# Retrofitting Reinforced Concrete Building by Using Steel Bracing

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Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Civil Engineering

Eastern Mediterranean University
February 2023
Gazimağusa, North Cyprus

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# ABSTRACT

The past many years have seen numerous earthquakes that affected many people, either physically or psychologically. During the emergency phase of these disasters, many people have been hurt, made homeless, displaced, or evacuated. In the aftermath of an earthquake, fallen objects, flying glass, and collapsing walls cause most injuries and deaths. Moreover, existing reinforced concrete structures may not be adequately seismically resistant due to their structural design and nonductile features. Rehabilitation is needed for existing inadequate or deteriorating structures help reduce seismic risk as well as other natural disasters. Buildings suffer moderate to severe earthquake damage due to their non-compliance with seismic requirements. Therefore, strengthening these buildings is needed to improve their seismic performance level. While there are a variety of methods to strengthen a structural building, like RC Jackets, RC shear walls and steel bracing, the main topic of this study will be the use of steel bracing to strengthen structures. The resistance to lateral loads is achieved through steel bracing used in retrofitting a structure.

To maintain lateral load stability, steel bracing is used in this study as a method for retrofitting existing buildings based on the Turkish Building Seismic Code 2018. There are many advantages of strengthening the structure against the seismic actions using steel bracing compared to other strengthening methods, including the lower cost, ease of construction, ability to take up less space, and ability to achieve the strength, stiffness, and stability needed. Additionally, steel bracing is maintained for retrofitted frames to achieve a satisfactory level of life safety. The study will be held in form of comparison analysis between eccentric and concentric diverse types of bracing (including V-bracing, Inverted V-bracing, and Diagonal Bracing) as well as Bulking restrained braces BRB using nonlinear analysis, the number of plastic hinges on beams and columns, the capacity curves, the performance level, and so on, under different braces layout pattern (defined as Case 1, Case 2, and Case 3). In addition, the seismic performance level of different patterns (Case 1, Case 2, and Case 3) is employed to stand for the best bracing seismic action using the Seismostruct program for building story 4, 6, 8, and 15. Finally, the study would make a comparison between Bulking restrained braces BRB and conventional steel bracing.

**Keywords:** Seismic design, Steel bracing, Earthquake design, Pushover analysis, Concentrically braced frame, Eccentrically braced frame, Lateral loads, Buckling restrained braced frame.

# ÖZ

Geçtiğimiz yıllarda birçok insanı fiziksel ve/veya psikolojik olarak etkileyen çok sayıda deprem görüldü. Bu felaketlerin sonucunda çok sayıda insan hayatını kaybetti, yaralandı, evsiz kaldı, yerinden edildi. Bir depremin ardından çoğu kez düşen nesneler, kırılan camlar, çöken duvarlarla birlikte yaralanma ve ölümler görülmektedir. Ayrıca, mevcut betonarme yapılar, yapısal tasarımları ve sünek olmayan özellikleri nedeniyle depremlerde yeterince dayanıklı olmayabiliyor. Deprem ve diğer doğal afetlerle ilgili risklerin azaltılabilmesi için yapılarımızın yeterli dayanıma sahip olması gerekmektedir. Yeterli dayanımı olmayan yapılar, orta ile şiddetli depremlerde büyük hasarlar görmektedirler. Bu nedenle, yapı performans seviyelerini iyileştirmek için bu binaların güçlendirilmesi gerekmektedir. Yapılarımızı güçlendirmek için birçok yöntem vardır. Bu çalışma kapsamında, betonarme binalarda çelik çaprazlar kullanılarak yapıların güçlendirilmesi incelenecektir. Yanal yüklere karşı talep edilen ek dayanım, bu elemanlarla kolayca elde edilebilir.

Yatay yük stabilitesini korumak için, bu çalışmada 2018 Türk Deprem Yönetmeliği'ne göre mevcut binaların güçlendirilmesi için bir yöntem olarak çelik çaprazlar kullanılmıştır. Diğer güçlendirme yöntemlerine kıyasla yapının deprem etkilerine karşı çelik çaprazlar ile güçlendirilmesinin daha düşük maliyet, inşaat kolaylığı, daha az yer kaplaması ve ihtiyaç duyulan dayanım, rijitlik ve stabiliteyi elde edebilmesi gibi birçok avantajı vardır. Ek olarak, tatmin edici bir can güvenliği seviyesi elde etmek için çerçevelere çelik çaprazlar konulur. Çalışmada, 4, 6, 8, ve 15 katlı binalar seçilerek, farklı şekillerde yerleştirilen burkulması engellenmiş çelik çaprazlara doğrusal olmayan analiz uygulanmış, merkezi ve dış merkezli çapraz türleri (V, ters-V ve diyagonal çaprazlar) yanı sıra, kapasite eğrileri, performans seviyeleri, rijitlikleri vb. Seismostruct programı yardımıyla karşılaştırılmıştır. Son olarak, burkulması engellenmiş çelik çaprazlarla geleneksel çelik çaprazlar arasında bir karşılaştırma yapılmıştır.

**Anahtar Kelimeler:** Sismik tasarım, Çelik çapraz, Deprem tasarımı, Statik itme analizi, Merkezi çapraz, Dış merkezli çapraz, Yanal yük, Burkulması engellenmiş çelik çapraz.

# DEDICATION

*In honor to my loving and caring family.*

# ACKNOWLEDGMENT

I want to start by expressing my sincere appreciation to my supervisor, Associate Professor Dr. GİRAY ÖZAY, for his guidance, knowledge, and recommendations during my Master's studies. Throughout my academic research and everyday life, his extensive knowledge and experience have inspired me.

Likewise, I would like to thank my jury members not just for their time and patience, but also for their intellectual contributions.

Especially, I would like to thank my sister Ala'a Alkhayyat for her steadfast support, dedication, and willingness to help when I needed it. Additionally, I am grateful for my parents' continued support throughout this process.

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# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| ATC-40 | Seismic Evaluation and Retrofit of Concrete Buildings |
| BRB | Bulking Restrained Braces |
| BRBFs | Buckling-Restrained Braced Frames |
| C | Controlled Damage Performance |
| CBF | Concentric Brace Frame |
| CO | Continued Operation Performance |
| CP | Collapse Prevention Performance |
| CSB | Concentric Steel Bracing System |
| D | Overall Beam Depth |
| DL | Dead Load |
| DRAIN-2DX | Static and Dynamic Analysis of Inelastic Structures |
| E | Link Length for Eccentric Element |
| EBF | Eccentric Brace Frame |
| ESBF | Eccentrically Steel Braced Frames |
| FEM | The Finite Element Method |
| FEMA | Guidelines for the Seismic Rehabilitation of Buildings |
| Fy | Specified Minimum Yield Strength |
| LD | Limited Damage Performance |
| LL | Live Load |
| Mp | Nominal Plastic Moment Capacity |
| RC | Reinforced Concrete Structure |
| RC-BF | Reinforced Concrete Braced Frames |
| SD | Design Spectral Acceleration |

| | |
|---|---|
| SHS | Square Hollow Section |
| tw | Web Thickness |
| Vp | Nominal Plastic Shear Capacity |
| Z | Plastic Section Modulus |

# Chapter 1

# INTRODUCTION

## 1.1 General

The recent decades have seen numerous earthquakes that have affected many people, either physically or psychologically, and earthquakes have the potential to damage buildings and collapse them, causing immediate and long-term health problems for humans. Therefore, earthquake-resistant construction is crucial to minimizing structural damage and injuries caused by earthquakes. This includes the fabrication of buildings and structures that can withstand sudden ground shaking caused by earthquakes. Buildings with non-ductile detailing and those designed for only gravity loads suffer moderate to severe damages in earthquakes because they do not meet seismic requirements. Many of the existing buildings display problems with seismic performance. Consequently, the increased importance of preventing earthquake disasters in recent years, it is possible and necessary to manage the difference between the actual and acceptable seismic risk, through rehabilitation and strengthening the building to meet the required seismic safety levels.

Therefore, it is essential to define the seismic performance of these buildings and develop a seismic strengthening solution if it is economically feasible. In retrofitting techniques, the old building can be strengthened by offering a variety of technological remedies for most seismic hazards while minimizing vulnerability by utilizing advanced design and construction techniques that reduce susceptibility to strong ground motions. Among the main approaches to strengthening, the installation of modern building materials, like steel braces, one of the key methods for strengthening structures is to improve their seismic performance. Although steel braces are frequently used in steel frames and shear walls of reinforced concrete (RC) structures, various studies have recently examined the potential applications of steel braces in RC structures [1].

Due to the increase in stiffness, steel bracing decreases the lateral drift and lateral damage to buildings structures. Because of this, lateral damage is reduced compared to that of a bare frame. As more heavily strained in this research, the braces behave as axially loaded members (truss elements) when subjected to lateral seismic stresses. Steel bracing offers several advantages over bracing in terms of its less expensive cost, ease of construction, space commitment, and ability to achieve the required strength, stiffness, and stability. Additionally, retrofitted frames are braced with steel to achieve satisfactory levels of life safety. It is therefore important to investigate the diverse types of retrofitting techniques under different story levels.

## 1.2 Literature Review of Previous Studies

It is essential to analyse the seismic behaviour of concentrically and eccentrically braced frames in order to keep the capacity design standards. To understand the seismic behaviour of braced structures, the following describes a summary audit of earlier research on the usage of steel bracing methods to strengthening RC frames. The current review focuses on previous works that have been published with the same consistency as this study's objectives.

A study conducted by Kamanli and Unal (2017) focuses on compares and assesses the specimens' load-displacement curves to determine where strengthening methods might boost the structure's carrying capacity for lateral loads, stiffness, and energy lost. This study used SAP2000 to perform pushover analyses on internal eccentric steel braced frames within reinforced concrete frames and reinforced concrete frames without internal eccentrical steel braces. Eccentrically steel braced frames (ESBF) from the Turkish Earthquake Codes of 2007 were included in the study samples, which are comprised of four types: V- braced, Inverted V- braced, Diagonal - braced, and Inverted Diagonal - braced. The pushover studies performed on the reinforced RC frames using these ESBFs yielded findings that were used to construct load-displacement curves for the specimens, which were then compared. [2].

Eskandari et al. (2017) conducted an investigation of the RC-BFs' (reinforced concrete braced frames) seismic response to close- and far-fault movements. RC-BFs with four, eight, twelve, and sixteen stories were designed using a code-design method for seismic zones of high risk. During the analysis of reinforced concrete's seismic performance braced frames, four different heights of frames were designed according to the Iranian Seismic Design Code 2014. The user design strategy was suitable, and the mean maximum drift of the frames was within acceptable bounds, according to the findings of the analytical investigation [3].

A study by Somase et al. (2021) has been aiming to compare the performance of different types of bracing systems for reinforced concrete buildings of 5 and 26 floors with and without bracing. The bare frame has been used as a comparison point for bracing systems including X, V, Inverted V, and diagonal bracing; V and Inverted V have also been compared with other techniques. For the RC structure, displacement results are compared between unbraced and braced models to determine the most appropriate bracing system. The result of the study shows greater safety for the building structure after the use of X and Inverted V braced frames [4].

As a result of a study by Ayaanle and Erdal (2020) concerning the retrofitting of a structure, steel bracing is employed as an active component in the lateral load resisting system, hence, steel bracing is used in this investigation to provide lateral load stability to the structure. The aim of this study is to verify whether the concentric bracing system performs well during seismic activities using static linear system and static nonlinear pushover analysis. It was established that several steels bracing techniques, including x bracing, diagonal bracing, inverted bracing, and zipper bracing, would be evaluated during this investigation. RC structures of three, five, nine, and twelve stories would also be tested during this study. Based on the results of this study, in comparison to the other systems, X bracing was the most effective [5].

Based on the fact that lateral stiffness plays a crucial role in the design of tall buildings, Khan et al. (2015) analyzes the seismic behavior of RC buildings using non-linear statics and linear statics analysis. This study examined the effects of different types of bracing systems (bare frame, concentric X bracing, eccentric X bracing, concentric Inverted V bracing, eccentric Inverted V bracing) for RC framed buildings in seismic zone IV as a means of providing lateral stiffness. For different models, a comparison was made between load resisting systems placed concentrically and eccentrically at different locations, in order to compare parameters such as story drift and story forces, and through the use of analytical based software ETABS, pushover curves were obtained both in X and Y directions. The results of the study indicate that for non-linear static analysis, the model with X bracing works better [6].

A study conducted by Ghobarah and Abou Elfath (2001) that shows the analysis of nonlinear static pushover and dynamic time-history data was used to determine the degree to which the repaired RC frames functioned during earthquakes using a variety of eccentrically braced steel frames (V-braces, K-braces, X-braces, and Y-braces). Using eccentric steel bracing for existing buildings was found to limit deformation when the link deformation angle was calculated based on the analysis of eccentric brace strengthening cases. Eccentric bracing strengthening are likely to improve seismic performance of nonductile buildings more than concentric bracing rehabilitations as long as the building deformation remains below the maximum allowable link deformation angle [7].

According to capacity design principles, Bosco and Rossi (2009) Assess the seismic response of eccentrically braced structures by analyzing damage distribution and capacity factor distribution. An analytical relationship between the overstrength factor of links, the damage distribution capacity factor, and the plastic rotation of links is established to obtain a quantitative assessment of structural damage in eccentrically braced structures following the first failure of links. As a result, substantial generic eccentrically braced structures are possible thanks to the overstrength factor of links, which is independent of the inelasticity of the damage distribution capacity factor. A wide distribution of plastic behavior is not guaranteed by seismic codes for traditional eccentrically braced structures in accordance with capacity design principles [8].

A study was carried out by Hamadamin (2014) conducting that buildings with RC frames can benefit from steel bracing systems to enhance seismic performance. RC frames that are seismically deficient can be retrofitted or strengthened using steel braces. It discusses various types of concentric steel braces used to strengthen RC buildings, Diagonal-braced, Inverted V-braced, Zipper-braced, and X-braced. Etabs has been used to design 3-story, 6-story, 9-story, and 12-story buildings. Compared to the cases without bracing, bracing upgraded the buildings' global capacity in terms of stiffness, displacement, and lateral load capacity; the X-braced system performed much better than the others [9].

## 1.3 Study Scope and Objectives

An examination of diverse types of concentric and eccentric steel bracing systems for existing RC buildings is the focus of this study. This study will be in a form of a comparative analysis of eccentric and concentric bracing types (V-bracing, Inverted V-bracing, and Diagonal Bracing), as well as Bulking Restrained Braces BRB analyzed using nonlinear analysis to determine the number of plastic hinges on beams and columns, the capacity curves, the performance level, and so on, under different braces layout patterns (described as Case 1, Case 2, Case 3). Moreover, the Seismostruct program is used to determine the best bracing seismic action based on seismic performance levels associated with different patterns (Case 1, Case 2, and Case 3). As the last step, bulking restrained braces BRB will be compared with conventional steel bracing.

## 1.4 Structure of the Study

There are five chapters in this thesis. In Chapter 1, the subject matter, research question, aims, previous studies, scope and objectives of the thesis are discussed, along with the structure of the thesis.

Chapter 2 defines general information in the study: provides in-depth information to build up the study, starting by giving general information about the earthquake, performance-based design in terms of structural integrity and system reliability, and the use of steel bracing to stiffen the structure in its two types (Concentric and Eccentric), and finally, the use of BRB bracing.

Chapter 3 describes the methods of analysis: focusing on the different methods used to analyze the study and summarizing them. Specifically, it explains how the static pushover analysis method works, the procedures involved, as well as its performance level.

Chapter 4 provides the design methodology of the study. In this part, information about the design of the building is described, such as the material properties, applied loads, element sections, and classes, using the 2018 Turkish Earthquake Code.

Chapter 5 gives a discussion of the results of the study. Thus, in this chapter, the study uses the SeismoStruct program to conduct case studies using the suggested methodology and application procedures, as well as, discuss the various structural parameters, that will give a detailed outcome. As well as provides a comparison between BRB and conventional steel bracing, considering the performance level of the structures.

Chapter 6 as a conclusion, present the results of this study, as well as a remarks and recommendations for future research.

# Chapter 2

# BEHAVIOR OF RC STEEL BRACED STRUCTURES

## 2.1 Introduction

In the natural world, earthquakes are among the most devastating events, since, each year, earthquakes kill an average of 27,000 lives per year people around the world [10]. Ground shaking occurs when underground rock breaks suddenly along a fault, causing seismic waves to cause ground shaking. An earthquake occurs when a fault in the underground rock suddenly breaks. Consequently, this issue has cost a lot of money to repair and rebuild the affected building structure over the years. However, these days, seismologists study earthquakes in greater detail with the use of computers and digital recorders [11].

For an understanding of earthquake bracing system design that prevents earthquake losses and can withstand seismic forces, it is essential to understand the factors that can adversely affect the structural system over time and to be aware of the factors that can adversely affect it. A comprehensive understanding of the load resisting system, specifically the bracing system used to resist lateral loads, and the type of bracing that would be used to reinforce a building against earthquake damage is provided in the following section.

## 2.2 Structural Integrity and System Reliability

Structural system reliability refers to the probability that the structural system will continue to function and/or be safe [12].

Performance-based design requires a comprehensive system-level assessment of structural reliability since structural integrity and system reliability have become increasingly important in structural engineering practice. Galambos provides comprehensive guidance on system reliability, and the report includes more detailed information; many member limit states cause little or no harm to a member. Noted that, once a limit state is reached, steel bracing systems are ductile; they do not lose their capacity. As well as, the system can carry a greater load because of redundancy and force redistribution options, meaning a structural system does not collapse when one component reaches its limit state. Thus, framed constructions typically serve to limit drift or the first hinge development, neither of which requires damage to take place [13].

## 2.3 Bracing System in Reinforced Concrete Structure

### 2.3.1 Steel Bracing

The bracing system is very effective and unyielding when it comes to resisting lateral loads. To guard buildings against the incidence of natural forces like earthquake forces, bracing systems play an important role in RC buildings for increasing stiffness and strength. It protects RC structural buildings from earthquake damage by absorbing axial loads, such as tension or compression, from earthquakes. Steel bracing is economical, simple to install, takes up less room, and can be made to fulfill strength and stiffness specifications. This system has been used in RC frames for the past two decades. Additionally, there are several ways to arrange the steel bracing in reinforced concrete frames, with either eccentric or concentric connection styles.

#### 2.3.1.1 Concentrically Braced Frame

Concentric braced frames (CBFs) are commonly used in low-rise buildings to resist seismic forces. As a result of the use of steel braces in this type of RC structural system, high elastic stiffness and strength are provided in order to dissipate earthquake energy. As its name implies, concentrated bracing consists of diagonal braces that run parallel to the frame's plane. As a result, a stiff frame is created by joining both ends of the brace at the endpoints of other framing members. Additionally, CBF's connections should be designed to be stronger than the members themselves in order to maximize the amount of energy dissipated and prevent bracing members from yielding and buckling [14].

Concentrically braced frames are designed to dissipate energy in a bracing system that is in harmony with the design and to maintain the elastic phase during load administration by ensuring the connections. It is also important to focus on and check strength drift control during the designing stage, especially for tall buildings [15]. Concentric bracing may be arranged in several different configurations, however, the ones that would be used in this study will be Inverted V, Diagonal bracing and V bracing as in Figure 1.

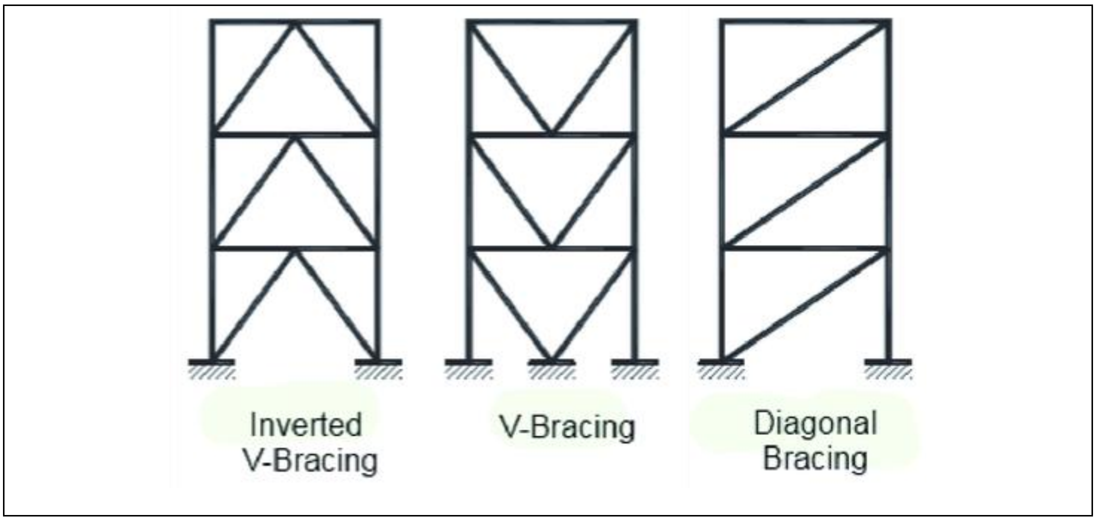



Figure 1: Define Concentric bracing frame types [16].

