

This case consists of 5 parametric models. In this case, TEC (2007) has been studied and the effects of A3 irregularities in other words excessive projection dimensions which cause irregular plan geometry is examined according to the chosen irregular plan geometry consisting L-shaped, H-shaped, T-shaped and U-shaped models. These models are generated to have the same storey gross area with different number of storey. Additionally, the sub model from parametric model Ia which is coded as Ia20x20 is taken in order to compare its earthquake behaviour with the models in case IV. Case IV consists of irregular plan geometries. However, the model which coded as Ia20x20 has regular plan geometry owing to the square plan geometry.

The main aim of case IV is to compare the regular plan geometry and irregular plan geometry in terms of earthquake behaviour on the basis of structural irregularities. The structures are all designed consisting of frame system. All parametric models are based on both low-storey R/C structure such as single-storey, three-storey, five-storey, eight-storey and multi-storey R/C structure such as ten-storey, twelve-storey, fifteen-storey and twenty-storey buildings. Moreover, all models have different projection dimensions. The beam span on both directions is 5 meter. Floors consist of R/C slabs of 0.15m in thickness. Floor heights are taken as 2.8 m in all floors. In this way, it is aimed to evaluate the effects of A3 or excessive projection in plan by minimizing the other variables. The structure is assumed to be in the first degree earthquake zone and located in Z2 soil class according to TEC (2007). The columns in all parametric models are designed using C25 class concrete and S420 class steel described in the TS-500 standard.

### 5.4.1. Parametric Model IVa: L Form

In this model, storey gross area is $400m^2$ and the plan geometry of the structure has been designed as frame system to have L-shaped plan geometry. Each beam span has a length of 5 meter. A3 irregularity or projections in plan is described in the TEC (2007) as the cases "where the projections in both of the two directions exceed the total plan dimensions of the structure in the respective directions by more than 20%". In L-shaped parametric model, the plan geometry has the same projection dimensions in both of the axes. The projection dimension is 15 meter and the total plan dimensions are 25 meter. A3 ratio in L-shaped parametric model is calculated as 60 %. A3 irregularity or in other words excessive plan projection in both directions exists in the model, because A3 irregularity coefficient is defined as 20 % in the TEC (2007) and the L-shaped parametric model exceed that ratio. Moreover, it is not symmetrical according to any horizontal or vertical axis. It has only a diagonal symmetry axis passing through the intersection of 1-1 and A-A axis between 6-6 and F-F axis.

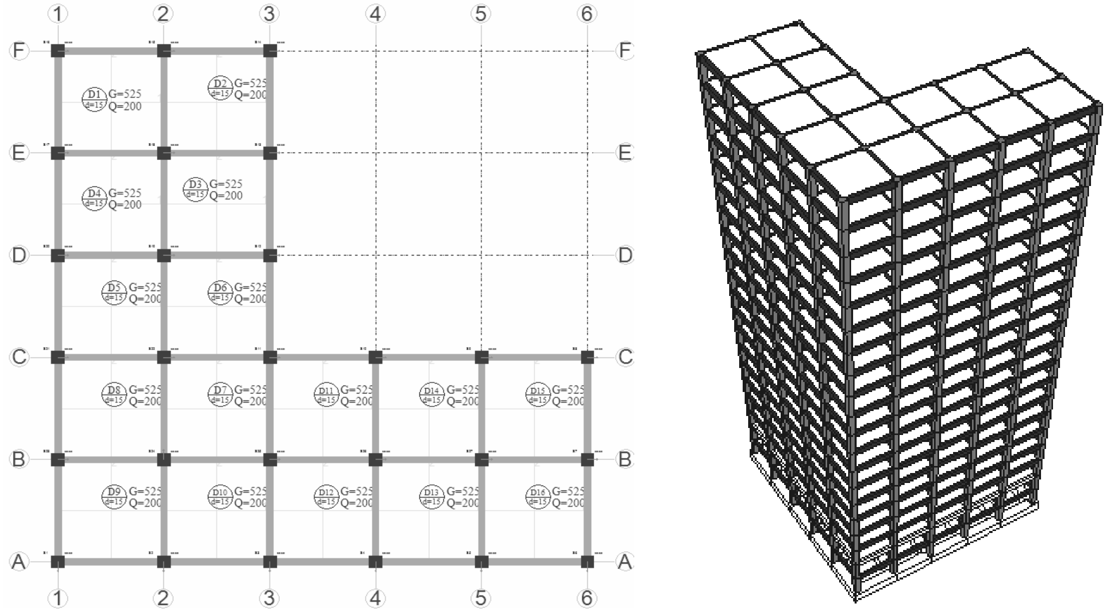


Figure 5.17. Structural plan and 3D view of parametric model IVa

According to the earthquake analysis report of structural irregularities, the maximum value of effective storey drift in L-shaped parametric model is obtained between 1.68 and 34.85 mm. The limit values in terms of interstorey drifts and second order effect have not been exceeded defined in the TEC (2007). It is noticed that all that values gradually increase from one storey model up to twenty storey sub model of IVa.

