T.C.
İSTANBUL KÜLTÜR UNIVERSITY
INSTITUTE OF GRADUATE STUDIES

BEHAVIOR OF IRREGULAR RC STRUCTURES SUBJECTED TO HORIZONTAL AND VERTICAL SEISMIC EXCITATIONS

Masters of Applied Science Thesis

SAED MOHAMED AHMED

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Members of Examining Committee:
Prof. Dr. Hüseyin Faruk KARADOĞAN
Assist. Prof Dr. Gökhan YAZICI

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University: **İstanbul Kültür University**

Institute: **Institute of Graduate Studies**

Department: **Civil Engineering**

Program: **Structural Engineering**

Supervisor: **Assist. Prof. Dr. Erdal COŞKUN**

ABSTRACT

The past earthquakes show that the structures are not designed well to prevent the effect of earthquakes. Irregular structures have become very popular, and they carry a risk of failure during strong ground motions. The aim of this study is to evaluate the behavior of vertical irregular structures when subjected to both components (horizontal and vertical) of seismic excitations. Stiffness and mass irregularities are considered throughout the study. In this study, Four 2D models with 6-storey each were chosen to represent this problem. All the models were analyzed insides SAP2000 V21 software and designed according to ASCE 7-16 seismic code. Analyses were performed using nonlinear time history analysis using Newmark's average method. However, five different ground motions for both components in the near field region were obtained from the PEER website and scaled inside the seismomatch 2020 program. All the frame models are analyzed under two different loading cases: 1) Horizontal Only and 2) Horizontal plus Vertical. The structure's response in the form of maximum inter-story drifts, the axial force of column, joint acceleration, and mass participation ratio are compared under two loading conditions.

Keywords: vertical irregularity; stiffness and mass; nonlinear time history analysis; vertical and horizontal components; ASCE 7-16 code;

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ÖZET

Geçmişte yaşanan depremler, yapıların deprem etkisini önlemek için iyi tasarlanmadığını göstermektedir. Düzensiz yapılar çok popüler hale geldi ve kuvvetli yer hareketleri sırasında kırılma riski taşıyorlar. Bu çalışmanın amacı, sismik uyarıların her iki bileşenine (yatay ve düşey) maruz kalan düşey düzensiz yapıların davranışını değerlendirmektir. Sertlik ve kütle düzensizlikleri çalışma boyunca dikkate alınır. Bu çalışmada, bu problemi temsil etmek için her biri altı katlı iki boyutlu dört bina seçilmiştir. Tüm modeller SAP2000 V21 yazılımı içerisinde analiz edilmiş ve ASCE 7-16 sismik koduna göre dizayn edilmiştir. Analizler, Newmark'ın ortalama yöntemi kullanılarak doğrusal olmayan zaman geçmişi analizi kullanılarak yapıldı. Ancak yakın alan bölgesindeki her iki bileşen için beş farklı yer hareketi PEER web sitesinden elde edilmiş ve sismomatch 2020 programı kapsamında ölçeklendirilmiştir. Tüm çerçeve modelleri iki farklı yükleme durumu altında analiz edilir: 1) Yalnızca Yatay ve 2) Yatay artı Dikey. Yapının maksimum katlar arası ötelenmeler şeklindeki tepkisi, kolonun eksenel kuvveti, eklem ivmesi ve kütle katılım oranı iki yükleme koşulunda karşılaştırılmıştır.

Anahtar kelimeler: dikey düzensizlik; sertlik ve kütle; doğrusal olmayan zaman geçmişi analizi; dikey ve yatay bileşenler; ASCE 7-16 kodu;

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LIST OF ABBREVIATIONS

RCC : Reinforced compacted concrete

ASCE : American Society Of civil Engineering

MKO : Miyagi Ken Oki japan earthquake

EC8 : Eurocode 8

UBC : Uniform Building Code

NBCC : National Building Code of Canada

DCH : High Ductility Class

DCM : Medium Ductility Class

DDBD : Direct Displacement Basic Seismic Design

NPO : Nonlinear Pushover Analysis

NTHA : Nonlinear Time History Analysis

KTP : Albanian seismic code

ECT : Turkish Earthquake code

FEMA : Federal Emergency Management Agency

PGA : Peak Ground Acceleration

MDOF : Multi Degree Of freedom

MCE : Maximum Considered Earthquake

H : Horizontal component

V : Vertical component

LIST OF SYMBOLS

S_S : short period spectral acceleration

S_1 : long period of 1s

M_w : Magnitude

M : Mass of the structure

C : Damping coefficient

K : Stiffness

$\ddot{u}_t$: Total acceleration

$\ddot{u}_r$: Relative acceleration or structural acceleration

$\ddot{u}_g$: Ground motion acceleration

$\dot{u}$: Relative velocity

u : Relative displacement

R : Reduction factor

I : Important factor

DL : Dead load

LL : Live load

E : Earthquake

CHAPTER 1

INTRODUCTION

1.1 General

During ground motions, failure of a building starts at the point of weakness. This weakness emerges because of irregularity in the vertical and the shape of the structure. Irregularities in elevation are the primary reasons for the failure of buildings during strong earthquakes. According to irregular buildings, structures with mass and stiffness irregularities were the most collapsed ones during the past earthquakes. The sudden change in height and weight, which are the stiffness and mass irregularities, impact the earthquake performance of the building. Vertical irregularities alters the dynamic properties of the structures, which are not the same as regular buildings [1].

The ground motion amplitude of the horizontal component usually plays an important part when compared to the vertical component of an earthquake. However, the past earthquake records such as the 1989 Loma Prieta, 1994 Northridge, 1995 Kobe, and 1999 Chi-Chi, showed that the vertical components may have an amplitude that is equal to or larger than the horizontal components of an earthquake in near field regions. With the growing concern in vertical seismic excitations, the target of this study is to examine the behavior of irregular structures subjected to horizontal and vertical seismic excitations. To compare the results, the horizontal component and the combination of vertical and horizontal components of the earthquake are applied to four different 2D Rc structures having vertical irregularities.

1.2 Structural Irregularities of Buildings

According to ASCE 7-16 code, irregularities in the structures can be classified into many different types, but in general they are divided into:

a) Vertical irregularities

b) horizontal/Plan irregularities

a) Vertical irregularities: vertical irregularities are the structures that have irregularity in elevation as shown from Figure 1.1 to Figure 1.3, and they are divided into:

i) a) Stiffness-soft story irregularity: soft story irregularity is one in which the lateral stiffness is less than 70% in the floors above or less than 80% of the average stiffness of the three story above.

b) Stiffness- extreme soft story irregularity: an extreme soft story irregularity is one in which the lateral stiffness is less than 60% of that in the floor above or less than 70% of the average lateral stiffness of the three floors above.

ii) Mass irregularity: mass (weight) irregularities are considered to exist where the effective mass of any story is more than 150% of the effective mass of an adjacent story. The effective mass is the real mass consisting of floor deadweight plus the actual weight of partition walls.

iii) Vertical geometric irregularity: is defined to exist where the horizontal dimension of the lateral force-resisting system in any story is more than 130% of that in an adjacent story.

Structures having irregularities in elevation have become very popular nowadays. However, they are carrying a risk of failure during strong earthquakes. Building owners always prefer the architectural beauty that those structures have instead of thinking about the building's safety, so the structural engineers must keep in mind the risk of these structures and design a structure buildings that can resist strong earthquakes.

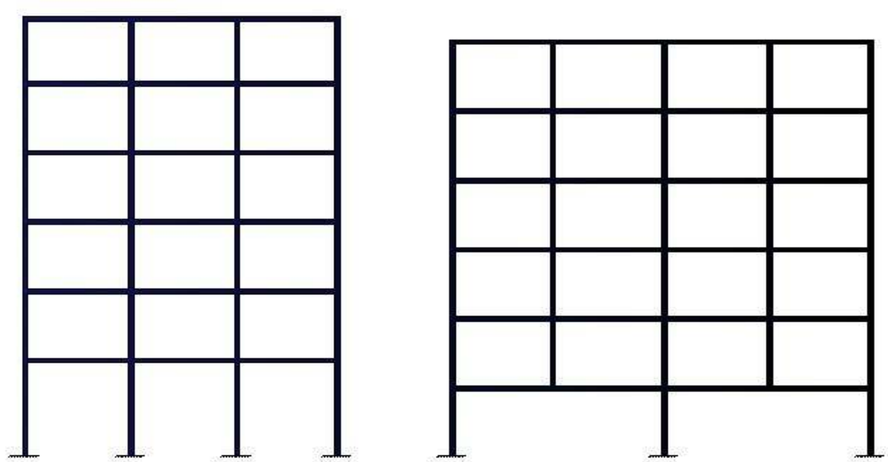


Figure 1.1: Irregular Distribution of Stiffness

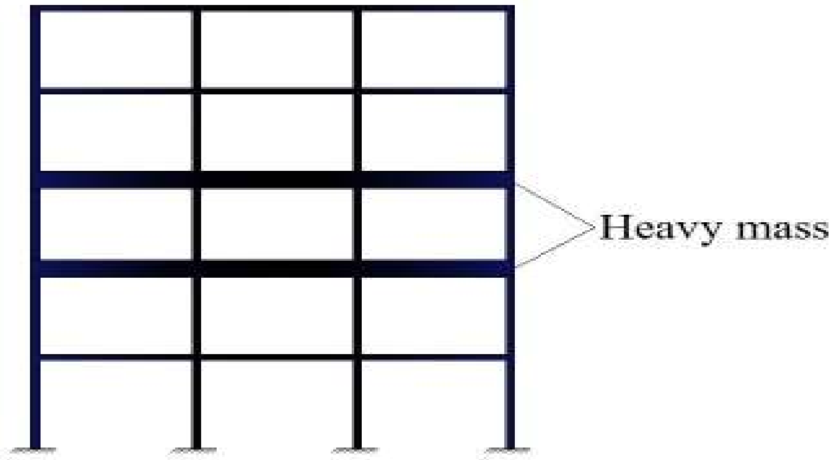


Figure 1.2: Mass Irregularity

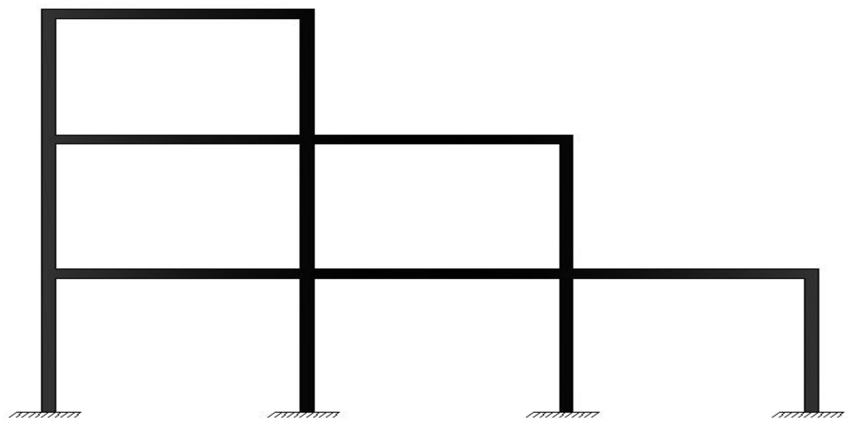


Figure 1.3: Vertical Geometric Irregularity

b) Horizontal/Plan irregularities: irregular structures having plan irregularities are those in which seismic response is translational and torsional and is a result of stiffness or mass eccentricity in the structure. The plan irregularity is also asymmetric of the structure in a T-shape plan, V-shape, and U-shape, etc.

Horizontal irregularity divided into torsional irregularity, extreme torsional irregularity, reentrant corner irregularity, diaphragm discontinuity irregularity, and out of plane offset irregularity. Irregular structures in Figure 1.4 and 1.5 shows irregular types of both horizontal and vertical irregularities

Figure 1.4: Elevation View of New Yorker Hotel [2].

Figure 1.5: Different Irregular Buildings in Manhattan City [3]

1.3 Failure Occurred During Past Earthquakes

Due to a rapid alteration in mass, stiffness, and irregularity along with a vertical or horizontal plane, a building may fail or suffer damage as a result of earthquake effects. The existence of irregularity, as we stated, causes structural collapse. This section focuses on structural collapses that happened during previous earthquakes as a result of various structural irregularities in the buildings.

1.3.1 Failure Due To Vertical Irregularities

Stiffness, mass, strength, and vertical geometric or setback irregularity are several types of irregularity in elevation. During the San Fernando earthquake in 1997, the Olive Medical Center was one of the structures that collapsed. The building had 6-floors with mass irregularity due to the presence of excess weight on the first floor. Furthermore, on the second-floor structural walls were presented, which causes irregularity in stiffness and strength. Therefore, the first two floors contained irregularities in mass, stiffness, and strength. After the earthquake, it was observed that the first two stories were damaged heavily while the upper four floors were damaged less, as shown in Figure 1.6. A similar failure of a four-story building was happening due to stiffness irregularity during the Northridge earthquake (1994), as shown in Figure 1.7.

The effect of soft stories in the building was the main reason for the collapse of many Rcc structures in Turkey during an earthquake that happened in the last decades. In Turkey, most of the structures had a soft story on the first floor due to residential and commercial purposes. Glass windows were used for these stories instead of brick infill walls to use as showroom or partition walls. The heavy masonry walls above the soft story created a large variety of mass, stiffness, and strength in the bottom floors. The previous studies and earthquake results showed that the soft-story structures led to a severe problem during an earthquake's shaking. As indicated by seismic records, the soft-story has been one of the major causes of structural collapse during earthquakes (EQE, 1995; youd et al, 2000; Yoshimura, 2003). As a result, it is recommended to prevent rapid mass, stiffness, and strength variations as the building height rises, particularly at the lowest floors.

Figure 1.6: Failure of Olive View Medical State Center

Figure 1.7: Failure of Parking Structure during Northridge Earthquake [4]

1.3.2 Failure of Building Due To Plan Irregularities

Buildings' failure caused structures to have irregular in the plan during strong and week Earthquakes in the past. Plan asymmetry is caused by the shifting centers of mass and stiffness of a structure, which generates torsional vibration. Figure 1.8 illustrates the collapse of a three-story building due to torsion caused by Japan (MKO) Earthquake in 1978. The center of stiffness was shifted towards the wall due to a stiff wall, which caused the building's twisting to the center of stiffness.

The torsional irregularity resulted in severe damage to the columns of the building. Figure 1.9 shows during the Haiti earthquake in 2010, the earthquake damaged many buildings, including the ministry of culture. The presence of torsional irregularity led to damage to the building lateral load resistant members away from the center of the stiffness. Due to these members' failure, the building led to total collapse, failing its structural members.

As previously mentioned, irregular structures perform poorly in earthquakes due to a lack of understanding of irregularity formulation and seismic codes (ASCE 7-16, EC8:2004, UBC 1997, NBCC 1995, NBCC 2005, etc.). However, neglecting structural irregularities may result in inaccuracies in the building's seismic response characteristics. However, an engineer must understand the behavior of irregular structures to design a building that perfumes well during earthquakes. Furthermore, previous research has mostly focused on the design of regular buildings and their response to severe earthquakes. As a result, it is necessary to estimate the impacts of various types of earthquakes on seismic characteristics to design better structures that can sustain and perfume effectively during great earthquakes.

Figure 1.8: Building Damage during 1978 Mko Japan Earthquake [5]

Figure 1.9: Building Damage during 2010 Haiti Earthquake

1.4 Purpose of the Thesis

Most residential buildings are designed without considering the impact of an earthquake's vertical component. The irregular structures have been used more when compared to regular buildings, especially high-rise buildings in developed countries and some residential buildings worldwide.

This thesis's main objective is to determine the behavior of irregular structures when subjected to both horizontal and vertical earthquake excitations. Another objective is to know the nonlinear behavior of irregular structures when nonlinear Time history analysis applies by using different ground motions inside the SAP2000 program.

1.5 Thesis Scope

The main scope of this study are as follows;

- For this study, four Rcc 2D structures are only considered
- vertical irregularity was only considered for this study
- For vertical irregularity, mass and stiffness irregularity were used.

- The impact of horizontal and vertical strong earthquakes on vertical irregular buildings was studied using nonlinear time history analysis.
- SAP2000 software was used to analyze and design Rcc frame models, and seismomatch software was used for scaling ground motions.
- The column models were fixed in the base, and the effect of soil is ignored.
- Scaled horizontal, and vertical ground motions were used for this study.
- All of the frame types are evaluated under two loading scenarios: 1) horizontal alone (H) and 2) horizontal plus vertical (H+V).

1.6 Thesis Overview

Chapter 1 presents a general introduction to irregular structures and their types with their limitations given by the ASCE 7-16 seismic code. Describes failure of buildings during the past earthquake, both vertical irregularity and plan irregularities. The final part states the thesis's primary purpose and thesis scope.

Chapter 2 introduces a literature review of previous studies titled irregular structures subjected to both components (horizontal and vertical) of seismic excitations. Scientific studies related to this study are presented in this section.

Chapter 3 presents the theoretical background of the study by defining the case study of the building, the vertical effect of ground motions, and type of analysis used, the p-delta effect, and plastic hinge definitions with their properties.

Chapter 4 presents the numerical modeling of a case study of the building. The modeling of four different 2D structures under two different components of an earthquake is presented using SAP2000 software [SAP2000, v21]. The first part of this chapter defines the general description of the building models by telling building elevations, material properties, a section detailing, and load combinations. The second part describes analysis procedure for this study by defining the two different load cases named case-1 (Horizontal only) and case-2

(Horizontal + Vertical). The final part of this chapter presents ground motions used for this study and their scaling using seismomatch software [seiemomatch, 2020].

Chap 5 presents analysis results and a discussion of the case study buildings. Nonlinear time history analysis comparison of inter-story drifts, column axial force, and acceleration between case-1 and case-2 under all ground motions were presented in terms of tables and graphs.

Chapter 6 highlights the summary, conclusion, and recommendations for future studies

CHAPTER 2

LITERATURE REVIEW

2.1 General

The seismic records subjected to the buildings are in three different dimensions in general, but the horizontal components of earthquakes is considered during earthquake design of the structures while the vertical components of earthquake record is generally neglected. Many building standards require the vertical components of an earthquake to be two-thirds of the horizontal components, as proposed by Newmark et al (1973). The horizontal and vertical ground motion acceleration of the El-Centro 1940 record is represented in Figure 2.1.

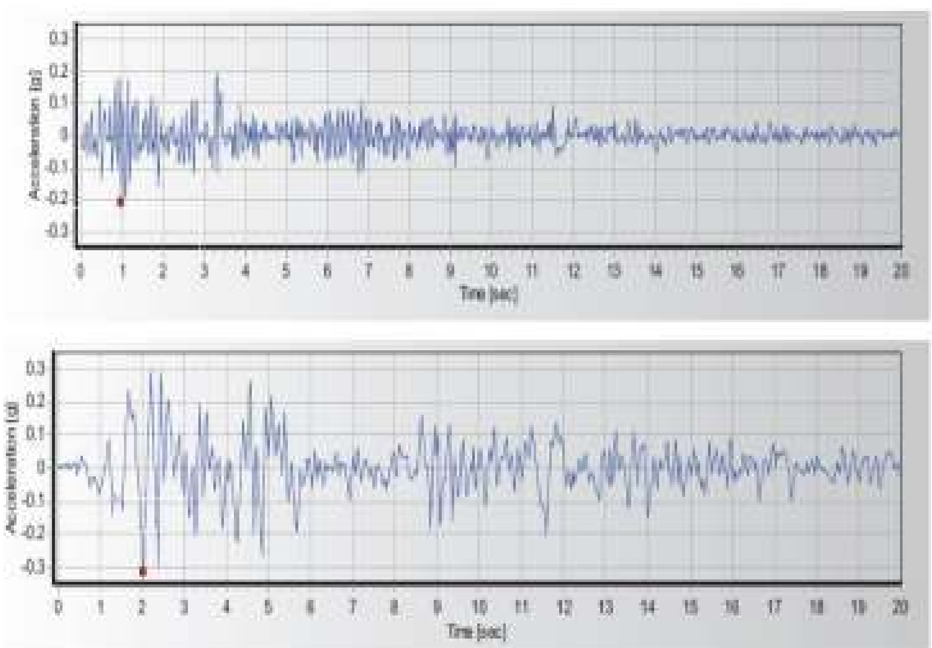


Figure 2.1: El-Centro 1940 Time History Record for Both Components (V & H). [6]

The earthquake records in far field region showed that the peak horizontal ground accelerations are larger than peak vertical acceleration [7]. However, in near fault region the past earthquakes shows that the peak vertical accelerations have exceeded the peak horizontal acceleration as shown in Table 2.1.

Table 2.1: Earthquake Record Information [8]

Event	Station(mw)	Hor1(g)	Hor2(g)	Ver(g)	V/H
Gazli, Uzbeksitan 1976	K.arakyr(6.8)	0.71	0.63	1.34	1.89
Imperial valley, USA 1979	El cenro array 6 (6.5)	0.41	0.44	1.66	3.77
Nahhani, Canada 1985	Site 1(6.8)	0.98	0.1	2.09	1.9
Morgan hill, USA 1984	Gilroy array#7(6.2)	0.11	0.19	0.43	2.25
Loma-prieta, USA 1989	LGPC(6.9)	0.56	0.61	0.89	1.47
Northridge, USA 1994	Arleta fire station(6.7)	0.34	0.31	0.55	1.61
Kobe,Japan 1995	Port Island (6.9)	0.31	0.28	0.56	1.79
Chi Chi, Taiwan 1999	TCU 076 (6.3)	0.11	0.12	0.26	2.07

2.2 Review of Research Works under Seismic Excitations

Vertical irregularities are considered when the building has irregularities in mass, stiffness, and vertical geometric irregularities. These irregularities may present one by one or two to determine the effects of irregularities in elevation on the structures. The effect of vertical irregularities should be taken into account and designed well according to seismic design codes. Chopra and Kan (1973), who examined the reaction of a building when subjected to ground motion data, launched the vertical irregularity research investigations in early 1970. The building was eight stories tall and had shear walls on all sides. They wanted to see how yielding in the first level affected the upper stories during their research. According to the findings of the analytical research, an optimum mechanism and a low yield force are necessary for the first story for the safety of upper levels.

According to recent studies on earthquakes like the 1989 Loma Prieto, 1994 Northridge, and 1999 Chi-Chi, the horizontal component of the earthquake was determined to be smaller than the vertical component, denying the code rules that require the vertical to horizontal (V/H) spectral ratio to be 2/3.

Ehsan Noroozinejad, and Abbas Ali. (2016) studied the influence of coupled vertical-horizontal seismic excitations on the collapse margins of modern reinforced concrete moment resisting frame structures (RC-MRFs). They selected the structures to be mid- to high-rise buildings during their study. Four reinforced concrete moment resisting frame structures ranging from 7 to 20 floors were selected to constitute medium- and high-rise structures. Twenty earthquake record are selected from PEER website having horizontal and vertical components to subject the building models. Two different software’s named ZEUS-NL and

OPENSEES were implemented to analyze the reference structures and compere their results. The structures were fixed in the base while soil interaction is neglected. Nonlinear time history analysis was performed by using selected ground motions. Two loading conditions were implemented in which the first loading is horizontal only (H) while the second one is the combination of horizontal and vertical (H+V) components of earthquake. The study result shows that the effect of the inclusion of vertical ground motions to axial force of column increases as the vertical to horizontal ratio increases. They proposed that the structures located within 25 km from fault lines be designed to the combination of horizontal and vertical ground motions [9].

Engin Keskin (2020) assessed on his study the vertical ground motion effect on the performance of high-rise structures. To determine the effect of vertical ground motions, 100 earthquake records were selected according to ground motion magnitude, soil class, and fault distance. Reinforced concrete high-rise building which is having 30 floors with typical floor height of 4m was considered throughout the study. The building was designed according to Turkish Building Code (TBSC18) and the result were evaluated in terms of inter story drift, overturning moment, column axial force, and story shear force. Nonlinear time history analysis were implemented to obtain the model results. The result shows that the vertical ground motion have moderately effect the inter-story drift ratio, overturning moment, and base shear. However, the researcher observed that vertical ground motions have more effect on axial force of column for both compression and tension. The result also shows that the vertical ground motion effect increases when the contribution of horizontal ground motion is very small and the inclusion of vertical ground motion during the analysis of high-rise buildings is very important [10].

Resat Oyguca, Cagatay Toros, and Adel E. Abdelnaby (2018) they investigated the behavior of irregular reinforced concrete structures under numerous seismic excitations. Their goal was to see how irregularly designed structures will react when subjected to Tohoku ground motions. Three irregular reinforced concrete structures were created using three-dimensional numerical modeling. The irregular building's features are then altered to obtain a regular case. N2 and extended N2 methods are used to assess the capabilities of both regular and irregular cases. They studied three types of numerical structures in Turkey: SPEAR, ICON, and school buildings. These buildings were investigated before and after the major shock of ground motion caused by the 9.0 magnitude Tohoku earthquake on March 11, 2011.The three models were subjected to a ground motion sequences of 23 selected stations, with no consideration of the near field, far-field, and fault effects. They compared the results of both regular and irregular cases. They concluded that the irregular structures have higher displacement than regular ones. The main shock damage is more in regular structures, and the N2 method is an effective way to determine the behavior of irregular structures when subjected to ground motions [11].

P. Giannakouras and C. Zeris (2019) studied the earthquake performance of irregular RC frames designed according to the DDBD approach. The Direct displacement basic seismic design (DDBD) method is a significant development of performance basic seismic design of reinforced concrete (Rc) frames. They examined the irregular Rc structures by assessing the DDBD method and their performance under nonlinear static and dynamic analysis. The DDBD method used regular and irregular setback RC frames of six and ten stories buildings. All the frames have been analyzed using nonlinear pushover Analysis (NPO) and nonlinear time history analysis (NHTSA) while using fourteen different ground motions. They concluded their study; the roof displacement under nonlinear time history analysis exceeded the roof displacement limits in the DDBD method. For storey drifts, the case of ten-storey setback irregularity and regular frames were having the most difference ground motions' excitations. The p-delta effect was considered for this study. It proved that during the p-delta, it affects the setback irregular frames and perfumes well while it's less susceptible than in regular tall frames. They concluded that irregular setback frames in seismic behavior is unacceptable since drift limits and deformation capacities were exceeded and found that these frames are susceptible to collapse mechanism and shear failure [12].