**2.3.1.2 Eccentrically Braced Frame**

Eccentric frames combine a bracing frame with a moment-resisting frame to provide a system with high elastic stiffness and a high inelastic response [17]. Due to its stiffness and ability to adapt during a large earthquake force and dissipation of energy, eccentrically braced frames resist the lateral load typically adopted in high seismic areas.

A link length is a beam section attached to the brace that allows the assembly to be connected to another brace or column. Through the decrease in link length, the frame becomes stiffer, and thus approaches the stiffness of a Concentrically Braced Frame. Alternatively, long links make the frame more flexible, thereby reducing stiffness to the level of a moment frame. The link acts as a weak point in the frame and enables more energy to be dissipated during a seismic event because of its plastic deformation capacity. So that, an eccentrically braced frame's lateral stiffness depends on the length ratio between the link and the beam. In Figure 2, the link (e) for the eccentrically braced frame is shown [18].

Aside from the fact that eccentric bracing has some factors that can affect its selection, such as the fact that eccentric bracing has connections between three elements while concentric bracing has connections between four elements. As a result, the connection details will be less complicated and there will be a decrease in costs. As well, links are considered to be part of the structure, increasing stiffness and supporting gravity loads.

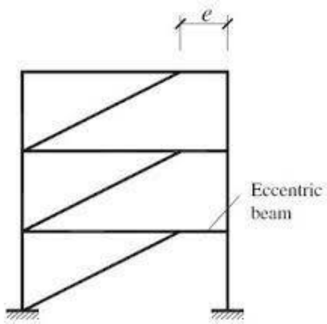



Figure 2: Define the link (e) on the structural system for an eccentric beam [19].

Eccentrically braced steel bracing in reinforced concrete buildings, arranged in different braced styles as shown in Figure 3.

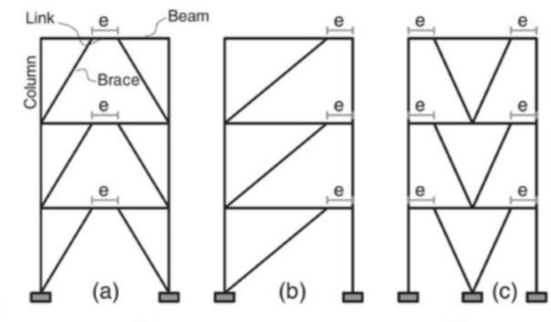



Figure 3: Eccentrically braced style used in the study. A) Eccentric Inverted V bracing, B) Eccentric Diagonal bracing, C) Eccentric V-bracing [20].

Alternatively, the bracing member and the column or beam are separated by space between their ends in eccentrically braced frames. The generated separation is known as a link (e). The main purpose of the connection is to give the frame a weak spot that may create plastic deform and hinges, as well as distribute the energy generated by an earthquake.

According to AISC code, links are calculated as:

Shear short links:

$$e < 1.6\ \frac{Mp}{Vp} \tag{1}$$

Where: $Mp =$ Nominal plastic moment capacity, (N. mm).

$Vp =$ Nominal plastic shear capacity, (N).

$e =$ Link length, (mm).

The plastic shear capacity is calculated as:

$$Vp = 0.6\ fy\ (d - 2tf)tw \tag{2}$$

Where: $Fy =$ Is the specified minimum yield strength.

$d =$ The overall beam depth.

$tw =$ The web thickness.

Plastic moment capacity is expressed as:

$$Mp = ZFy \tag{3}$$

Where: $Z =$ Is the plastic section modulus" [21].

## 2.4 BRB- Bulking Restrained Braces

BRBs can provide a uniform distribution of stiffness throughout a reinforced concrete (RC) building structure with the help of the optimal design procedure. By doing so, it minimizes the story drift response on a structure with BRBs of specified stiffness. BRBFs (buckling-restrained braced frames) are structural steel frames that offer lateral resistance to buckling during earthquakes. The system consists of a steel core enclosed by hollow steel sections coated with low-friction materials, which are grouted with a special mortar [22].

A high lateral stiffness system for wind and low-level seismic stresses is provided by conventionally braced frames using conventional bracing elements. However, it is expected that these bracing may lose tension and buckle during a moderate to severe earthquake. Buckling-restrained braces are a trustworthy and useful substitute to traditional methods for improving the earthquake resistance of existing and new structures, in contrast to the behavior of usual bracing components [23].

Figure 4, illustrates the concept of BRB, which is the simple process of restraining the brace's buckling so that the brace behaves the same both in tension as in compression, thereby increasing the energy absorption and simplifying the hysteretic property of the brace.

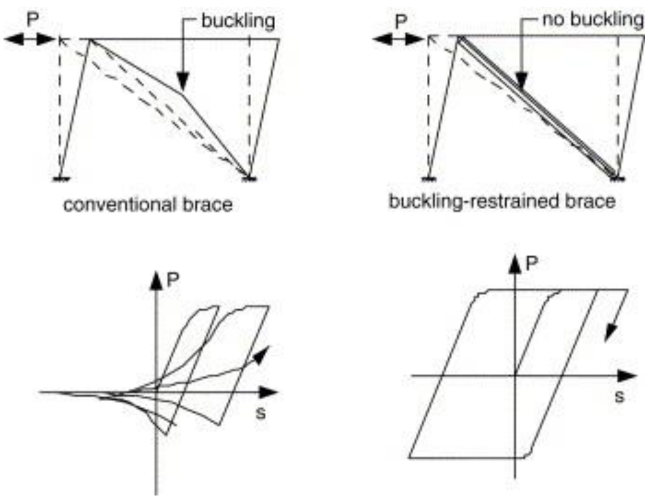



Figure 4: Behavior of structural elements with and without BRB- Bulking restrained braces [24].

# Chapter 3

# ANALYZING METHODS

## 3.1 Introduction

The development of convenient software and the availability of fast and simple electronic equipment has made seismic analysis grown significantly in practice and research. For new insights in research, it is essential to use the most advanced analytical, numerical, and experimental methods.

Civil engineers deal with a vast majority of static, linear, and deterministic problems (or at least those that can be roughly approximated). It is therefore important that the designer has a working knowledge and understanding of seismic data. Furthermore, seismic codes offer methods that can be applied to analyze earthquakes in a practical manner.

To analyze a structure's response to seismic ground waves, several methods can be used as static pushover analysis. This chapter will consider information about capacity curve, plastic hinges, target displacement, base shear, and performance level according to Turkish Code 2018.

## 3.2 Static Pushover Analysis

### 3.2.1 An Overview

Buildings are subjected to pushover analysis to determine how far they can go before collapsing totally or partially. To simulate this phenomenon, loads are applied until a weak link is found, and then the model is revised to reflect the changes caused by the weak link. There are a number of recent guidelines and regulations for retrofit seismic design that use pushover analysis for assessing the seismic capacity of existing structures. A performance-based design approach can also be applied to new buildings that are intended to withstand earthquake forces through ductility or redundancy [25].

A computer design for a model of a building showing load-resisting elements, their force-deformation relationships before and after yielding, and dead loads as well as average live loads is used to check a structure's performance. To simulate ground movements, horizontal forces are applied, and deformations are calculated. A plot of deformation versus base motion is then developed by increasing the forces in steps. By using this approach, existing buildings can be analyzed to identify the most effective schemes for strengthening them and making them more ductile. In addition to evaluating the expected performance of new building designs, pushover analysis is also frequently used [26].

### 3.2.2 Analyze the Capacity Curve

For a given earthquake buildings and component peak responses must be considered. Hence, the Capacity Curve or Pushover Curve represents nonlinear behavior of the structure and is a function of the horizontal displacement of the building's roof versus the force exerted by it. Using pushover analysis, a dynamic problem is turned into a static one [27].

In a Pushover analysis, the interaction between the base shear and displacements is used to calculate the capacity curves and capacities of structures [28]. For a design seismic load, a demand spectrum is also generated based on the design response spectrum. A structure's maximum inelastic capacity is determined by the intersection of its capacity spectrum and demand spectrum at a given damping ratio.

In contrast, demand curves are formed by the response spectrum determined by earthquake zone, soil type, and damping level. These two curves intersect at the structure's performance point. The pushover curve can be used to determine the location of hinges at various stages under varying levels of lateral load [29].

### 3.2.3 Plastic Hinges

By predicting hinges at potential weak points and following the sequence of damage at those hinge points, pushover analysis helps predict collapses. The hinge represents the localized force-displacement relationship of a structural member under lateral loads through its elastic and inelastic phases [30]. In essence, it is a fully compliant cross-section of a component that allows the components on either side to rotate under a constant force (the plastic moment).

Several factors determine the load-carrying capacity of a plastic joint, including its curvature and length. It is possible to obtain different deformation capacities when using different criteria for fracture curvature and the length of the plastic joint. Therefore, ultimate rotations are calculated based on the length of the plastic joint.

### 3.2.4 Target Displacement

Estimating the damage pattern and deformation patterns of a structure by establishing a target displacement for the building, as the first step in the process. An estimation of the top displacement of the building is based on the earthquake excitation in the design. Based on the known displacement target, components and elements of the structure are evaluated using the accumulated forces and deformations.

The target displacement can be calculated automatically during adaptive pushover analysis. When the Calculate Target Displacement checkbox is selected, an Eigenvalue analysis will be run before to the pushover analysis. A Target Displacement can be calculated by defining the following parameters:

1) Choose TBDY (Turkish Seismic Evaluation Building Code).
2) Assign the control node and direction.
3) In the case of TBDY, the Target Displacement is calculated for the Limit States (or Performance Levels).
4) Based on the code used in the specific project, the elastic response spectrum can be derived (Code-Based Spectra option). Code-Based Spectra require the assignment of some basic parameters for their generation (e.g. damping, spectrum type, ground type, and important class).

By intersecting the target displacement with the elastic response spectrum (in the acceleration-displacement format) corresponding to the seismic action, the target displacement can be calculated. This point corresponds to the inelastic acceleration and the target displacement and is called the performance point.

### 3.2.5 Base Shear of the Lateral Forces

As a result of seismic activity, base shear estimates the maximum lateral force that will exert on a structure's base. Basically, it means the structure is subjected to monotonously increasing lateral loads until it reaches its peak response as shown in Figure 5.

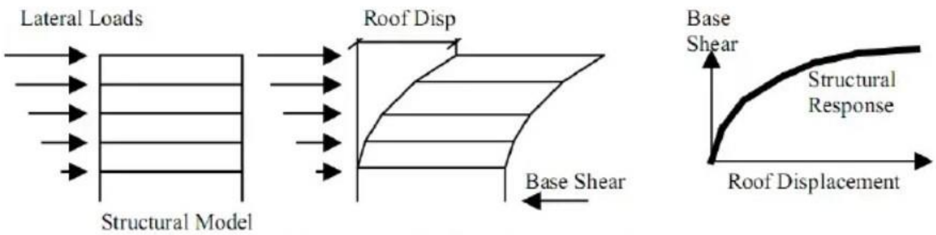


Figure 5: Roof displacement under lateral force on the structure base [31].

It is also important to consider the soil conditions at the site, the geological conditions surrounding the site, the likelihood of significant ground movements during earthquakes, the ductility and strength of various structural configurations, and the fundamental period of vibration when dynamic loading is applied to a structure [32].

### 3.2.6 Performance Level of Turkish Code 2018

A Seismic Code has been in place in Turkey since the 1940s and is regularly updated in response to new earthquake engineering developments and changes in societal needs. As compared with the previous seismic code version, the 2018 version gives better definitions of site-specific ground motions, pile foundations, and tall buildings.

In the 2018 Seismic Code, there are four levels of earthquake ground motion with varying performance targets. "In return times, these are described as DD-1 (maximum expected earthquake ground motion level) with a 2% probability of exceeding in 50 years, DD-2 (standard design earthquake ground motion level) with a 10% probability of exceeding in 50 years, DD-3(frequently expected earthquake ground motion level) with a 50% probability of exceeding in 50 year, DD-4 (service level earthquake ground motion) with a 50% probability of exceeding in 30 years" [33].

In the 2018 Code, several building categories are used to guide seismic design, such as building height categories, building use categories, and seismic design categories, as shown in Figure 6.

**Building Use Categories (BKS)**

| | | |
|---|---|---|
| I=1.5 | : | BKS=1 |
| I=1.2 | : | BKS=2 |
| I=1.0 | : | BKS=3 |

**Seismic Design Categories (DTS)**

| $S_{DS}$ (g) | BKS=1 | BKS=2, 3 |
|---|---|---|
| < 0.33 | 4a | 4 |
| 0.33-0.50 | 3a | 3 |
| 0.50-0.75 | 2a | 2 |
| > 0.75 | 1a | 1 |

**Building Height Categories (BYS)**

| Bina Yükseklik Sınıfı | Bina Yükseklik Sınıfları ve Deprem Tasarım Sınıflarına Göre Tanımlanan Bina Yükseklik Aralıkları [m] | | |
|---|---|---|---|
| | DTS = 1, 1a, 2, 2a | DTS = 3, 3a | DTS = 4, 4a |
| BYS = 1 | $H_N > 70$ | $H_N > 91$ | $H_N > 105$ |
| BYS = 2 | $56 < H_N \leq 70$ | $70 < H_N \leq 91$ | $91 < H_N \leq 105$ |
| BYS = 3 | $42 < H_N \leq 56$ | $56 < H_N \leq 70$ | $56 < H_N \leq 91$ |
| BYS = 4 | $28 < H_N \leq 42$ | $42 < H_N \leq 56$ | |
| BYS = 5 | $17.5 < H_N \leq 28$ | $28 < H_N \leq 42$ | |
| BYS = 6 | $10.5 < H_N \leq 17.5$ | $17.5 < H_N \leq 28$ | |
| BYS = 7 | $7 < H_N \leq 10.5$ | $10.5 < H_N \leq 17.5$ | |
| BYS = 8 | $H_N \leq 7$ | $H_N \leq 10.5$ | |

Figure 6: Categorization of building uses, building heights, and seismic design.

Based on Turkish 2018, the performance level was defined as shown in Figure 7.

| Classification | Definition |
|---|---|
| ***Continued Operation Performance (CO)*** | Damage in structural members is negligible (hairline cracks in concrete) |
| ***Limited Damage Performance (LD)*** | Limited damage in structural components leading to very limited inelastic behavior. |
| ***Controlled Damage Performance (CD)*** | Damage in structural components is significant, but possible to repair. |
| ***Collapse Prevention Performance (CP)*** | Damage in structural components is severe, however partial or total collapse of the building is prevented. |

Figure 7: Building performance level definition of Turkish 2018 [34].

# Chapter 4

# METHODOLOGY

## 4.1 Introduction

This chapter describes information about the buildings such as structural material properties, applied loads on the elements, section of the element as beams, columns, and braces. Turkish seismic code was used to design the buildings for both BRB frames and Conventional Steel Brace. It also defines the different patterns and types of various concentric and eccentric braces. Seismostruct and Seismobuild are the software used to design the structure in this thesis.

This chapter describes the design of BRBs and conventional steel bracing for eccentric and concentric bracing (including V-bracing, Inverted V-bracing, and Diagonal Bracing). There are three different bracing pattern layouts (defined as case 1, case 2, and case 3) for different building stories (4, 6, 8, and 15).

## 4.2 Seismostruct

Geometric nonlinearities can be considered in SeismoStruct's large displacement performance under static or dynamic loadings. The loading phases of the pushover analysis are fully defined in the Loading Phases module. By default, Response Control is defined as a phase type with a corresponding displacement target. On the last floor, one node faces the X direction of loading, with 100 steps of the analysis assigned. A controlled node is defined as the one with the highest applied load.

In SeismoStruct, large displacements and rotations are accounted for, as well as independent large deformations. The beam-column element has six-degree-of-freedom of displacements and six internal forces which correspond to their local chord systems, as shown in, Figure 8.

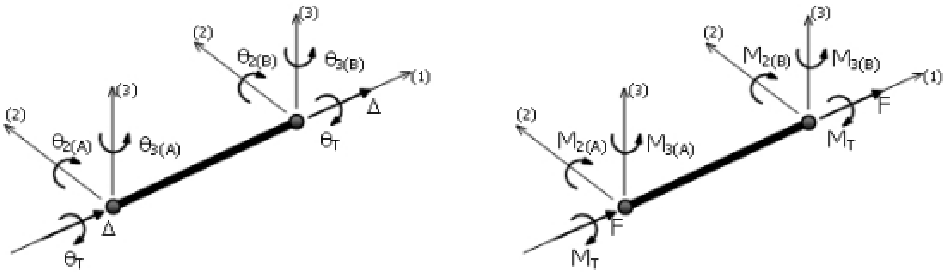



Figure 8: Beam-column local chord system.

Increasingly, earthquake engineering applications use distributed inelasticity elements. The cross-sectional behavior of beam-column elements is represented in SeismoStruct using the fiber approach. Individual fibers must be integrated with this process to ensure nonlinear stress-strain behavior, as shown in Figure 9.

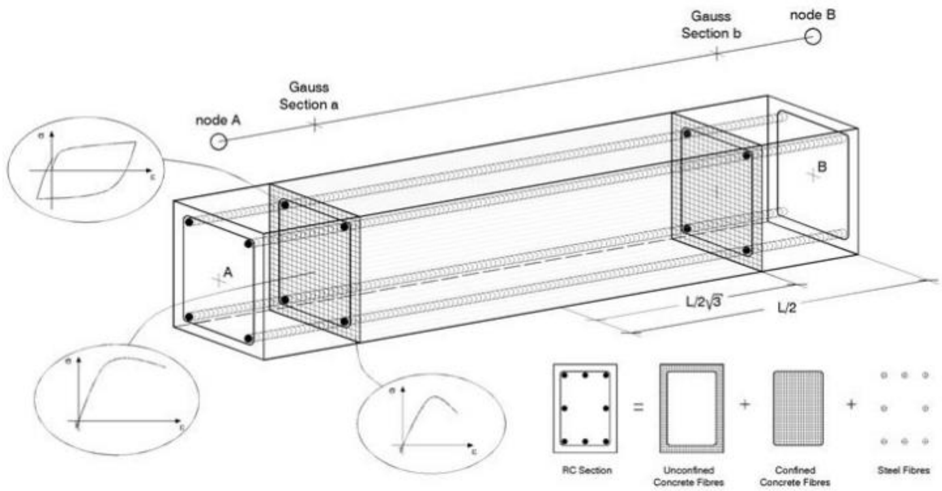



Figure 9: Discretization of a typical reinforced concrete cross-section [35].

## 4.3 Performance Level Due to Turkish Code

In this thesis, the soil class for all the structures is considered soil class C (ZC), and the damping ratio is 5%.

The performance level and a seismic action are combined in the Turkish seismic Code. The target displacements performance level according to 2018 Turkish Seismic Code well be: Continued Operation Performance (CO), Limited Damage Performance (LD), Controlled Damage Performance (CD), and Collapse Prevention Performance (CP).

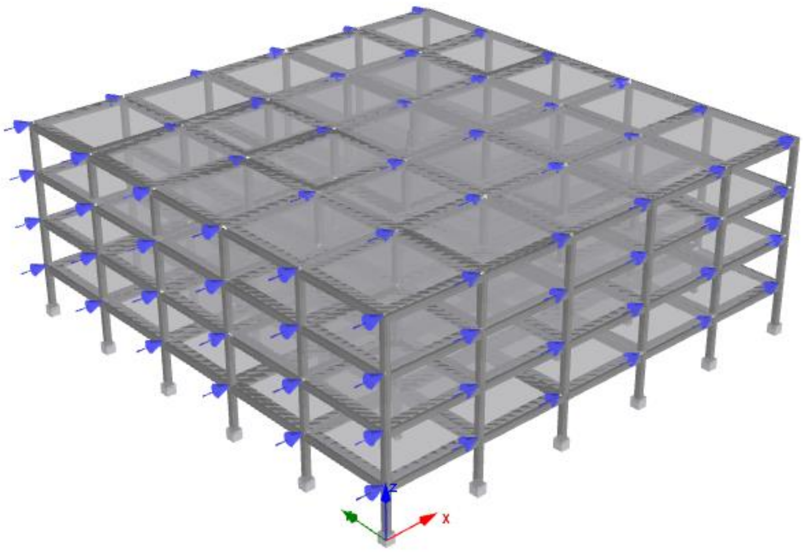
Existing buildings shall be assessed and designed based on performance by the 2018 Seismic Code, which has a controlled damage (CD) target for the next 475 years under the DD-2 earthquake. A return period of 475 years exists for the DD-2 with a 10% probability of exceeding 50 years. Buildings with existing displacements are fitted with a new linear elastic model based on displacements.