Based on the analysis, the torsional irregularity coefficient ($\eta_{bi}$) varies between 1.14 and 1.24 for the maximum torsional irregularity coefficients of L-shaped sub models. The most critical value is noticed as 1.24 in twenty storey sub model. Thus, the limit value of 1.20 is exceeded. Therefore, there is torsional irregularity in the L-shaped parametric model. Moreover, it is observed that if the number of storey in L-shaped parametric model increase, the maximum torsional irregularity coefficient will gradually increase from one storey sub model to twenty storey sub model of L-shaped parametric model (IVa). Additionally, the torsional irregularity coefficient gradually increase from ground floor to upper floors within the own stories of each different storied parametric models of L-shaped structure (Table 5.18).

Stiffness irregularity coefficient or soft storey irregularity coefficient ($\eta ki$) shows normal ranges in the L-shaped parametric model. The range varies between 1.50 and 1.67. There is a favorable soft storey irregularity coefficient because the coefficients remain under the limit coefficient of 2.00. The highest soft storey irregularity coefficient is calculated as 1.67 in five storey sub model of L-shaped structure (IVa). Moreover, the highest soft storey coefficient is observed on the first storey of the L-shaped parametric model. Besides, it is realized that there is not a balanced decrease or increase in the maximum soft storey coefficients and within the own stories of each different storied sub models of L-shaped structure.

## 5.4.2. Parametric Model IVb: H Form

In this model, storey gross area is 400 $m^2$ and the plan geometry of the structure has been designed as frame system to have H-shaped plan geometry shown in Figure 5.18. Each beam span has a length of 5 meter. In H-shaped parametric model, the plan geometry has 15 meter projection dimension on X-axis and there is not any projection on Y-axis. For that reason, there is not a projection ratio on Y-axis. The total plan dimensions are 35 meter on X-axis and 20 meter on Y-axis. A3 ratio in H-shaped parametric model is calculated as approximately 43 % on X-axis. In results, there is A3 irregularity in the structure according to the X-axis because the projection dimension on X-axis exceeds the limit ratio of 20 %. Furthermore, the H-shaped parametric model is exactly symmetrical both X and Y earthquake direction.

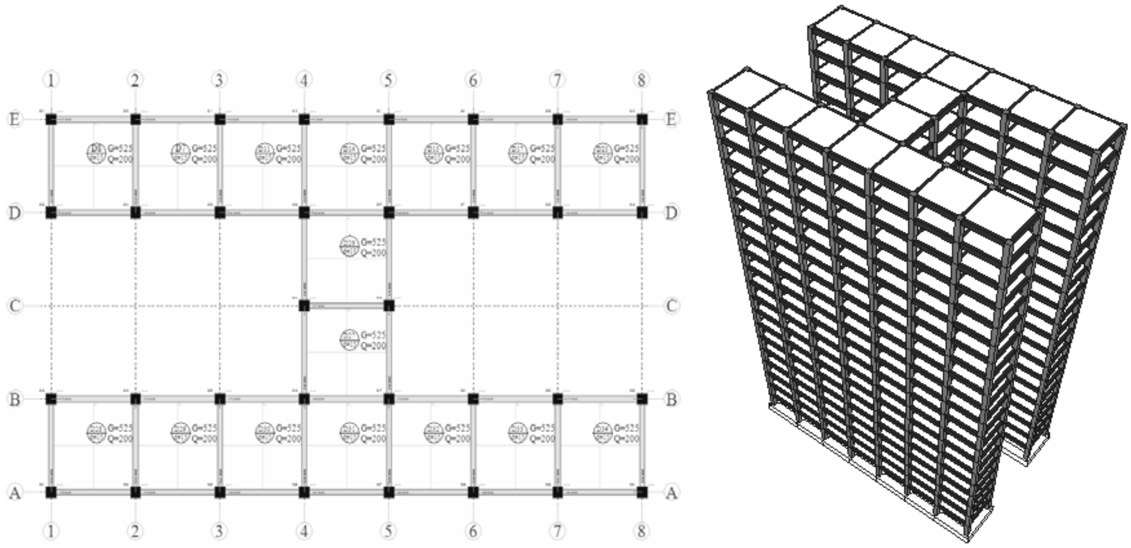


Figure 5.18. Structural plan and 3D view of parametric model IVb

Following the earthquake analysis report of structural irregularities, the maximum value of effective storey drift in H-shaped parametric model varies between 1.54 and 37.79 mm. The limit values in terms of interstorey drifts and second order effect have not been exceeded. All that values gradually increase from one storey structure up to twenty storey structures.