Saugat Tiwari and Sailesh Adhikari (2020) observed seismic analysis of stiffness and mass irregularities using numerical modeling. Ten-story reinforced concrete moment resisting frame building with mass and stiffness variation is considered for their study. Response spectrum analysis was used to analyze the structures. Total of four buildings with ten-story each which is modeled with different mass and stiffness irregularities. The buildings were designed according to IS 1893 (Part 1):2016 and IS 456:2000 codes. The structures were modeled inside sap2000 to obtain story displacement, story drifts, and base shear of each model. They concluded that an increase in story height, which brings stiffness irregularity to the structure, increases the base shear and lateral loads. Mass in the top floors increases the displacement. In contrast, mass in the lower floors decreases lateral displacement. Irregularities in mass and stiffness should be exerted on the structure's base, not the top, to reduce ground motions. Frames that have more irregularities will have the maximum story drifts, and more rebar in the beams and columns are required [13].

Choppa Sravan Kumar (2016) studied on his master's degree the seismic analysis of buildings having mass irregularity and vertical geometry irregularities. The vertical irregular structures do not perform well during strong ground motions. The study conducted to implement and decide the structures' seismic response spectrum analysis and pushover analysis. The irregular high-rise buildings are more susceptible to collapse during an earthquake, so the researcher took an 8-story building inside sap2000 software. The mass and vertical geometric results were compared, and pushover curves were obtained. Regular and irregular structured were considered to decide which structures have the least effective during strong ground motions. The study conclusion and results stated that the mass irregular structures have more significant base shear than a regular one, lateral load for irregular structures decreases while the lateral load for regular structure increases, the seismic weight of regular structures is more when compared to irregular structures. The story shear is maximum in the base floors for both regular and irregular structures [14].

Arvindreddy and R.J.Fernandes (2015) observed the seismic analysis of regular and irregular Reinforced concrete structures. The study was conducted the static and dynamic analysis to find the structures located in severe zone v. for zone I and zone II. Equivalent static analysis was performed, and zone IV and zone V time history analysis and response spectrum analysis were considered. Six models with 15-storey each were used for both regular and irregular cases inside ETABS software. The study results show that the story displacement results of response spectrum analysis are more significant than the results obtained from static analysis. The story drifts and story displacement of regular structures are less compared to irregular ones for both static and dynamic analysis. The curves obtained from pushover analysis show that the stiffness irregularity indicates nonlinear behavior at an initial stage, and time history analysis the results shows that the stiffness irregularity case has the least base force when compared to other regular and irregular cases [15].

Hasan Hüsnü Korkmaz (2018) investigated the earthquake behavior of overhang structures having torsional irregularity. The study shows the torsional irregularity has more effect on structures having large overhangs during strong earthquakes. Six different models were used throughout the study. The model was classified as a base model, which is a torsional irregular model with no overhang, model having one overhang (case-D), two overhangs (Case-E and F), three overhang (case-G), and four overhangs (case H). The models have been analyzed by using response spectrum analysis inside ETABS software. Dynamic analysis is very important for irregular structures, so the researcher took the nonlinear dynamic analysis to compare model results. The stories of all models were the same, and the mode supper position method was used to determine each model's seismic response. The study results were concluded as follows; the torsional irregularity factor of the base case was 1.06 while the case d & g exceeded the limitation, which was 1.2. The case-h is below the limitation, and the case-f is equal to the reference model limit, the base case having irregular torsional model with no overhangs has the least torsional moment in the edge column, while case-d has the most significant Torsional moment in all cases, and case-f torsional moment remains constant. This study is significant, and it shows that the Architectural configuration of the structure is essential during strong ground motions [16].

Chatpan Chintanapakdee and Anil K. Chopra (2004) studied vertical irregular frames by using modal pushover analysis. They compared the results of two familiar analyses named pushover analysis and nonlinear time history analysis to determine which analysis has the perfect results for vertical irregular structures. Forty-eight different models with 12-storey each were considered through the study. Three different types of vertical irregularities named stiffness, strength, and a combination of both were used. The study results are summarized as follows; the prejudice of modal pushover analysis does not increase. The modal pushover analysis detects well for stories having more story drifts, so cases 6-8 have the greatest drift demands. The distribution of story drift ratios of irregular buildings is the same as the regular ones, and the modal pushover analysis performs well in some cases. However, the nonlinear time history analysis is more accurate for irregular structures. This study is unique and clarifies the importance of nonlinear time history analysis for irregular structures [17].

S. Varadharajan, V. K. Sehgal, and Babita Saini (2012) investigated the seismic response of reinforced concrete frame with vertical stiffness, and mass irregularities 2332 building models with stories ranging from 6 to 18 were considered throughout the study. The stiffness irregularity ratio is different from 25% to 75%. The mass irregularity ratio varies from 200% to 600%. The models were subjected to 27 different ground motions to determine and compare the modal results such as fundamental period, story drifts, and story displacements. The study's results are concluded as follows; the suggested index to measure the irregularities was found to work better than the code-defined approach. The fundamental period of structural models having the same magnitude and placed different locations have the same fundamental period with those estimated by code approach. This study provides us some useful information, and it is very important for structures having mass and stiffness irregularities [18].

B V Chiniwalar, T D Doshi, and Manjunath S Pujar (2015) investigated in their study the seismic response of vertical irregular structures with soil-structure interaction. The behavior of regular and setback irregular models with soil-structure interaction was considered. Sixteen different models with regular and setback irregularity each were used throughout the study. Response spectrum and equivalent static analysis were carried out to implement all models' analysis and design inside staad-pro software. The study results concluded as follows; the increase in stiffness irregularity increases the natural period, leading to increases in the base shear of regular and irregular structures. The story displacement of setback irregular structures is less than regular ones, which means that the regular structures have larger base shear. Whenever the structure's seismic response increases, the soil-structure interaction also increases, so the soil-structure interaction must be considered. The study is significant for investigating the vertical irregular structures having soil-structure interaction, and it concludes that the soil interaction influences the structures [19].

Akhilesh Rathi and Dr. Ashwin Raut (2018) investigated the analysis and design of a reinforced concrete regular and vertical irregular building in their study. The study was limited to two cases, namely regular and vertical geometric irregular cases. They were considered two models with 20-storey, each having regular and vertical geometric irregularity throughout the study. Response spectrum analysis and time history analysis inside ETABS software were used. The study results concluded as follows; they found that the regular buildings have a larger fundamental period than regular models. The fundamental period difference does not depend on the building height only. FEMA 356 proposed that the pushover analysis works well for the results related to base shear and roof displacement. However, the study shows that the pushover analysis didn't work well for irregular vertical buildings, exceptionally high-rise buildings. The response spectrum capacity curves show that they are similar to those obtained from nonlinear time history analysis, so response spectrum analysis can be used to analyze the vertical geometric irregular buildings [20].

C. A Aiyappa et al. (2019) studied the seismic performance of soft story and vertical geometric irregular structures. The study investigates the effect of irregular structures when subjected to seismic excitations. Two models with four cases, both regular and irregular cases, were considered throughout the study. The first two cases are regular base models. The second three cases are vertical geometric irregularity, and the last three cases are structures having stiffness irregularity, which makes eight models for all cases. Pushover analysis was used inside ETABS software. The study results are summarized as follows; whenever the building has more vertical irregularity story shear increases than the structures having one vertical irregularity. Expanding the building's height results in an increase of lateral displacement for both regular and irregular structures, which means high-rise building has more displacement than low-rise buildings [21].

Faizan Ahmed (2017) studied the significance use of vertical ground motions in earthquake analysis for isolated structures. Throughout the study he focused on the horizontal ground motion with the inclusion of vertical seismic excitations. A 3- story building having isolator in the base was modeled inside SAP2000 program. Twenty different ground motions were used and obtained from PEER website while the selection of ground motions were based on station distance, magnitude, and peak ground acceleration. The ground motions are subjected to the structures in three different ways. Firstly, the building is subjected to horizontal only. Secondly, the combination of horizontal and vertical accelerations are subjected the building at same time. Finally, the structure is subjected horizontal acceleration first then vertical component is subjected later. The result shows that the inclusion of vertical ground motion effects more for isolated structures when compared to code limitations for isolated structures. Vertical ground motions also expose higher strength demand for isolated structures when combined parallel to horizontal excitations [22].

Hongyang Wu (2016) investigated on his study the effect of vertical ground motions on earthquake response of steel frame structures.in general the earthquake have three components which are two horizontal and one vertical acceleration. Eight different steel structures were selected to represent the study results inside SAP2000 program. Equivalent lateral force method was used to design the steel structures based on ASCE 7-10 while nonlinear time history analysis was used for the analysis of the building models. A group of 40 different ground motions records were selected from PEER website including horizontal and vertical components of earthquake. All the steel structures were analyzed under two different loading conditions; 1) Horizontal only and 2) combination of horizontal and vertical components. The study result shows that the vertical ground motions have less effect on story drift ratio, although some reasonable effects exist on the 6-story moment frame. The inclusion of vertical ground motions also increases the axial force of column for both interior and exterior columns. However, the effect of vertical ground motions on interior column are larger than the exterior ones due to higher mass on the joints of interior columns [23].

CHAPTER 3

THEORETICAL BACKGROUND

3.1 Introduction

The existence of irregularities in the building structures effects the building's reaction when subjected to seismic excitations. The seismic codes doesn't evaluated probably the aspects of structural irregularities. The seismic records in the past shows that regular shape structures perform better when compared to irregular ones during strong earthquakes.

Non-uniform load distribution in various members of the building is caused by structural imperfections. There have been several studies on the irregularities of a building like study of irregular Rc building under seismic effect (s.varad harajan, 2014), study of structurally irregular building frames subjected to seismic excitations (Anshul sharma, 2016), Etc. in this study 4 different models having 6 story each with mass and stiffness irregularity in elevation were considered.

There are different types of building irregularities depending on their scope and location, but mainly, they are divided into: -plan irregularity and vertical irregularities.in the present chapter the vertical irregularities are considered especially mass and stiffness irregularities and they are described in Table 3.1 according to ASCE7-16 seismic code.

3.2 Stiffness Irregularity

The 1st and fourth floors of building models have 4m in height while the other floors are 3m, making the building irregular in stiffness Figure 3.1 part (a). According to ASCE 7-16, stiffness irregularity is divided into;

1. Soft story irregularity
2. Extreme soft story irregularity

1. Soft story irregularity: is one in which the lateral stiffness is less than 70% of that in the story above or less than 80% of the average stiffness of three stories above.

2**.** Extreme soft story irregularity: is one in which the lateral stiffness is less than 60% of that in the story above or less than 70% of the three stories' average stiffness above.

3.3 Mass Irregularity

When the effective mass of one level exceeds 150 percent of the effective mass of the neighboring story, mass irregularity is present. Increased inertial forces, lower ductility of vertical load resisting elements, and an increased inclination to collapse owing to the P-effect can all result from the excess mass. Mass irregularities can lead to irregular responses and complicated dynamics. The 1st and fourth floors are heavier than the other floors, making the building irregular in mass.

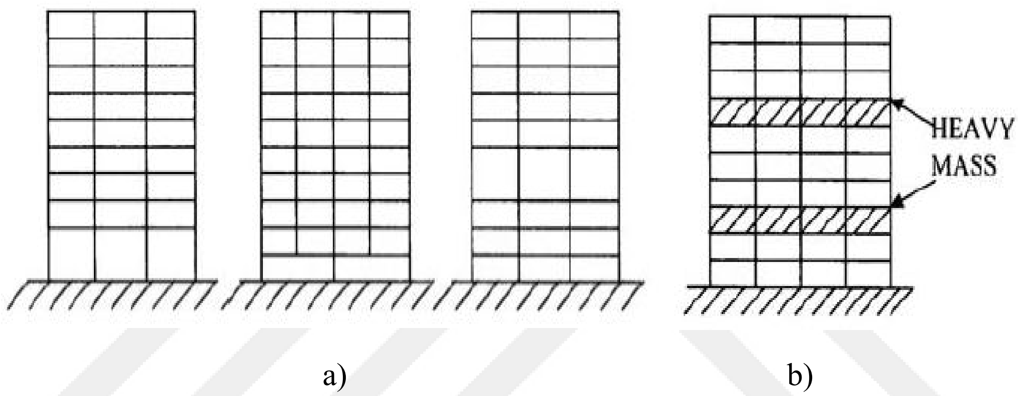


Figure 3.1: vertical irregularity in a) Stiffness b) mass

Table 3.1: vertical structural irregularity according to ASCE 7-16 [24]

Type	Description	Reference Section	Seismic Design Category Application
1a.	**Stiffness–Soft Story Irregularity:** Stiffness–soft story irregularity is defined to exist where there is a story in which the lateral stiffness is less than 70% of that in the story above or less than 80% of the average stiffness of the three stories above.	Table 12.6-1	D, E, and F
1b.	**Stiffness–Extreme Soft Story Irregularity:** Stiffness–extreme soft story irregularity is defined to exist where there is a story in which the lateral stiffness is less than 60% of that in the story above or less than 70% of the average stiffness of the three stories above.	12.3.3.1 Table 12.6-1	E and F D, E, and F
2.	**Weight (Mass) Irregularity:** Weight (mass) irregularity is defined to exist where the effective mass of any story is more than 150% of the effective mass of an adjacent story. A roof that is lighter than the floor below need not be considered.	Table 12.6-1	D, E, and F

3.4 Effect of Earthquake on Rc Structures

The effect of strong earthquake to the structure and human properties were increasing for the past years. Hence, the evaluation and earthquake damage on structures are the real concerns of structural and earthquake engineers. The components of earthquake are proudly categories into Horizontal and Vertical components. The horizontal component of ground motions have an influence more than vertical component of earthquakes. However, the past earthquakes including Northridge earthquake in the USA showed that the vertical component may have magnitude larger than or less than the horizontal component. For this study four different irregular reinforced concrete structures are subjected to horizontal and the combination of horizontal and vertical components to testify the effect of strong ground motions especially vertical irregular structures having mass and stiffness irregularity [25].

3.4.1 Effect of Vertical Component of Earthquake

Vertical seismic excitations produce significant damage to reinforced concrete frames, according to recent earthquakes (Northridge earthquake (1994) in the United States, Hyogo-ken earthquake (1995) in Japan, Yojakarta earthquake (2006) in Indonesia, and Christchurch earthquake (2011) in New Zealand). When compared to horizontal earthquake ground motion, vertical seismic excitations cause story shear and axial force. Moment-resistant frames subjected to both vertical and horizontal components of earthquakes might sustain greater damage than those that are just subjected to horizontal ground motions only.

It was observed that high vertical forces can cause high risks to the structures which may lead to a failure and collapse of reinforced concrete frames. The general idea for vertical ground motions has become highly interested for the structures especially for bridge structures. As the p-wave of vertical ground motions has more frequency content then the s-wave related to the horizontal component the vertical to horizontal (V/H) spectra ratio will be very large. Moreover, it has been presented that the vertical ground motions should be sufficient to take into consideration for seismic design of structures, where high vertical acceleration are expected [26].

3.5 Review of Analysis Method

The analysis methods are very important to obtain the building model results. The seismic effect of the structures was increasing for the past years and the engineers were dealing to reach a better way to prevent the structures to fail. Nonlinear time history analysis was adopted in this study under two loading conditions. Nonlinear time history analysis were implemented to obtain the seismic parameter results such as axial forces, and inter-story drift ratios while earthquake lateral load were used to design the structure.

3.5.1 Time History Analysis

A time history analysis is a step-by-step analysis of the building's dynamic response to identifying the loads that may vary over time. The seismic response of a structure under the dynamic loading of a typical earthquake is determined via time history analysis. [27].

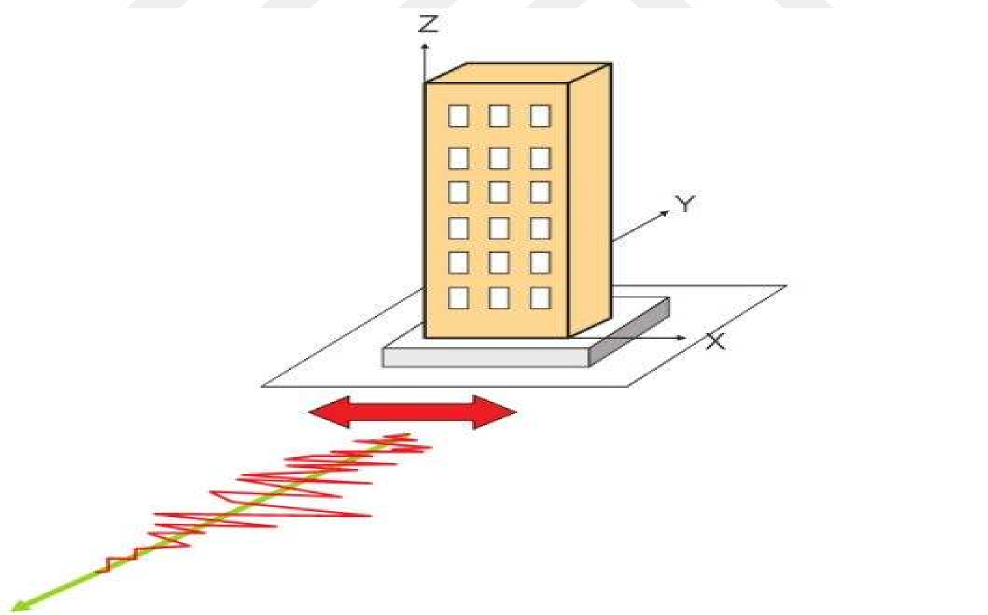


Figure 3.2: Schematic Representation of a Building Model Subjected To Seismic Excitation in the X-Direction

In this method, nonlinear analysis has been considered to determine irregular structure responses when subjected to different earthquake excitation under two loading cases.

Time history is a dynamic analysis method, so the Equation of motion of multi-degree of freedom systems (MDOF) is given in Equation (3.1) and (3.2).

$$M\ddot{u} + C\dot{u} + Ku = -M\ddot{u}_t \quad (3.1)$$

$$\ddot{u}_t = \ddot{u}_r + \ddot{u}_g \quad (3.2)$$

Where,

M = mass of the structure

C = damping coefficient

K = stiffness

$\ddot{u}t$ = total acceleration

$\ddot{u}r$ = relative acceleration or structural acceleration

$\ddot{u}g$ = ground motion acceleration

$\dot{u}$ = relative velocity

u = relative displacement

3.5.2 Nonlinear Time History Analysis

In this study, response of the building under seismic excitations has been examined by using the nonlinear step-by-step time history method. This approach allowed us to estimate the structure's response through dynamic analysis by subjecting the building model to a group of ground motions. The analysis is carried out for more than one ground motion to perform the nonlinear dynamic analysis. Seismic design codes described dynamic analysis for medium and tall structures; therefore, the nonlinear dynamic analysis method has been used to determine irregular building model’s seismic response.

Seismic analysis is a type of earthquake engineering that is used to quickly understand how buildings react when they are subjected to earthquake excitations. Previously, buildings were simply built to withstand gravitational loads. Seismic analysis, on the other hand, has been done developed in recent years, which allowed the structure to be analyzed and designed using ground motion data through structural software. In this study direct integration was used which are more sensitive to time steps without effecting the result.

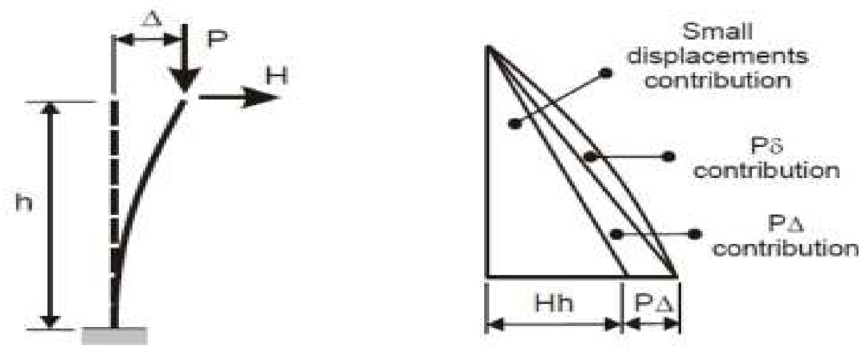
Geometric nonlinearity including p-delta effect was used during nonlinear direct integration time history analysis. Damping ratio is assumed to be 5% while Newmark method was taken to solve nonlinear equations. The gamma and beta values for Newmark method are taken as 0.5 and 0.25 respectively,

3.6 P-Delta Effect

P-Delta effect is also termed as geometric nonlinearity, which is related the equilibrium compatibility relationship of a structural system assigned about its deflected configuration. The p-delta is the application of gravity load on laterally displaced of building structures and it increase the story drift and certain parameters while reducing deformation capacity. P-Delta effect tend to include large external forces onto relatively small displacement. However, in general p-delta can be classified into two types, one is P- Δ (large p-delta or big p-delta) and other is P- δ (small p-delta) effects [28]. The two sources of p-Delta effect are shown in Figure 3.3 and described as flows:

a) P- δ (small p-delta) effect: P- δ effect related with local deformation relative to the element chord between end nodes. Small p-delta effect is very important for local buckling load and the moment which may affect the structural behavior of the building.

b) P- Δ (large p-delta) effect: P -Δ effect related to the displacement of the member at the ends. Large p-delta effect is very essential for structural behavior under axial loading. For implementing the large p-delta effect in nonlinear analysis gravity load should be presented. As shown in Figure 3.4, gravity loading influence the response of the structure under lateral loading.



a) **b)**

Figure 3.3: P-Delta effect around column: a) column b) bending moments

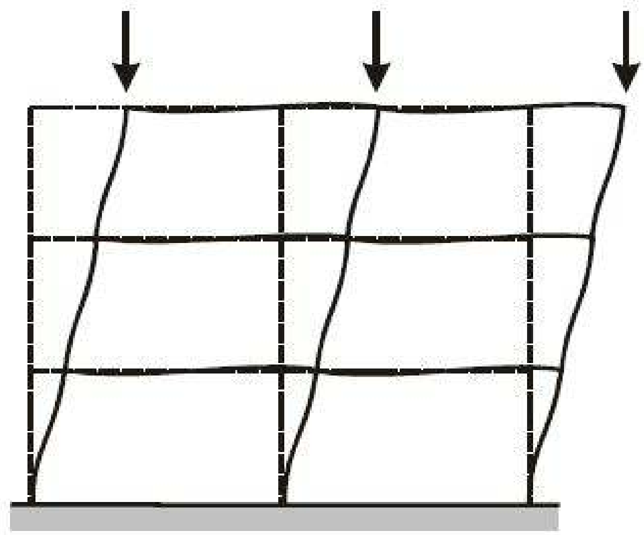


Figure 3.4: P-Delta effect about structure

3.7 Properties of Plastic Hinges and Their Definition

Plastic hinges is defined the deformation that happen at the beam or column section where plastic bending take place. In nonlinear time history analysis, users may imitate post-yield behavior by inserting concentrating plastic hinges to the frames. Elastic behavior happen on top of member length, while deformation after elastic limit happens in the hinges. Plasticity is related with the force displacement behavior (axial and shear) or moment rotation (torsion or bending). However, the hinges can be assigned to any of the six degree of freedom.

The plastic hinges are very important for checking the building performance under seismic excitations. For plastic hinge formation the behavior of stress strain ductile material like steel, they end elastic limit of the body by starting from plastic behavior. Then the strain and stress will be alter at different rate as shown in Figure 3.5.

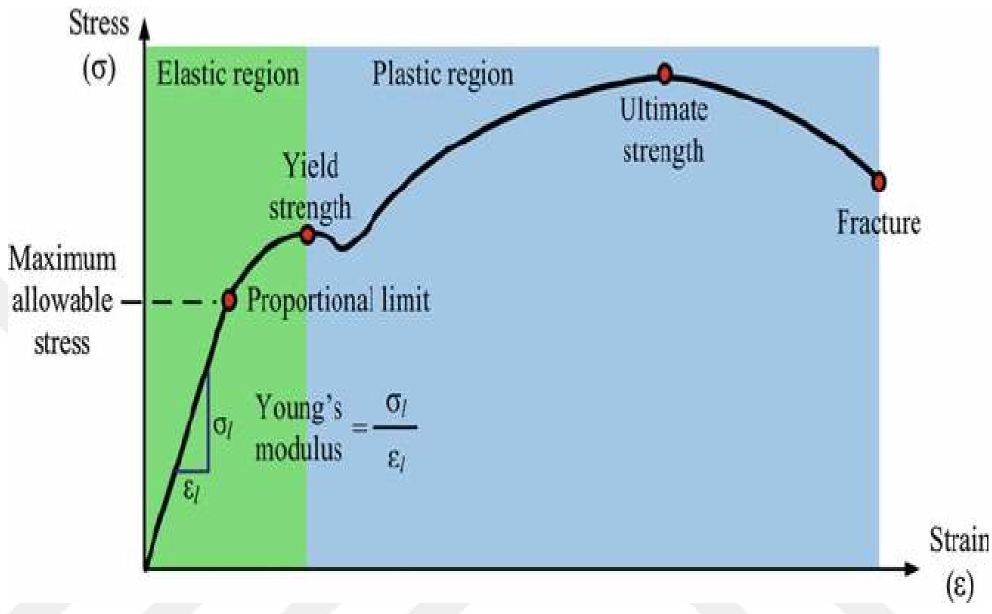


Figure 3.5: Stress-Strain Relationship [29]

In this study plastic hinges were assigned at the end of beams and columns in all models. Moreover, the plastic hinges in beams are assigned M3 degree of freedom while column are assigned at the P-M2-M3 degree of freedom inside SAP2000 software.