## 4.4 Modelling of the Frames

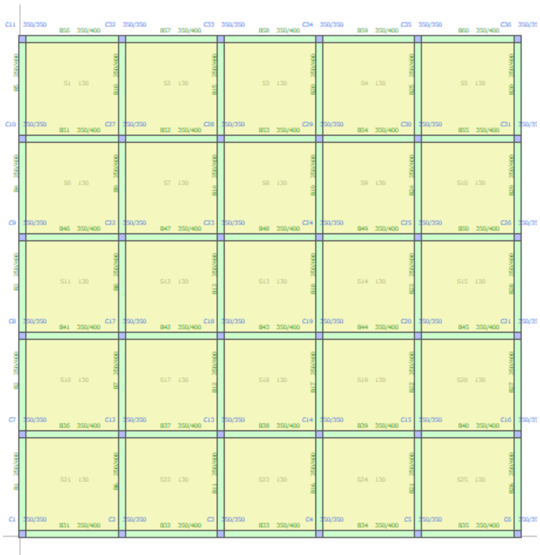
This section will consider the frame section as the column, beam, and brace data. The buildings are three-dimensional reinforced concrete structures designed by Seismostruct. Different height buildings are designed as 4, 6, 8, and 15 stories as shown below. All the elements for all the building's height design as inelastic force-based plastic hinge frame element type (infrmFBPH) for concentric braces building. For eccentric braces building all the elements are designed as inelastic force-based plastic hinge frame element type (infrmFBPH) except the short beams, the element type is inelastic displacement-based frame element type (infrmDB). Section fiber for the element designed in infrmDB is 150.

### 4.4.1 Four Story Building

Figure 10 shows the three dimensions for low rise building (four story building) as well as the top view of the plan 5x5 bays. As well as section properties as element section and element class will be shown from Figure 11-17.




a) 3D view of four-story plain building



b) Plan of the four-story building

Figure 10 (a and b): Provide a Four-story geometric view.

- **Structure Element Section**

**1. Column**

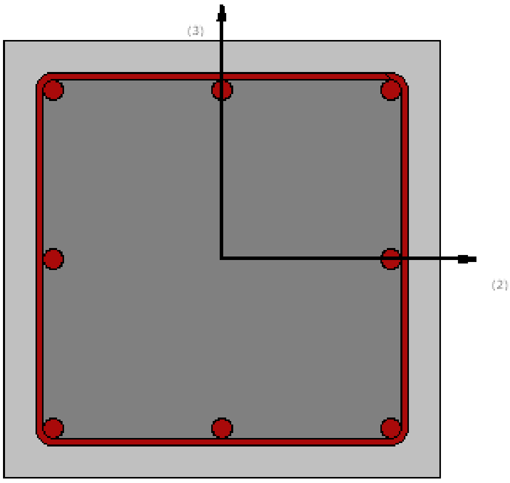
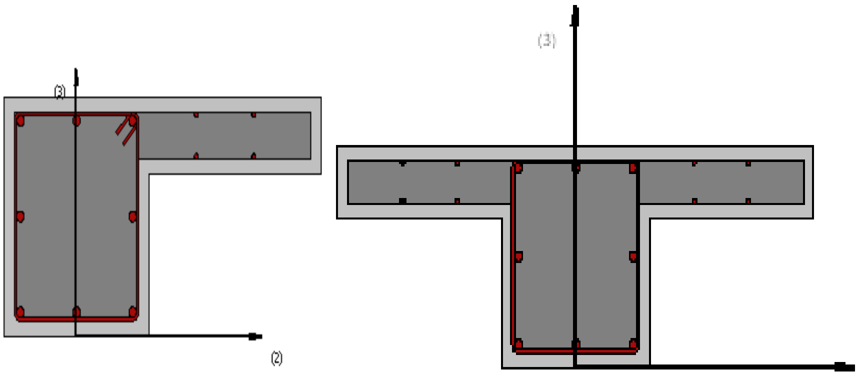



Figure 11: Rectangular Column section 0.35x0.35 (8 No.16) for 4 story building.

**2. Beam**




a) Outer beam b) Inner beam

Figure 12: T- beam section 0.4x0.35 (8 No.18) for 4 story building: a) Outer beam and b) Inner beam.

3. **Brace**

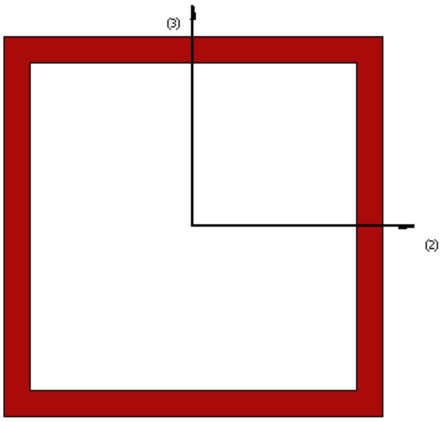



Figure 13: Square hollow section SHS 0.15X0.15.

- **Element Class**

1. **Column**

The number of the section fibers is 62 and the Plastic-hinges length (%) is 16.67% as shown in Figure 14.

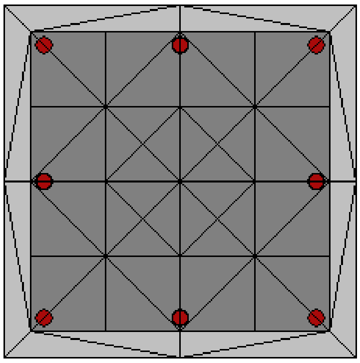


Figure 14: Column fiber section of Rectangular Column section 0.35x0.35 (8 No.16) for 4 story.

## 2. Beam

The number of the section fibers in the outer beam is 78 and the Plastic-hinges length (%) is 16.67% as shown in Figure 15. Figure 16 shows that the number of the section fibers in the inner beam is 91 and the Plastic-hinges length (%) is 16.67%.

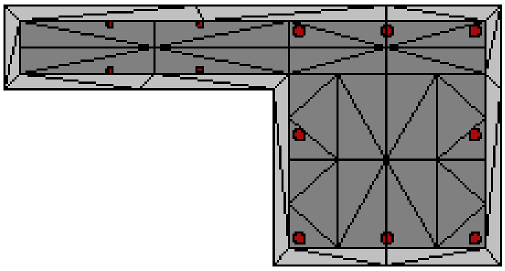


Figure 15: Outer beam fiber section of T- beam section 0.4x0.35 (8 No.18) for 4 story.

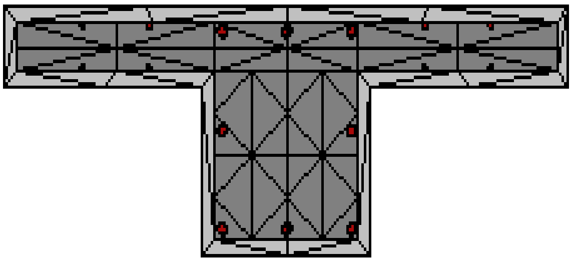
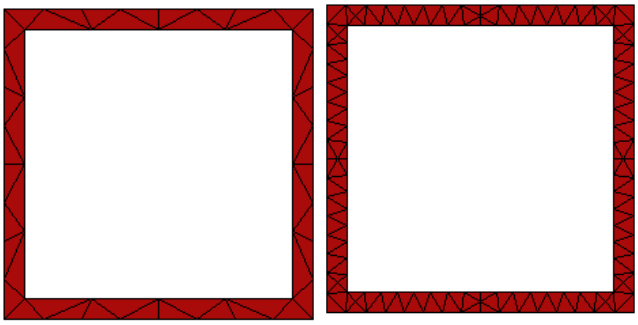


Figure 16; Inner beam fiber section of T- beam section 0.4x0.35 (8 No.18) for 4 story.

## 3. Brace

The number of the section fibers for BRB is 50 and for conventional steel brace is 150 as well as the Plastic-hinges length for both type is (%) is 16.67% as shown in Figure 17.

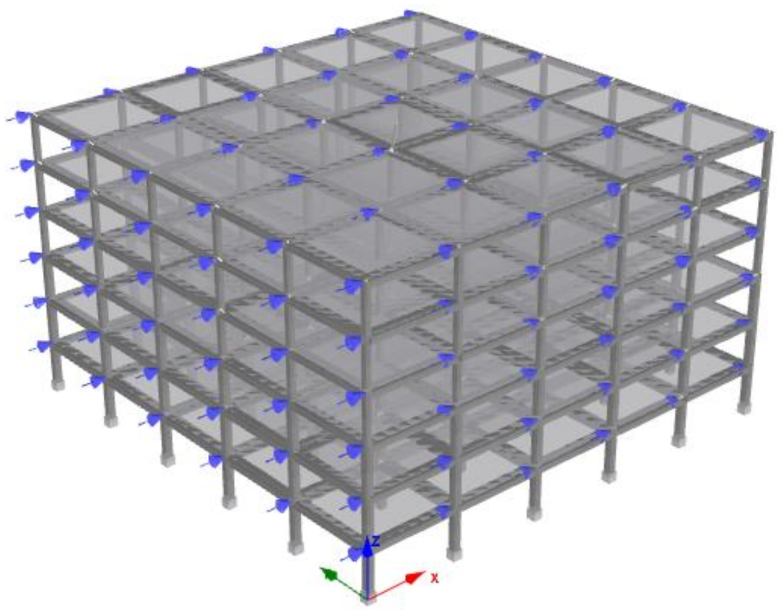


a) BRB b) Conventional Steel Brace

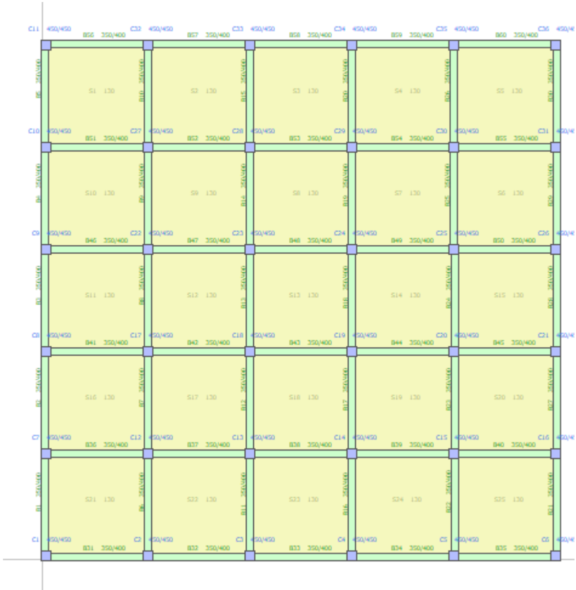
Figure 17: Brace fiber section of Square hollow section SHS 0.15X0.15: a) BRB, and b) Conventional Steel Brace for 4 story.

### 4.4.2 Six Story Building

Figure 18 shows the three dimensions for mid-rise building (six story building) as well as the top view of the plan 5x5 bays. As well as section properties as element section and element class will be shown from Figure 19-27.



a) 3D view of six story plain building



b) Plan of the six-story building

Figure 18 (a and b): Provide six-story geometric view.

- **Structure Element Section**

**1. Columns**

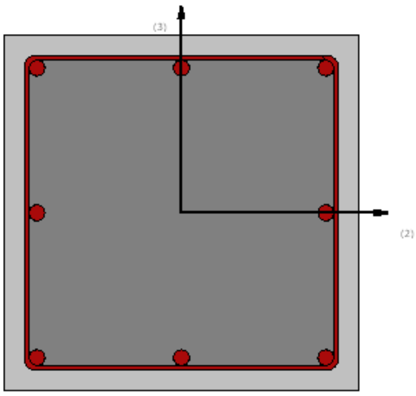



Figure 19: Rectangular column section 0.45x0.45 (8 No.20) for floor (1, 2, and 3).

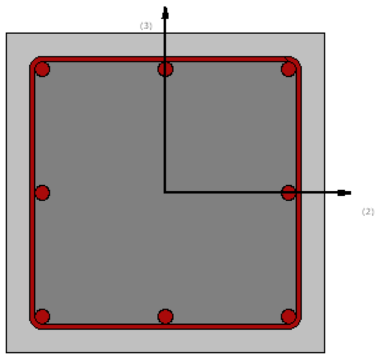
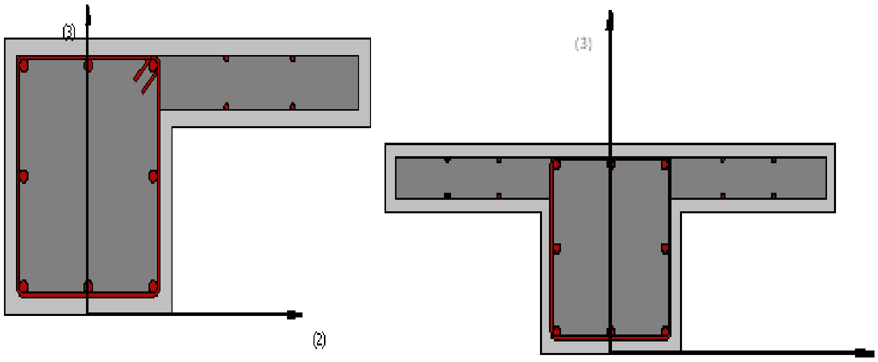


Figure 20; Rectangular Column section 0.35x0.35 (8 No.16) for floor (4, 5, and 6).

## 2. Beam



a) Outer beam b) Inner beam

Figure 21: T- beam section 0.4x0.35 (8 No.18) for 4 story building: a) Outer beam and b) Inner beam.

## 3. Brace

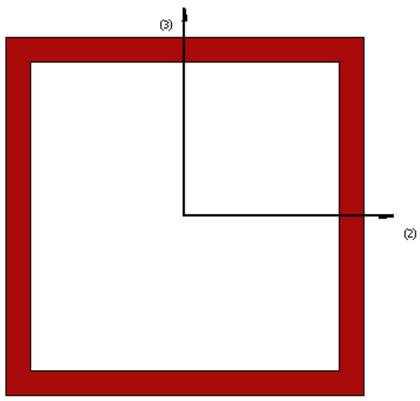


Figure 22: Square hollow section SHS 0.15X0.15.

- **Element Class**

**1. Column**

The number of the section fibers in C 0.45x0.45 is 75 and the Plastic-hinges length (%) is 16.67% as shown in Figure 23. Figure 24 shows that the number of the section fibers in C 0.35x0.35 is 62 and the Plastic-hinges length (%) is 16.67%.

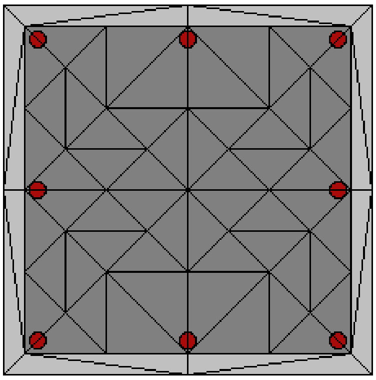


Figure 23: Column C 0.45x0.45 (8 No.20) fiber section for 6 story.

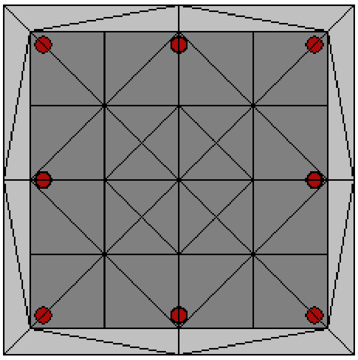


Figure 24: Column C 0.35x0.35 (8 No.16) fiber section for six story.

**2. Beam**

The number of the section fibers in the outer beam is 78 and the Plastic-hinges length (%) is 16.67% as shown in Figure 25. Figure 26 shows that the number of the section fibers in the inner beam is 91 and the Plastic-hinges length (%) is 16.67%.

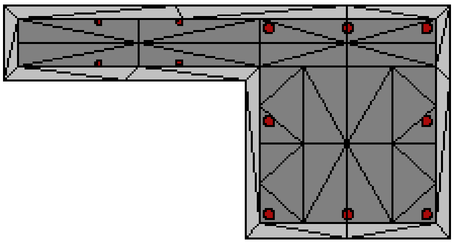


Figure 25: Outer beam fiber section of 0.4x0.35 (8 No.18) for 6 story.

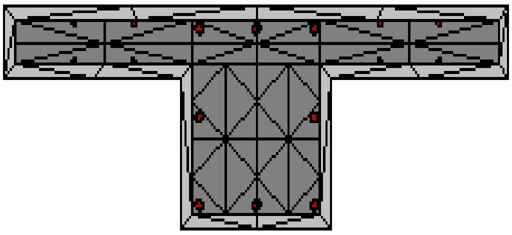
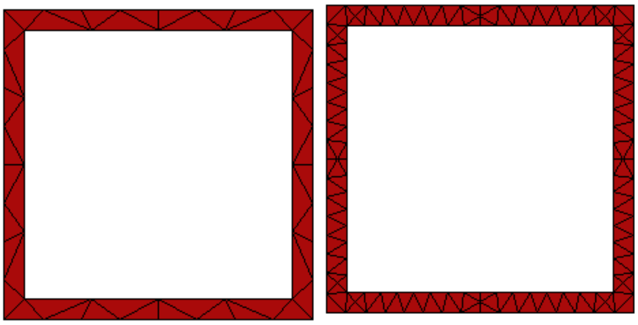


Figure 26: Inner beam fiber section of 0.4x0.35 (8 No.18) for 6 story.

### 3. Brace

The number of the section fibers for BRB is 50 and for Conventional Steel Brace is 150 as well as the Plastic-hinges length for both type is (%) is 16.67% as shown in Figure 27.

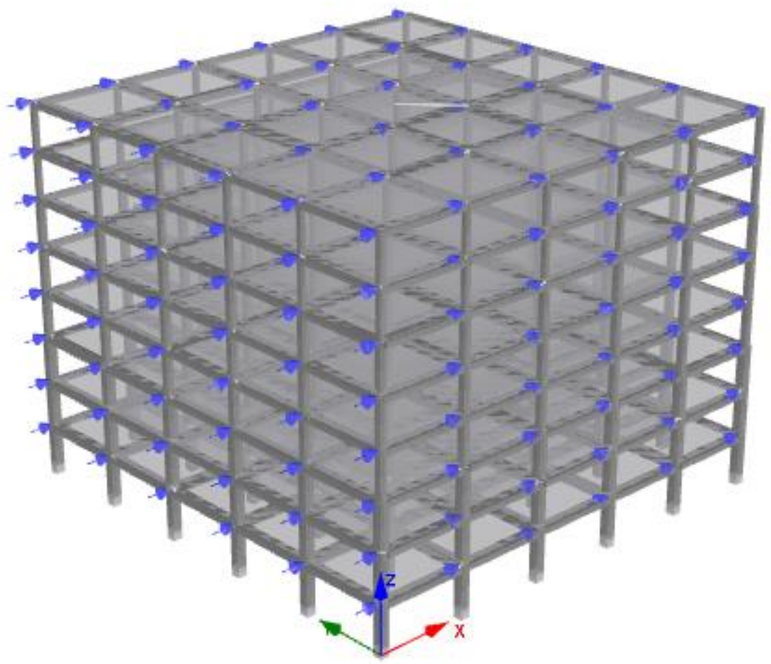


a) BRB b) Conventional Steel Brace

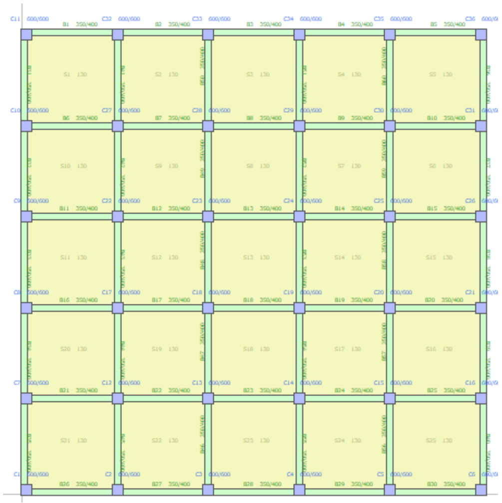
Figure 27: Brace fiber section of Square hollow section SHS 0.15X0.15: a) BRB, and b) Conventional Steel Brace for 6 story.

### 4.4.3 Eight Story Building

Figure 28 shows the three dimensions for mid-rise building (eight story building) as well as the top view of the plan 5x5 bays. As well as section properties as element section and element class will be shown from Figure 29-39.




a) 3D view of eight story plain building



b) Plan of the eight-story building.

Figure 28(a and b): Eight-story geometric view.

- **Structure Element Section**

**1. Column**

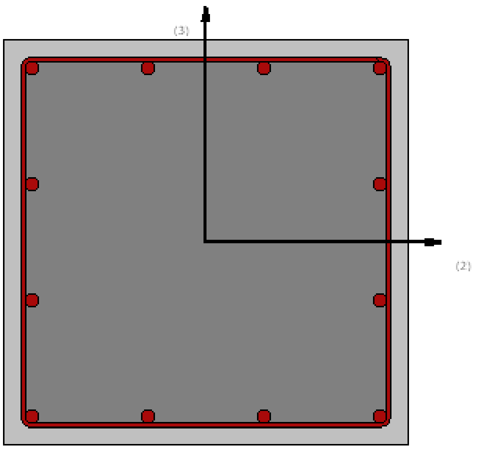



Figure 29: Rectangular column 0.60x0.60 (12 No.20) for floor (1, 2, and 3).