Based on the analysis, it is realized that the maximum torsional irregularity coefficient ($\eta_{bi}$) is 1.17. The limit value for the torsional irregularity, 1.20 is not transcended. Therefore, there is no torsional irregularity in parametric model IVb. Moreover, it is observed that if the storey number of the H-shaped parametric model increase, the maximum torsional irregularity coefficient remain constant as 1.17. Furthermore, the torsional irregularity coefficient gradually decrease towards upper floors within the own stories of each different storied sub models of H-shaped structure.

Stiffness irregularity coefficient ($\eta_{ki}$) shows normal ranges in parametric model IVb. The range varies between 1.52 and 1.69. There is a suitable soft storey irregularity coefficient, for the coefficients remain under the limit coefficient of 2.00. The highest soft storey coefficient is calculated as 1.69 in five storey sub model of IVb. Moreover, the highest soft storey irregularity coefficient is observed on the first storey of the sub models of H-shaped structure. Besides, it is concluded that there is not a balanced decrease or increase in the maximum soft storey coefficients in different storied sub models and within the own stories of each different storied sub models of IVb. The earthquake analysis checks of H-shaped parametric model are comprehensively shown in Table 5.18.

### 5.4.3. Parametric Model IVc: T Form

In this model, storey gross area is 400 m$^2$ and the plan geometry of the structure has been designed as frame system to have T-shaped plan geometry. It is illustrated in Figure 5.19. Each beam span has a length of 5 meter. In T-shaped parametric model, the plan geometry has the same projection dimensions in both of the axes. The projection dimensions are 10 meter on both X and Y axis and the total plan dimensions are 30 meter on X-direction and 20 meter on Y-direction. A3 ratio in T-shaped parametric model is calculated as approximately 33 % on X-axis and 50 % on Y-axis. Consequently, there is A3 irregularity in the T-shaped parametric model (IVc) depending on both axes, because the limit ratio is exceeded. Furthermore, it is symmetrical according to only Y axis.

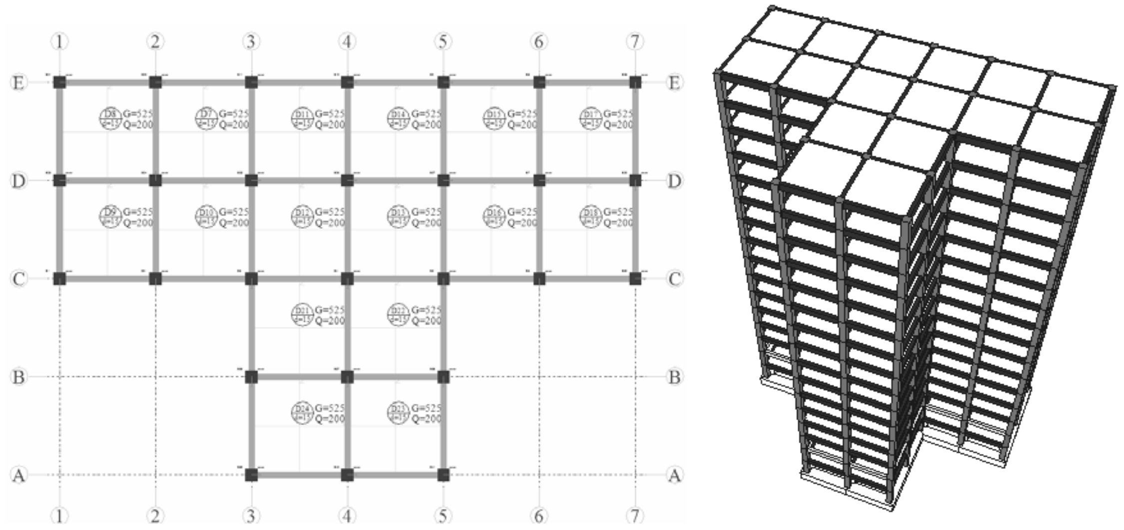


Figure 5.19. Structural plan and 3D view of parametric model IVc

Depending on the analysis, it is noticed that the maximum value of effective storey drift in T-shaped parametric model varies between 1.73 and 35.68 mm. The limit values in terms of interstorey drifts and second order effect have not been exceeded. All that values gradually increase from one storey structure up to twenty storey structures.

Moreover, they are all increase for each different storied sub models of T-shaped structure (IVc).

According to the analysis report, the highest torsional irregularity coefficient ($\eta$bi) is obtained as 1.21 in twenty storey sub model of T-shaped structure (IVc). Therefore, there is torsional irregularity in H-shaped parametric model. Moreover, it is observed that there is not a balanced increase or decrease in the maximum torsional irregularity coefficients.