CHAPTER 4

NUMERICAL MODELING OF THE CASE STUDY OF BUILDING

4.1 Introduction

This chapter presents the modeling of irregular structures subjected to vertical and horizontal earthquake excitations with stiffness and mass irregularities. Four different 2D models have been used for this study. The models have been analyzed by using sap2000 v21. Nonlinear time history analysis have been used to obtain the seismic parameters of the structure. Five Input ground motions have been taken in both components and scaled by using seismomatch software. Firstly, the building is described in general by telling the material properties of the structures, reinforced details of models, and load combinations. Secondly, the steps for modeling inside sap2000 were presented by defining nonlinear time history analysis and plastic hinges. Finally, the ground motion data is presented in detail for both horizontal and vertical components.

4.2 General Description of the Building models

In order to achieve the aim of this study four 2D reinforced concrete building models with six-story each having different height and different story mass was considered throughout the study. The model cases are multi-storied 2D reinforced concrete buildings composed of beams and columns. All the models are designed and analyzed inside SAP2000 software .The MIM-01 and KIM-01 building models have 4 bays by 4m while MIM-02 and KIM-02 models have 5m bays by 4m in x direction. Table 4.1 shows the description of considered models used for this study while Figure 4.1 shows the building elevations.

Table 4.1: Considered Building Frames

Reference Name	Modal name description
MIM-01	Mass irregularity model-01
KIM-01	Stiffness irregularity model-01
MIM-02	Mass irregularity model-02
KIM-02	Stiffness irregularity model-02

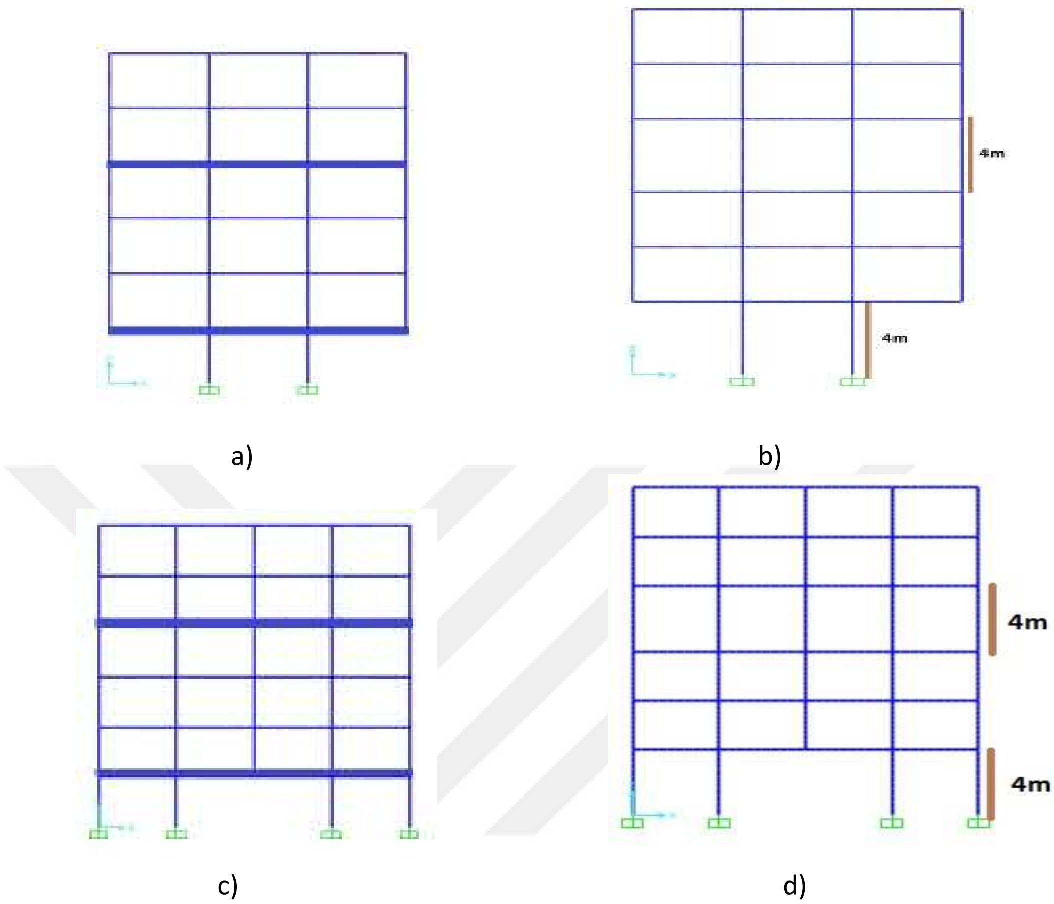


Figure 4.1: Model Elevations: a) MIM-01, b) KIM-01, c) MIM-02, d) KIM-02

The beam and column dimension of all models are presented in Table 4.2. However, the KIM-01 and KIM-02 building models have stiffness irregularity in the first and fourth floors while MIM-01 and MIM-02 building frames have excess weight in first and fourth floor.

Table 4.2: Building Section Dimensions

Section Name	MIM-01 & KIM-01	MIM-02 & KIM-02
Beam	650x300mm	600x300mm
Column	750x550mm	700x500mm

4.2.1 Material Properties

Material properties used for this study are based on American standard. The irregular models for this study are considered to be moment resistant frame. The detail of material properties in all models are presented in Table 4.3.

Table 4.3: Material Properties of All Frames

Description	MIM-01 & KIM-01	MIM-02 & KIM-02
Grade of concrete	fc5000psi(35Mpa)	fc4000psi(28Mpa)
Density of concrete	24KN/m3	24KN/m3
Modulus of elasticity of concrete	27Gpa	24Gpa
Poison ratio of concrete	0.2	0.2
Grade of steel	Fe615	Fe615
yield strength of steel	414 Mpa	414 Mpa
Ultimate strength of steel	455 Mpa	455 Mpa
Modulus of elasticity of steel	200Gpa	200Gpa
Poison ratio of steel	0.3	0.3

4.2.3 Reinforcement Details of Building Model

The building models were analyzed and designed inside SAP2000 program. To obtain the required reinforcement for all structures the required area of the reinforcement obtained from the SAP2000 was divided by the area of the chosen rebar type to get the number of rebar in each member. The section reinforcements are presented in Table 4.4 while the reinforcement details are shown in Figure 4.2.

Table 4.4: Section reinforcement detail

MIM-01 & KIM-01	Bar size & Number
Column 750x550mm	8φ25
Beam 650x300mm	Top= 4φ18
	Bottom=2φ18
MIM-02 & KIM-02	**bar size & Number**
Column 700x500mm	8φ25
Beam 600x300mm	Top= 4φ18
	Bottom=2φ18

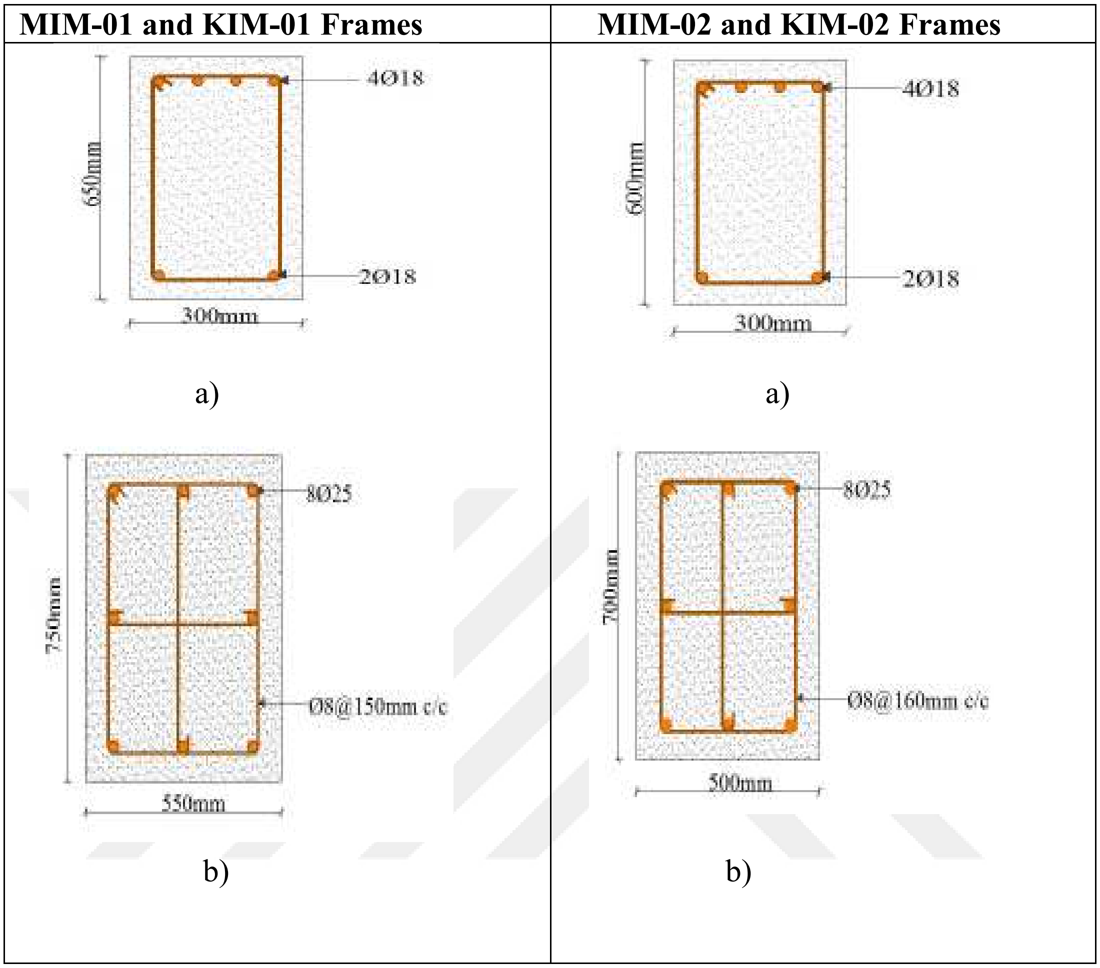


Figure 4.2: Reinforcement details of all building models: a) beam, b) column

4.2.4 Load Combination

Individual loads, such as dead loads, superimposed dead loads, and live loads, are integrated to form a rise for strength design and allowed stress design. The following is a list of design load combinations:

- ✓ 1.4DL
- ✓ 1.2DL + 1.6 LL
- ✓ 1.5DL + LL + EX
- ✓ 1.4DL + LL – EX
- ✓ 0.6DL + EX
- ✓ 0.6DL – EX

Where DL is the dead load, LL is live load, and EX is earthquake load in the x-direction.

4.2.5 Building Frame Design Loads

The building models were considered to be residential buildings and the loads were designed as gravity and lateral loads (Earthquake loads). The gravity loads were taken with a dead load of 14KN/m2 and a live load of 8KN/m2 while some floors have excess loads due to the presence of mass irregularity. For the seismic loading parameters, ASCE 7-16 code were considered and the parameters taken for design are presented in Table 4.5 while the parameters taken inside sap2000 are shown in Figure 4.3.

Table 4.5: Earthquake Load Input Parameters

NO	Parameters	Values
1	Site class	ZD
2	occupancy important (I)	1.00
3	Response modification factor (R)	8.00
4	Short period spectral acceleration (Ss)	1.668
5	Map spectral acceleration coefficient (S1)	0.457

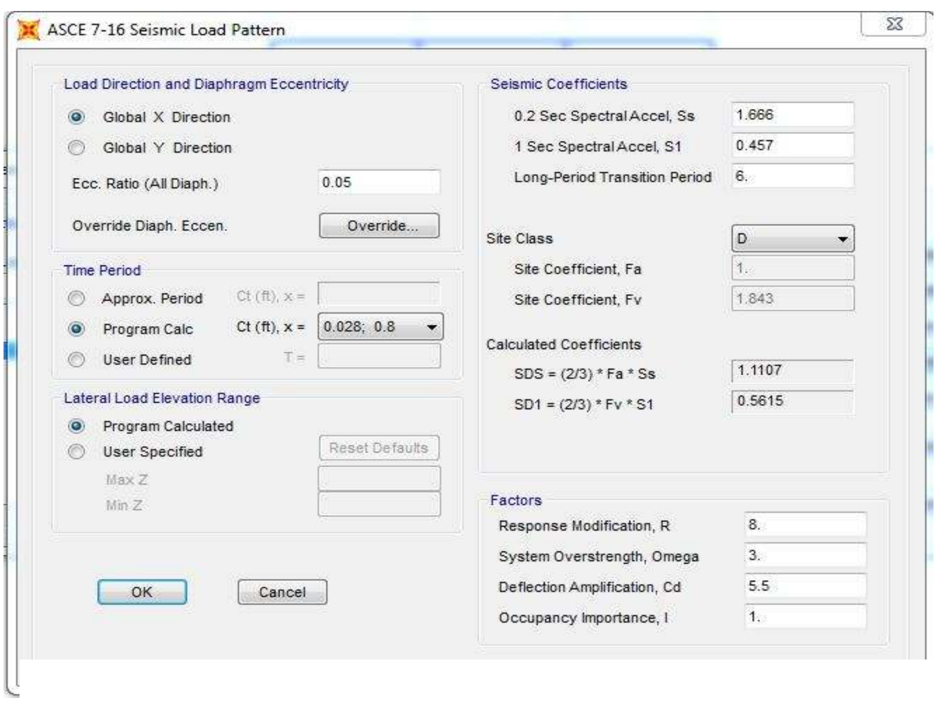


Figure 4.3: ASCE 7-16 Seismic Load Pattern Parameters inside SAP2000.

4.2.6 Plastic Hinges Definition

Plastic hinges are assigned to both beams and columns at a distance of 10 percent of the length of the beam or column. The plastic auto hinges were taken from ASCE 41-13 code. Plastic hinges assigned in beams were taken M3 degree of freedom while columns were taken to be P-M2-M3 degree of freedom. However. The below figures show how plastic hinges are defined and assigned at the end of beams and columns in all models inside the SAP2000 program.

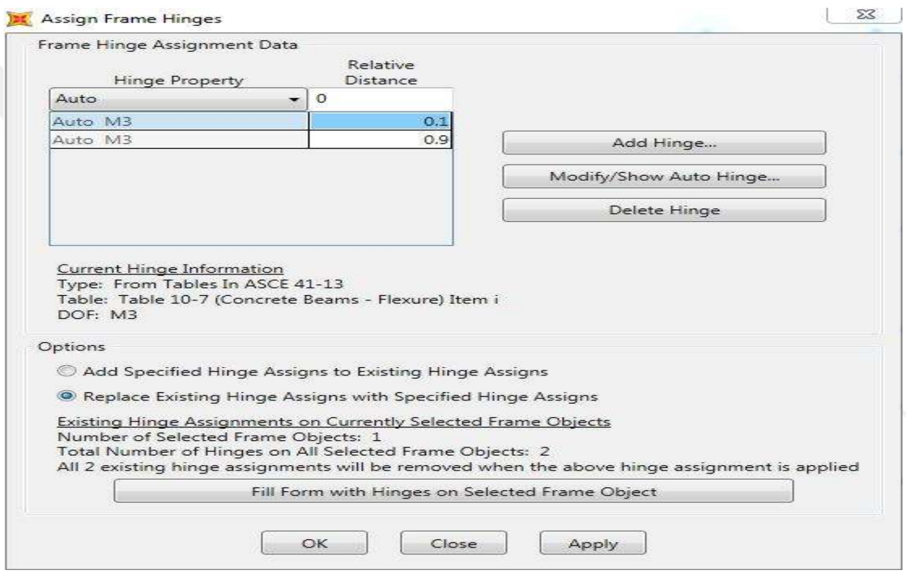


Figure 4.4: Assigned Hinges to the Beam

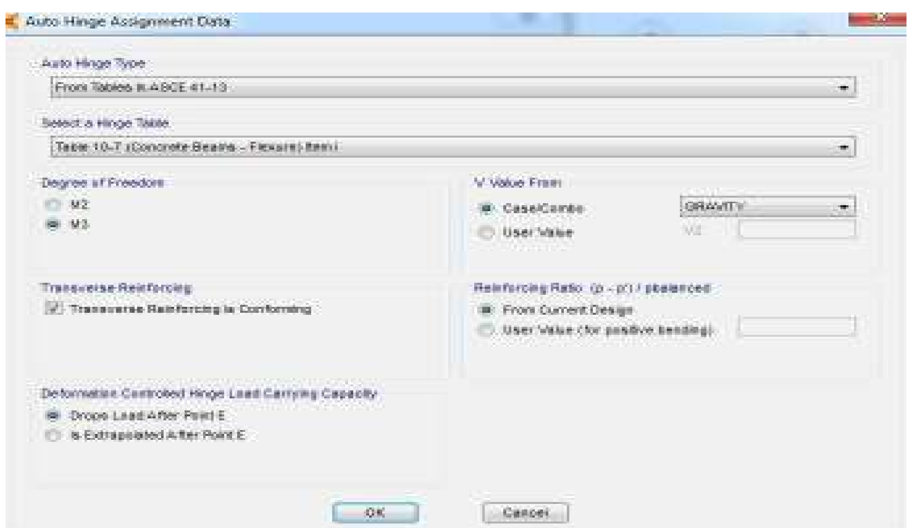


Figure 4.5: Assigned Hinges to the Beams in Gravity Load

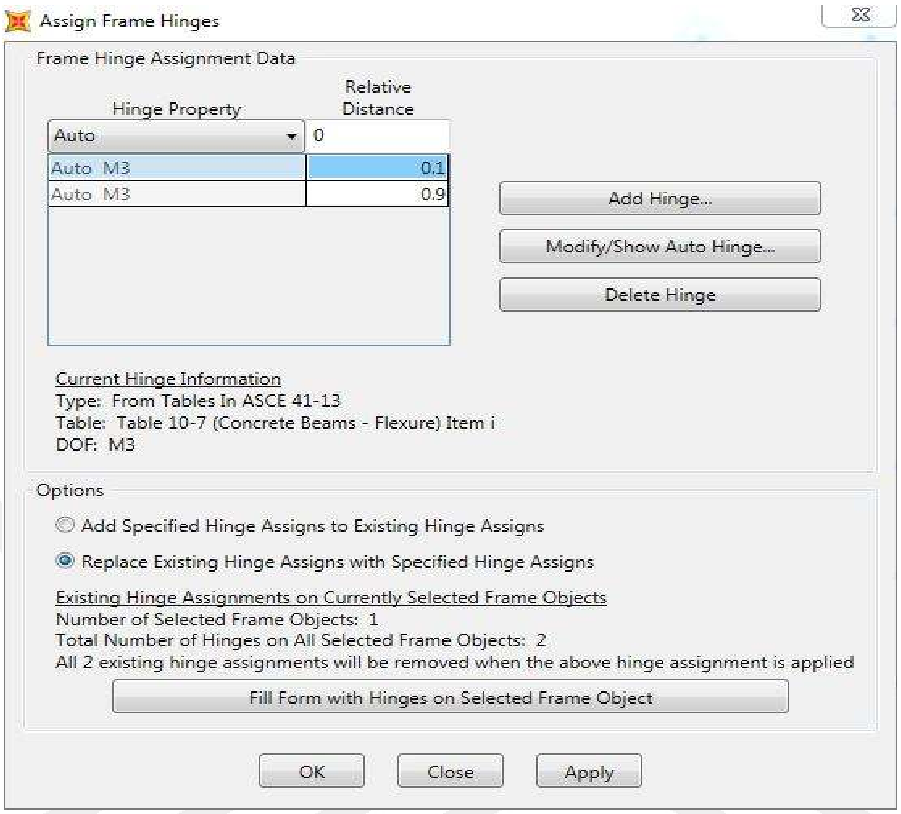


Figure 4.6: Assigned hinges to the columns

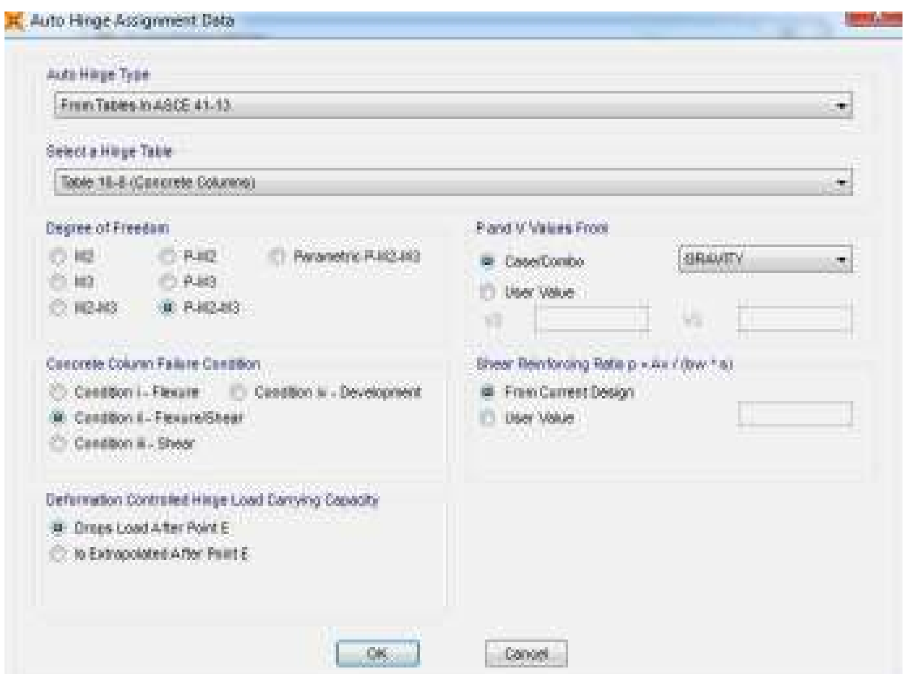


Figure 4.7: Assigned hinges to the column in gravity load

4.3. Analysis procedure

In this study four 2D Rc structures are considered having fixed base without considering soil interactions. To determine the effect of the inclusion of vertical seismic excitations two cases are implemented and they are as follows;

- Case 1: The horizontal components of earthquake is applied in each model in one direction (U1). No vertical component is considered.
- Case 2: The combination of horizontal and vertical components are subjected in each models in direction U1 and U3, respectively.

The two load cases considered for this study are then defined in sap2000 program to apply ground motions. Nonlinear direct integration are defined for each case at each model. Ground motions were scaled inside seismomatch program.

Case-1 is established using only horizontal component of earthquake application without any vertical excitations. Based on earthquake data obtained from PEER website, number of time steps as well as time step interval are used in each loading case. Figure 4.8 shows the case input inside SAP2000.

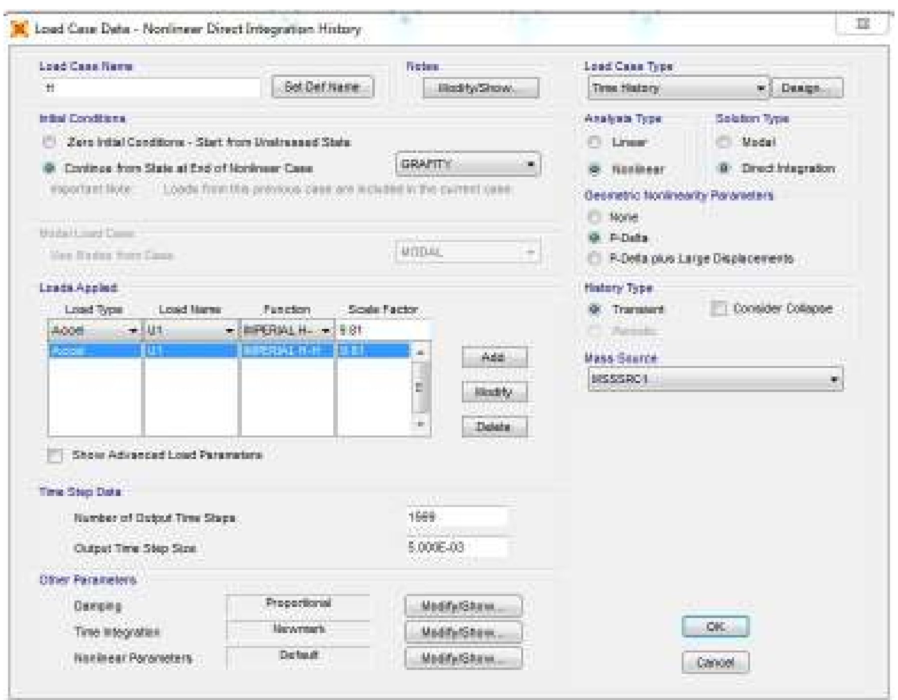


Figure 4.8: Load Case Definition inside SAP2000 for Case-1

Case-2 is developed with a combined input of horizontal and vertical ground motion. For each ground motion, a maximum of one horizontal ground acceleration and one vertical ground acceleration in upward direction is taken. Figure 4.9 shows the load case defined for the combination of horizontal and vertical ground motions in SAP2000 program.