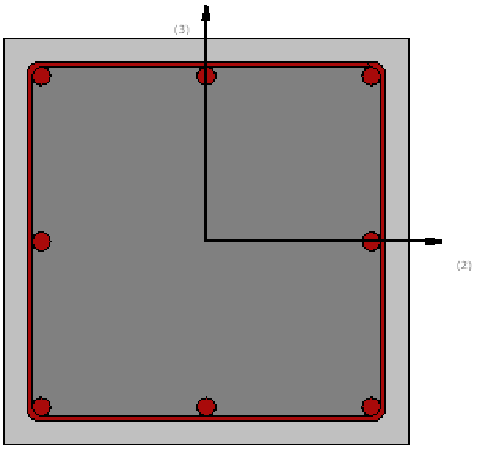



Figure 30: Rectangular column section 0.45x0.45 (8 No.20) for floor (4, 5, and 6).

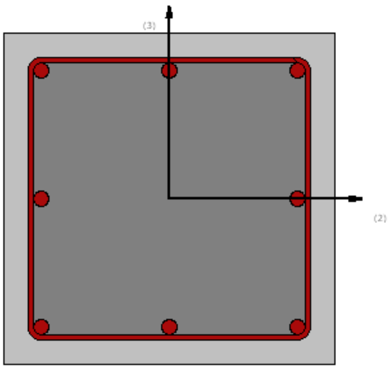
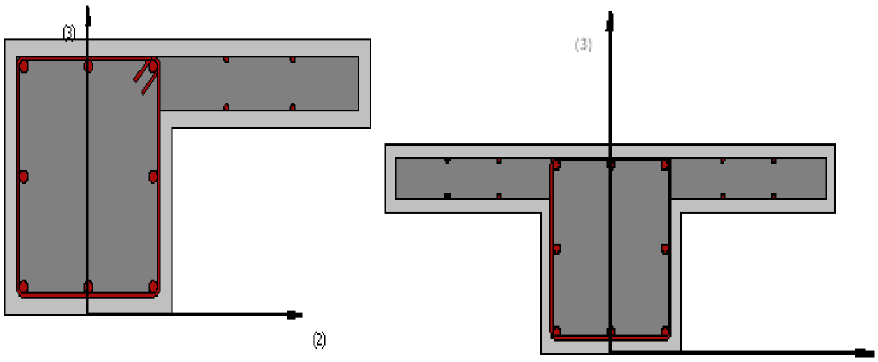


Figure 31: Rectangular Column section 0.35x0.35 (8 No.16) for floor (7 and 8).

## 2. Beam




a) Outer beam b) Inner beam

Figure 32: T- beam section 0.4x0.35 (8 No.18) for 4 story building: a) Outer beam and b) Inner beam.

## 3. Brace

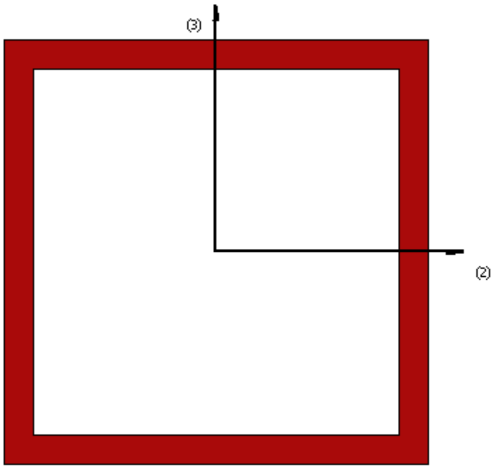



Figure 33: Square hollow section SHS 0.15X0.15.

- **Element Class**

**1. Column**

In Figure 34 the number of fiber section for C 0.60x0.60 is 105 and the Plastic-hinges length (%) is 16.67%. The number of the section fibers in C 0.45x0.45 is 75 and the Plastic-hinges length (%) is 16.67% as shown in Figure 35. Figure 37 shows that the number of the section fibers in C 0.35x0.35 is 62 and the Plastic-hinges length (%) is 16.67%.

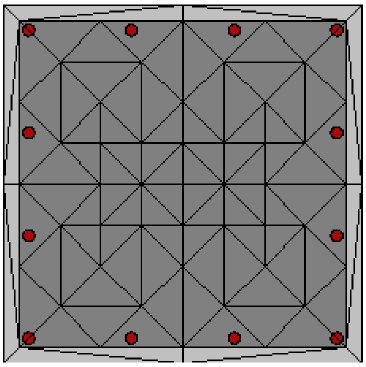


Figure 34: Rectangular column C 0.60x0.60 (12 No.20) fiber section for 8 story.

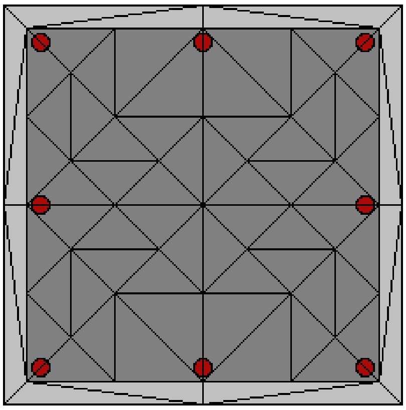


Figure 35: Rectangular column C 0.45x0.45 (8 No.20) fiber section for 8 story.

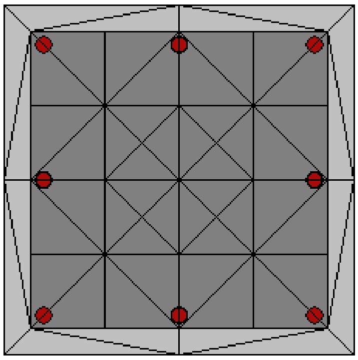


Figure 36: Rectangular column C 0.35x0.35 (8 No.16) fiber section for 8 story.

## 2. Beam

The number of the section fibers in the outer beam is 78 and the Plastic-hinges length (%) is 16.67% as shown in Figure 37. Figure 69 shows that the number of the section fibers in the inner beam is 91 and the Plastic-hinges length (%) is 16.67%.

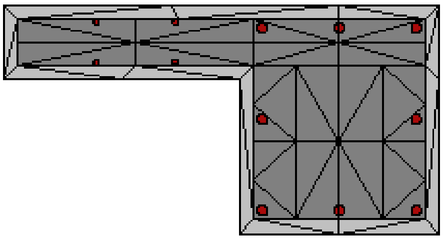


Figure 37: Outer beam fiber section of T- beam section 0.4x0.35 (8 No.18) for 8 story.

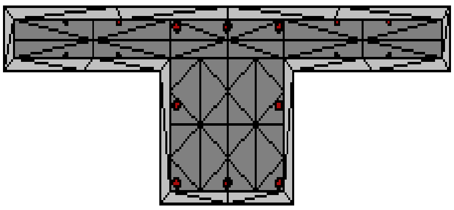
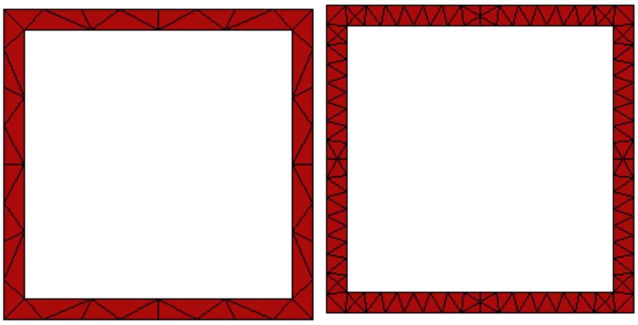


Figure 38: Inner beam fiber section of T- beam section 0.4x0.35 (8 No.18) for 8 story.

### 3. Brace

The number of the section fibers for BRB is 50 and for Conventional Steel Brace is 150 as well as the Plastic-hinges length for both type is (%) is 16.67% as shown in figure 39.

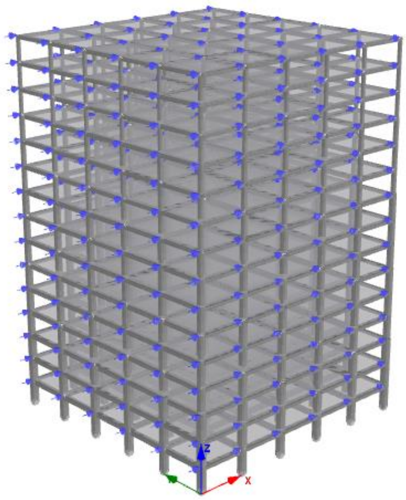


a) BRB b) Conventional Steel Brace

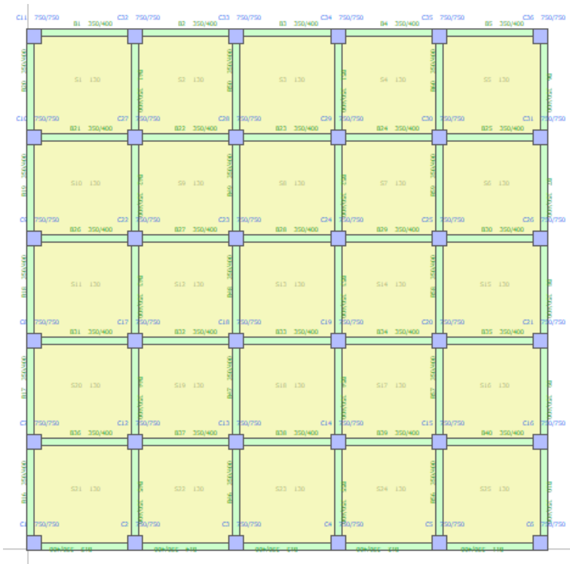
Figure 39; Brace fiber section of Square hollow section SHS 0.15X0.15: a) BRB, and b) Conventional Steel Brace for 8 story.

### 4.4.4 Fifteen Story Building

Figure 40 shows the three dimensions for mid-rise building (fifteen story building) as well as the top view of the plan 5x5 bays. As well as section properties as element section and element class will be shown from Figure 41-51.



a) 3D view of fifteen story plain building



b) Plan of the fifteen-story building

Figure 40 (a and b): Fifteen-story geometric view.

- **Structure Element Section**

**1. Column**

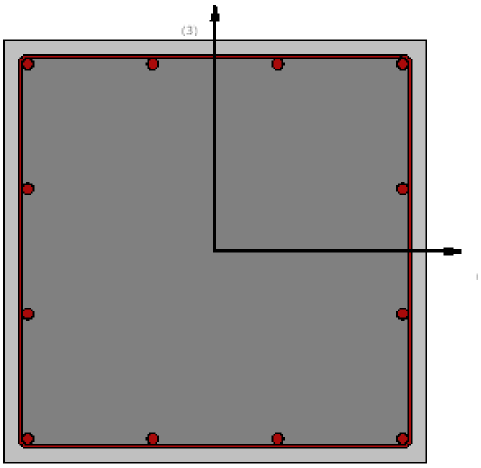


Figure 41: Rectangular column 0.75x0.75 (12 No.20) for floor (1, 2, and 3).

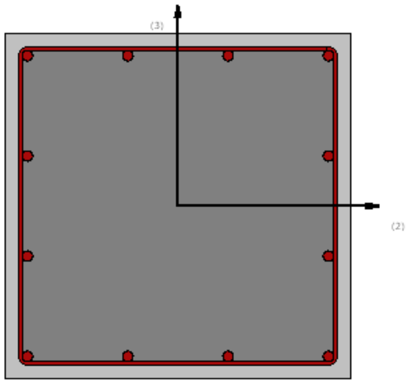



Figure 42: Rectangular column 0.70x0.70 (12 No.20) for floor (4, 5, and 6).

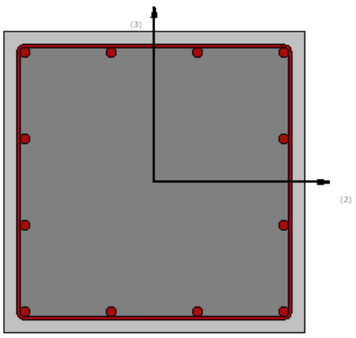



Figure 43: Rectangular column 0.60x0.60 (12 No.20) for floor (7, 8, and 9).

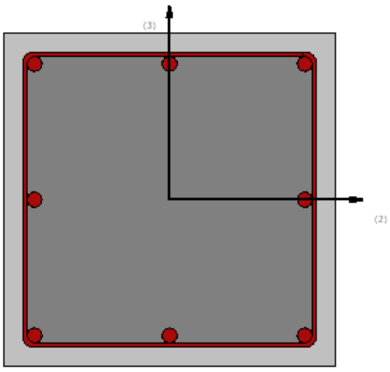



Figure 44: Rectangular column section 0.45x0.45 (8 No.20)
for floor (10, 11, and12).

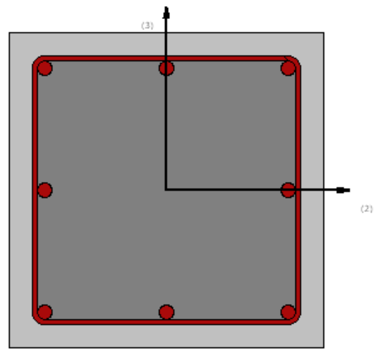
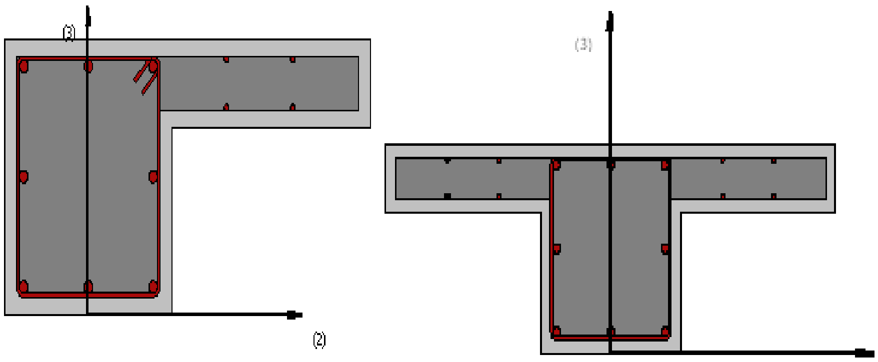


Figure 45: Rectangular Column section 0.35x0.35 (8 No.16) for floor (13, 14, and 15).

## 2. Beam




a) Outer beam b) Inner beam

Figure 46: T- beam section 0.4x0.35 (8 No.18) for 4 story building: a) Outer beam and b) Inner beam.

## 3. Brace

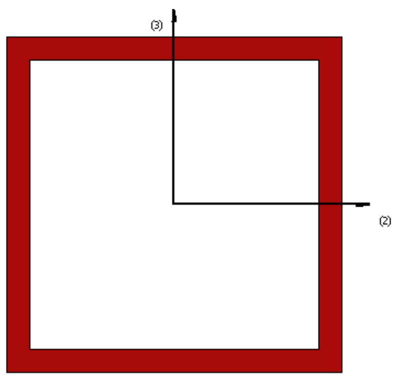



Figure 47: Square hollow section SHS 0.15X0.15.

- **Element Class**

**1. Column**

In Figure (48, 49, and 50) the number of fiber section for C 0.75X0.75, C 0.70X0.70, and C 0.60x0.60 is 139, 116, and 105, respectively and the Plastic-hinges length for all of them (%) is 16.67%. The number of the section fibers in C 0.45x0.45 is 75 and the Plastic-hinges length (%) is 16.67% as shown in Figure 51. Figure 52 shows that the number of the section fibers in C 0.35x0.35 is 62 and the Plastic-hinges length (%) is 16.67%.

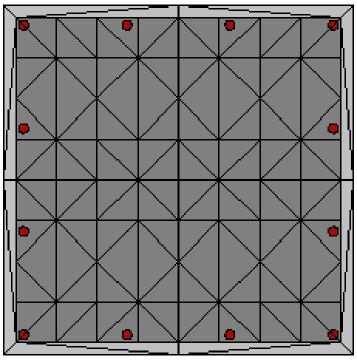


Figure 48: Rectangular column C 0.75x0.75 (12 No.20) fiber section for 15 story.

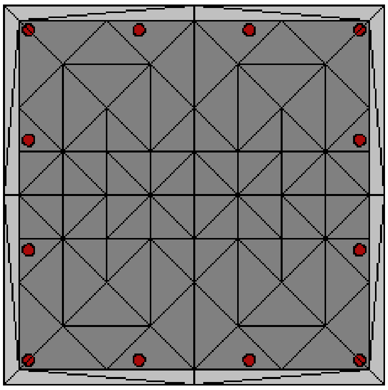


Figure 49: Rectangular column C 0.70x0.70 (12 No.20) fiber section for 15 story.

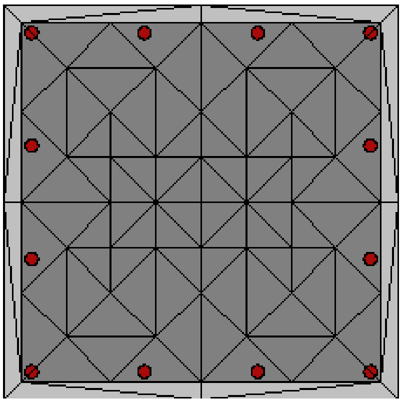


Figure 50: Rectangular column C 0.60x0.60 (12 No.20) fiber section for 15 story.

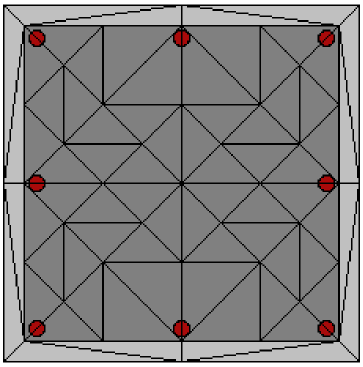


Figure 51: Rectangular column C 0.45x0.45 (8 No.20) fiber section for 15 story.

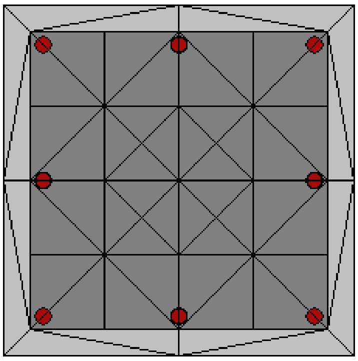


Figure 52: Rectangular column C 0.35x0.35 (8 No.16) fiber section for 15 story.

## 2. Beam

The number of the section fibers in the outer beam is 78 and the Plastic-hinges length (%) is 16.67% as shown in Figure 53. Figure 54 shows that the number of the section fibers in the inner beam is 91 and the Plastic-hinges length (%) is 16.67%.

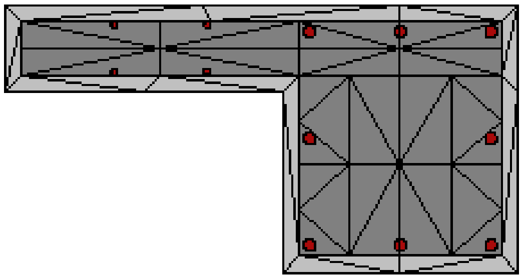


Figure 53: Outer beam fiber section of T- beam section 0.4x0.35 (8 No.18) for 15 story.

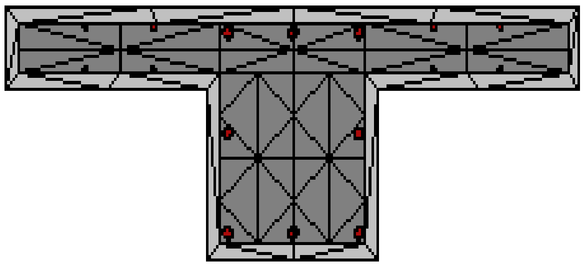
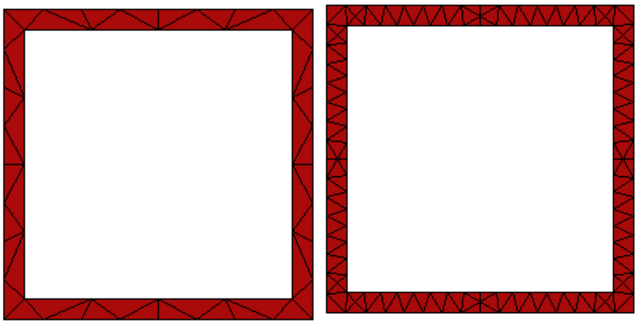


Figure 54: Inner beam fiber section of T- beam section 0.4x0.35 (8 No.18) for 15 story.

## 3. Brace

The number of the section fibers for BRB is 50 and for Conventional Steel Brace is 150 as well as the Plastic-hinges length for both type is (%) is 16.67% as shown in Figure 55.



a) BRB b) Conventional Steel Brace

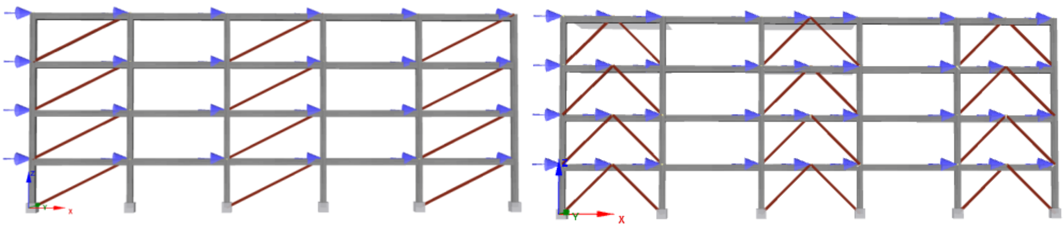
Figure 55: Brace fiber section of Square hollow section SHS 0.15X0.15: a) BRB, and b) Conventional Steel Brace for 15 story.