Stiffness irregularity coefficient or soft storey irregularity coefficient ($\eta$ki) shows normal ranges in the sub models of T-shaped structure. The range varies between 1.52 and 1.86. There is an agreeable soft storey coefficient because the coefficients remain under the limit coefficient of 2.00. The highest soft storey coefficient is calculated as 1.86 in five storey sub model of T-shaped structure. Moreover, the highest soft storey coefficients are observed on the first storey. Furthermore, it is observed that if the number of storey in T-shaped parametric model increase, the maximum soft storey irregularity coefficient will gradually increase in each different storey sub models of T-shaped structure. On the other hand, there is not a balanced increase or decrease within the own stories of each different storied parametric models of T-shaped structure from ground floor to the upper floors (Table 5.18).

## 5.4.4. Parametric Model IVd: U Form

In this model, storey gross area is 400m$^2$ and the plan geometry of the structure has been designed as frame system to have U-shaped plan geometry. The model is shown in Figure 5.20. Each beam span has a length of 5 meter. In U-shaped parametric model, the plan geometry does not have any projections on X axis. However, it has 5 meter projection on Y axis. The total plan dimension is 30 meter on X-axis and 15 meter on Y-axis. While the A3 ratio in U-shaped parametric model is calculated as approximately 33 % on Y-axis, there is not any projection on X axis. Therefore, A3 irregularity does not exist in the structure according to the X axis. On the other hand, there is A3 irregularity in the structure according to the Y-axis, for the projection dimension on Y-axis exceeds the limit ratio of 20 %. Consequently, there is A3 irregularity in U-shaped parametric model (IVd). Furthermore, it is only symmetrical according to Y axis.

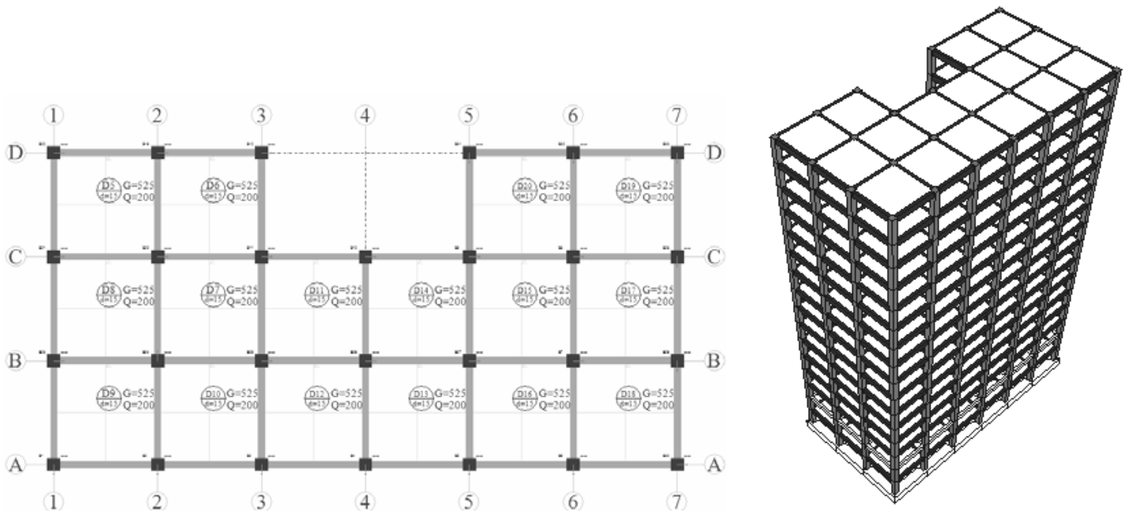


Figure 5.20. Structural plan and 3D view of parametric model IVd

According to the earthquake analysis report of structural irregularities which is shown in Table 5.18, the maximum value of effective storey drift in U-shaped parametric model is obtained between 1.70 and 35.02 mm. The limit values in terms of interstorey drifts and second order effect have not been exceeded. Also, these values gradually increase from one storey model up to twenty storey models. Moreover, they are all increase for each different storied sub models of T-shaped parametric structure (Table 5.18).

The maximum torsional irregularity coefficient is 1.17 in parametric model IVd. There is not any torsional irregularity in the U-shaped parametric model because torsional irregularity coefficients remained under the limit coefficient of 1.20. Moreover, it is observed that if the number of storey in U-shaped parametric model increase, the maximum torsional irregularity coefficient remains constant as 1.17 similar with H-shaped structure. Furthermore, the torsional irregularity coefficient gradually decrease towards upper floors within the own stories of each different storied parametric models of U-shaped structure (IVd).

Stiffness irregularity coefficient ($\eta_{ki}$) shows normal ranges in the parametric models U-shaped structure. The range varies between 1.52 and 1.68. There is a favorable soft storey irregularity coefficient because the coefficients remained under the limit coefficient of 2.00. The highest soft storey coefficient is calculated as 1.68 in five storey sub model of U-shaped structure. Moreover, the highest soft storey coefficients are discovered on the first storey of the sub models of U-shaped structure. Furthermore, it is realized that if the number of storey in U-shaped parametric model increase, it does not cause a regular increase or decrease in the different storied sub models and within the own stories of each different storied sub models of T-shaped towards upper floors.