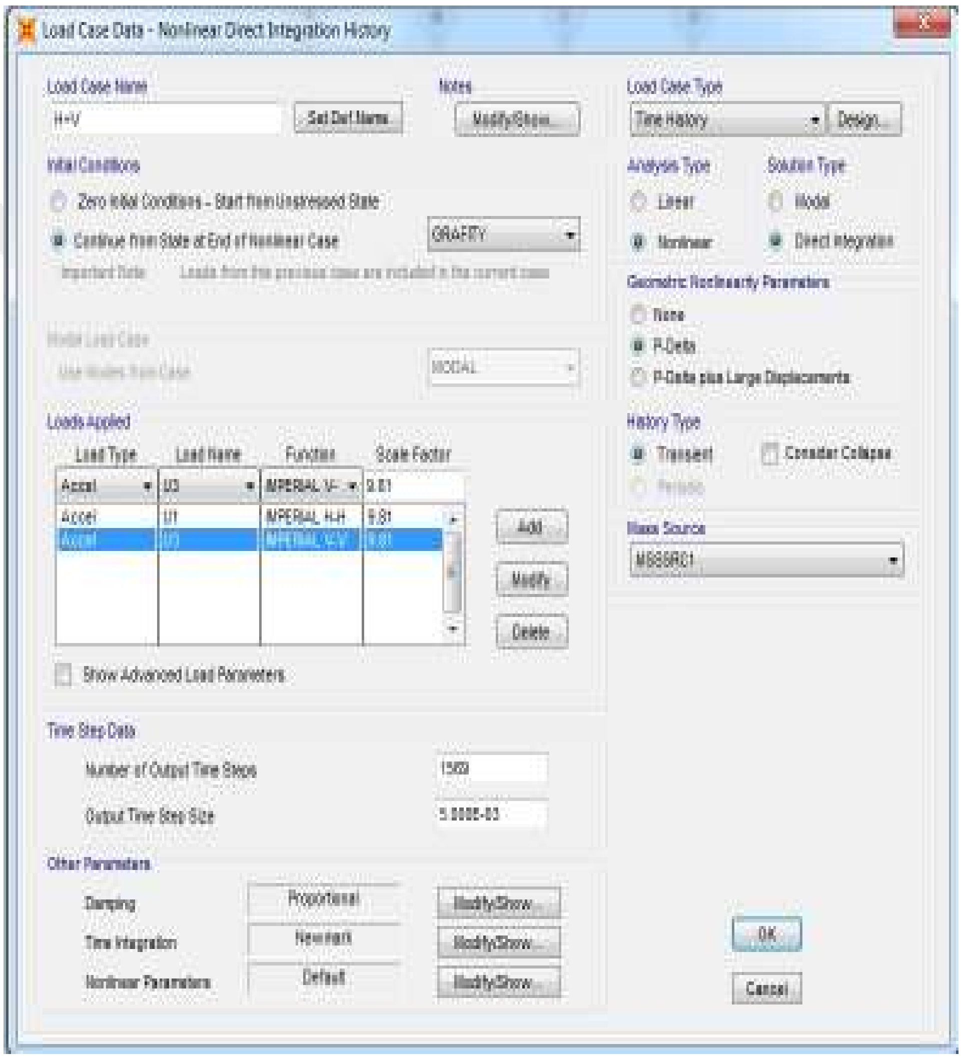


Figure 4.9: Load Case Definition inside SAP2000 for Case-1

4.4. Ground Motion Data

4.4.1 Selection of ground motions

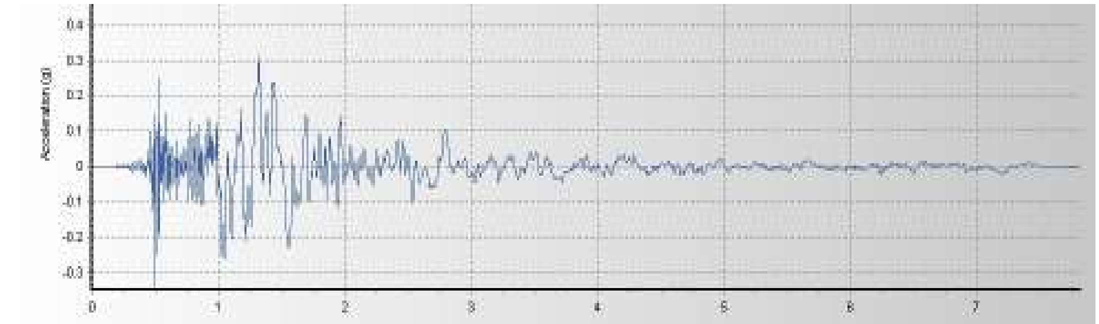
This study aims to determine the response of irregular structures when subjected to vertical and horizontal earthquake excitations. The earthquake records used for this study have been obtained from the PEER database. The Peak ground acceleration (PGA) ranges from 0.5 to 0.8g, and the magnitude of the ground motions ranges from 6 to 9 in both excitations, as shown in Table 4.6. The V/H ratio of all ground motions is less than 3/2. The ground acceleration records for both components are shown in Figure 4.10 to Figure 4.14.

A ground motion record within 10km from the fault is referred to as near-fault earthquakes while ground motion recorded in a site located 10km away from is called Far-field earthquakes, so the earthquake records selected for this study are all near-fault earthquakes with distance from the fault which is less than 10km. Each of the earthquake records obtained from the PEER database contained time histories in two directions H1 and V representing ground motion time histories in horizontal and vertical components of an earthquake.

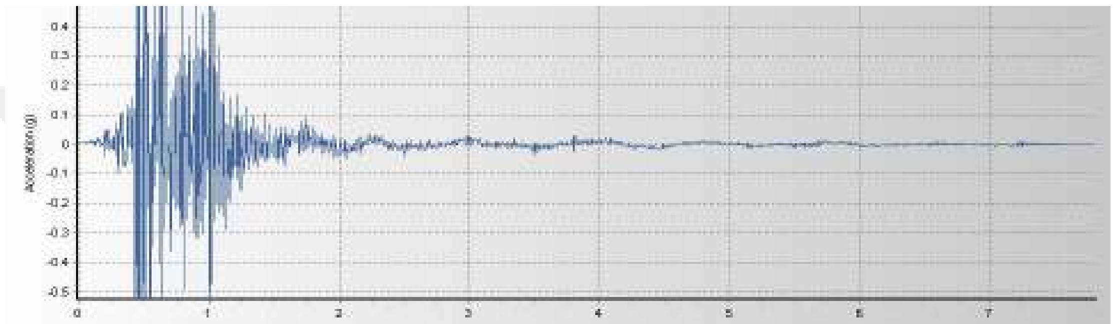
Table 4.6: Selected Ground Motion Records

No	Earthquake Name	Year	Station	Mw	PGA (g) H	PGA(g) V	V/H
1	Imperial Valley-06	1979	El Centro #6	6.53	0.65	0.84	1.29
2	Kobe_ Japan	1995	KJMA	6.9	0.64	0.72	1.13
3	Kocaeli_ Turkey	1999	Yarimca	7.51	0.52	0.68	1.31
4	Denali_ Alaska	2002	TAPS Pump #1	7.9	0.59	0.62	1.05
5	Darfield_ New Zealand	2010	HORC	7	0.66	0.75	1.14

Where Mw is the magnitude of Earthquake and PGA is peak ground acceleration.

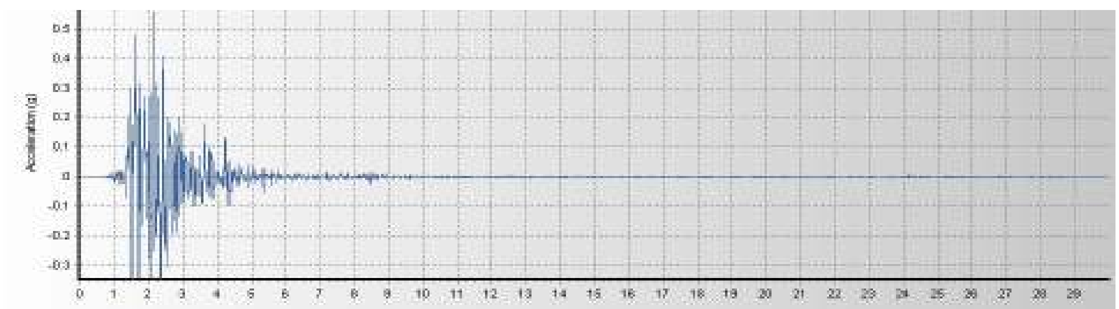


a)

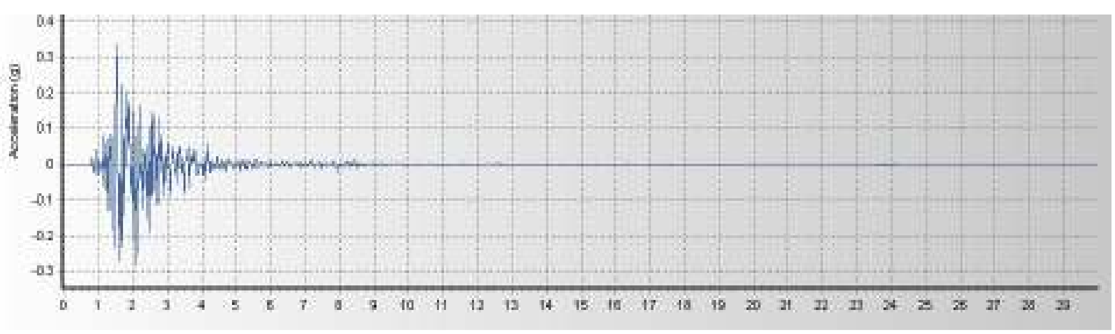


b)

Figure 4.10: Imperial Ground Acceleration: a) Horizontal, b) Vertical components

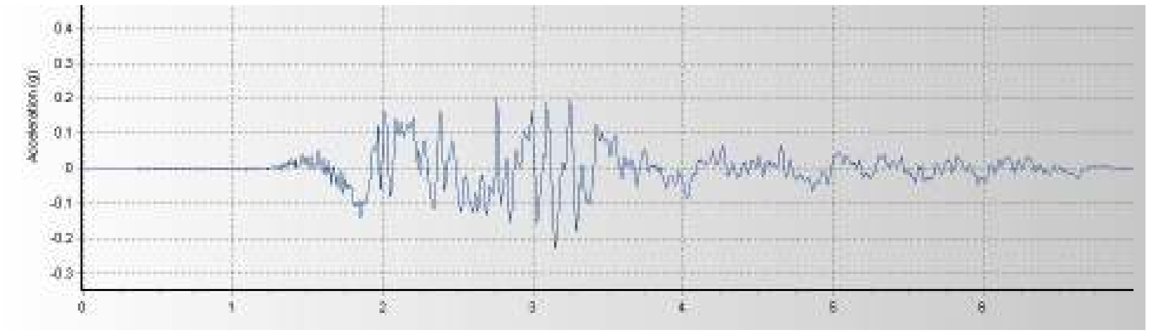


a)

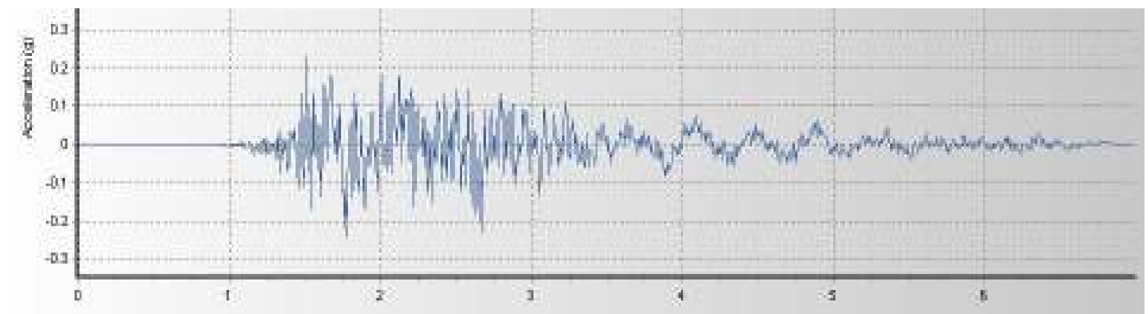


b)

Figure 4.11: Kobe Ground Acceleration: a) Horizontal, b) Vertical components

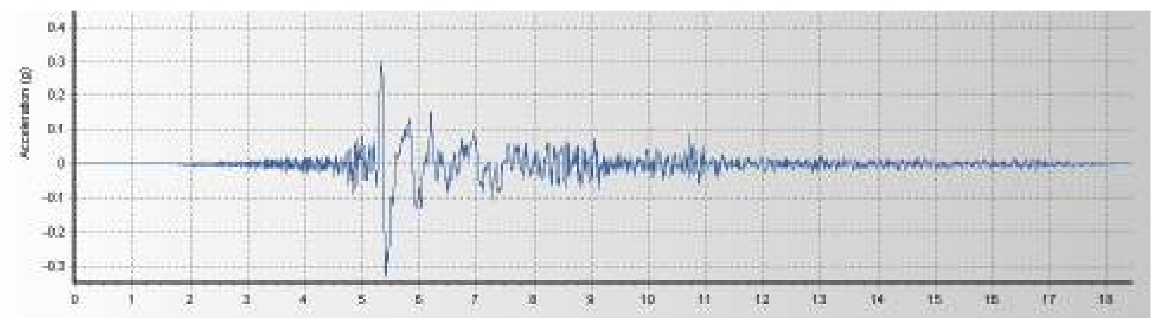


a)

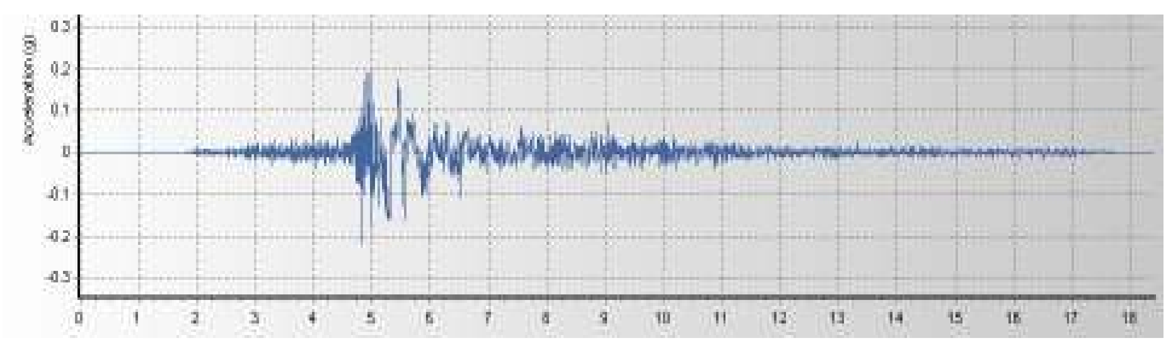


b)

Figure 4.12: Kocaeli Ground Acceleration: a) Horizontal, b) Vertical components

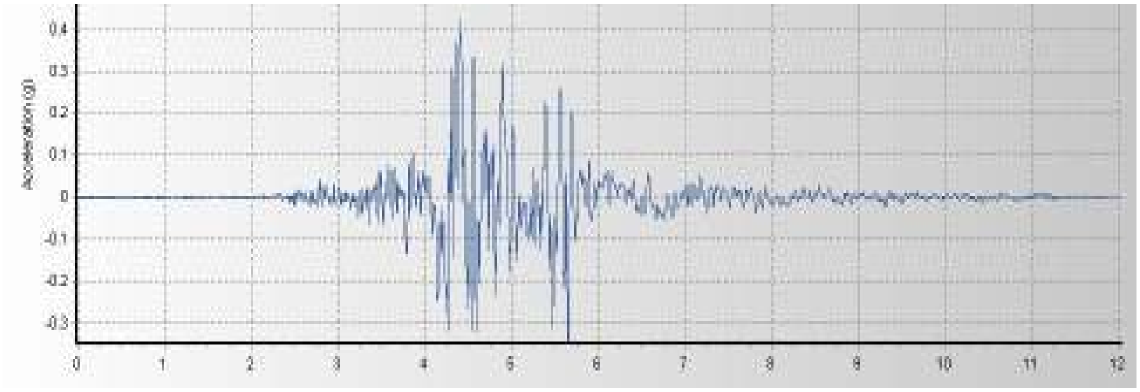


a)

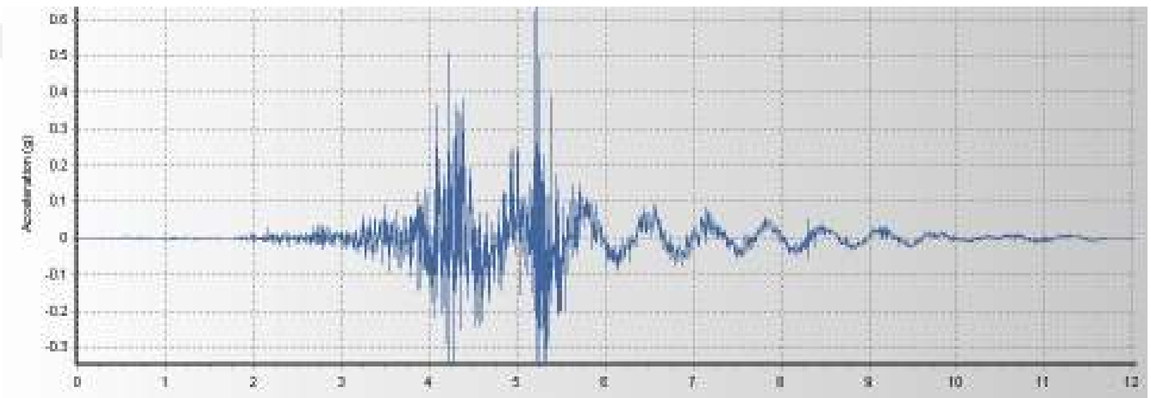


b)

Figure 4.13: Denali Ground Acceleration: a) Horizontal, b) Vertical components



a)



b)

Figure 4.14: Darfield Ground Acceleration: a) Horizontal, b) Vertical components

4.5.2 Scaling of Ground Motion Records

Seismomatch software was used to scale earthquake recordings and bring them to a consistent intensity level. Scaling allows multiple ground motion recordings and the structure's seismic reaction to being combined. Previous research has provided details on many scaling aspects (Miranda 1993: Vidic 1994: Kalkan and Chopra 2011). The ground motion recordings were pre-scaled to a PGA=0.689g modal spectrum for this investigation. Figure 4.15 illustrates a collection of pre-scaled accelerograms representing motions. Figure 4.16 shows the target spectrum to which these accelerograms were pre-scaled in the PEER website and also scaled in seismomatch software.

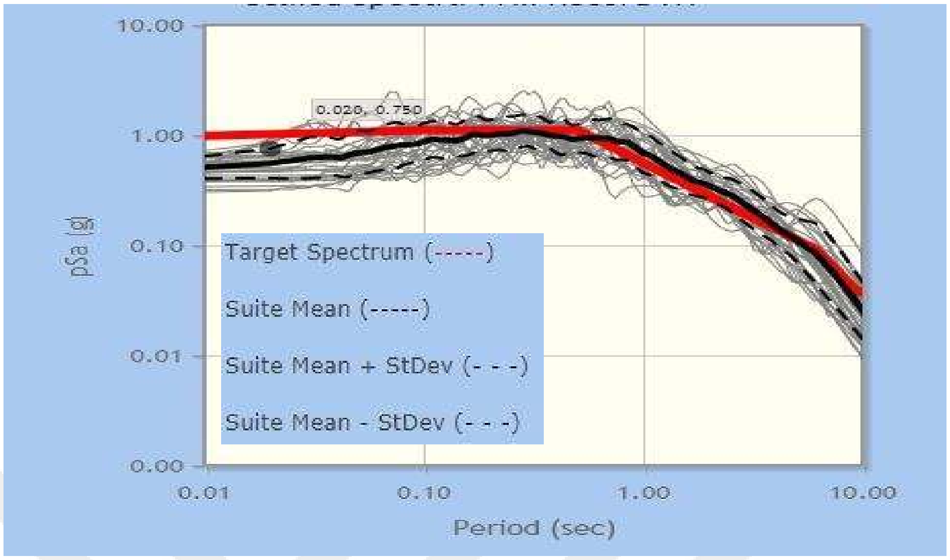


Figure 4.15: Mean Of Ground Motions to Target Spectrum (PEER) [29]

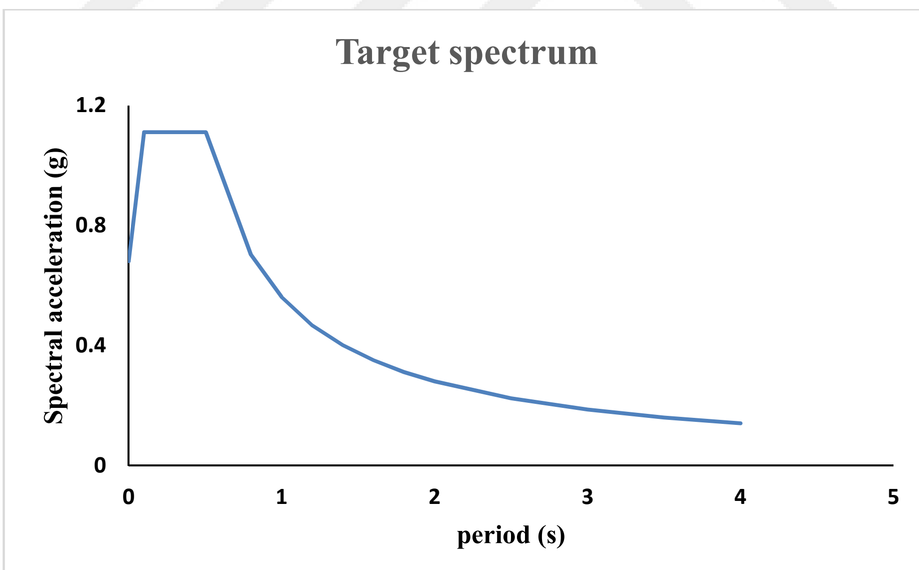


Figure 4.16: Target Spectrum to Which the Ground Motions Have Been Scaled

CHAPTER 5

ANALYSIS RESULT AND DISCUSSION

5.1 General

In this study nonlinear dynamic history analysis has been conducted for four different models which are named mass irregularity model-I (MIM-01), mass irregularity model-II (MIM-02), stiffness irregularity model-I (KIM-01), and stiffness irregularity model-II (KIM-02) inside SAP2000 program. All the models have exerted two loading conditions which consist of five horizontal and vertical components of earthquakes to investigate the effect of horizontal and vertical ground motions on irregular structures. An overall comparison will be done between the two loading conditions (Horizontal and Horizontal + Vertical). The structure's response is represented by tables and graphs representing the effective modal mass, inter-story drifts, axial forces, roof horizontal acceleration, and plastic hinge formation.

5.2 Analysis Results

Nonlinear time history analysis is carried out by using SAP2000 V21 software. The two loading conditions (Horizontal and Horizontal + vertical) which consist of horizontal and vertical seismic components have been compared to determine the effect of seismic excitations on vertical irregular structures. A total of four models have been used for both cases with five different ground motions. The two loading conditions have been compared in each model to evaluate the effect of the inclusion of vertical ground motions. However, the acceleration values less than 0.5g causes normal damage to the structures, acceleration values 0.5g to 1g may cause moderate damage to the buildings, and acceleration values greater than 1g causes severe damage to the structures. According to the ASCE 7-16 seismic code, the inter-story drift ratio of the structure should not be greater than 2% of the inter-story height.

5.2.1 Mass Participation Ratio

The modal mass participation ratio is how much the mass of the building is participating in each mode. A percentage increase of the mass in each mode indicates that each mode participates and represents the building's effective model mass.

According to ASCE 7-16 seismic code, the sum of effective modal masses should not be less than 90% of the building's total mass. The results obtained from stiffness and mass irregular models show that the effective modal masses are more than 90% for the first twelve modes, so the modal results are accurate and acceptable. Table 5.1 shows the cumulative sum of the first twelve mode mass participation ratio (x-direction). The stiffness irregular models have an effective mass of more than 96%, while irregular mass models have an effective mass which is more than 97%.