## 4.5 Strengthen Braces Layout

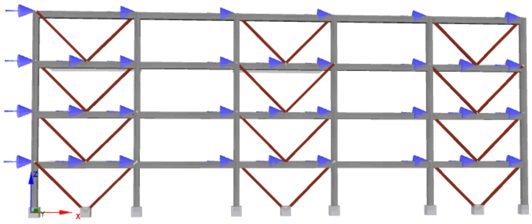
The height of the story is 3m and the plan for all the building same the number of bays in the X and Y direction are 5 bays and the width of the bays in the X and Y directions are 6m. The condition of all the supports is fixed. And the link length (e) for all the eccentric braces is 0.6m. So, this section contains three different steel bracing pattern cases for three types of concentric and eccentric braces which are IV, V, and Diagonal braces for different story height buildings 4, 6, 8, and 15 stories as shown in the Figures 56 -79.

### 4.5.1 Four Story Building

- Case 1

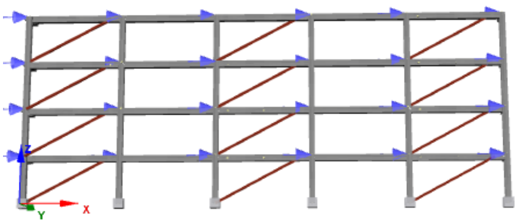


a) Diagonal brace b) IV- brace

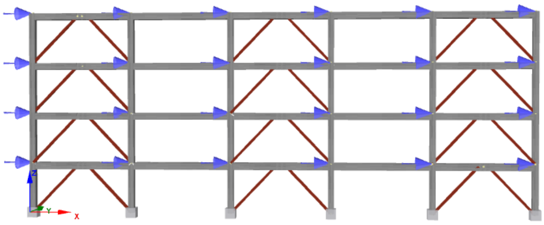


c) V-brace

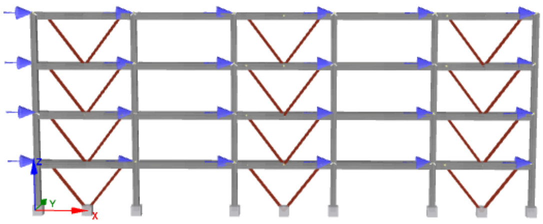
Figure 56: First pattern of concentric braces for four story building: a) Diagonal brace, b) IV-brace, and c) V-brace.



a) Diagonal brace



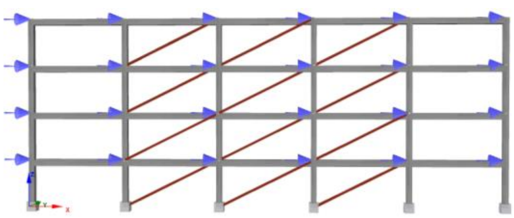
b) IV- brace



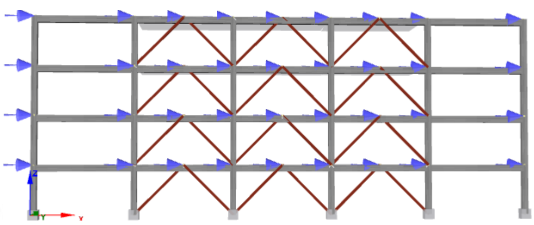
c) V-brace

Figure 57: First pattern of eccentric braces for four story building: a) Diagonal brace, b) IV-brace, and c) V-brace.

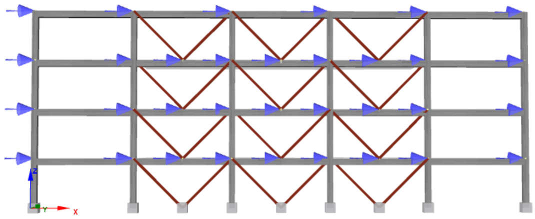
- Case 2



a) Diagonal brace

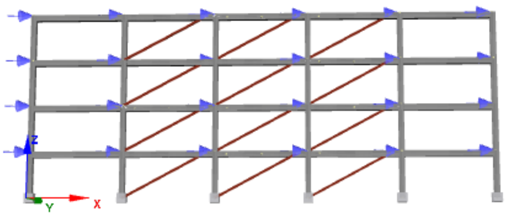


b) IV- brace

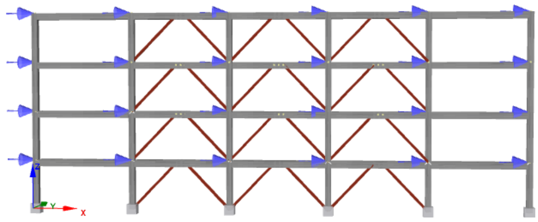


c) V-brace

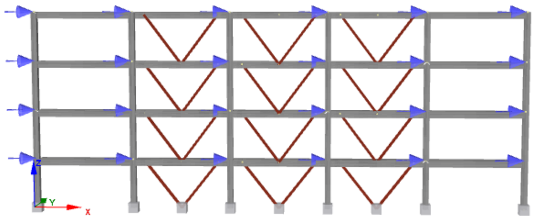
Figure 58: Second pattern of concentric braces for four story building: a) Diagonal brace, b) IV-brace, and c) V-brace.



a) Diagonal brace



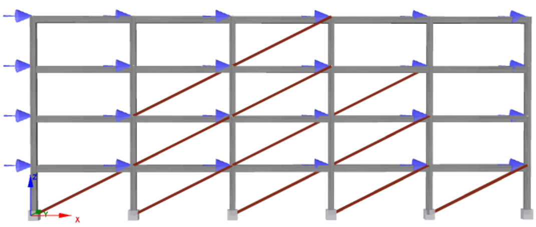
b) IV- brace



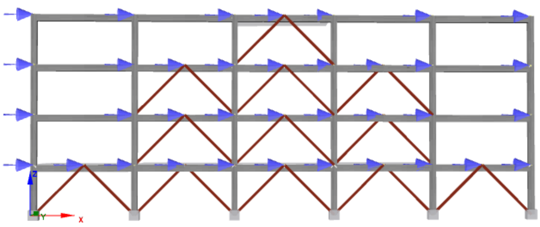
c) V-brace

Figure 59: Second pattern of eccentric braces for four story building: a) Diagonal brace, b) IV-brace, and c) V-brace.

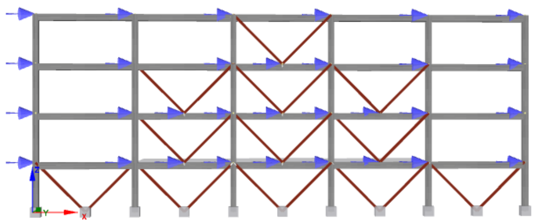
- Case 3



a) Diagonal brace

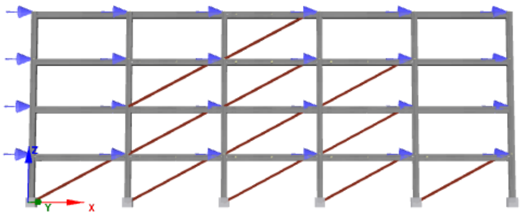


b) IV- brace

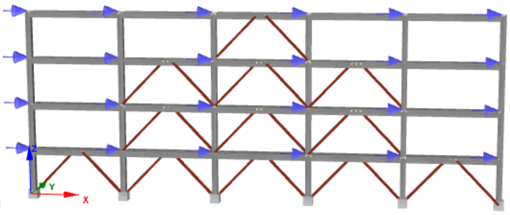


c) V-brace

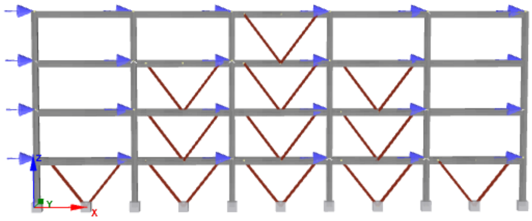
Figure 60: Third pattern of concentric braces for four story building: a) Diagonal brace, b) IV-brace, and c) V-brace.



a) Diagonal brace



b) IV- brace

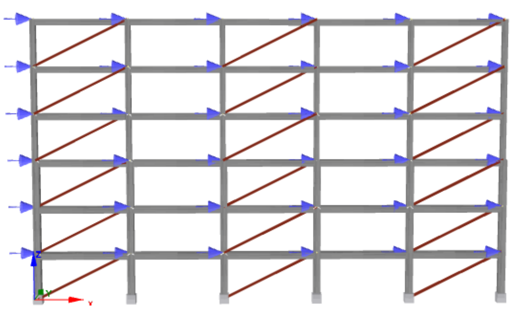


c) V-brace

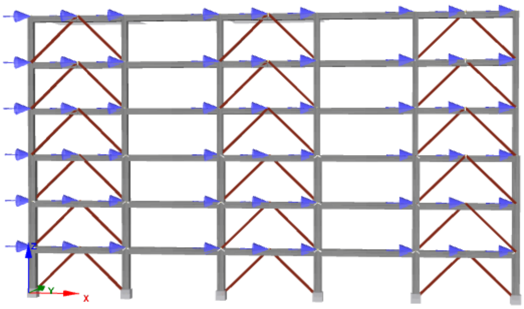
Figure 61: Third pattern of eccentric braces for four story building: a) Diagonal brace, b) IV-brace, and c) V-brace.

### 4.5.2 Six Story Building

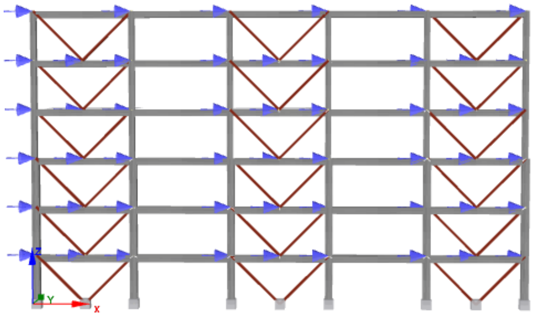
- Case 1



a) Diagonal brace

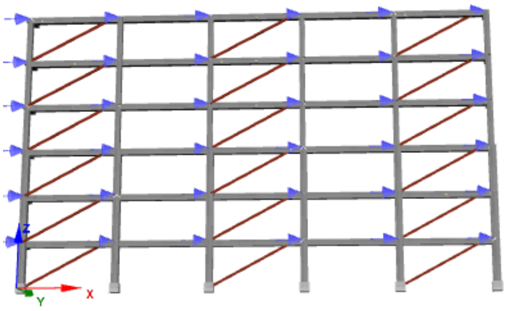


b) IV- brace

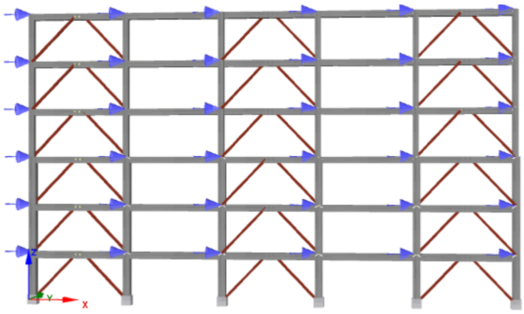


c) V-brace

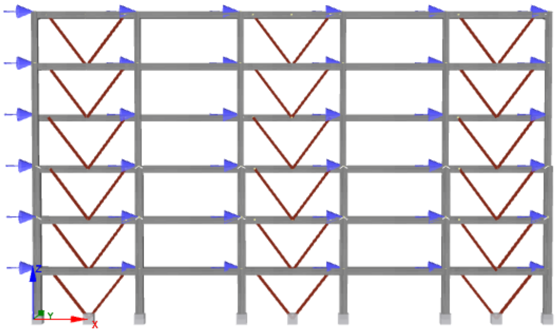
Figure 62: First pattern of concentric braces for six story building: a) Diagonal brace, b) IV-brace, and c) V-brace.



a) Diagonal brace



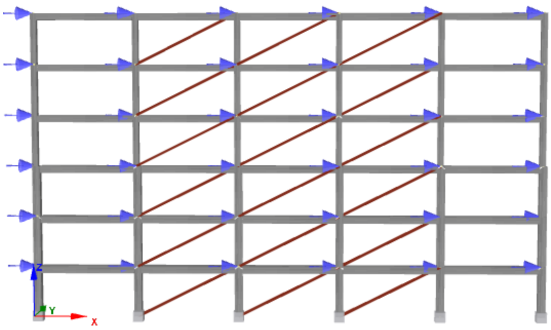
b) IV- brace



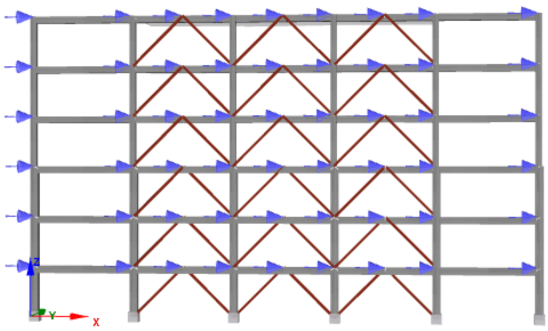
c) V-brace

Figure 63: First pattern of eccentric braces for six story building: a) Diagonal brace, b) IV-brace, and c) V-brace.

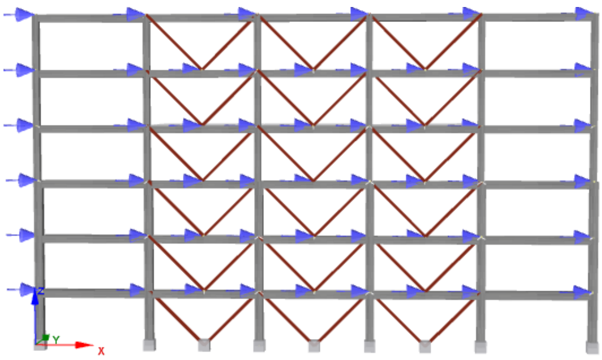
- Case 2



a) Diagonal brace

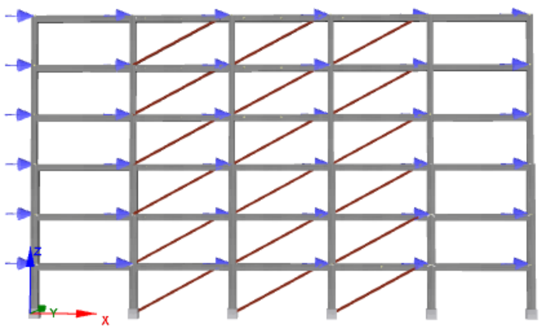


b) IV- brace

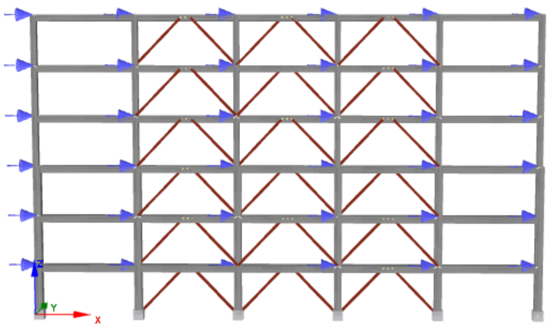


c) V-brace

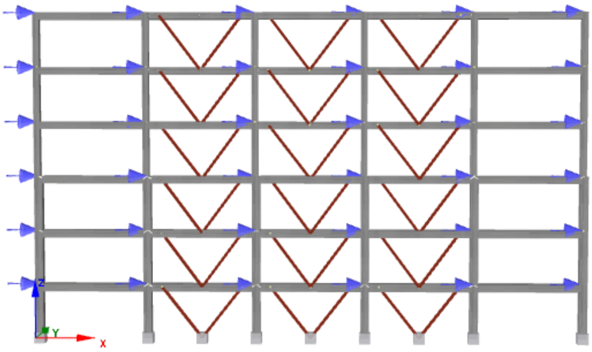
Figure 64: Second pattern of concentric braces for six story building: a) Diagonal brace, b) IV-brace, and c) V-brace.



a) Diagonal brace



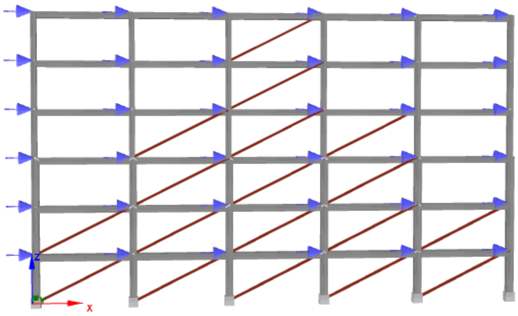
b) IV- brace



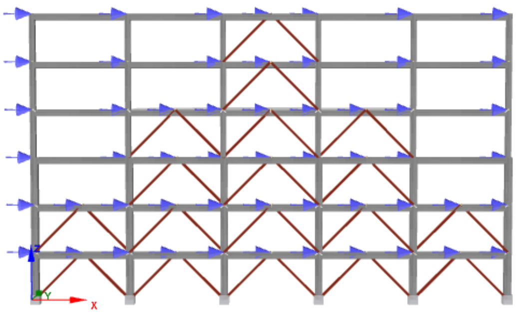
c) V-brace

Figure 65: Second pattern of eccentric braces for six story building: a) Diagonal brace, b) IV-brace, and c) V-brace.

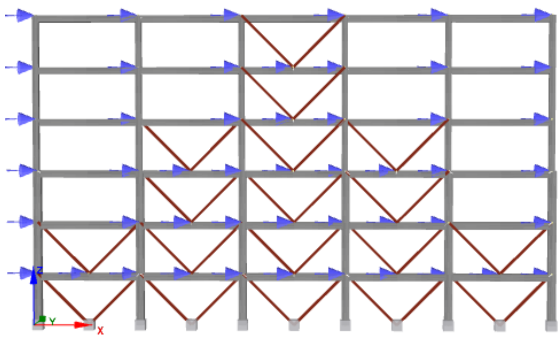
- Case 3



a) Diagonal brace

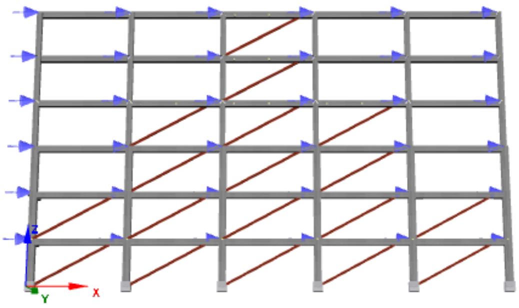


b) IV- brace

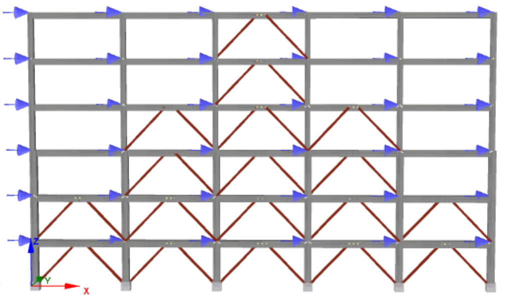


c) V-brace

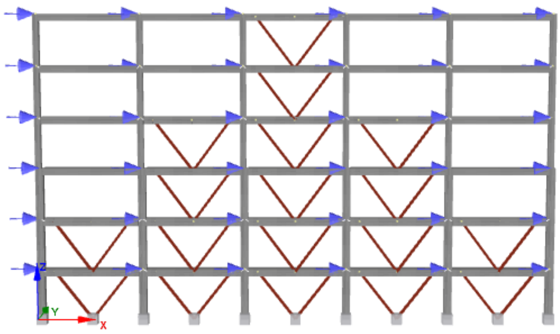
Figure 66: Third pattern of concentric braces for six story building: a) Diagonal brace, b) IV-brace, and c) V-brace.



a) Diagonal brace



b) IV- brace

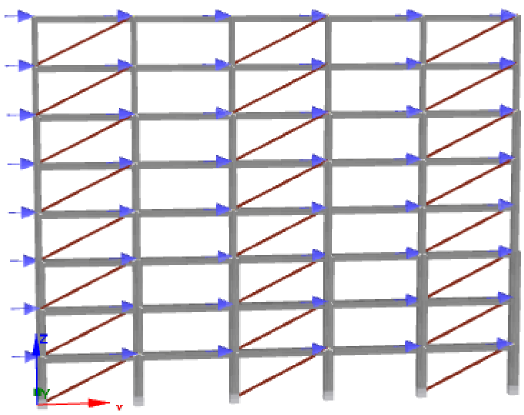


c) V-brace

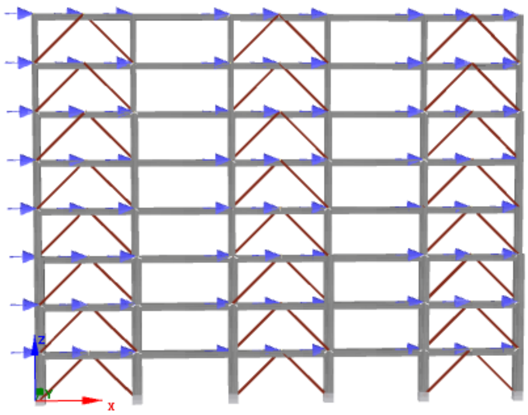
Figure 67: Third pattern of eccentric braces for six story building: a) Diagonal brace, b) IV-brace, and c) V-brace.