### 5.4.5. Parametric Model IVe: Square Form

The necessary description and earthquake analysis report has been carried out in detail in case IV coded as Ia20x20. For that reason; they are not retailed in this part. It has a square plan geometry which makes it regular in terms of plan geometry. The main aim of choosing the model of Ia20x20 in this part is to compare its behaviour with the irregular plan geometries. The differences between the parametric models are evaluated comprehensively in the following section.

### 5.4.6. Discussion and Results of Case IV

A set of 5 models, 4 of which had A3 or excessive projection dimensions and 1 of which had no projections were analyzed during the case IV. The aim of this case was to investigate the seismic behaviour of irregular plan geometries consisting with different projection dimensions. All models are designed as frame systems. The irregular plan geometries are generated as symmetrical on both sided, on one sided or non symmetric. The effects of projection dimension ratio and the symmetry axis are evaluated. In the TEC (2007), a limit percentage of 20 % was given for the A3 irregularity. In this case, the importance of symmetry in plan geometry and the ratio for A3 irregularity are examined. The results were evaluated according to the several criteria containing torsional irregularity coefficient, soft storey coefficient, effective storey drifts, relative storey drifts and second order effects. On the bases of the carried out numerical analysis in case IV for the A3 irregularity, the following conclusions could be drawn up:

- As seen on Figure 5.21, structural model which is symmetrical according to the both axis, show the best seismic behaviour. The changes in the torsional irregularity coefficients are illustrated in Figure 5.21. Square plan geometry has no projections and regular in terms of plan geometry. Moreover, it is symmetrical according to the both axis. Therefore, it shows the best seismic behaviour. Apart from the other models, an effective storey displacement shows lower values.

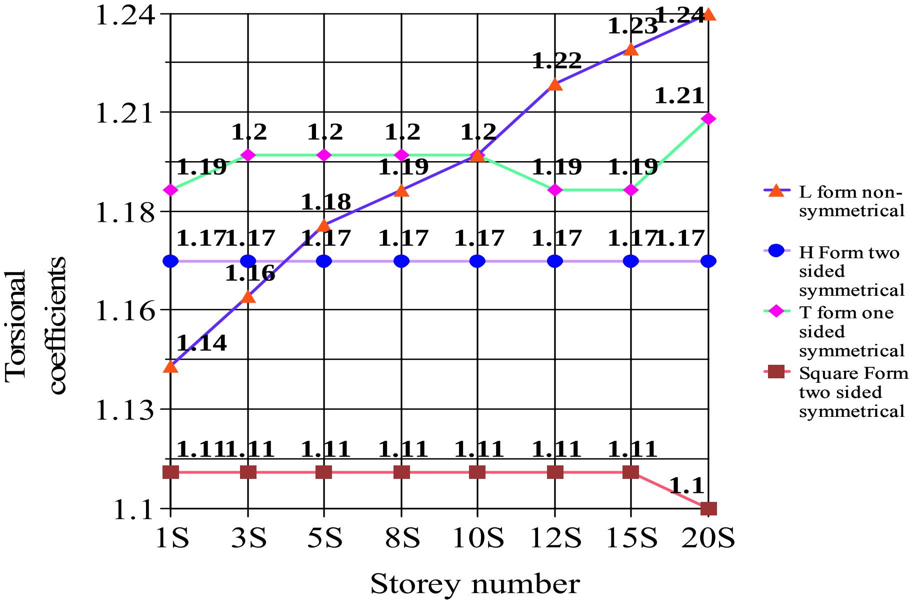
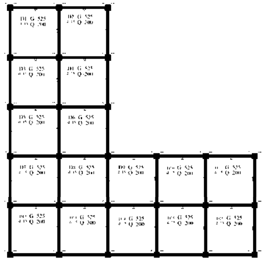
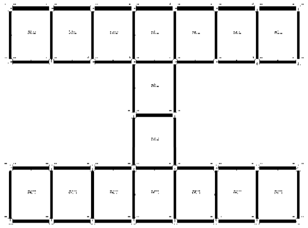
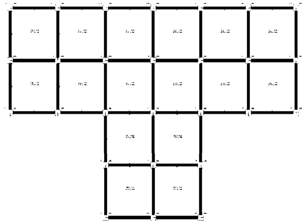
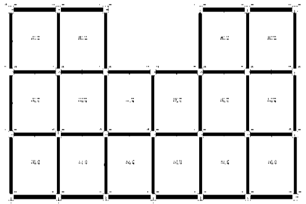
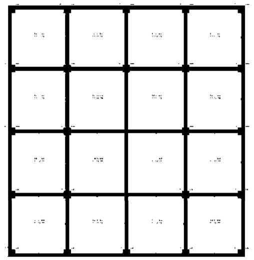


Figure 5.21. Maximum torsional irregularity coefficients according to the different storied sub models of case IV