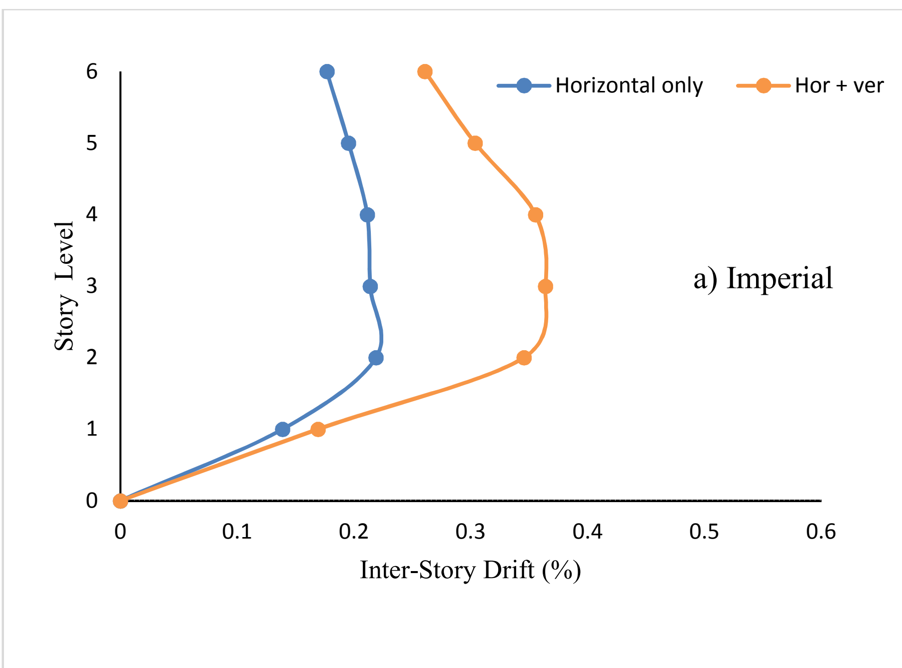
Table 5.1: Mass Participation Ratio of Cumulative Sum % in the X-Direction

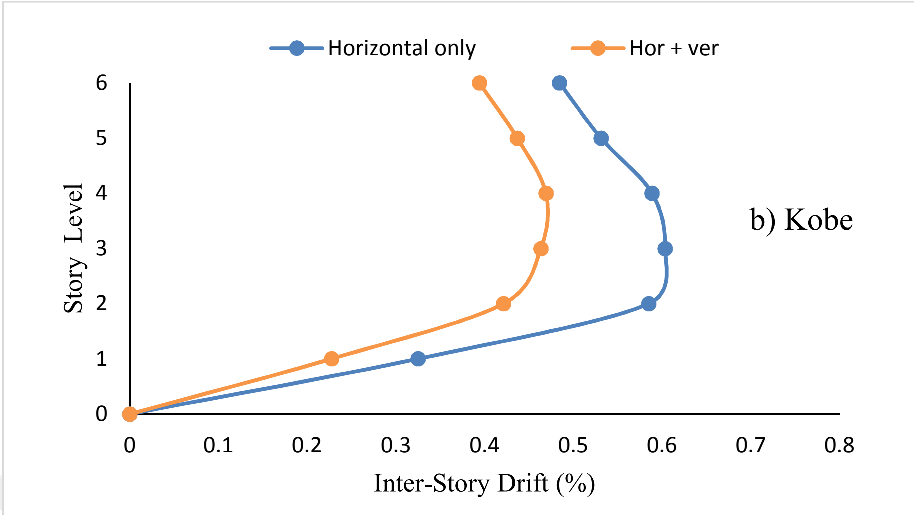
	Mass Irregularity		**Stiffness irregularity**	
	Relative Mass (%)		**Relative Mass (%)**	
Mode No	**MIM-01**	**MIM-02**	**KIM-01**	**KIM=02**
1	0.72113	0.78	0.73	0.80464
2	0.92471	0.89	0.92	0.92687
3	0.92471	0.89	0.92	0.92687
4	0.92913	0.94	0.93	0.95395
5	0.96939	0.97	0.95	0.96999
6	0.98249	0.97	0.96	0.96999
7	0.98249	0.97	0.96	0.96999
8	0.98253	0.98	0.96	0.97238
9	0.98525	0.98	0.96	0.97238
10	0.98569	0.98	0.96	0.97239
11	0.98569	0.98	0.96	0.97384
12	0.9857	0.98	0.96	0.97384

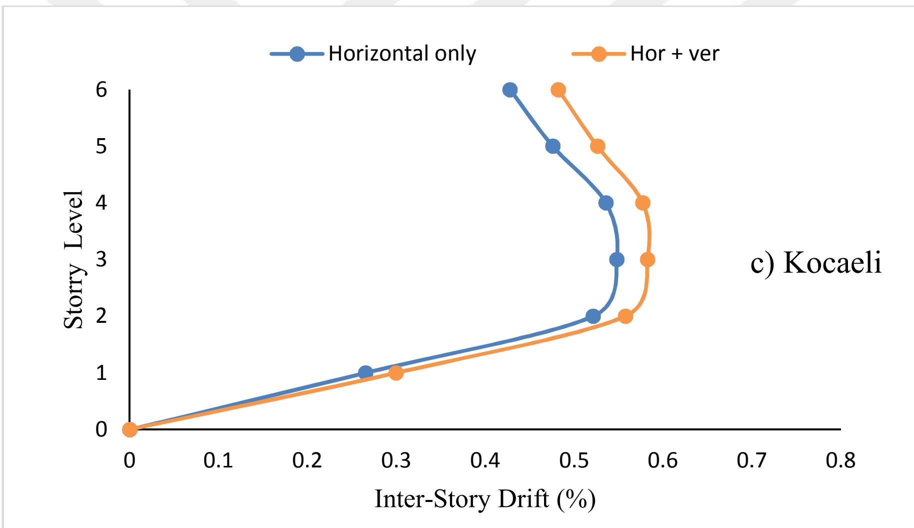
5.2.2 Inter-Story Drift

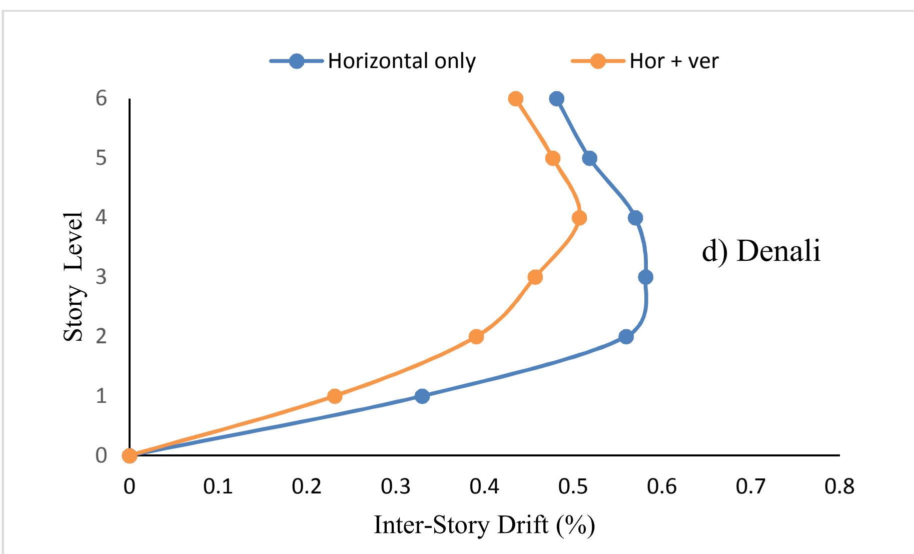
The overall stability of a building during strong earthquakes is increased by designing the structure well and controlling the deformation of the structure. The inter-story drift ratio describes the structural performance of the building. The drift ratio has defined the percentage among the two adjacent floors divided by the height of the story. However, drift ratio results are plotted below graphs in all models under the five horizontal and vertical components of ground motions between the two different loading conditions (Horizontal only and Horizontal + Vertical).

Figure 5.1 and Figure 5.2 show the maximum inter-story drift for each story under five selected ground motions including horizontal and vertical components of an earthquake in the KIM-01 and MIM-01 building models. For Imperial record (Figure 5.1) in KIM-01 frame, the horizontal only and horizontal + vertical loadings have a maximum inter-story drift of 0.21% and 0.36%, respectively in the middle floors. However, the result for both models shows that the inter-story drift ratio may increase or decrease when the vertical ground motion accelerations are applied to the structure.




Horizontal only
Hor + ver
b) Kobe
Story Level
Inter-Story Drift (%)
0
1
2
3
4
5
6
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8


Horizontal only
Hor + ver
c) Kocaeli
Storry Level
Inter-Story Drift (%)
0
1
2
3
4
5
6
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8


Horizontal only
Hor + ver
d) Denali
Story Level
Inter-Story Drift (%)
0
1
2
3
4
5
6
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

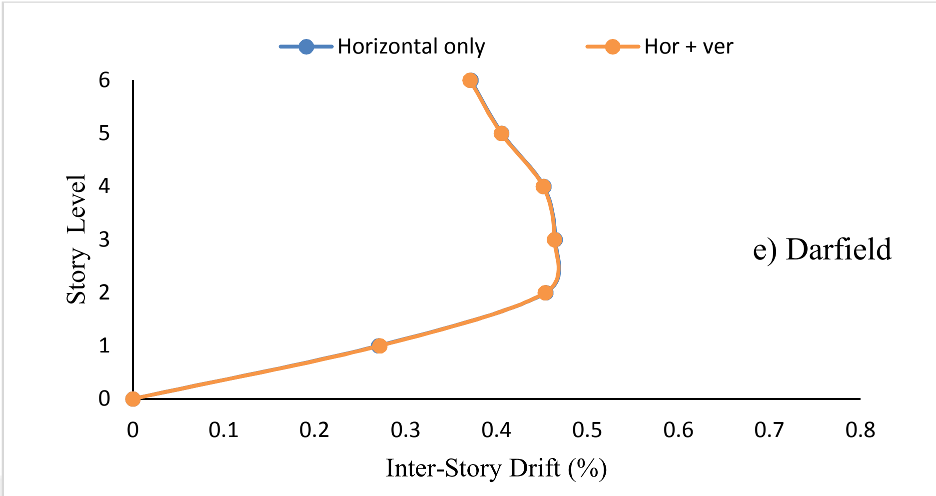
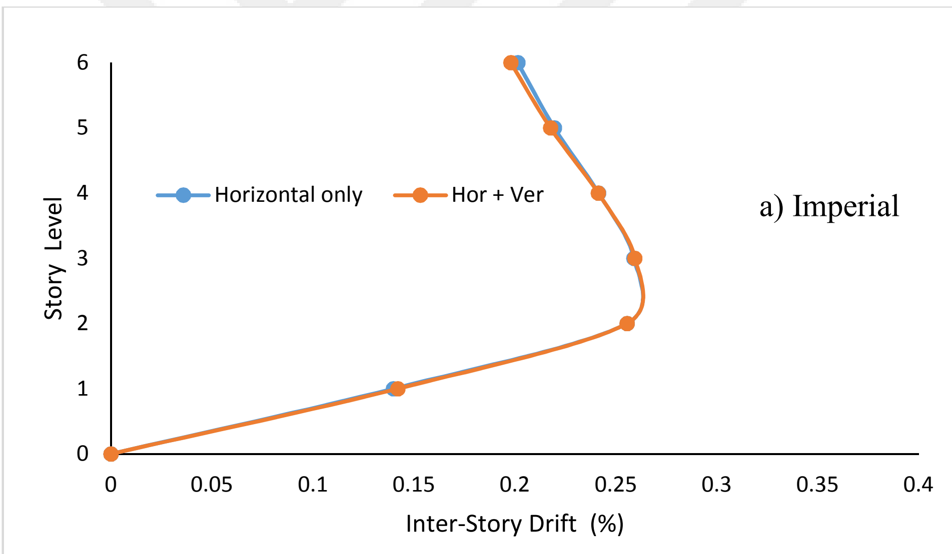
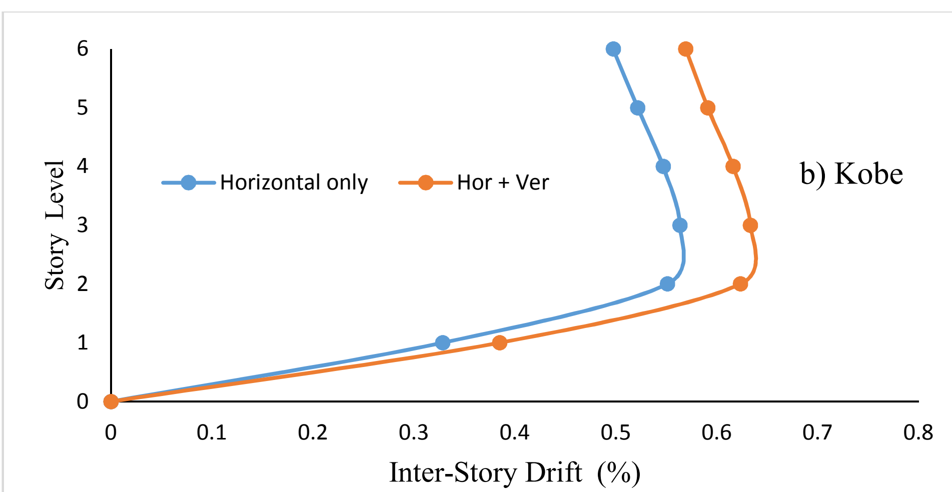


Figure 5.1: Inter-Story Drift Ratio of KIM-01 Building Model





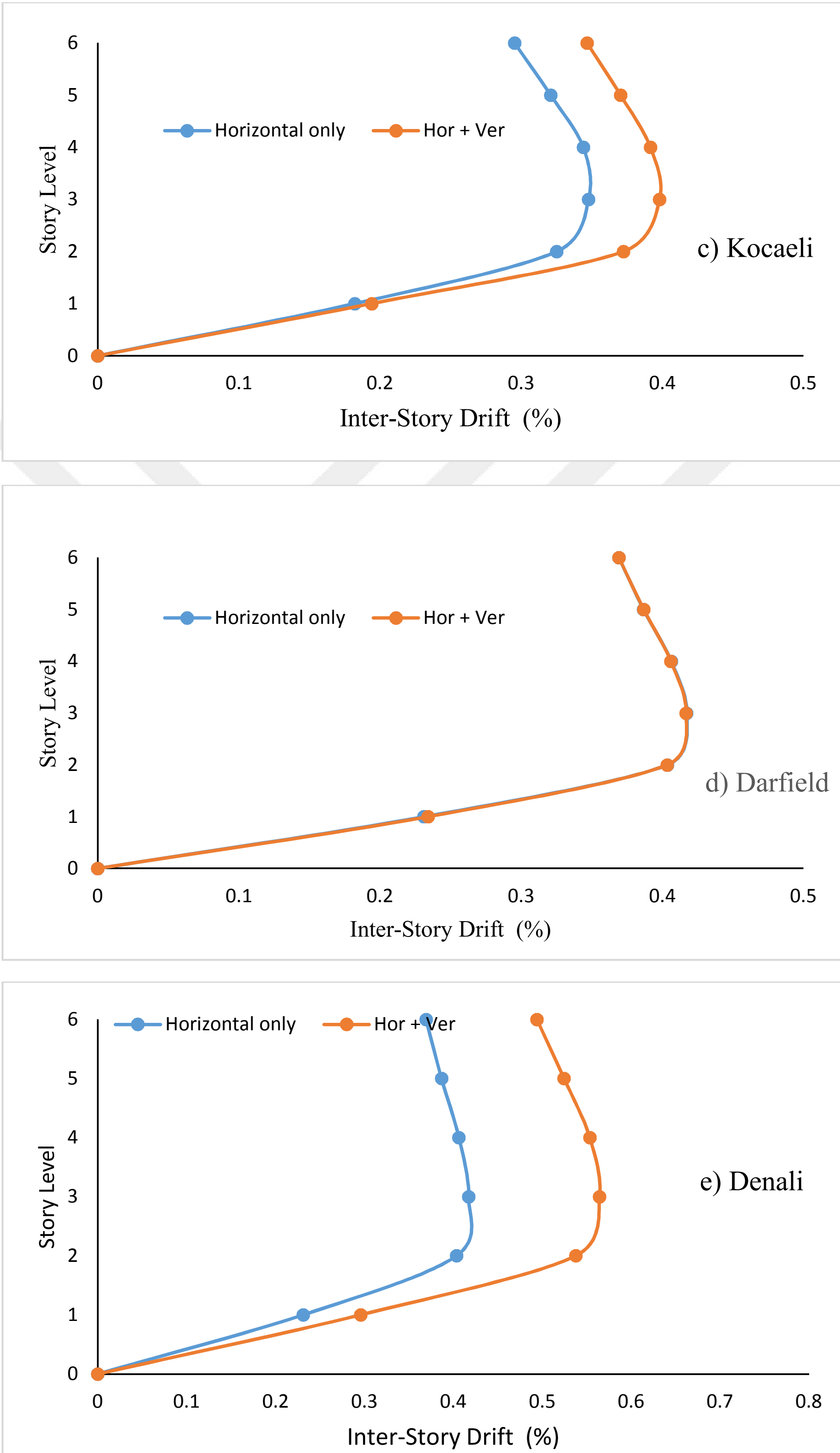
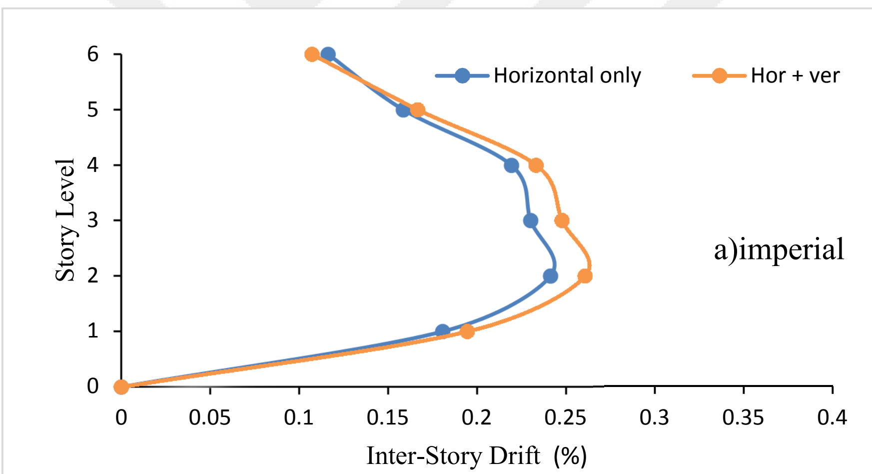
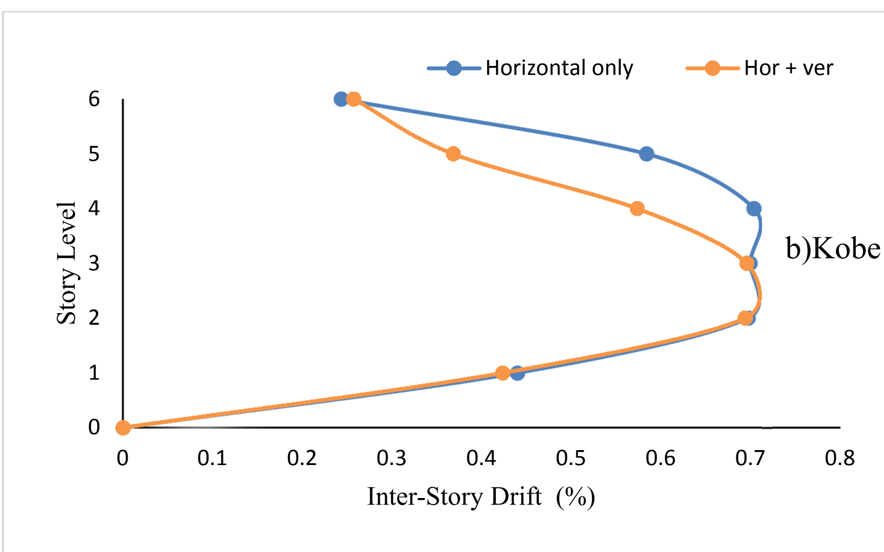


Figure 5.2: Inter-Story Drift Ratio of MIM-01 Building Model

Figure 5.3 and Figure 5.4 show the maximum inter-story drift for each story under five selected ground motions including horizontal and vertical components of earthquake for both loading conditions (Horizontal only and Horizontal + Vertical) in the stiffness irregular model-02 (KIM-02) and mass irregular model-02 (MIM-02). For Kobe's record (Figure 5.3) in the KIM-02 frame, the horizontal only and horizontal + vertical loadings have a maximum inter-story drift of 0.70% and 0.57%, respectively on the fourth floor. The inter-story drift ratio for mass irregular model-02 (MIM-02) under the Kocaeli record has a maximum drift ratio of 0.44% and 0.43% for both loading conditions, respectively. However, the result of all models shows that the two loading conditions are very close and the effect of the inclusion of vertical components is very small for inter-story drifts.





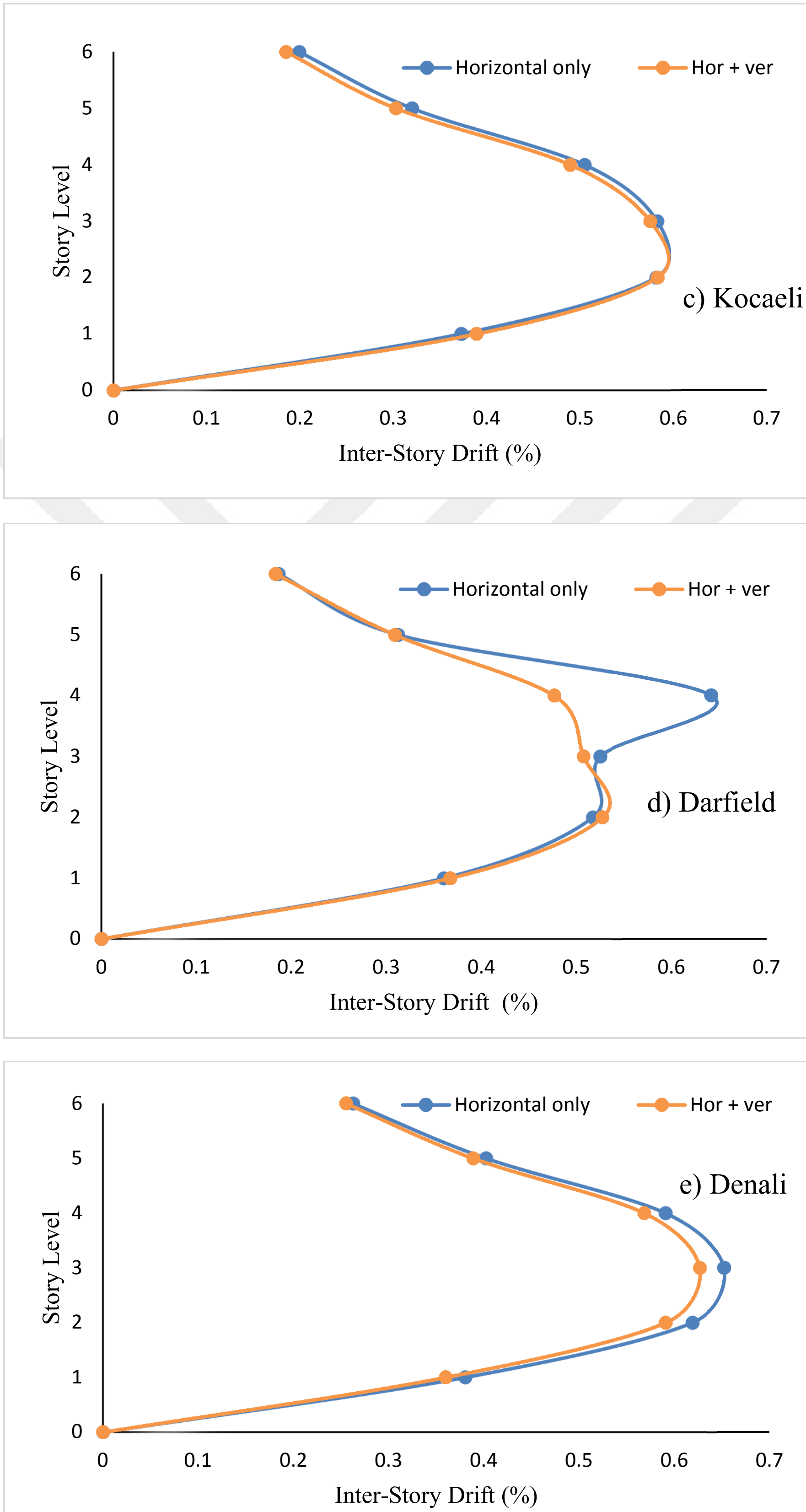
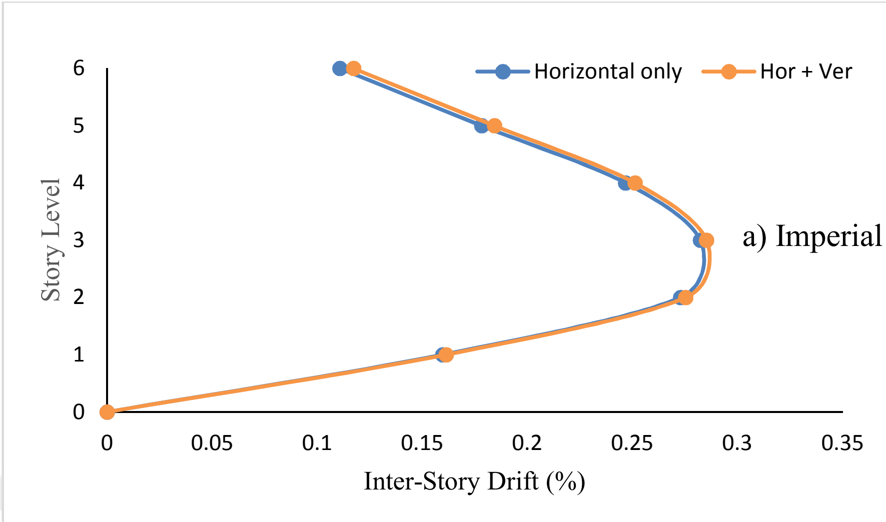
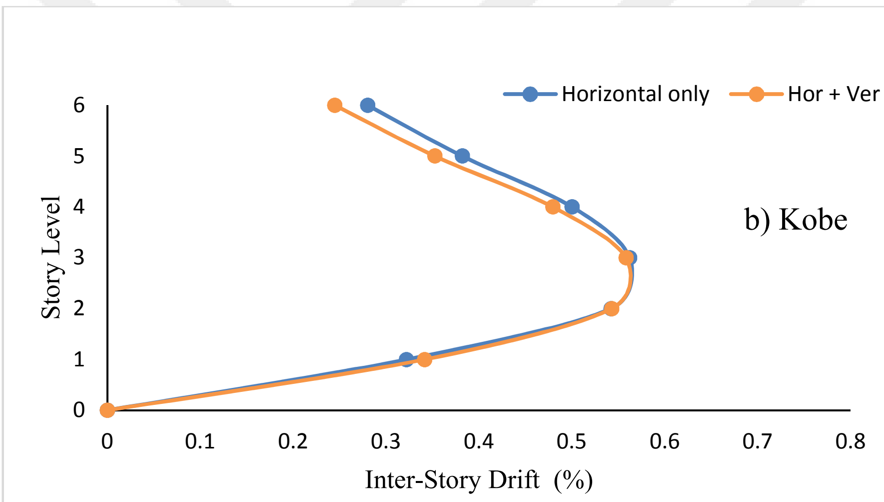
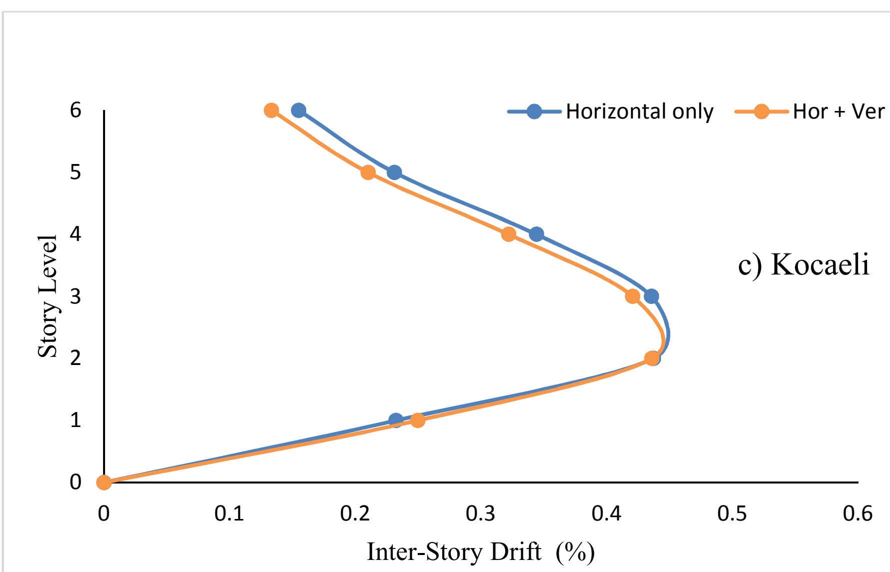