### 4.5.3 Eight Story Building

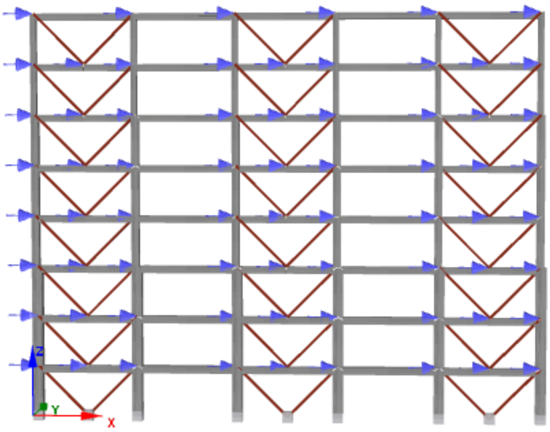
- Case 1



a) Diagonal brace

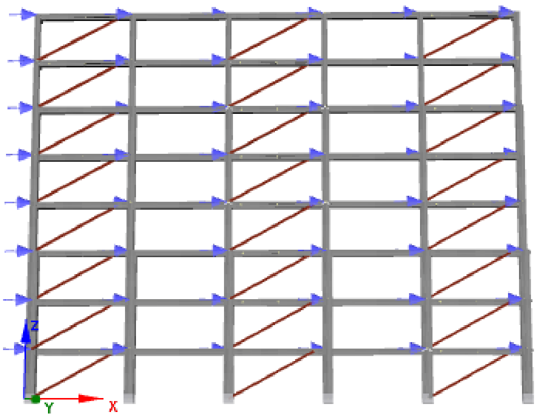


b) IV- brace

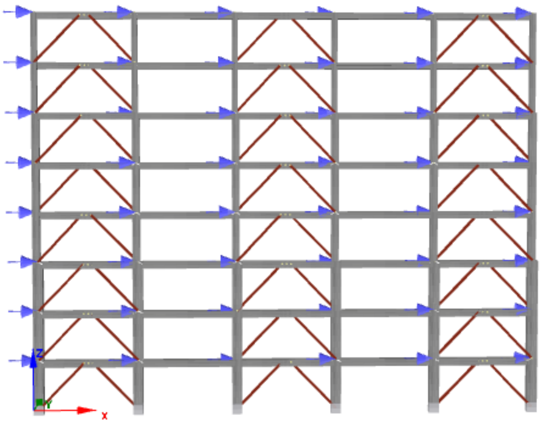


c) V-brace

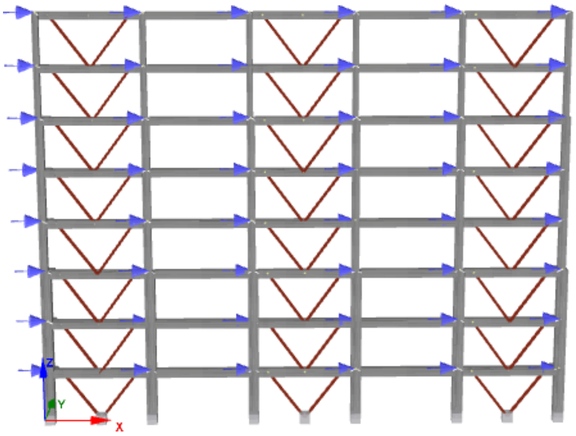
Figure 68: First pattern of concentric braces for eight story building: a) Diagonal brace, b) IV-brace, and c) V-brace.



a) Diagonal brace



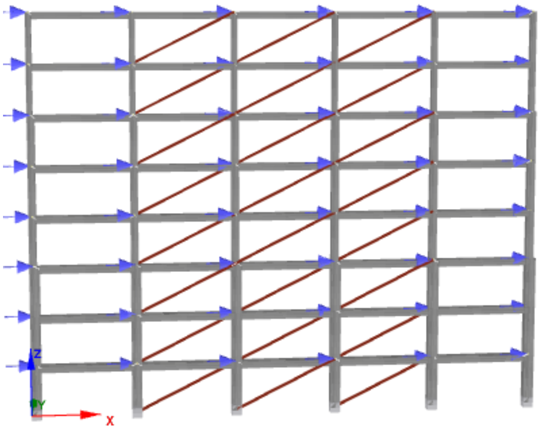
b) IV- brace



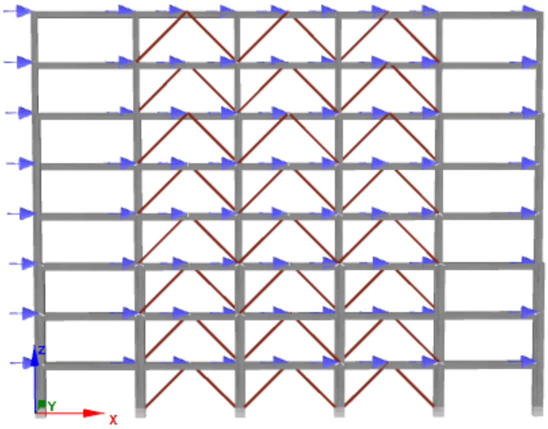
c) V-brace

Figure 69: First pattern of eccentric braces for eight story building: a) Diagonal brace, b) IV-brace, and c) V-brace.

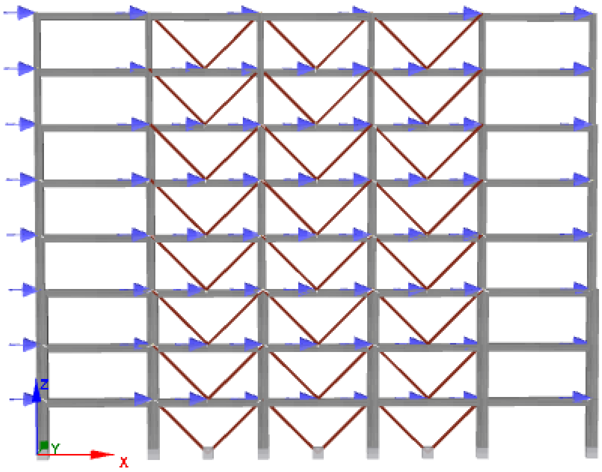
- Case 2



a) Diagonal brace

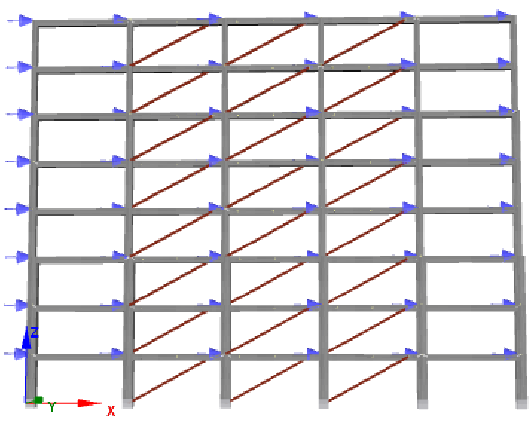


b) IV- brace

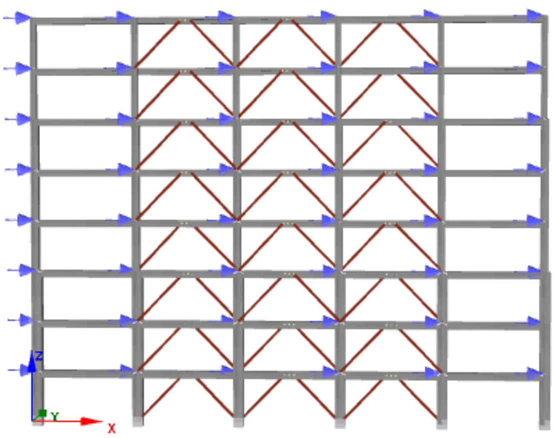


c) V-brace

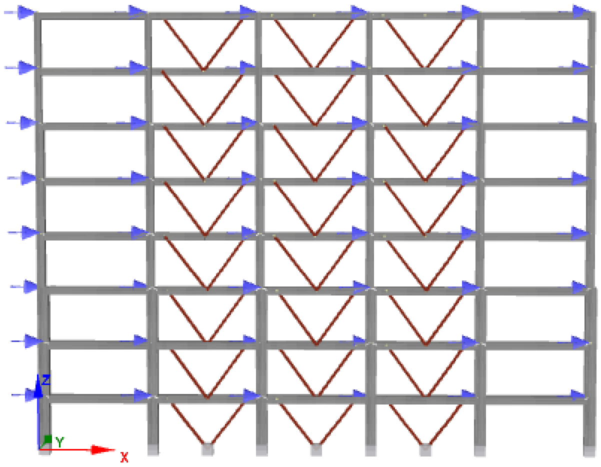
Figure 70: Second pattern of concentric braces for eight story building: a) Diagonal brace, b) IV-brace, and c) V-brace.



a) Diagonal brace



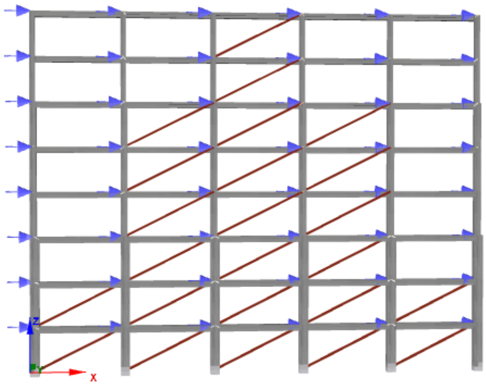
b) IV- brace



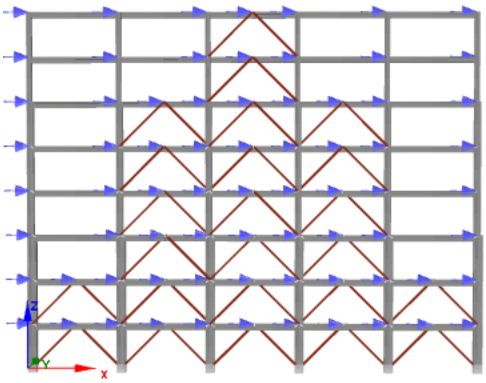
c) V-brace

Figure 71: Second pattern of eccentric braces for eight story building: a) Diagonal brace, b) IV-brace, and c) V-brace.

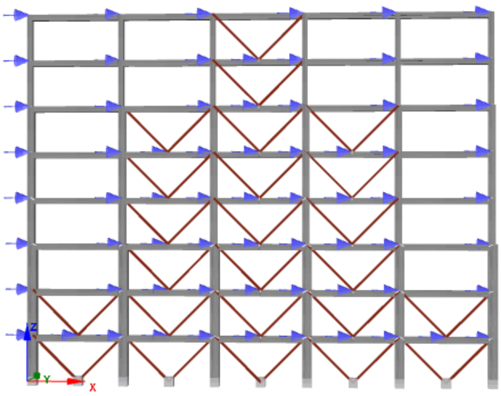
- Case 3



a) Diagonal brace

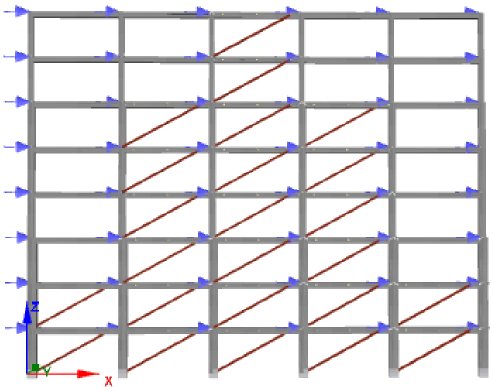


b) IV- brace

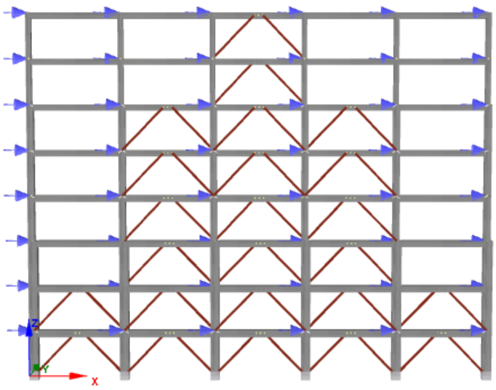


c) V-brace

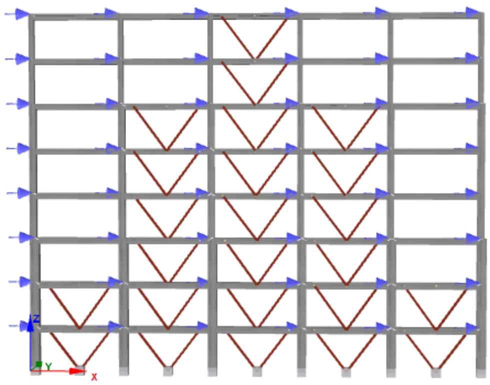
Figure 72: Third pattern of concentric braces for eight story building: a) Diagonal brace, b) IV-brace, and c) V-brace.



a) Diagonal brace



b) IV- brace

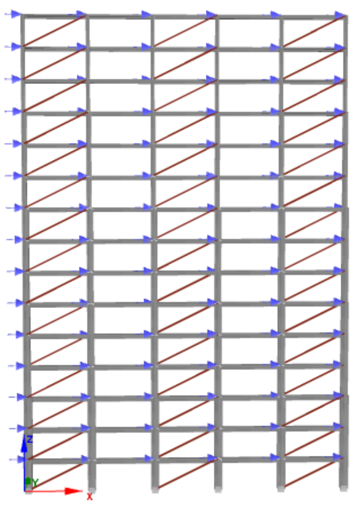


c) V-brace

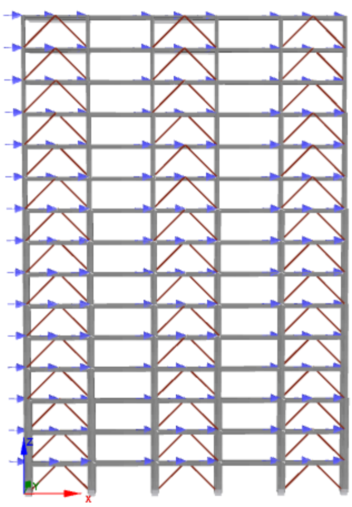
Figure 73: Third pattern of eccentric braces for eight story building: a) Diagonal brace, b) IV-brace, and c) V-brace.

### 4.5.4 Fifteen Story Building

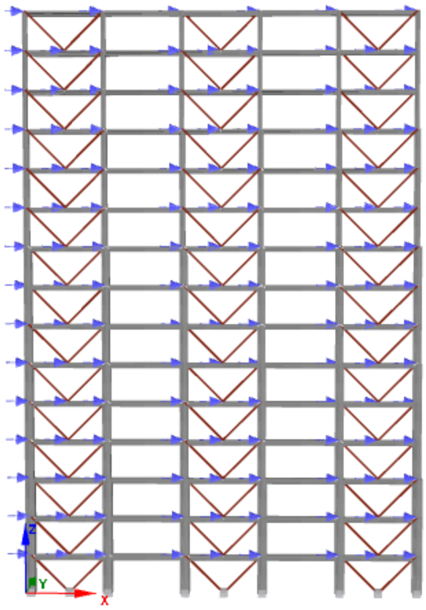
- Case 1



a) Diagonal brace

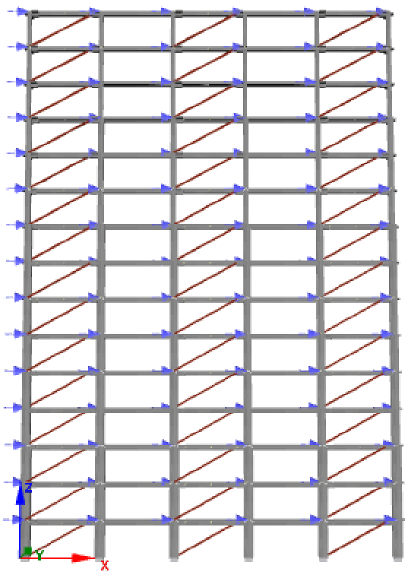


b) IV- brace

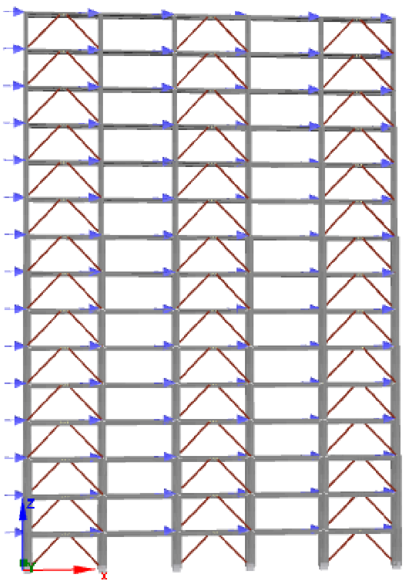



c) V-brace

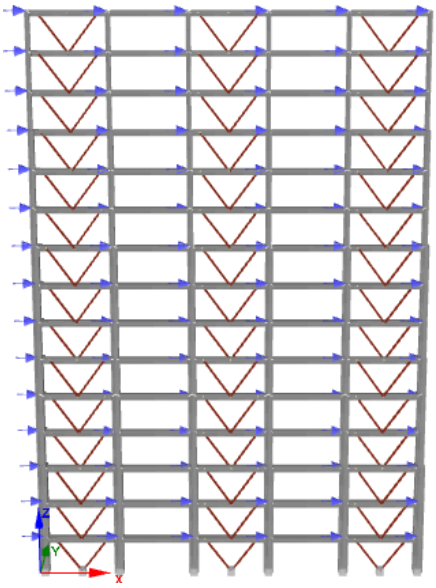
Figure 74: First pattern of concentric braces for fifteen story building: a) Diagonal brace, b) IV-brace, and c) V-brace.




a) Diagonal brace



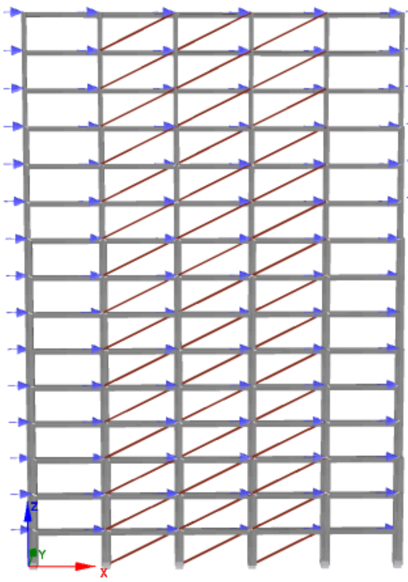

b) IV- brace



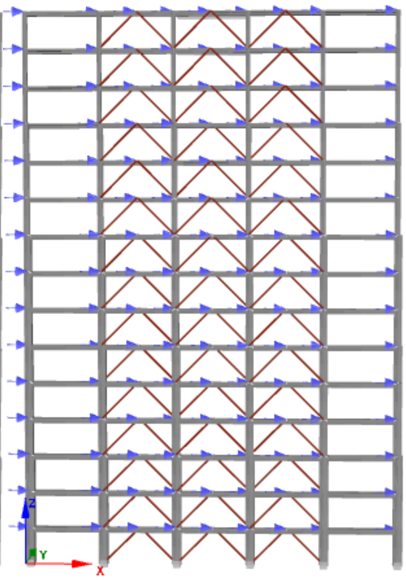
c) V-brace

Figure 75: First pattern of eccentric braces for fifteen story building: a) Diagonal brace, b) IV-brace, and c) V-brace.