- H-shaped plan geometry is symmetrical according to both X and Y axis. On the other hand, it has 48 % projection dimensions which exceed the limit coefficient of 20 %. When the maximum torsional coefficients for different storied parametric models of H-shaped plan geometry is investigated, it is observed that the maximum torsional irregularity coefficients show a linear behavior, and consistently show the value of 1.17 as in the U-shaped model.
- U-shaped plan geometry shows similar seismic performance with H-shaped plan geometry in terms of torsional irregularity. For that reason, its values are not shown in the Figure 5.21. U-shaped plan geometry has 33 % projection dimension on Y axis. It exceeds the A3 limit coefficient. On the other hand, it is symmetrical on one-sided. With the interaction of symmetry and projection ratio, it shows similar performance in terms of torsional irregularity although it is symmetrical on one-sided. Because, projection dimension ratio is lower than the U-shaped plan geometry.

- T-shaped plan geometry is symmetrical according to only Y axis. On the other hand, it has 33 % A3 ratio which exceed the limit percentage of 20 %. When the maximum torsional coefficients for different storied parametric models of T-shaped plan geometry is investigated, it is observed that torsional irregularity coefficients draw an uneven curve. In the 20 storey T-shaped parametric models, maximum torsional irregularity coefficients begin to draw an increasing linear curve and the maximum value takes the value of1.21.
- L-shaped plan geometry is both non-symmetrical and has 60 % projection ratio which is three times of the limit coefficient of 20 %. Therefore, it shows the worst seismic performance among the models in case 3. Torsional irregularity coefficients draw a continuously increasing curve. The maximum torsional coefficient is calculated as 1.24 in twelve storey sub model of L-shaped structure.
- It is observed that all models shows better seismic performance against the earthquake loads which come from the symmetry axis.
- There is not observed soft storey irregularity in any of the models.
- It is concluded from the case IV that structures having regular plan geometry and symmetrical according to the both sides shows best seismic performance.
- The T and U-shaped plan geometry are designed to have the same projection dimension ratio of 33 % which is under the limit coefficient of 20 %. They are both one-sided symmetrical. (according to the Y axis) On the other hand, although there is torsional irregularity in the T-shaped parametric model, The U-shaped parametric model does not have torsional irregularity. It has projections in plan only on Y direction.
- In conclusion, there should be made a sanction in the TEC (2007) related to the percentage of the projection dimensions. The percentage should be considered according to the different plan geometry and may be its structural system types.

Table 5.18. Analysis results of case IV

| | L-Shape - IVa | | | H-Shape - IVb | | | T-Shape - IVc | | | U-Shape - IVd | | | Square – IVe | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| |  | | |  | | |  | | |  | | |  | | |
| | (δi)max | (ηbi) | ηki | (δi)max | ηbi | ηki | (δi)max | ηbi | ηki | (δi)max | ηbi | ηki | (δi)max | ηbi | ηki |
| 1S | 1.68 | 1.14 | - | 1.54 | 1.17 | - | 1.73 | 1.19 | - | 1.70 | 1.17 | - | 1.38 | 1.11 | - |
| 3S | 5.46 | 1.16 | 1.51 | 5.25 | 1.17 | 1.52 | 5.60 | 1.20 | 1.52 | 5.49 | 1.17 | 1.52 | 4.90 | 1.11 | 1.52 |
| 5S | 10.16 | 1.18 | 1.67 | 9.88 | 1.17 | 1.69 | 10.47 | 1.20 | 1.69 | 10.28 | 1.17 | 1.68 | 9.27 | 1.11 | 1.67 |
| 8S | 17.11 | 1.19 | 1.66 | 17.32 | 1.17 | 1.68 | 17.67 | 1.20 | 1.71 | 17.32 | 1.17 | 1.67 | 13.02 | 1.11 | 1.64 |
| 10S | 22.08 | 1.20 | 1.64 | 22.61 | 1.17 | 1.64 | 22.88 | 1.20 | 1.71 | 22.43 | 1.17 | 1.63 | 14.07 | 1.11 | 1.57 |
| 12S | 26.95 | 1.22 | 1.61 | 28.27 | 1.17 | 1.65 | 28.04 | 1.19 | 1.75 | 27.49 | 1.17 | 1.57 | 14.88 | 1.11 | 1.53 |
| 15S | 31.90 | 1.23 | 1.57 | 32.75 | 1.17 | 1.67 | 32.81 | 1.19 | 1.84 | 32.14 | 1.17 | 1.58 | 15.84 | 1.11 | 1.54 |
| 20S | 34.85 | 1.24 | 1.59 | 37.79 | 1.17 | 1.69 | 35.68 | 1.21 | 1.86 | 35.02 | 1.17 | 1.59 | 17.38 | 1.10 | 1.56 |

**(Cont. on next page)**

Table 5.18. (Cont.)