Figure 5.3: Inter-Story Drift Ratio of KIM-02 Building Model


Horizontal only
Hor + Ver
a) Imperial
Story Level
Inter-Story Drift (%)
0
1
2
3
4
5
6
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35


Horizontal only
Hor + Ver
b) Kobe
Story Level
Inter-Story Drift (%)
0
1
2
3
4
5
6
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8


Horizontal only
Hor + Ver
c) Kocaeli
Story Level
Inter-Story Drift (%)
0
1
2
3
4
5
6
0
0.1
0.2
0.3
0.4
0.5
0.6

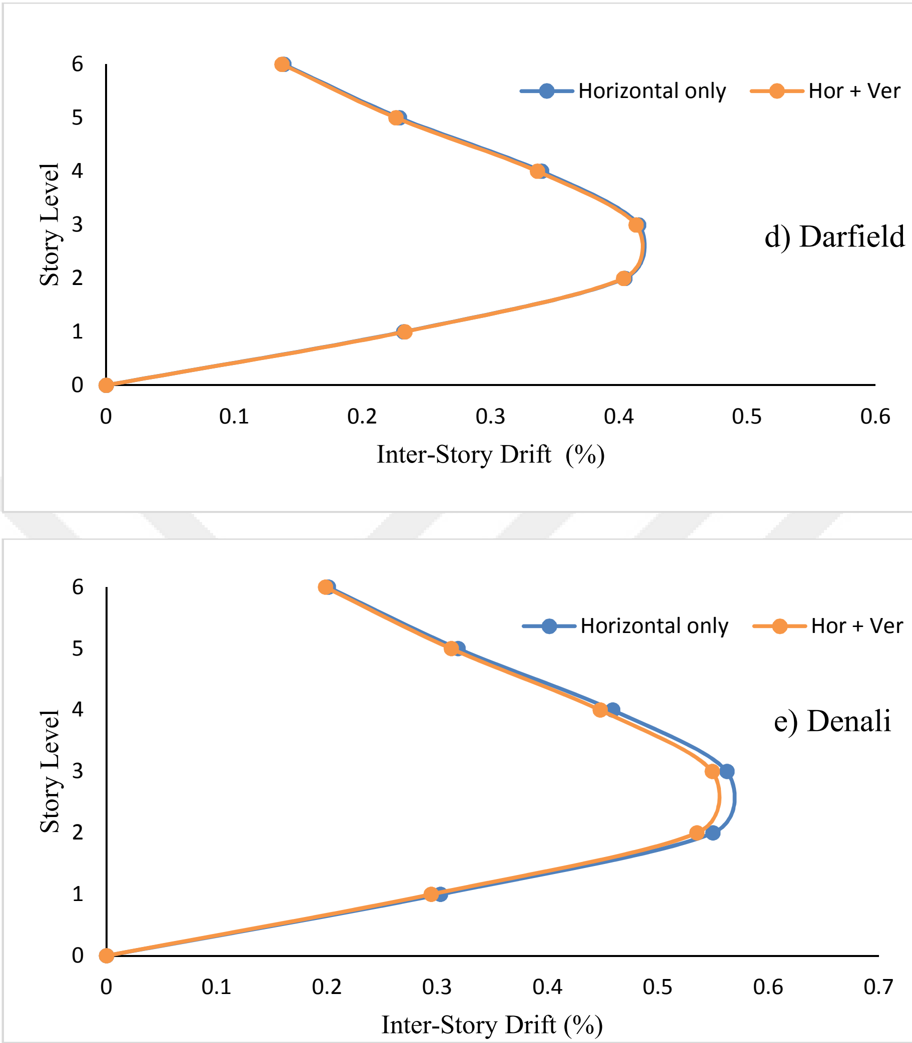
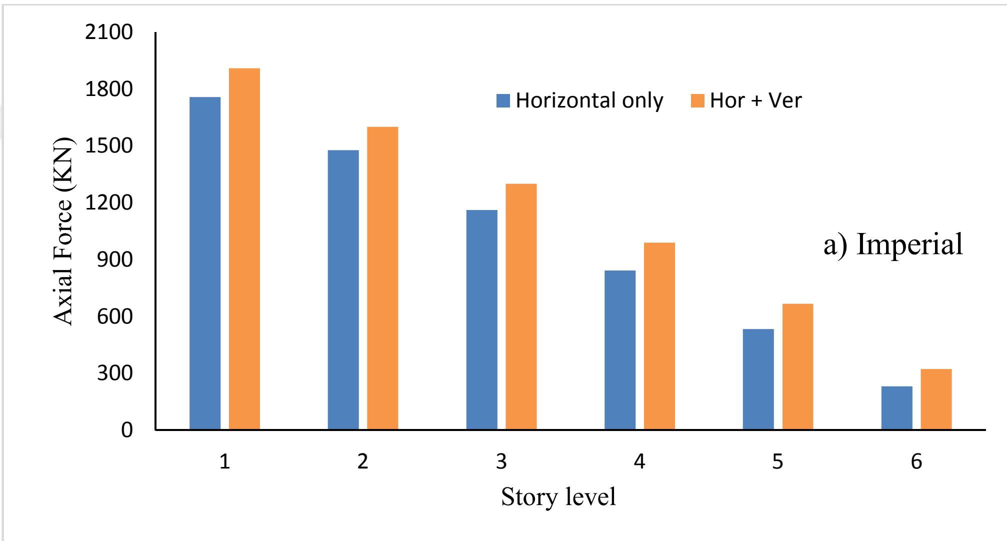


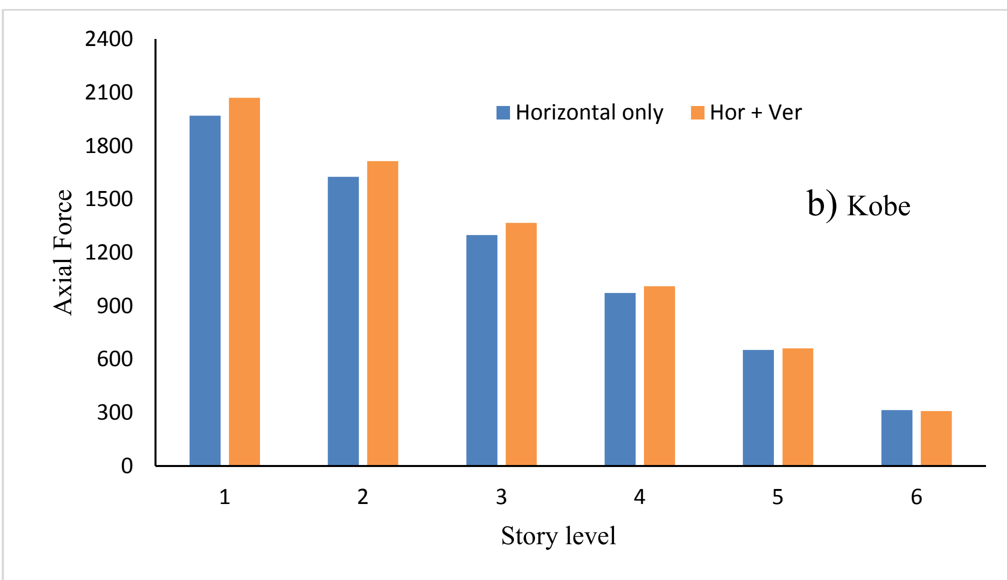
Figure 5.4: Inter-Story Drift Ratio of MIM-02 Building Model

5.2.3 Axial Force of Column

The axial force affects the behavior of structural elements especially columns in framed structures. In general, the axial force is the compression or tension force acting on the member. However, the seismic excitations on structures affect the axial force of the column depending on the component and magnitude of an earthquake.

Figure 5.5 and Figure 5.6 shows the column axial force for each floor under five horizontal and vertical ground motions with two loading condition (Horizontal and Horizontal + Vertical) in the stiffness irregular model-01 (KIM-01) and mass irregular model-01 (MIM-01). The KIM-01 model result under imperial record (Figure 5.5) shows that the loading case-2 (Horizontal + vertical) makes the column have the highest axial force when compared to case-1 (Horizontal only) while the Mass irregular model-01 result under imperial record (Figure 5.6) shows the same behavior. However, the result shows that the axial force of the column increases with the inclusion of vertical components of an earthquake.





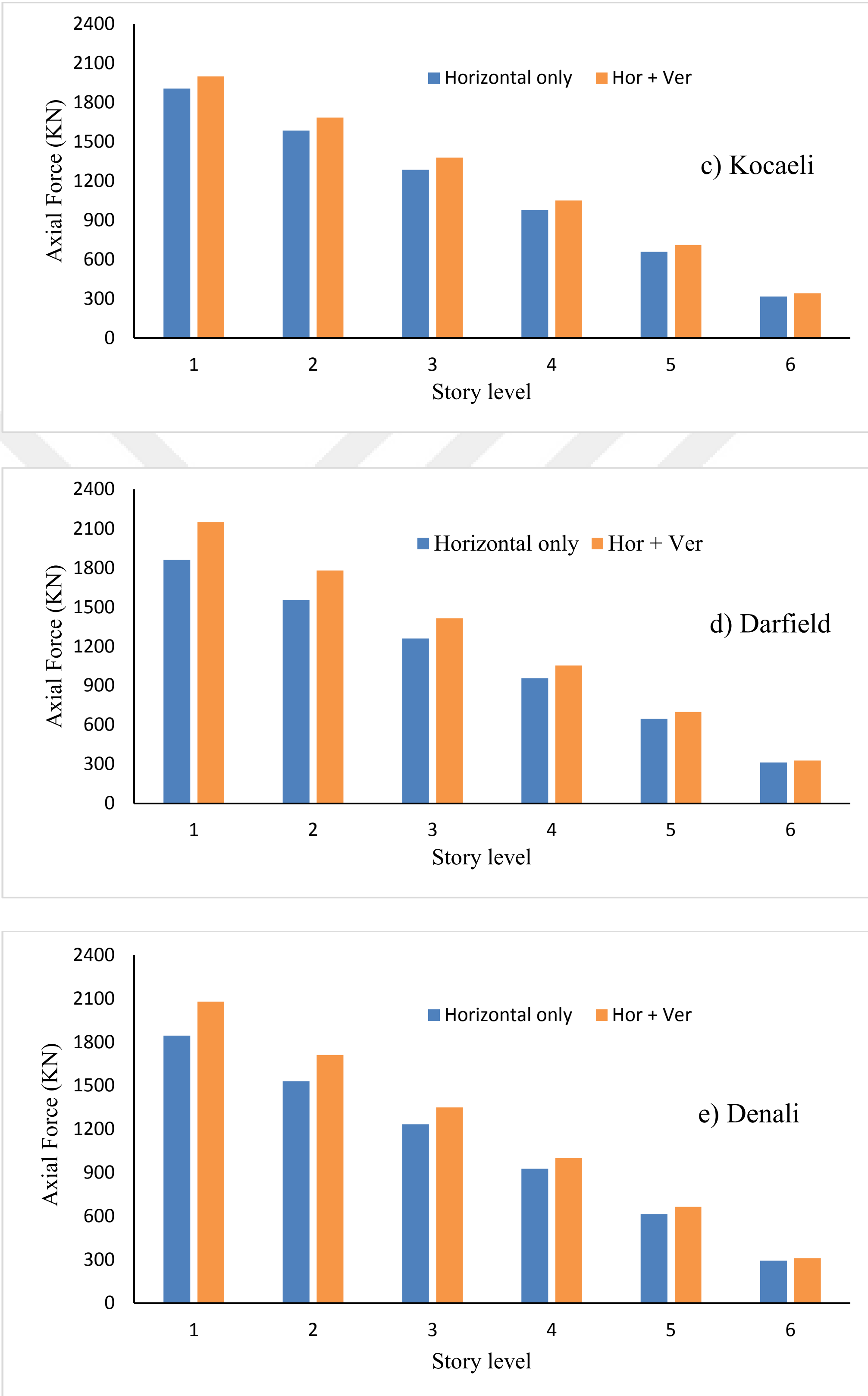
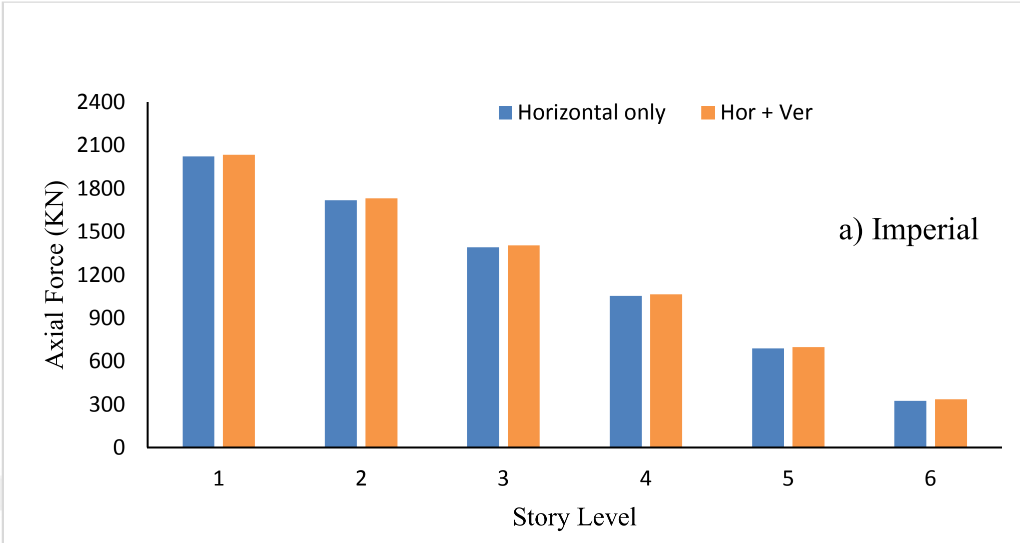
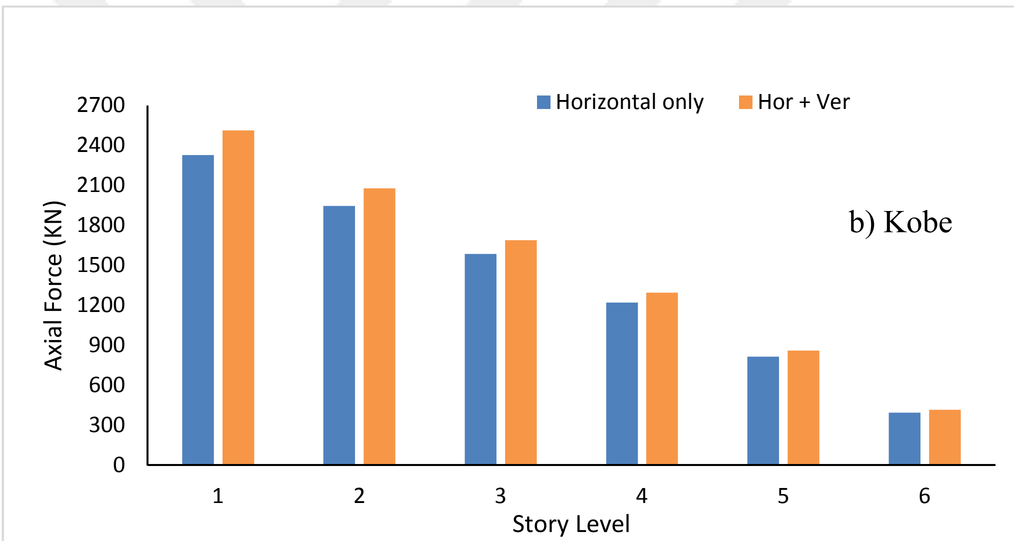
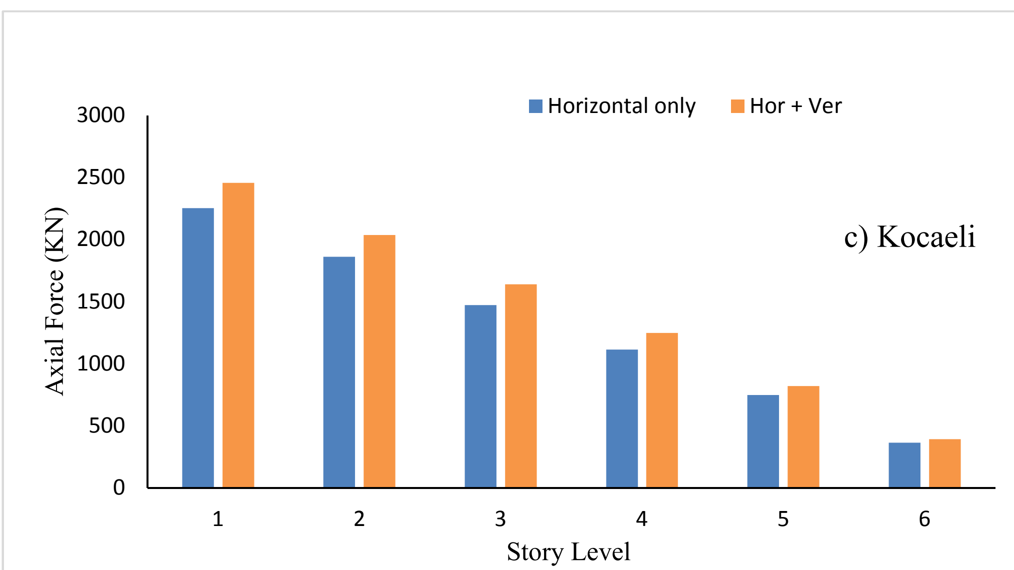


Figure 5.5: Story Column Axial Force of KIM-01 Building Model


a) Imperial
Horizontal only
Hor + Ver
Axial Force (KN)
2400
2100
1800
1500
1200
900
600
300
0
1
2
3
4
5
6
Story Level


b) Kobe
Horizontal only
Hor + Ver
Axial Force (KN)
2700
2400
2100
1800
1500
1200
900
600
300
0
1
2
3
4
5
6
Story Level


c) Kocaeli
Horizontal only
Hor + Ver
Axial Force (KN)
3000
2500
2000
1500
1000
500
0
1
2
3
4
5
6
Story Level

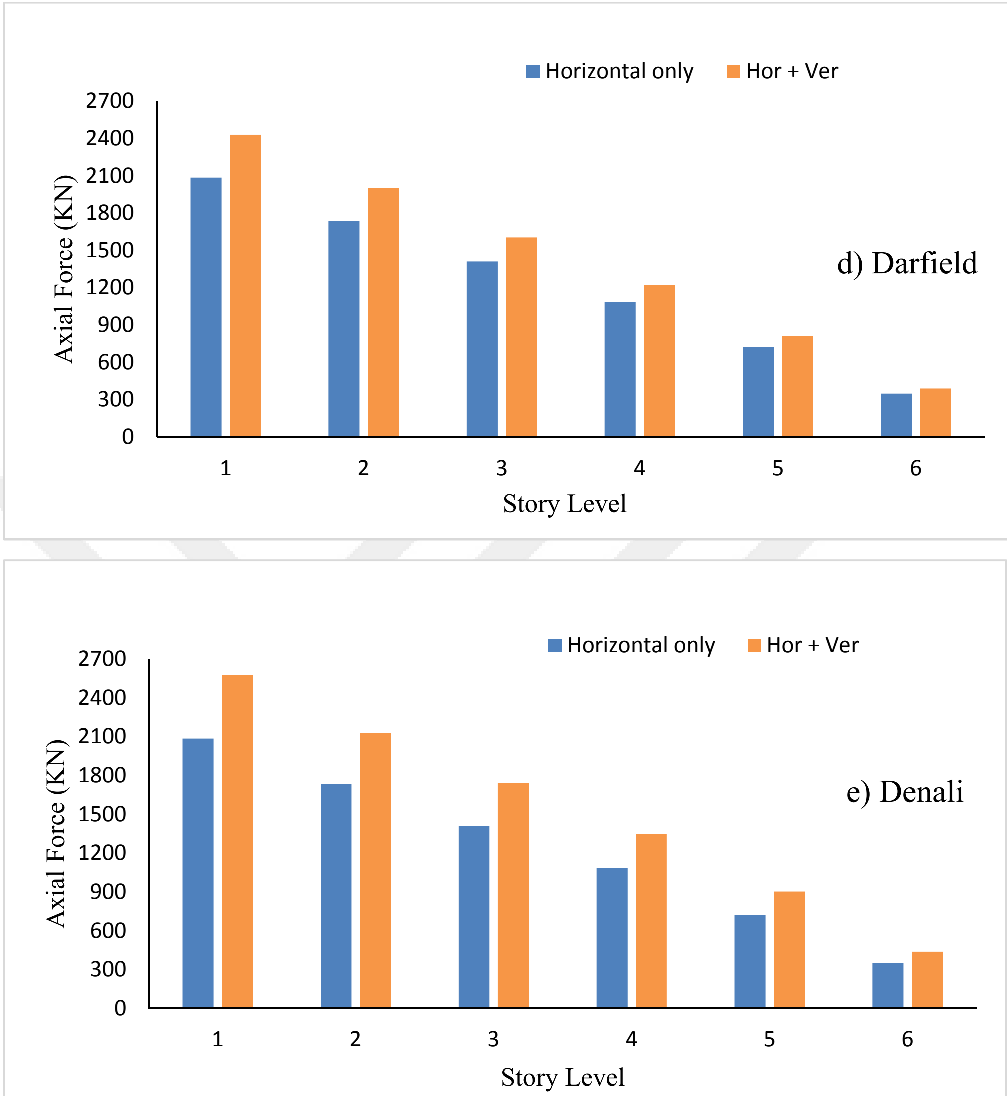
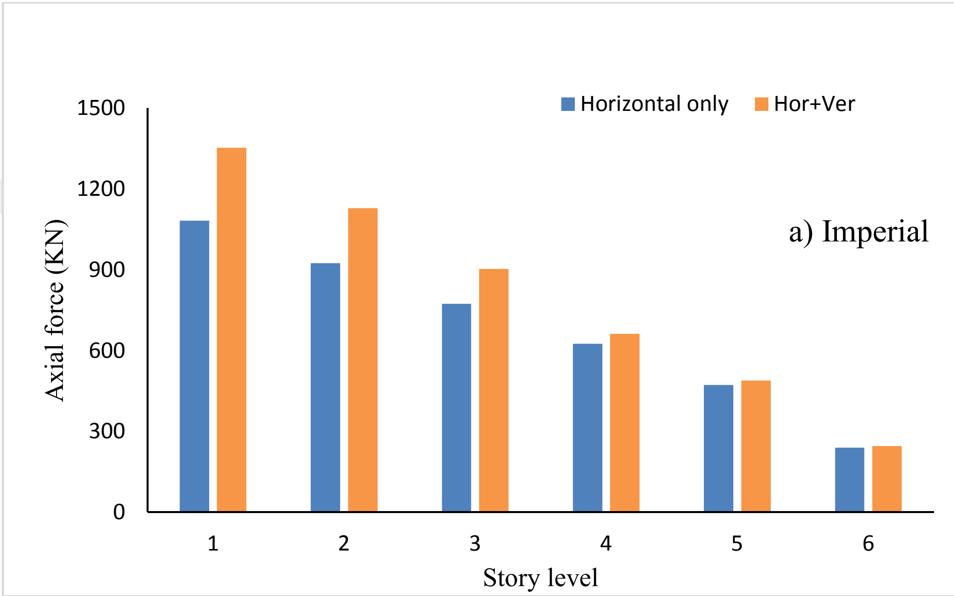
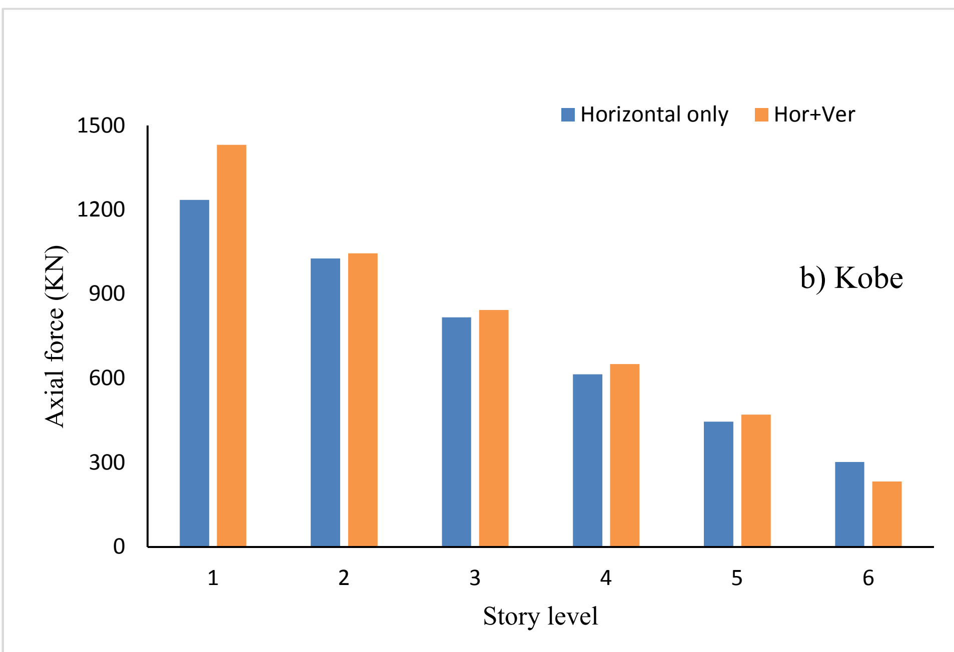


Figure 5.6: Story Column Axial Force of MIM-01 Building Model

Figure 5.7 and Figure 5.8 show the axial force of column for each story under five selected ground motions including horizontal and vertical components of earthquake for both loading conditions (Horizontal only and Horizontal + Vertical) in the stiffness irregular model-02 (KIM-02) and mass irregular model-02 (MIM-02). For the Kobe record (Figure 5.7) in the KIM-02 frame, the horizontal only case have an axial force of 1235KN while the horizontal + vertical case has an axial force of 1432 in the lowest column, which shows that the axial force is increased 16% when the vertical component of the earthquake is included in the analysis.

The axial force of mass irregular model-02 (MIM-02) under the Kocaeli record (Figure 5.8) has a maximum axial force of 986 KN and 1382 KN for both loading conditions, respectively. However, the result of all models shows that the column located in the lowest floors experience the highest axial force in both loading conditions (Horizontal and Horizontal + Vertical) under all seismic excitations.