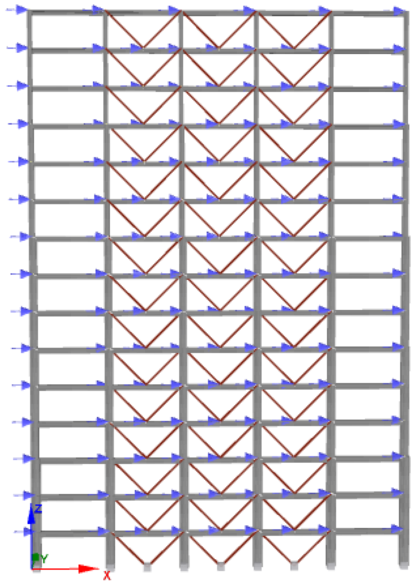
- Case 2



a) Diagonal brace

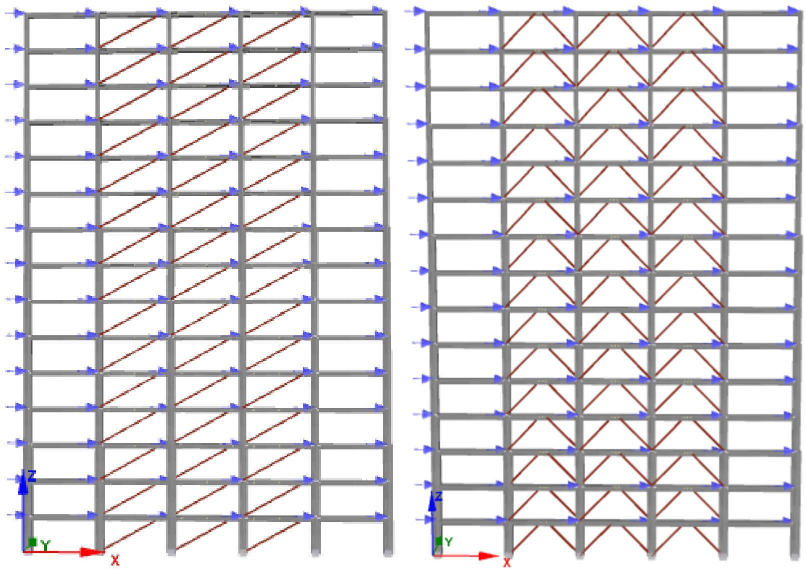


b) IV- brace

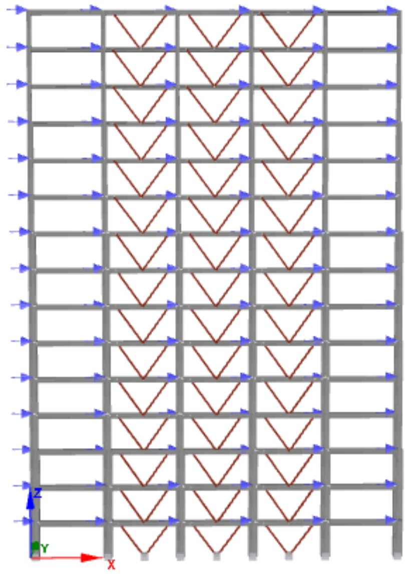



c) V-brace

Figure 76: Second pattern of concentric braces for fifteen story building: a) Diagonal brace, b) IV-brace, and c) V-brace.



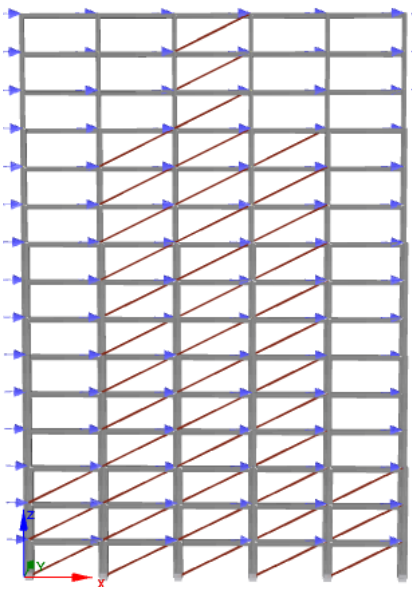

a) Diagonal brace b) IV- brace



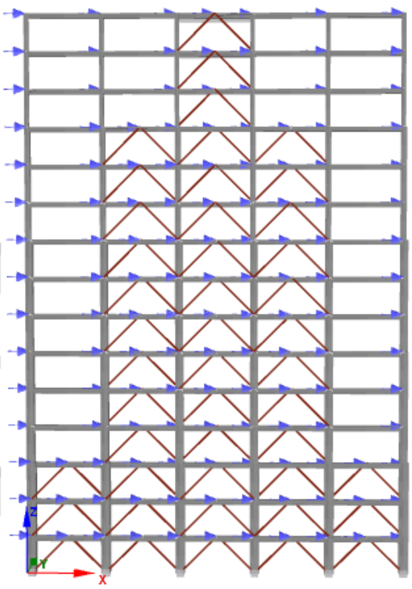
c) V-brace

Figure 77: Second pattern of eccentric braces for fifteen story building: a) Diagonal brace, b) IV-brace, and c) V-brace.

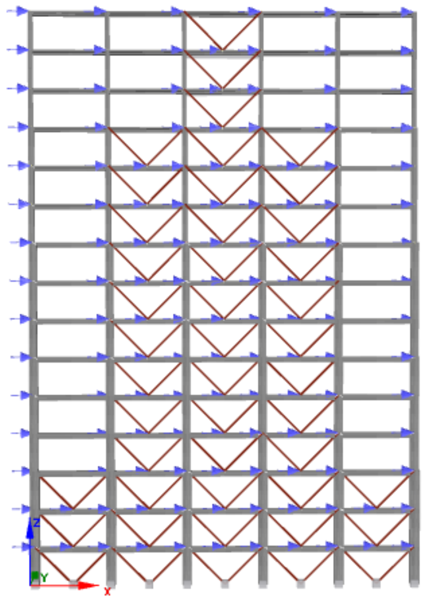
- Case 3



a) Diagonal brace

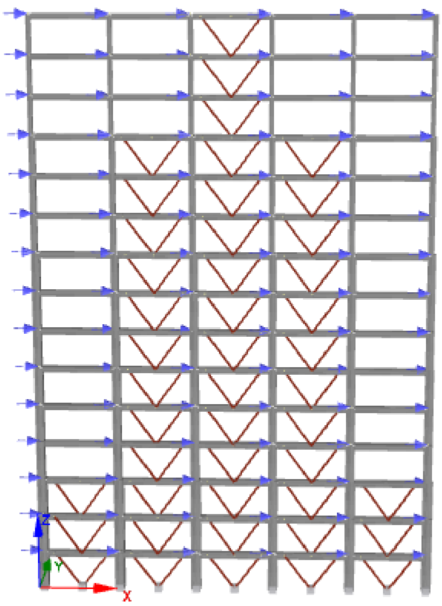


b) IV- brace

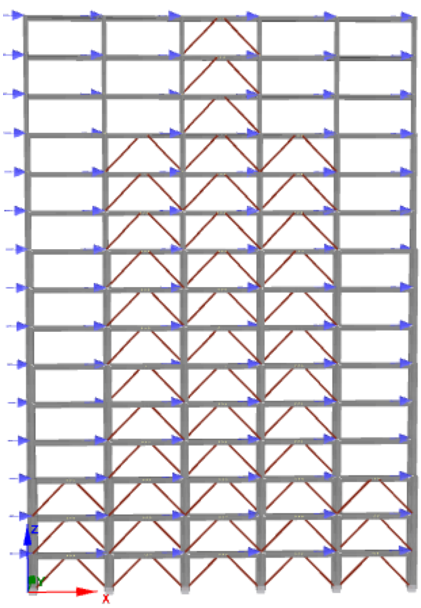



c) V-brace

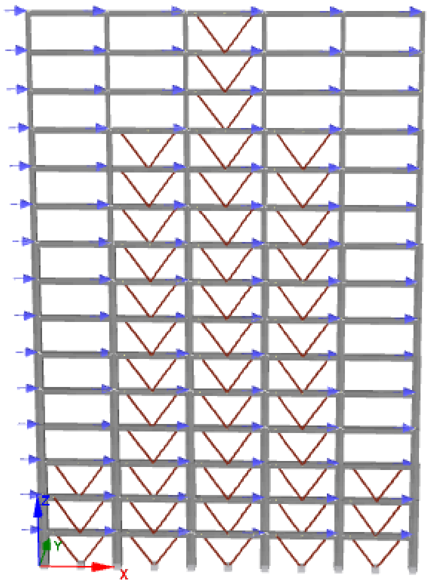
Figure 78: Third pattern of concentric braces for fifteen story building: a) Diagonal brace, b) IV-brace, and c) V-brace.




a) Diagonal brace




b) IV- brace



c) V-brace

Figure 79: Third pattern of eccentric braces for fifteen story building: a) Diagonal brace, b) IV-brace, and c) V-brace.

## 4.6 Materials Properties

This chapter describe the properties of the materials used in the design according to 2018 Turkish seismic code. It will describe concrete and steel for RC part and for the steel brace part the steel for BRB and conventional steel brace will be shown in the tables below.

1) Concrete:

- Concrete strength (KPa): 33000
- Tensile strength (KPa): 2600
- Modulus of elasticity (KPa): 2.6999E +007
- Strain at peak stress (m/m): 0.0022
- Specific weight ($kN/m^3$): 24

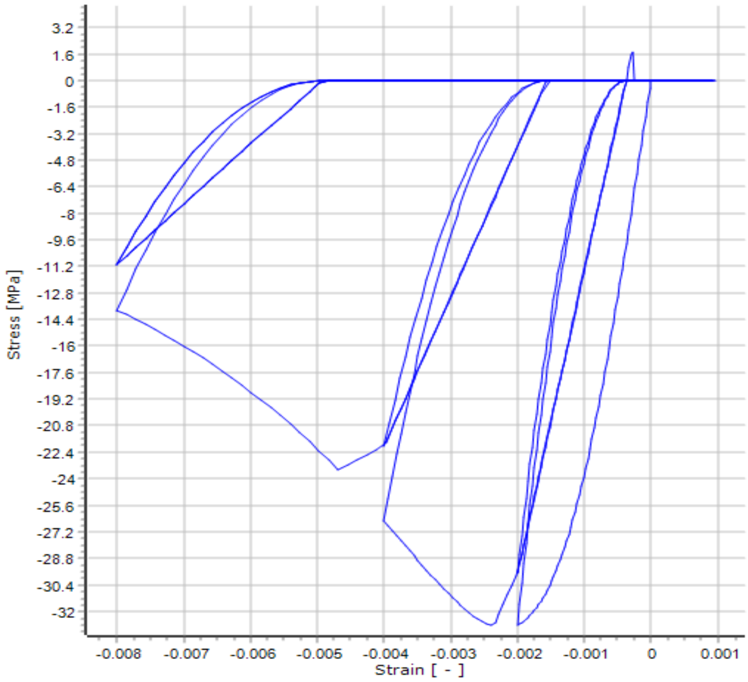


Figure 80: Concrete stress-strain diagram.

2) Steel and Conventional steel brace:

- Modulus of elasticity (KPa): 2E +008
- Yield strength (KPa): 250000
- Strain hardening parameter: 0.005
- Transition curve initial shape parameter: 20
- Transition curve shape calibrating coefficient, A1: 18.50
- Transition curve shape calibrating coefficient, A2: 0.15
- Isotropic hardening calibrating coefficient, A3: 0
- Isotropic hardening calibrating coefficient, A4: 1
- Fracture /buckling strain: 1
- Specific weight (KN/m3): 78

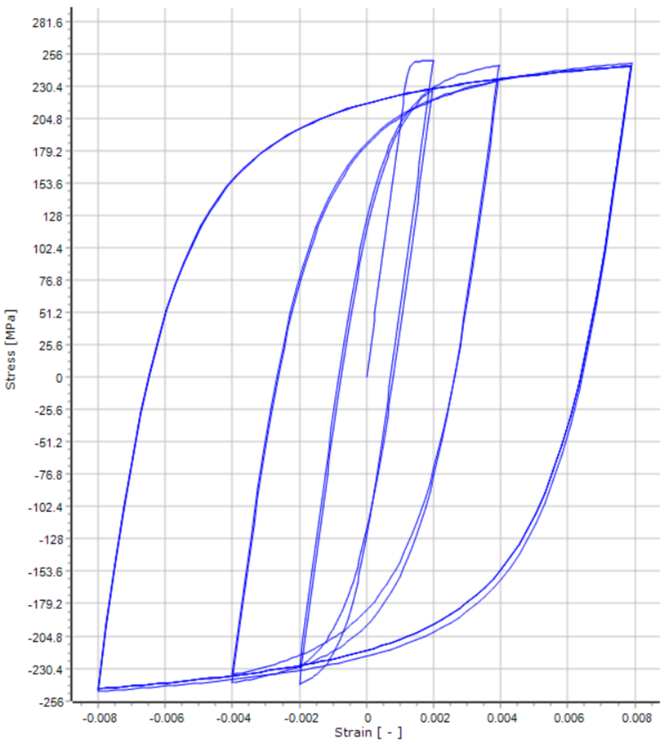


Figure 81: Steel stress-strain diagram (stl¬_mp)

3) BRB steel brace:

- Modulus of elasticity (KPa): 2E +008
- Yield strength (KPa): 250000
- Strain hardening parameter: 0.005
- Transition curve initial shape parameter: 20
- Transition curve shape calibrating coefficient, A1: 18.50
- Transition curve shape calibrating coefficient, A2: 0.15
- Isotropic hardening calibrating coefficient, A3: 0
- Isotropic hardening calibrating coefficient, A4: 1
- Fracture /buckling strain: 1
- Specific weight (KN/m$^3$): 78

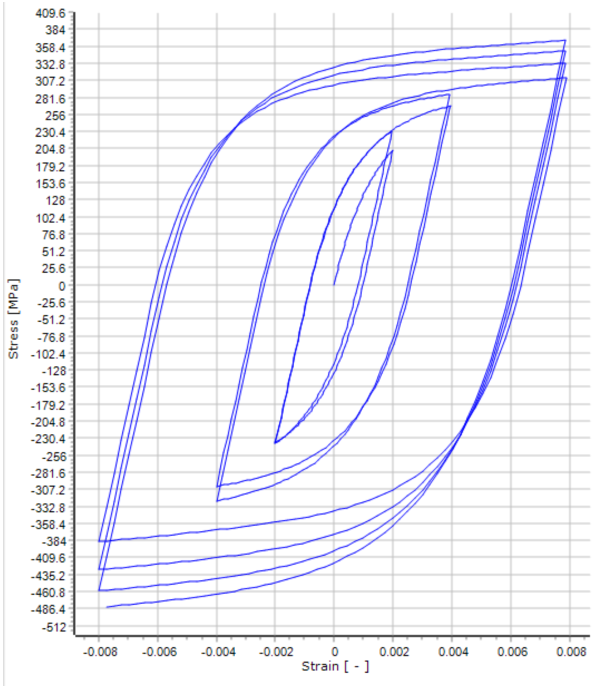



Figure 82: Buckling restrain brace stress-strain diagram (stl_brb).

# Chapter 5

# RESULTS AND DISCUSSIONS

## 5.1 Introduction

An analysis of Pushover was conducted in the Seismostruct program for the modelled buildings. For the RC building, Seismostruct has been used to determine the response of the 4, 6, 8, and 15 floors in terms of capacity curves, performance levels, lateral loads and displacements, plastic hinges and stiffness. This chapter discusses pushover analysis results as a comparison between concentric and eccentric bracing frames, which were investigated and analyzed based on their pattern design (Cases). Furthermore, it well discusses the comparison between the BRB frames and Conventional Steel Brace Frames.

## 5.2 Capacity Curve

Capacity curve is the base shear- displacement diagram that show the structure behavior after the limitation of plasticity. In this part different capacity curves compared together for various bracing types and patterns (Case 1, Case 2, and Case 3).

### 5.2.1 Four Story Building

1) Case 1:

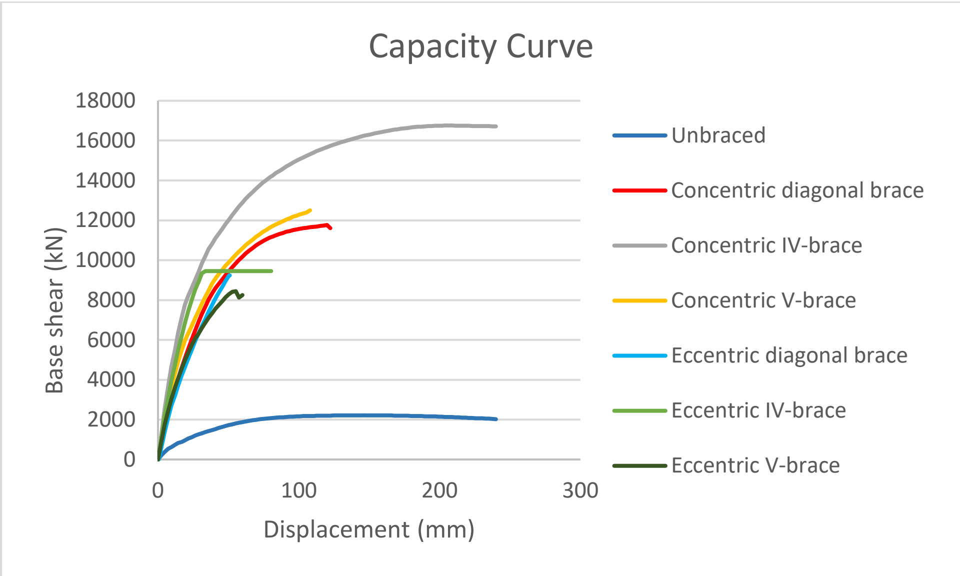



Figure 83: Base shear vs displacement (capacity curve) of Case 1 for four story building.

2) Case 2:

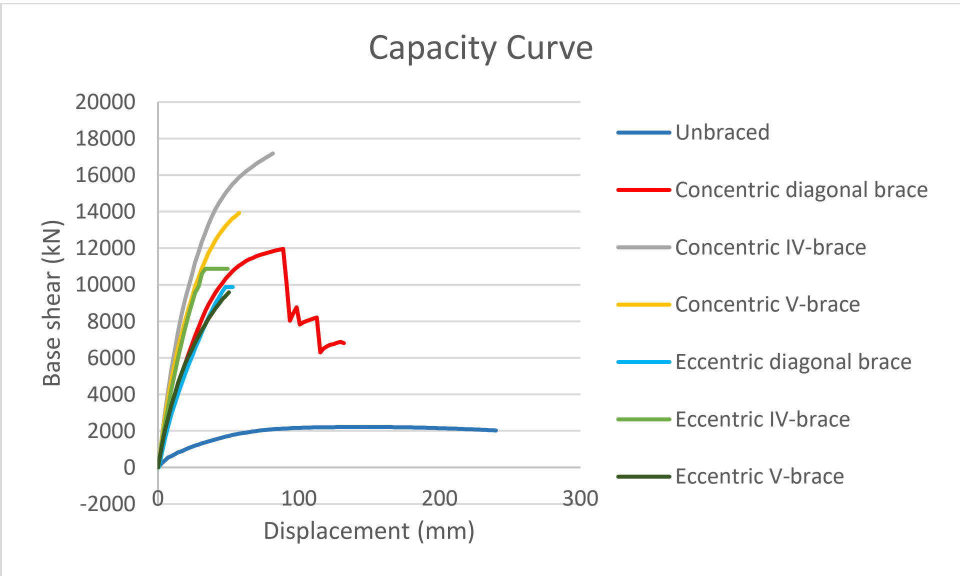



Figure 84: Base shear vs displacement (capacity curve) of Case 2 for four story building.

3) Case 3:

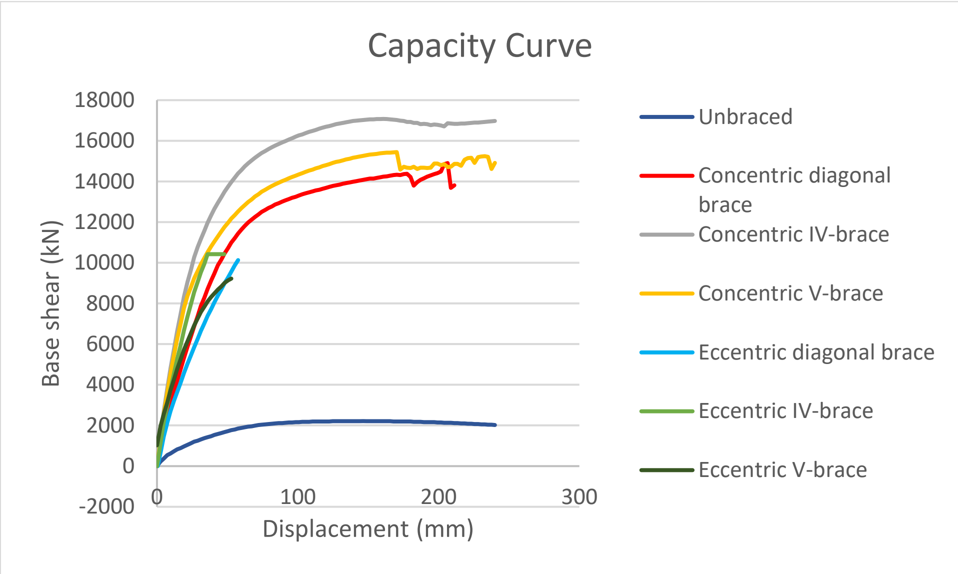



Figure 85: Base shear vs displacement (capacity curve) of Case 3 for four story building.

From the pushover analysis, it was found that adding braces had a great impact on the building's strength and stiffness. Variable results for base shear were found under different cases or patterns, all the braced buildings show a better performance than the unbraced one. The highest performance curve in Cases 1, 2, and 3 was the concentrically (CBF) inverted- V brace with increasing the shear load (lateral load) by 86.78 %, 87.12%, and 87.03 %, respectively, from the unbraced structure as shown in Figure 83, 84, and 85. For all cases in the four-story building, the best performance brace was the concentric inverted-V brace (Case 2) with increased the base shear load by 87.12 % from the unbraced as shown in Figure 84. Eccentric braces (EBF) have a lower shear load than the concentric, the highest increasing of lateral load was eccentric inverted- V brace (Case 2) by 79.64 %. Which means EBF reached the plasticity before CBF, that means CBF have larger stiffness and strength.