| | L-Shape | | H-Shape | | T-Shape | | U-Shape | | Square | |
|---|---|---|---|---|---|---|---|---|---|---|
| | (δi)max/hi | θi | (δi)max/hi | θi | (δi)max/hi | θi | (δi)max/hi | θi | (δi)max/hi | θi |
| 1S | 0.0006 | 0.0004 | 0.0006 | 0.0004 | 0.0006 | 0.0004 | 0.0006 | 0.0004 | 0.0005 | 0.0004 |
| 3S | 0.0020 | 0.0016 | 0.0019 | 0.0015 | 0.0021 | 0.0016 | 0.0020 | 0.0016 | 0.0018 | 0.0015 |
| 5S | 0.0038 | 0.0034 | 0.0037 | 0.0032 | 0.0039 | 0.0033 | 0.0038 | 0.0033 | 0.0034 | 0.0032 |
| 8S | 0.0063 | 0.0060 | 0.0065 | 0.0059 | 0.0065 | 0.0059 | 0.0064 | 0.0059 | 0.0048 | 0.0057 |
| 10S | 0.0082 | 0.0078 | 0.0084 | 0.0077 | 0.0085 | 0.0077 | 0.0083 | 0.0077 | 0.0052 | 0.0073 |
| 12S | 0.0100 | 0.0097 | 0.0105 | 0.0097 | 0.0104 | 0.0095 | 0.0102 | 0.0095 | 0.0055 | 0.0090 |
| 15S | 0.0118 | 0.0124 | 0.0121 | 0.0130 | 0.0122 | 0.0123 | 0.0119 | 0.0123 | 0.0059 | 0.0116 |
| 20S | 0.0071 | 0.0176 | 0.0140 | 0.0190 | 0.0132 | 0.0174 | 0.0130 | 0.0175 | 0.0064 | 0.0162 |

# CHAPTER 6

# CONCLUSIONS

## 6.1. Conclusions

The main objective of this thesis was to explore the effective factors on structural irregularities to develop a substantial design guide for architects and students of architecture in order to design earthquake resistant buildings. Because, earthquake resistance of a building is strongly related to the interaction of architectural design with structural configuration. This thesis consists of a comparative analytical study of various R/C skeleton structures. The behaviour of the R/C structures was investigated on the bases of the structural irregularities that defined in the TEC (2007). R/C structures were chosen for the analysis due to the its widespread usage in Turkey. An understanding or perception tried to be given to architects or students of architecture about earthquake resistant design (ERD) criteria in order to abstain from the design faults. The study aims to contribute to the general understanding and perception of ERD in order to contribute to the development of a tradition of earthquake resistant architectural design in Turkey.

In the thesis, firstly the theoretical information related to the earthquake resistant design of R/C buildings in terms of structural irregularities was described comprehensively with drawings and damaged building photographs in Chapter 3 according to the TEC (2007). Then, to demonstrate the validity of the mentioned theoretical information, in Chapter 5, a series of cases consisting of many parametric models were developed for each structural irregularity. The number of structural axis and the number of stories were increased in each parametric model of the cases to evaluate structural irregularity coefficients

Based on the analysis performed in the case studies, following conclusions were drawn:

- According to the results obtained from the model analysis, the following factors were realized as effective in the variation of the structural irregularity coefficients:

1. Plan geometry of the structure (Architectural form)
2. Rigidity distribution in the structure
3. Configuration of structural walls in the plan
4. The number of structural axis
5. The number of stories
6. Positions of floor openings in the plan with its ratio.(A2)
7. Projection ratio, projection directions and symmetry condition in the plan geometry
8. The number of overhangs, overhang directions and building mass

- Results of the model analysis demonstrate that if the structural axis increases, the torsional irregularity coefficient will increase. Moreover, it was observed that the change in the torsional irregularity coefficients do not show a consistent behaviour by the increasing or decreasing the number of stories. Increase or decrease in the torsional irregularity coefficient which formed by changing the number of stories, depend on the structural configuration. Therefore, each structural system displayed different behaviour in terms of torsional irregularity coefficient.
- It was concluded that the symmetrical models which consists of shear-frame systems with a central rigid core show better earthquake behaviour than the models which consists of only shear-frame system.
- It is noticed that the models designed as frame systems shows acceptable torsional irregularity coefficients. However, a central rigid core added to the system, the structures expose to high torsional irregularity coefficients. This condition demonstrates that if the shear walls get closer to the gravity centre, the torsional irregularity coefficient will increase.
- The positions of shear walls change the torsional irregularity coefficient despite both of the structure have similar rigidity quantity. The models without any floor openings which have shear walls on the corner of the structure shows better seismic performance in terms of torsional irregularity rather than the models which have shear walls in the middle of the outer axis. In those models, the structural irregularity coefficients were observed under the limit coefficient for structural irregularity or closer to that value.