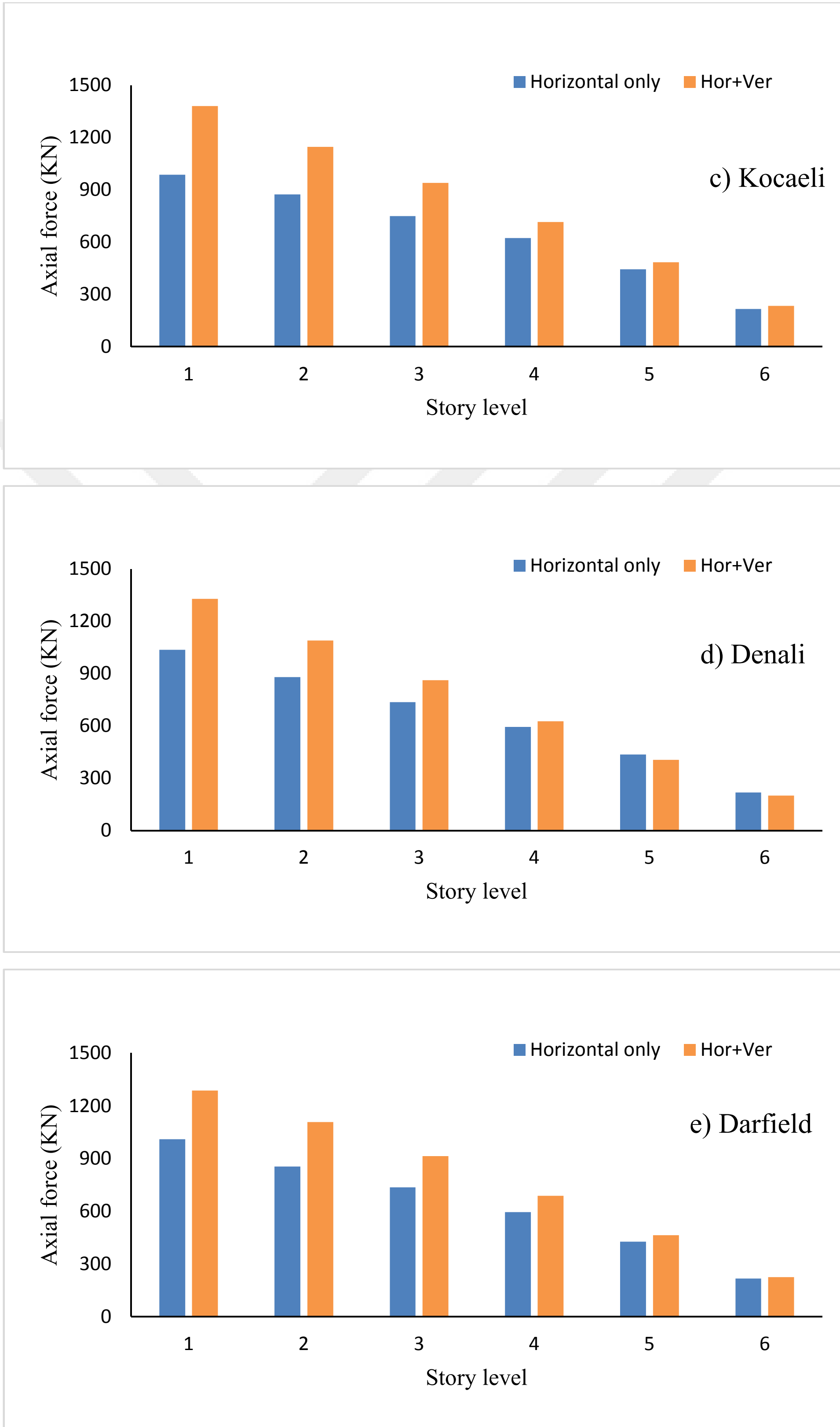
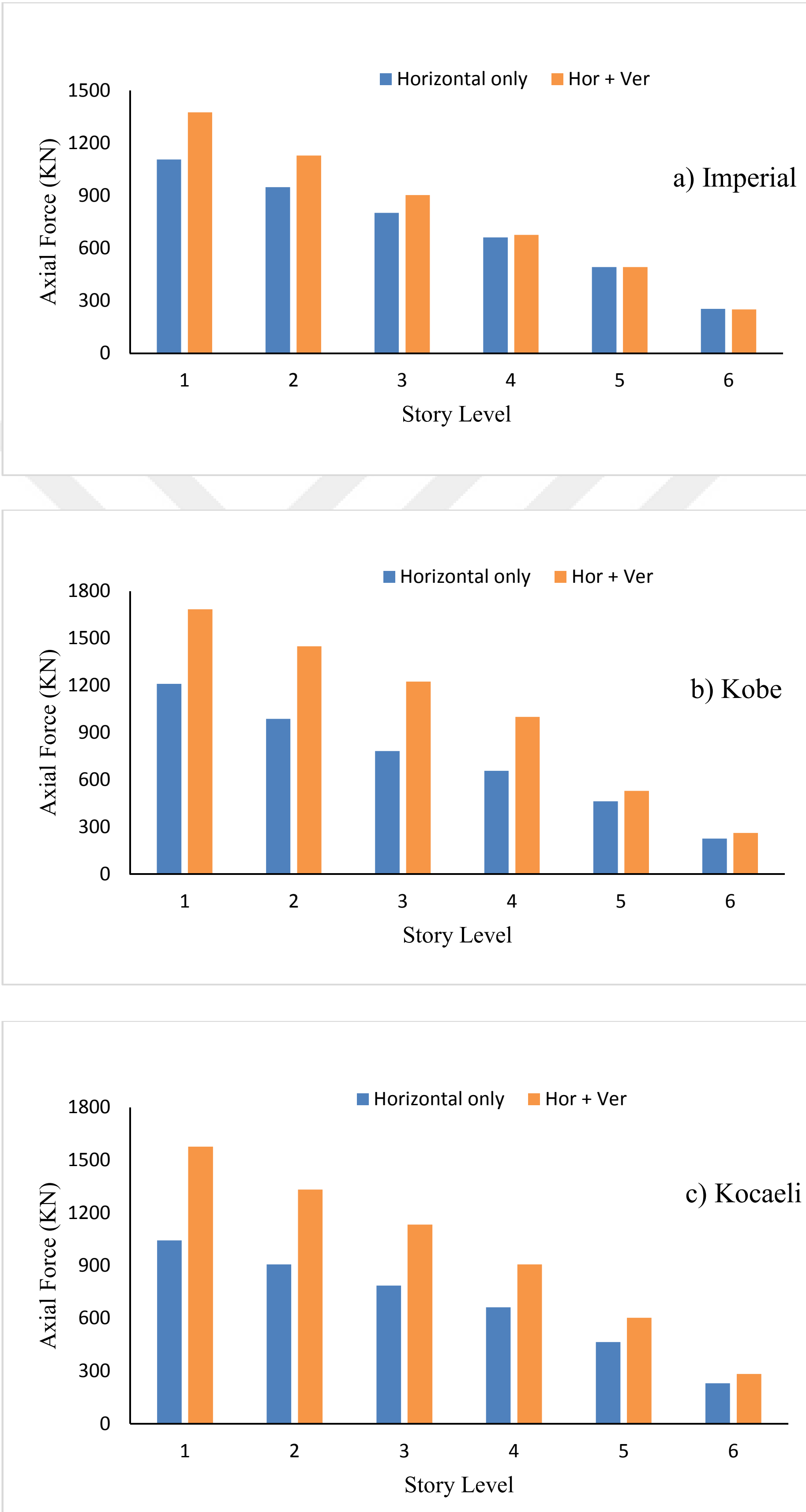


Figure 5.7: Story Column Axial Force of KIM-01 Building Model


Horizontal only
Hor + Ver
a) Imperial
Axial Force (KN)
1500
1200
900
600
300
0
1
2
3
4
5
6
Story Level
Horizontal only
Hor + Ver
b) Kobe
Axial Force (KN)
1800
1500
1200
900
600
300
0
1
2
3
4
5
6
Story Level
Horizontal only
Hor + Ver
c) Kocaeli
Axial Force (KN)
1800
1500
1200
900
600
300
0
1
2
3
4
5
6
Story Level

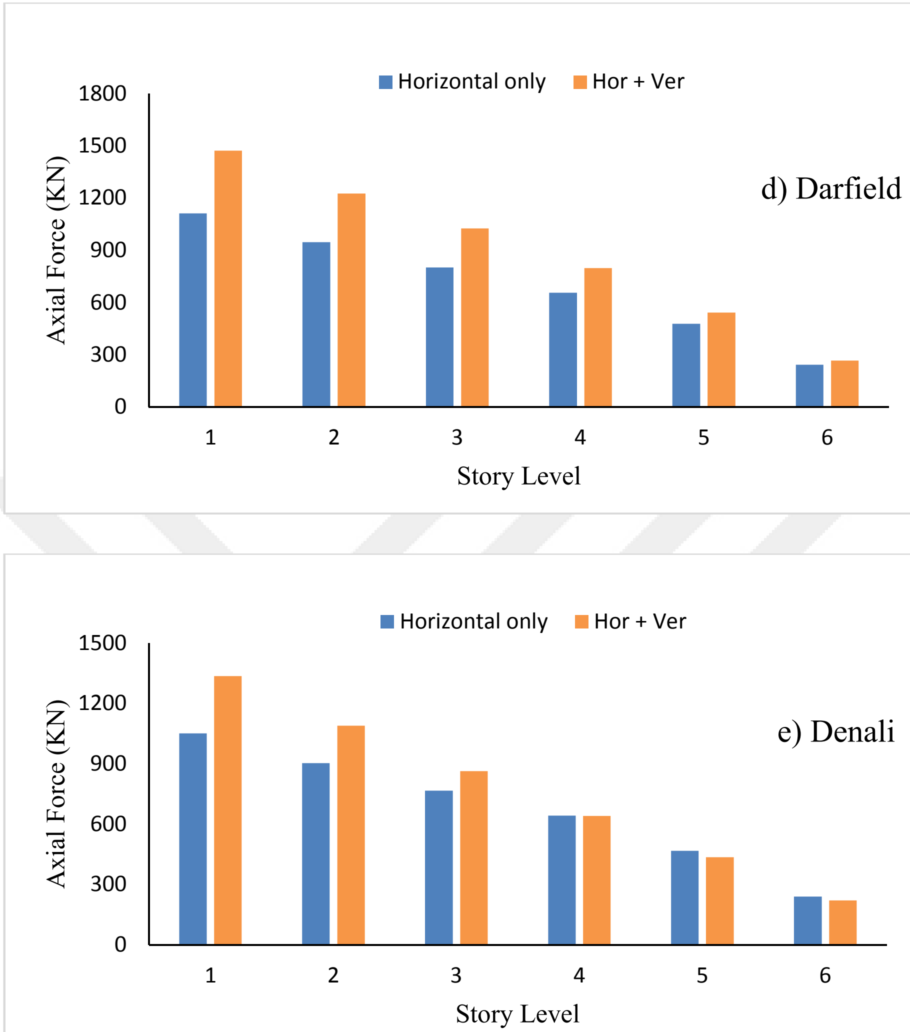


Figure 5.8: Story Column Axial Force of MIM-02 Building Model

5.2.4 Roof Horizontal Acceleration

The ground motions generate large floor acceleration to the structures due to the presence of large seismic excitations. The reference model was exerted both horizontal and vertical earthquake components, to determine which loading condition (Horizontal and Horizontal + Vertical) has the largest acceleration in near-fault regions. However, the roof horizontal acceleration is calculated according to the nodal absolute acceleration.

Tables 5.2 to Table 5.5 show the average value of maximum roof horizontal acceleration under five selected earthquakes including horizontal and vertical ground motions in the stiffness irregular model-01, mass irregular model-01, stiffness irregular model-02 and mass irregular model-02, respectively. According to the tables below, the average value of maximum roof acceleration for most records in the study are very close to each other between the two different loading conditions (Horizontal and Horizontal + Vertical). The KIM-01 frame result shows that the average value of roof maximum horizontal acceleration increased by 12.1% and 10.2% under Kobe and Kocaeli records, respectively, when the vertical and horizontal ground motions are subjected to the structure at the same time. However, the result of all models shows that the vertical component of an earthquake may affect the roof's horizontal acceleration, although the effect is very small under all ground motions.

Figure 5.9 shows the response of roof absolute horizontal acceleration in the stiffness irregular modal-01 (KIM-01) under all records for both loading conditions.

Table 5.2: Roof Horizontal Acceleration for the KIM-01 Building Model

	Roof Horizontal Acceleration		
Record Name	Horizontal Only	Horizontal + Vertical	Difference
Imperial	9.38	9.48	1.07%
Kobe	9.07	10.17	12.1%
Kocaeli	7.74	8.53	10.2%
Denali	9.37	9.70	3.52%
Darfield	8.11	8.27	1.97%

Table 5.3: Roof Horizontal Acceleration for the MIM-01 Building Model

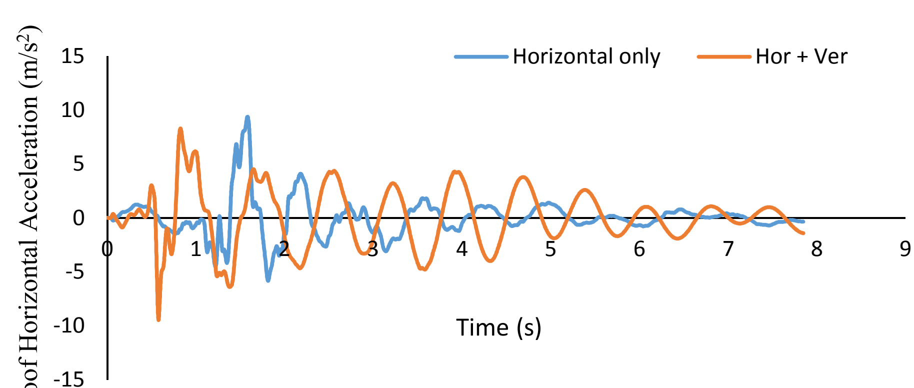
	Roof Horizontal Acceleration		
Record Name	Horizontal Only	Horizontal + Vertical	Difference
Imperial	11.65	11.68	0.30%
Kobe	8.695	8.698	0.03%
Kocaeli	8.312	8.383	0.85%
Denali	9.810	9.658	-1.55%
Darfield	9.810	9.300	-5.19%

Table 5.4: Roof Horizontal Acceleration for the KIM-02 Building Model

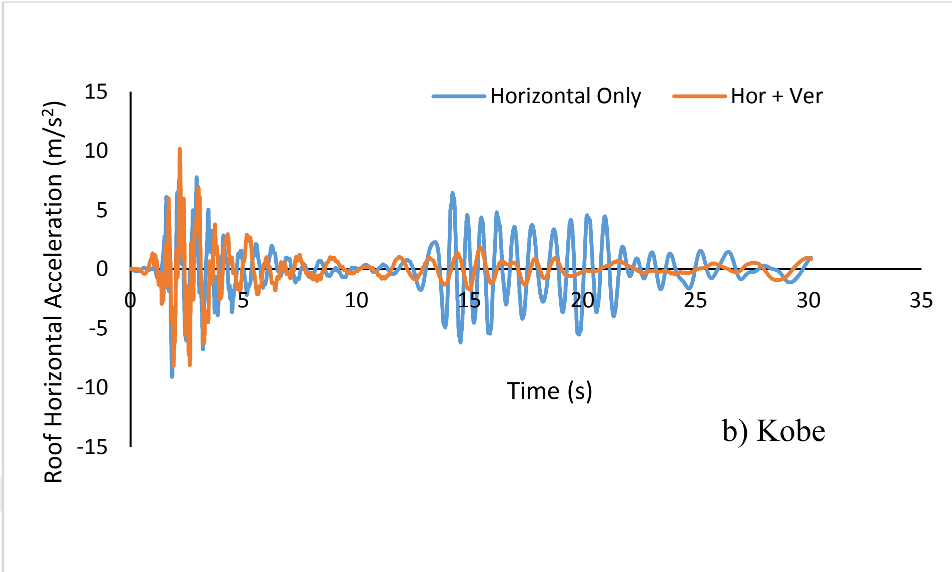
	Roof Horizontal Acceleration		
Record Name	Horizontal Only	Horizontal + Vertical	Difference
Imperial	11.06	11.08	0.22%
Kobe	11.36	10.75	-5.38%
Kocaeli	10.20	10.61	4.34%
Denali	13.04	13.10	0.48%
Darfield	10.61	10.47	-1.29%

Table 5.5: Roof Horizontal Acceleration for the MIM-02 building Model

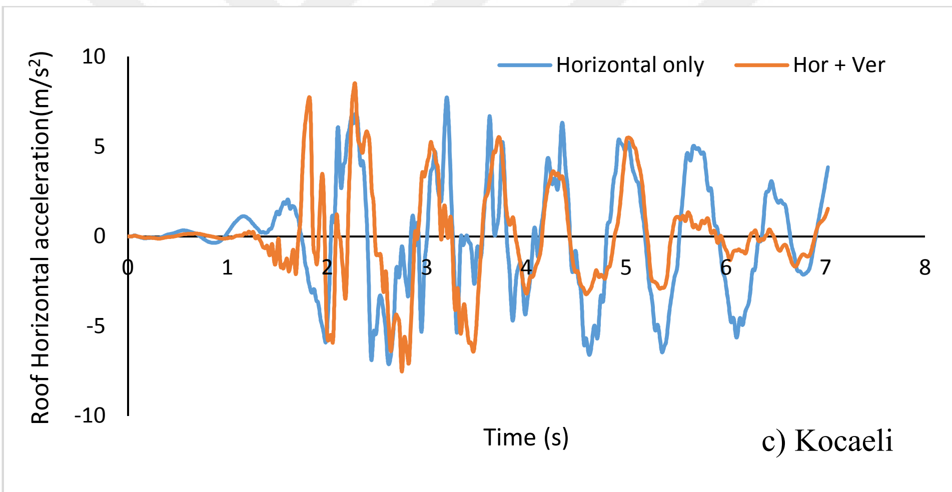
	Roof Horizontal Acceleration		
Record Name	Horizontal Only	Horizontal + Vertical	Difference (%)
Imperial	10.32	10.37	0.47%
Kobe	10.53	10.42	-1.03%
Kocaeli	9.639	9.831	1.99%
Denali	11.02	10.97	-0.39%
Darfield	12.02	12.54	4.33%



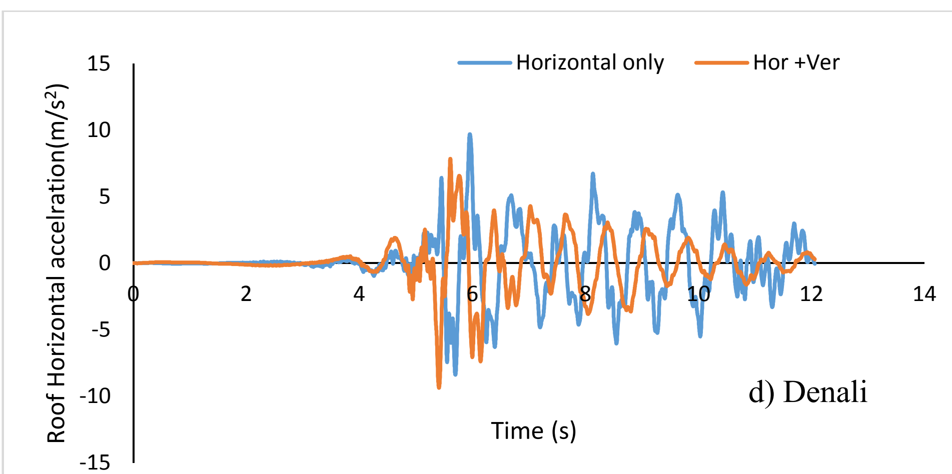
a)Imperial



Roof Horizontal Acceleration (m/s²)
Horizontal Only
Hor + Ver
15
10
5
0
-5
-10
-15
0
5
10
15
20
25
30
35
Time (s)
b) Kobe



Roof Horizontal acceleration(m/s²)
Horizontal only
Hor + Ver
10
5
0
-5
-10
0
1
2
3
4
5
6
7
8
Time (s)
c) Kocaeli



Roof Horizontal accelration(m/s²)
Horizontal only
Hor +Ver
15
10
5
0
-5
-10
-15
0
2
4
6
8
10
12
14
Time (s)
d) Denali

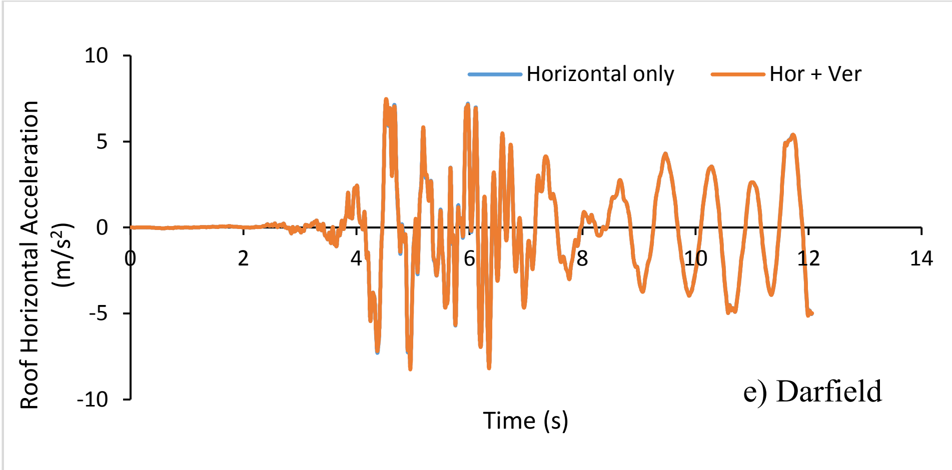


Figure 5.9: Roof Absolute acceleration of KIM-01 building model

5.2.5 Plastic Hinge Formation

Plastic hinge damage on beam and column under Imperial record in two loading conditions (Horizontal and Horizontal + Vertical) were illustrated in the middle of ground motion loading in KIM-01 and MIM-02 building models. Figure 5.10 and Figure 5.11 show the plastic hinge formation for both loading conditions under imperial record in which the inclusion of vertical ground motions increases plastic hinge formation. However, the plastic hinges mostly appeared in beams since the idea of a strong column weak beam was implemented to resist the seismic design loads.

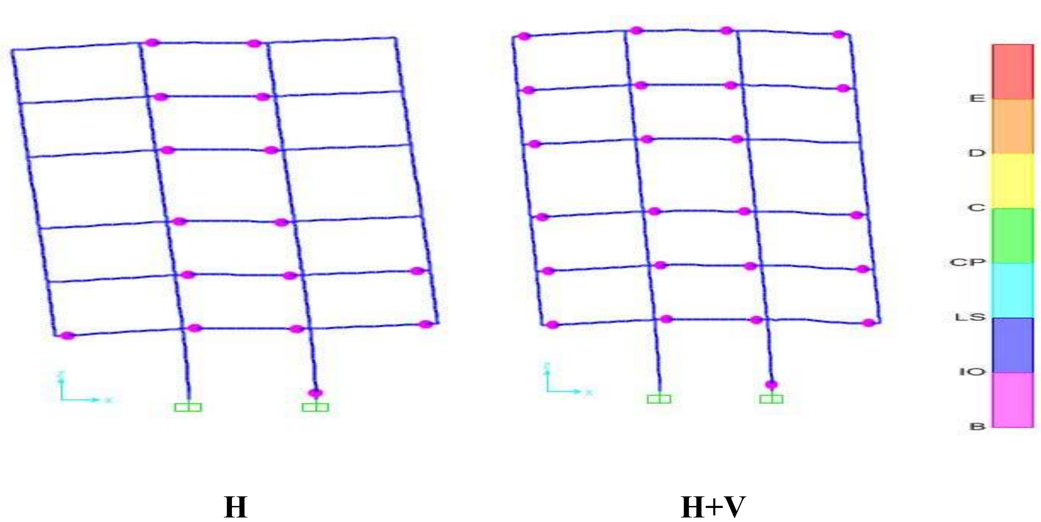


Figure 5.10: Formation of Plastic Hinges in KIM-01 Model under Imperial Data

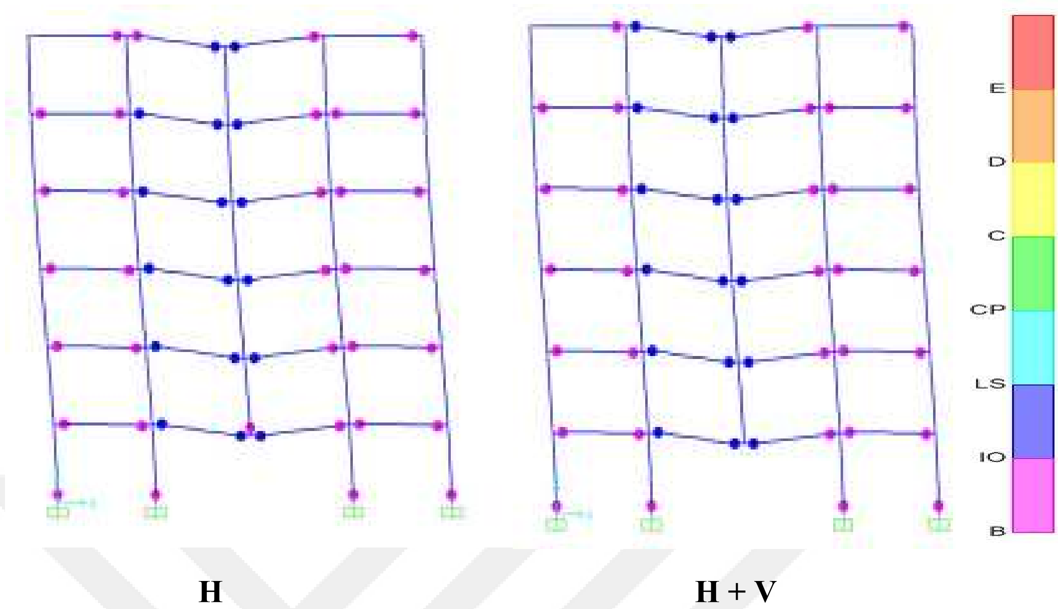


Figure 5.11: Formation of Plastic Hinges in MIM-02 Model under Imperial Data

5.3 Comparison of Nonlinear Time History Results to the Related Studies

The results obtained from this study were compared to the previous studies to get a comparative baseline for the study. Hongyang Wu (2016) investigated in his thesis study, the Impact of Vertical Ground Motion on Seismic Response of Steel Frame Structures. Four three-story and four six-story steel frame structures have been selected. The structures were designed by using the equivalent lateral method and analyzed by using nonlinear time history analysis. Different ground motions records were selected including horizontal and vertical components of earthquakes. Two different loading conditions (Horizontal and Horizontal + Vertical) were taken same as this study as described in section 4.3. The comparison of the two studies shows no significant difference in the result obtained in terms of the inter-story drifts, column axial force, and roof horizontal acceleration.