- It was realized that if the rigidity distribution in the system arranged randomly in any of the earthquake direction, the structure will failure on the flexible side. Distributions of the structural member’s regularly in both earthquake directions improve the seismic behaviour of the structure.
- It was noticed that shear walls should be placed on the outer axis as possible. If a central rigid core added to the structure due to the architectural aims, at least additional shear walls should be placed on the outer axis of the structure in order to balance the rigidity in the structure.
- Sufficiency in rigidity can be changed according to the number of storey and axis in the structure. Excessive usage of shear walls does not mean excessive resistant structure under earthquake loads. The usage of shear walls largely improves the seismic behaviour of the structure provided that they were used efficiently in the right place.
- It is noticed that despite the regular plan geometry and rigidity distribution, structural elements type, their location in the plan and their sufficiency in terms of rigidity, strength and stability according to the each R/C structural system play the most effective role in determining the earthquake behaviour of structures.
- It was realized that rigidity distribution on the structure plays the main role under earthquake loads rather than the simple plan geometry.
- It is observed that all models show better torsional irregularity coefficients against the earthquake loads coming from the symmetry axis.
- Earthquake loads are directly proportional with the building mass. It was detected that if the overhangs were added to the structure, the building mass directly increased. Furthermore, the directions of overhangs were as important as the number of overhangs. For instance, when the two model one of which has one-sided overhang, and the other has quadral-sided overhang were compared, it was realized that although excessive building mass, the model which has quadral-sided overhang shows lower torsional irregularity coefficient than the model which has one-sided overhang. This condition occurs because the model consisting of one-sided overhang was symmetrical only according to the earthquake direction of X axis. On the other hand, the model consisting of quadral-sided overhang was symmetrical

according to the both X and Y earthquake direction. The rigidity and gravity centre coincide in that model.

- It is concluded from the model analysis that location of the floor openings has a significant role rather than the floor opening ratio. For this reason, there should be made a sanction in the TEC where floor openings should be left. Alternative solutions for different R/C structural system type and with different arrangements of floor openings should be considered.
- The location of shear walls and its interaction with floor openings are effective in earthquake behavior of the structure. According to the results obtained from the model analysis made for researching the effects of floor discontinuity, it was noticed that shear walls should be positioned on the corners of the structure if the model has a central floor opening. On the other hand, it was realized that if the floor openings are placed symmetrically on the corners of the structure, and a central rigid core added to the structure, shear walls should be placed in the middle of the outer axis instead of the corners of the structure in order to balance of the rigidity.
- On the bases of the carried out numerical analysis with different plan geometries, it was noticed that symmetric plan geometry displays better seismic behaviour. Square plan geometry which has no projection in plan shows the best seismic behaviour. Moreover, H shaped form shows better seismic behaviour due to the its symmetric condition according to the both X and Y earthquake direction. On the other hand, L form which is asymmetrical according to the both earthquake direction shows the worst earthquake behaviour.
- Symmetrical configuration is not only provided in the plan geometry of a building, but also must be provided in the rigidity distribution. The analysis has revealed that regularity in the rigidity distribution is much more important than the regularity in the plan geometry.
- In conclusion from the model analysis which was created in order to investigate the effects of projection percentage and the effects of symmetry, it was realized that there should be made a sanction in the TEC (2007) related to the percentage of the projection dimensions. The percentage

should be considered according to the different plan geometry and may be its structural system types.

- It was noticed that in all models effective storey drift values consistently increased when the storey number in the models were increased. Moreover, the limit values in terms of interstorey drifts and second order effect have not been exceeded according to the limit coefficients described in the TEC (2007). It was noticed that all that values gradually increase with an increase in the storey number.
- Results of the model analysis demonstrate that increase in the storey number cause increase in the soft storey irregularity coefficients in especially first storey of the structure due to the load bearing capacity of the structural elements. Besides, storey loads accumulated in lower stories of the structure. For this reason, the load bearing capacity of structural members in lower stories should be increased in order to provide sufficiency in the stiffness or rigidity.

## 6.2. Recommendations for Further Studies

This thesis includes a comprehensive research on structural irregularities according to the TEC (2007). For further studies, increasing the number of case studies what were found and criticized in the thesis may contribute to the TEC with providing a new solution suggestion or a new sanction in the structural irregularity evaluation in TEC (2007). Moreover, the results from the obtained model analysis can be compared with other regulations such as Eurocode 8 FEMA 356, ATC 40 in order to compare the structural irregularity results with other codes. Thereby, the study also provides a comparative assessment on structural irregularities. Furthermore, a three dimensional time history analysis can be performed for the comparison of actual damage observed during the earthquake of the worst model in each structural irregularity case. Solutions should be developed for the existing building stock in Turkey which was constructed previous earthquake codes with having many structural irregularities. Moreover, a perception in the phenomenon of earthquake architecture should be popularized among architects in order to prevent design faults in newly constructed structures.

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