In general, the vertical ground motions have a minor effect on inter-story drift ratios in which the inclusion of vertical ground motion may increase or decrease the inter-story drifts. The vertical ground motions have more effect on axial force on a column. However, the below graphs show the result of that study, although the axial force is normalized while the roof accelerations are presented in terms of g, the behavior remains the same for both studies.

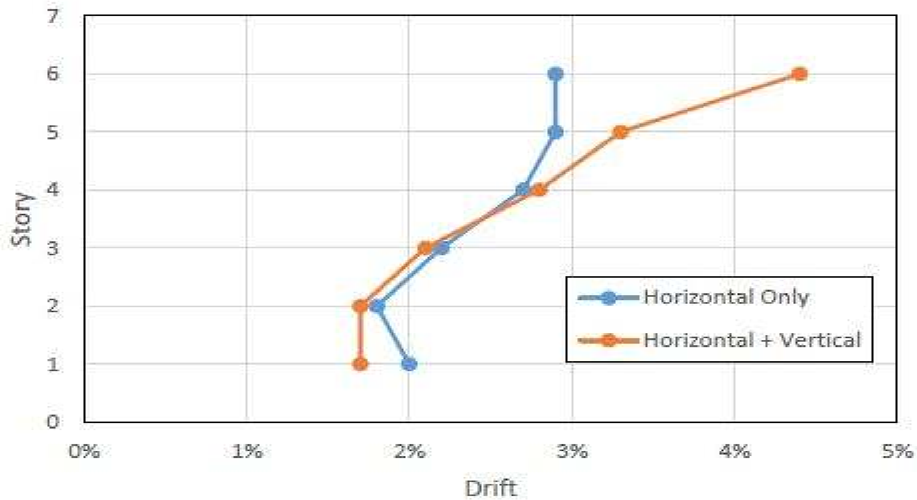


Figure 5.12: Inter-Story Drift for Each Story in the Moment Frame as Beam Model under FF13

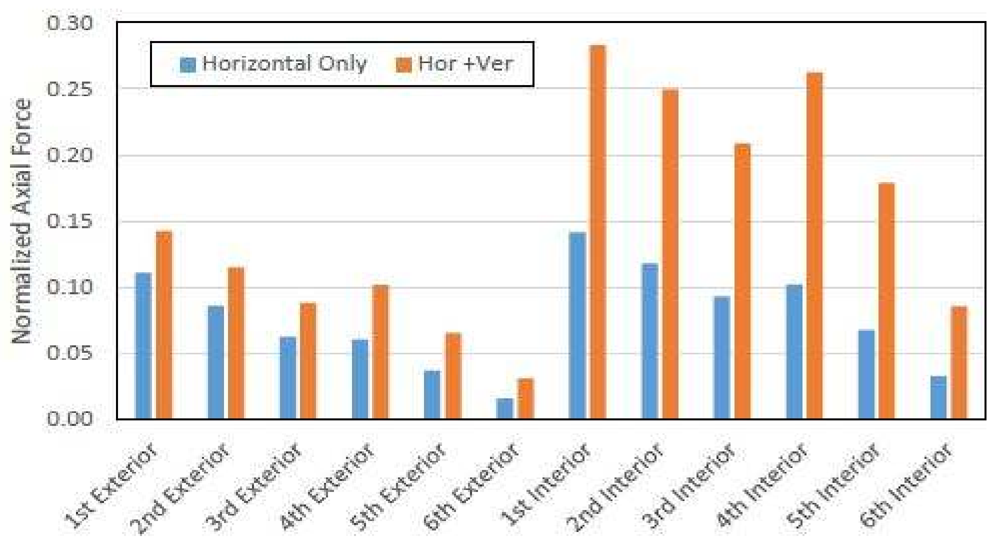


Figure 5.13: Story Axial Force for Six-Story Moment Frame as Beam Model

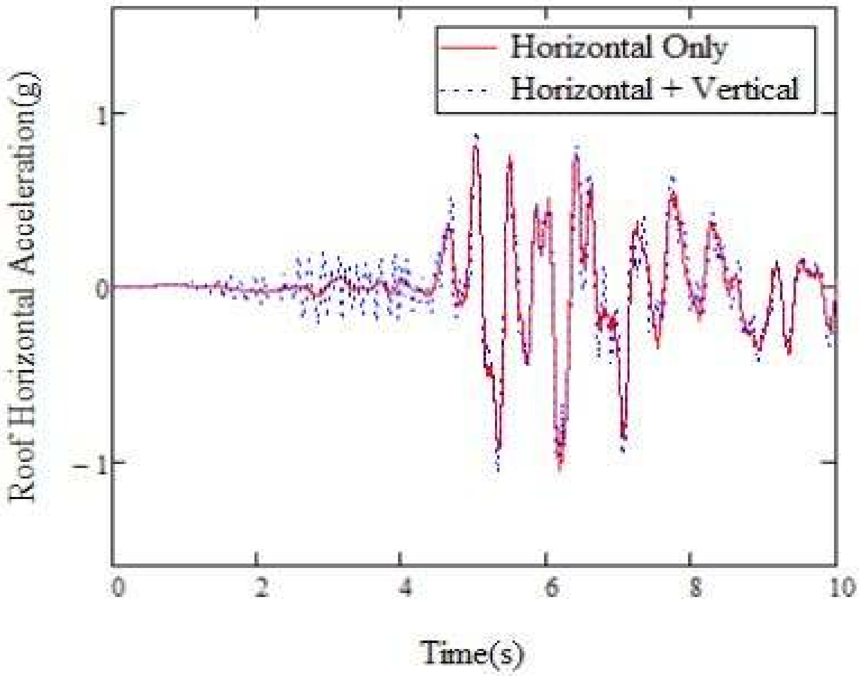


Figure 5.14: Detail of Time History Response of Roof Absolute Horizontal Acceleration (g) in the Six-Story Moment Frame as Girder Model under NF-14-1

CHAPTER 6

SUMMARY, CONCLUSION AND RECOMMENDATION

6.1 Summary

This study's main objective is to evaluate irregular structures behavior when subjected to horizontal and vertical seismic excitations. Irregular structures are classified into a plan and vertical irregularity, so in this study, a vertical irregularity was considered, especially mass and stiffness irregularity. Vertical irregular structures are buildings having irregular in elevation. For this study, Stiffness irregular buildings have story height differences while irregular mass buildings have excess heaviness on some floors. The following specific objectives were proposed;

- ❖ To evaluate the seismic behavior of stiffness and mass irregular structures under two loading conditions (Horizontal and Horizontal + vertical).
- ❖ To determine which case has the highest impact on irregular structures in near fault regions during strong earthquakes.
- ❖ Analysis of different 2D models by exerting number of ground motions under horizontal and the combination of horizontal and vertical seismic components.

To identify the study needs, building selection, analysis types, ground motions, and obtained result to compare the outcomes, a very detail of the literature review were conducted throughout the study. Appropriately, two stiffness irregular models and two mass irregular models were used and perfumed inside SAP2000 V21. Following the American society of civil Engineering [ASCE 7-16] seismic code.

All the building models are analyzed using Nonlinear Time History Analysis in a site Area in Turkey (earthquake zone-v). All the models were designed and checked to testify the structure's safety before applying ground motions. Finally, two loading conditions (Horizontal and Horizontal + vertical) have been applied in all models, and their result is discussed in detail, such as inter-story drift ratio, axial forces on column, mass participation ratio, and roof horizontal acceleration.

6.2 Conclusion

This study evaluates the behavior of irregular structures when subjected to horizontal and vertical seismic excitations. Stiffness and mass irregularity are created at the first and fourth floor by increasing the height and heaviness of floors, respectively. Four 2D models have been used, and nonlinear time history analyses were performed. Finally, all models' results under two loading conditions (Horizontal and Horizontal + vertical) were compared and discussed in terms of seismic parameters such as maximum inter-story drift ratio, axial force, and joint acceleration. Therefore, the conclusion for this study are summarized as follows:

- The main reason for this study is to evaluate the seismic behavior of irregular structures under horizontal and vertical components of earthquake.

- The inter-story drift result shows that the inclusion of vertical ground motion has minor effect, which may increase or decrease the inter-story drift ratio. However, the comparison of the two loading conditions shows that horizontal plus vertical component load case may be more than or less than the horizontal only load case. The story drift result is less than 1% for both loading cases.

- The result of Axial forces on column shows that the axial forces increases after the vertical ground motions are added to the model. Moreover, the increase of axial force variation of column causes a reduction of shear capacity and increases the potential for shear failure as V/H ratio increases

- Roof horizontal acceleration result in all models shows that the two loading cases have approximate results except stiffness irregular model_01 (KIM-01) under Kobe and Kocaeli record in which the percentage difference is increased by 12.1% and 10.2%, respectively when the vertical ground motion is added. However, the result shows that the inclusion of vertical ground motion may affect the absolute roof horizontal acceleration.

- ❖ Most of the plastic hinges in all models appeared below the immediate occupancy level a few hinges passed this stage at the maximum step of displacement. Therefore, all the building models were modeled and designed safely to resist the seismic loading without failure of the structural members.

The study result shows that reinforced concrete buildings subjected to combined horizontal and vertical seismic components can have more damage than those subjected to horizontal only ground motion in near field regions. However, to assess the seismic response of reinforced concrete structures in near fault regions, it’s recommended that vertical component of earthquake be included, where the ratio of V/H is probably to be high. The result also prove that the vertical irregular structures are harmful, and the effect of stiffness and mass irregularity is more dangerous in a seismic zone. Therefore, the structure's irregularity must be avoided, or they must be designed well according to ASCE 7-16 seismic code.

6.3 Recommendation

Recommendations for prolonging studies and future work research related to the behavior of irregular structures subjected to Horizontal and vertical seismic excitations are listed below;

- ❖ The building models used for this study are regular in a plan. Therefore, for future study, structures with asymmetric in plan with vertical irregularity can be studied.

- ❖ Soil interaction, base isolation, shear wall, and infill wall are not considered for this study. The present and future studies can be added to such structures.

- ❖ In this study, only stiffness and mass irregularity are considered. The future study will cover these cases with vertical geometric irregularity over high-rise buildings with many floors. Moreover, reinforced concrete frames were only considered, so for the future studies steel structures under two loading conditions in near and far fault areas will be very interested to expose the effect of seismic excitation including vertical effect.

REFERENCES

[1] S.Varadharajan. "Study of Irregular RC Buildings under Seismic Effect". *no. 01, 2014, pp.1-404, MSc thesis.*

[2] Schwen, Daniel "New Yorker hotel in New York City, USA", *24 May 2008,* https://commons.wikimedia.org/wiki/File:New_Yorker_building.jpg

[3] Hakilkon "Overview of Manhattan from the Empire State Building*", 24 December 2011,* https://commons.wikimedia.org/wiki/File:Blick_auf_Manhattan.JPG.

[4] Dogˇangu.¨ Performance of reinforced concrete buildings during the May 1, 2003 Bingo¨ *Earthquake in Turkey—, Engineering Structures, Vol.26, pp. 841 – 856.*

[5] Poonam, et al. "Study of Response of Structurally Irregular Building Frames to Seismic Excitations." *International Journal of Civil, Structural, Environmental and Infrastructure Engineering Research and Development (IJCSEIERD), vol. 2, no. 2, 2012, pp. 25–31.*

[6] Shrestha. "Vertical Gound Motions and Its Effect on Engineering Structure: A State-of the art Review". *International Seminar on Hazard Management for Sustainable Development".2009.pp. 190-202*

[7] Yang, J. and Lee, C.M. "Characteristics of vertical and horizontal ground Motions recorded during the Niigata-ken Chuetsu, Japan Earthquake of 23 October 2004", *Engineering Geology, 2007, Vol. 94, No. 1-2.*

[8] Collier, C, and Elnashai, A. “A Procedure and Spectra for Combining Vertical and Horizontal Seismic Action Effect. Journal of Earthquake Engineering”, *2001.Vol.5 (4), pp.521-539.*

[9] Noroozinejad, Ehsan, and Ali Abbas “The Influence of Coupled Horizontal–Vertical Ground Excitations on the Collapse Margins of Modern RC-MRFs.” *International Journal of Advanced Structural Engineering, vol. 8, no. 2, Springer Berlin Heidelberg, 2016, pp. 169–92.*

[10] Keskin, Engin. “Effect of vertical ground motion on the performance of high-rise buildings”. *2020, pp.1-159.*

[11] Oyguca, Resat, et al. “Seismic Behavior of Irregular Reinforced-Concrete Structures under Multiple Earthquake Excitations.” *Soil Dynamics and Earthquake Engineering, vol. 104, no. June 2017, Elsevier Ltd, 2018, pp. 15–32.*

[12] P. Giannakouras and C. Zeris. “Seismic Performance of Irregular RC Frames Designed According to the DDBD Approach.” *Engineering Structures, vol. 182, no. January 2018, Elsevier, 2019, pp. 427–445.*

[13] Tiwari, Saugat, and Adhikari Sailesh. “Seismic Analysis on Mass and Stiffness Variation in RC Buildings by Numerical Modelling.” *International Journal of Engineering Research and, vol. V9, no. 04, 2020, pp. 123–127.*

[14] Sravan Kumar, Choppa. “Seismic Analysis of Building with Mass Irregularity”. *2016, pp.1-53, MSc Thesis.*

[15] Arvindreddy and R.J.Fernandes. "Seismic Analysis of RC Regular and Irregular Frame Structures." *International Research Journal of Engineering and Technology (IRJET), vol. 02, no. 2015, 2015, pp. 44–47.*

[16] Hüsnü Korkmaz, Hasan. "Overhangs in Structural Systems and Earthquake Behavior from Torsional Irregularity Point of View." *Selcuk University Journal of Engineering, Science and Technology, vol. 6, no. 3, 2018, pp. 406–416.*

[17] Chintanapakdee, chatpan and K. Chopra, Anil. "Evaluation of Modal Pushover Analysis Using Generic Frames." *Earthquake Engineering and Structural Dynamics, vol. 32, no. 3, 2003, pp. 417–431.*

[18] S. Varadharajan, et al. "Seismic Response of Multistory Reinforced Concrete Frame with Vertical Mass and Stiffness Irregularities S." *The Structural Design of Tall and Special Buildings, vol. 26, 2012, pp. 421–449.*

[19] B V Chiniwalar, et al. "Seismic Response of Vertical Irregular Structures with Soil-Structure Interaction." *The IUP Journal of Structural Engineering, vol. 8, no. 2, 2015, pp. 7–19.*

[20] Rathi, Akhilesh and Raut, Dr. Ashwin. "Design and analysis of regular and vertical irregular building by using e-tabs." *International Journal of Management Technology and Engineering, vol. 8, no. 47, 2018, pp. 47–55.*

[21] C. A Aiyappa , et al. "Seismic Performance of Soft Storey and Vertical Geometrical Irregular Structures." *International Journal of Research in Engineering, Science and Management, vol. 2, no. 7, 2019, pp. 83–87.*

[22] Ahmed, Faizan. "Importance of Use of Vertical Ground Motion in Seismic Analysis for Isolated Structures", *2017, pp.1-79.*

[23] Wu, Hongyang. "Impact of Vertical Ground Motion on Seismic Response of Steel Frame Structures". *2016.*

[24] ASCE 7-16. Minimum Design Loads and Associated Criteria for Buildings and Other Structures.

[25] S. K. Kunnath, et al, "Effect of near-fault vertical ground motions on seismic response of highway overcrossings," *Journal of Bridge Engineering, vol. 13, no. 3, 2008, pp. 282–290.*

[26] S. J. Kim, et al, "Analytical assessment of the effect of vertical earthquake motion on RC bridge piers," *Journal of Structural Engineering, vol. 137, no. 2, 2011, pp. 252–260.*

[27] Wilkinson S and Hiley R, "A Non-Linear Response History Model for the Seismic Analysis of High-Rise Framed Buildings", *Computers and Structures, Vol. 84.2006.*

[28] CSI knowledge base "knowledge base which is searchable online encyclopedia that provides information to the structural engineering community". https://wiki.csiamerica.com/display/kb/P-Delta+effect.

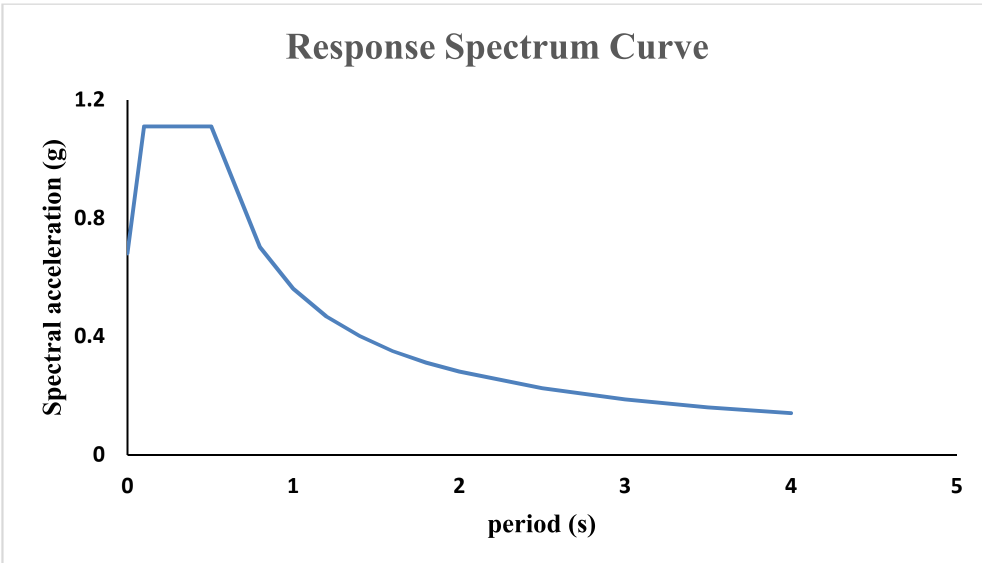
[29] https://www.quora.com/What-are-%E2%80%9Cplastic-hinges%E2%80%9D-in-structural-engineering

[30] PEER (Pacific Earthquake Engineering Research Centre). 2006. Strong ground motion database 2006: http://peer.berkley.edu/.

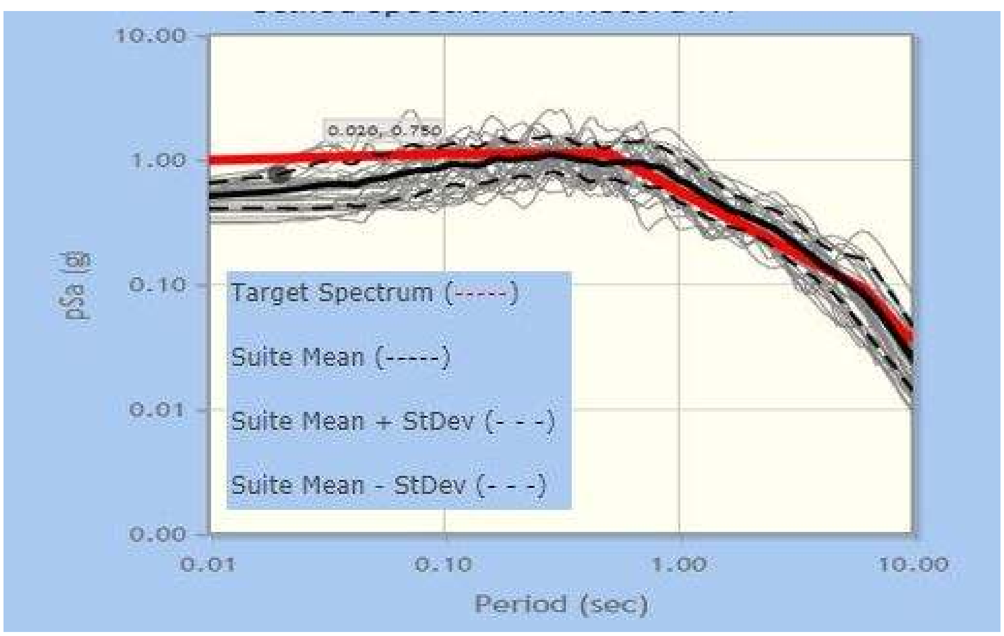
APPENDIX

SCALING OF GROUND MOTIONS

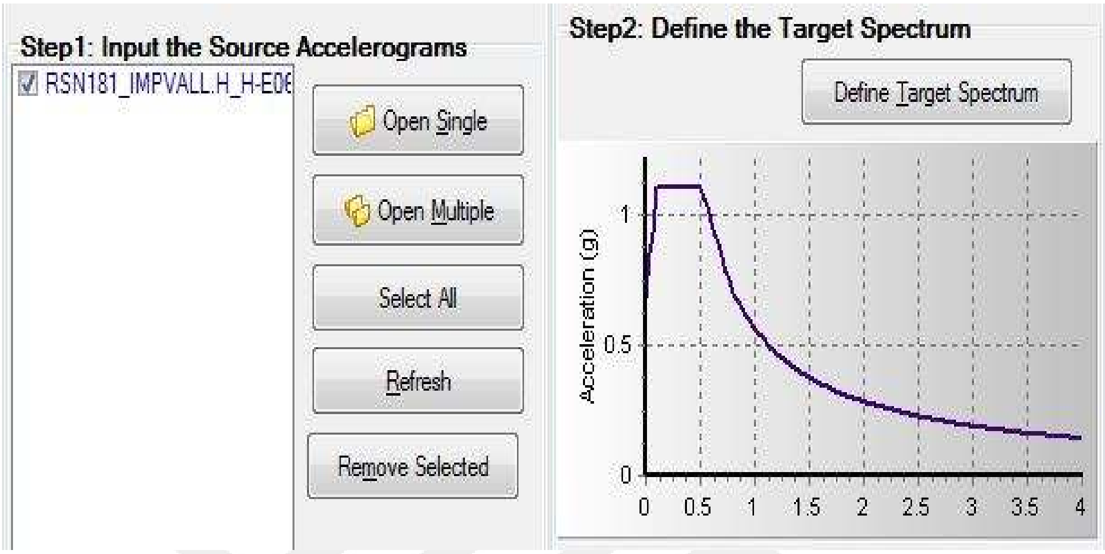
Step 1: construct target spectrum to match ground motions



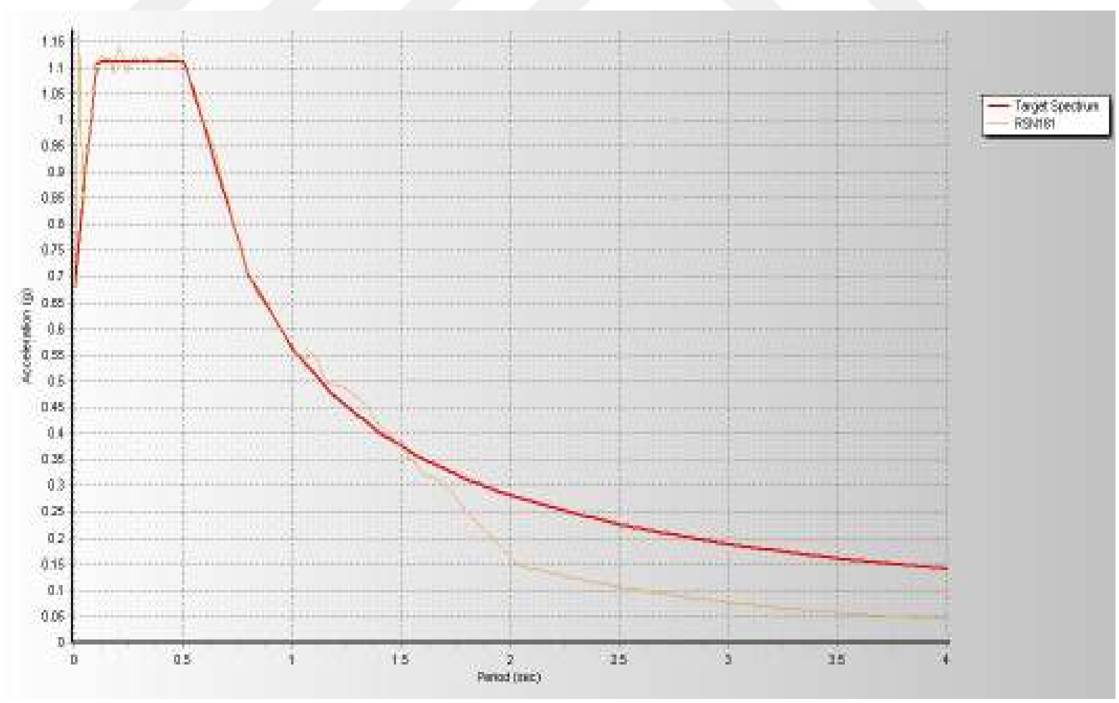
Step 2: obtain ground motion data from PEER by matching target spectrum curve



Step 3: Input the ground motion data inside siesmomatch and define target spectrum



Step 4: Do matching and obtain matched response spectrum



Step 5: Obtain scaled ground motion Data from seismomatch to use Nonlinear Time history Analysis inside SAP2000 software.