### 5.2.2 Six Story Building

1) Case 1:

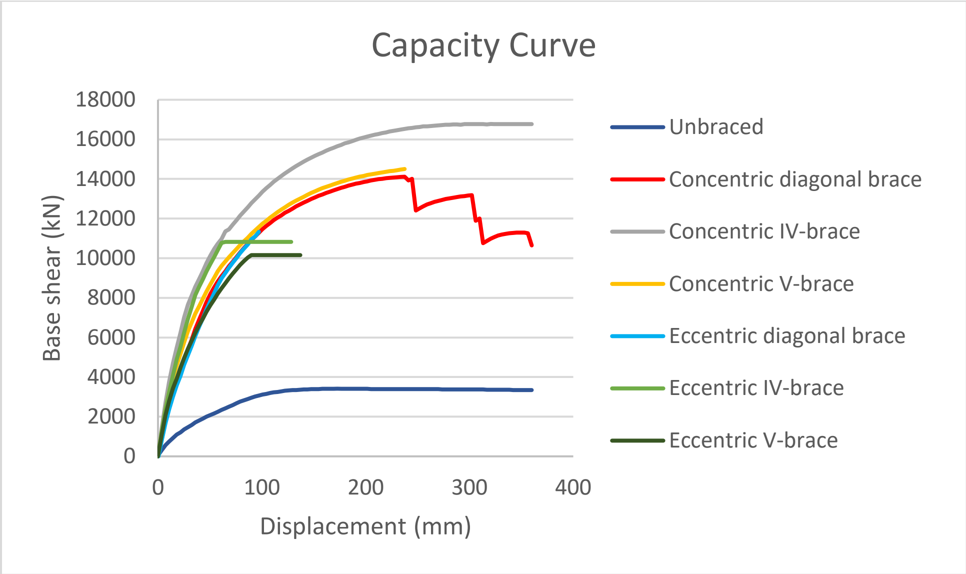



Figure 86: Base shear vs displacement (capacity curve) of Case 1 for six story building.

2) Case 2:

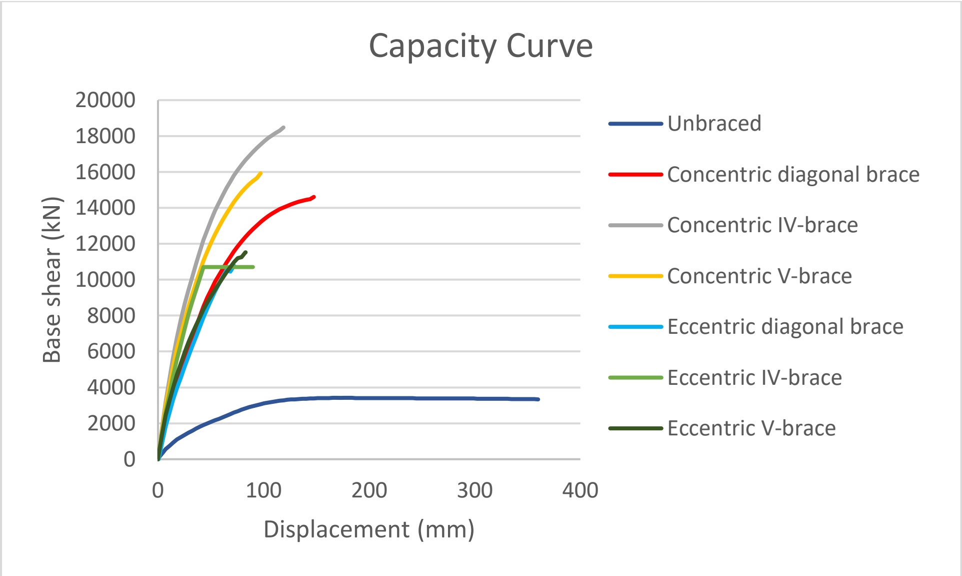



Figure 87: Base shear vs displacement (capacity curve) of Case 2 for six story building.

3) Case 3:

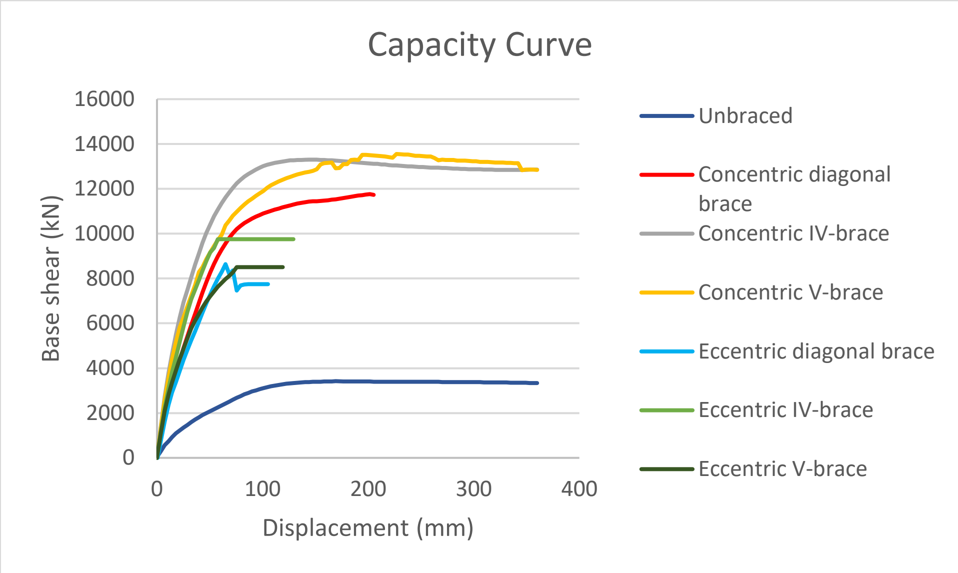



Figure 88: Base shear vs displacement (capacity curve) of Case 3 for six story building.

Figures (86, 87, 88) shows the shear load for various type of braces under three patterns (Cases), in Case 2 the concentric Inverted-V brace have the highest performance among all the cases, by increasing 81.51 % compared to unbraced build. The Inverted-V brace was apical shear load in Case 1 as 79.64 % and the V brace in Case 3 was higher by 74.80 % than the unbraced building. For EBF diagonal brace Case 1 was higher than the rest of the eccentric bracing by 69.86 % compared to unbraced structure.

### 5.2.3 Eight Story Building

1) Case 1:

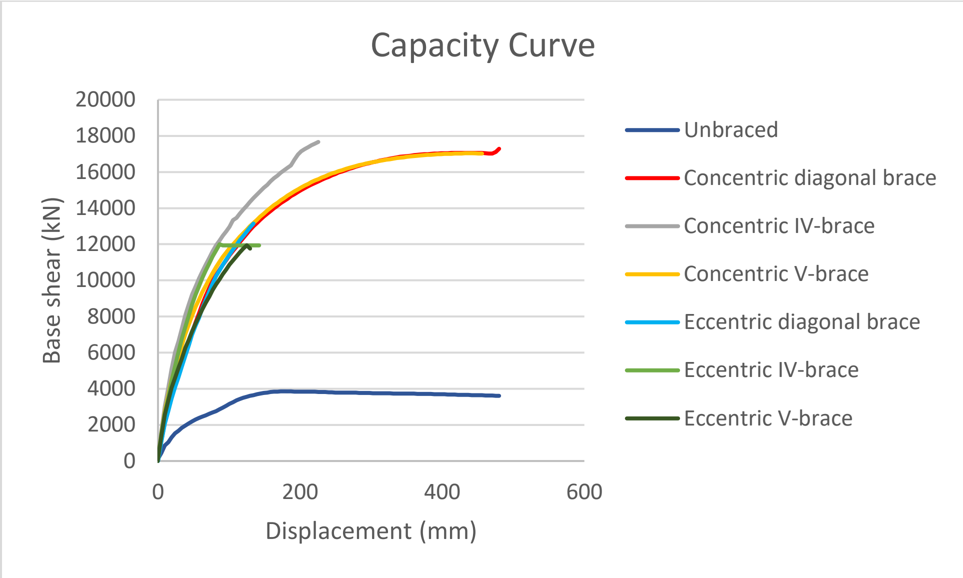



Figure 89: Base shear vs displacement (capacity curve) of Case 1 for eight story building.

2) Case 2:

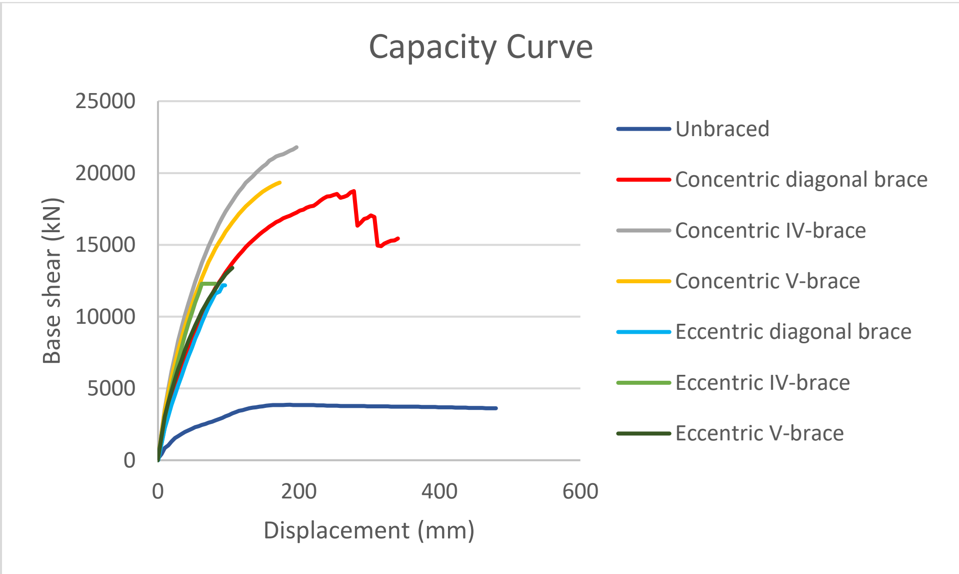



Figure 90: Base shear vs displacement (capacity curve) of Case 2 for eight story building.

3) Case 3:

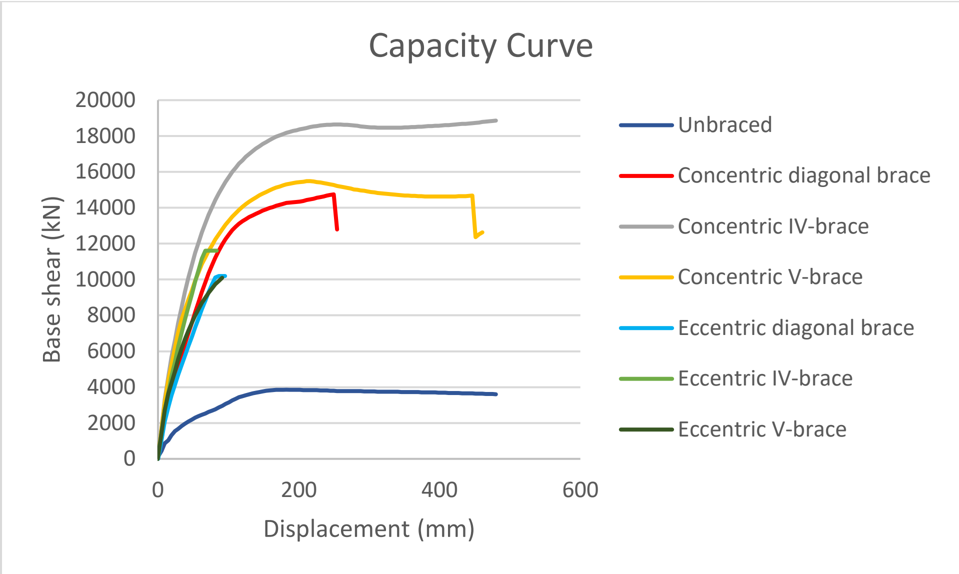



Figure 91: Base shear vs displacement (capacity curve) of Case 3 for eight story building.

In figure (89, 90, 91) all of the Cases 1, 2, and 3 show that the Inverted-V brace have the beast shear load which the increasing percentage than the unbraced is 78.17%, 82.31 %, and 79.56%, respectively. The best performance load between the case is Inverted-V brace in Case 2.

### 5.2.4 Fifteen Story Building

1) Case 1:

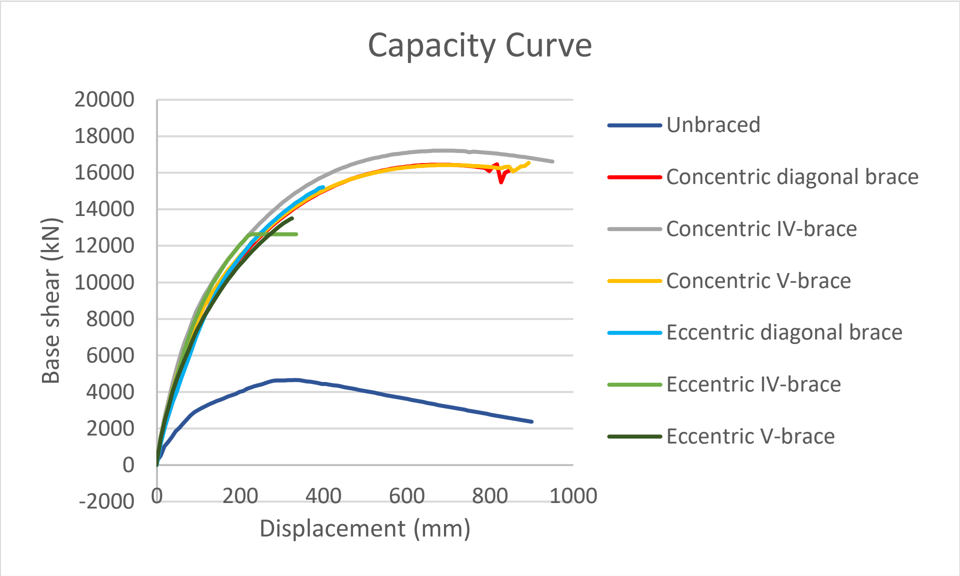



Figure 92: Base shear vs displacement (capacity curve) of Case 1 for fifteen story building.

2) Case 2:

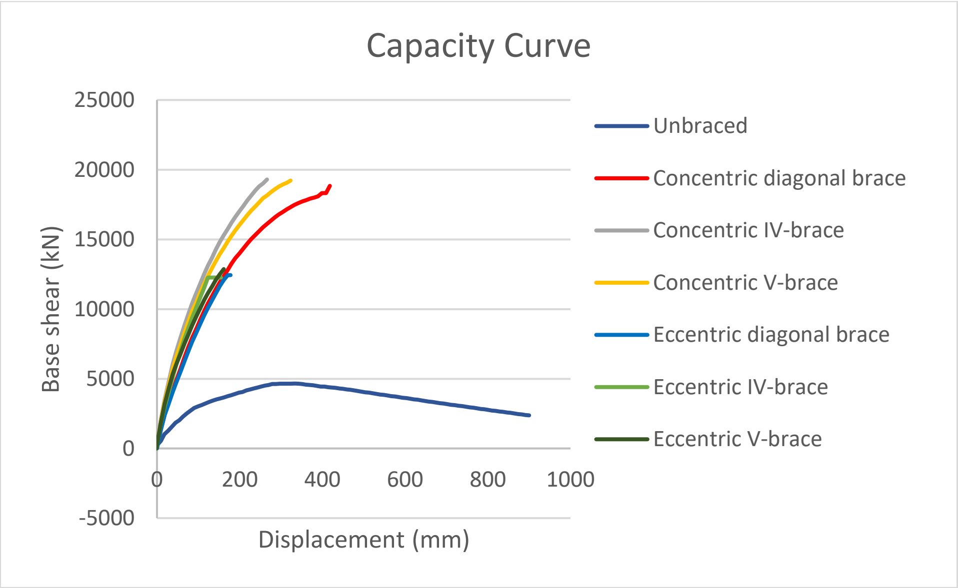



Figure 93: Base shear vs displacement (capacity curve) of Case 2 for fifteen story building.

3) Case 3:

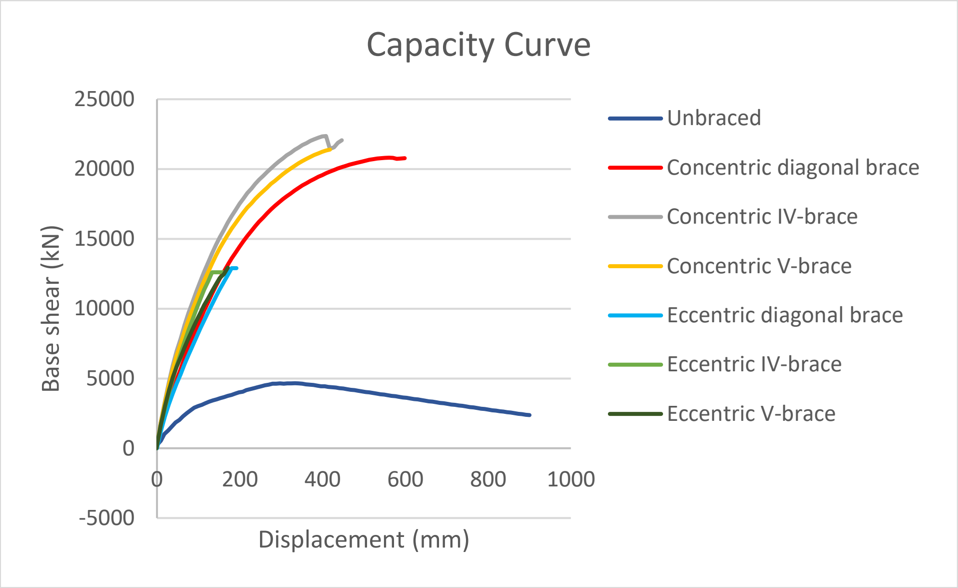



Figure 94: Base shear vs displacement (capacity curve) of Case 3 for fifteen story building.

For fifteen story building the capacity curve for the braces shows some similarities. The highest base shear load locates in Case 3 which is the Inverted – V brace that increased by 79.17 %. As well as Inverted-V brace has the highest increase of load in Cases 1 and 2 by 72.94% and 75.86%, respectively.

## 5.3 Performance Level

To determine the target performance level the number of plastic hinges should be calculated in every story. Both X and Y direction was considered to find the plastic hinges in beams and columns. The below tables (1, 2, 3, and 4) view the performance level for all the target performance in various building heights 4, 6, 8, and 15 stories.

### 5.3.1 Four Story Building

Table 1: Performance level of four-story building

| Plastic hinges for Four story building | | | | | | |
|---|---|---|---|---|---|---|
| Type of braces | | | CO | LD | CD | CP |
| unbraced | | | | | | ✓ |
| Concentric | Case 1 | Diagonal brace | | ✓ | | |
| | | IV-brace | ✓ | | | |
| | | V-brace | | ✓ | | |
| | Case 2 | Diagonal brace | | ✓ | | |
| | | IV-brace | ✓ | | | |
| | | V-brace | ✓ | | | |
| | Case 3 | Diagonal brace | ✓ | | | |
| | | IV-brace | ✓ | | | |
| | | V-brace | ✓ | | | |
| Eccentric | Case 1 | Diagonal brace | | ✓ | | |
| | | IV-brace | | ✓ | | |
| | | V-brace | | ✓ | | |
| | Case 2 | Diagonal brace | | ✓ | | |
| | | IV-brace | | ✓ | | |
| | | V-brace | | | ✓ | |
| | Case 3 | Diagonal brace | | ✓ | | |
| | | IV-brace | | ✓ | | |
| | | V-brace | | | ✓ | |

### 5.3.2 Six Story Building

Table 2: Performance level of six story building.

| Plastic hinges for Four story building | | | | | | |
|---|---|---|---|---|---|---|
| Type of braces | | | CO | LD | CD | CP |
| unbraced | | | | | | ✓ |
| Concentric | Case 1 | Diagonal brace | | ✓ | | |
| | | IV-brace | | ✓ | | |
| | | V-brace | | ✓ | | |
| | Case 2 | Diagonal brace | | ✓ | | |
| | | IV-brace | ✓ | | | |
| | | V-brace | ✓ | | | |
| | Case 3 | Diagonal brace | | | ✓ | |
| | | IV-brace | | | ✓ | |
| | | V-brace | | ✓ | | |
| Eccentric | Case 1 | Diagonal brace | ✓ | | | |
| | | IV-brace | | ✓ | | |
| | | V-brace | | ✓ | | |
| | Case 2 | Diagonal brace | | ✓ | | |
| | | IV-brace | | ✓ | | |
| | | V-brace | | ✓ | | |
| | Case 3 | Diagonal brace | | ✓ | | |
| | | IV-brace | | ✓ | | |
| | | V-brace | | | ✓ | |

### 5.3.3 Eight Story Building

Table 3: Performance level of Eight story building.

| Plastic hinges for Four story building | | | | | | |
|---|---|---|---|---|---|---|
| Type of braces | | | CO | LD | CD | CP |
| unbraced | | | | | | ✓ |
| Concentric | Case 1 | Diagonal brace | | | ✓ | |
| Concentric | Case 1 | IV-brace | | | ✓ | |
| Concentric | Case 1 | V-brace | | ✓ | | |
| Concentric | Case 2 | Diagonal brace | | ✓ | | |
| Concentric | Case 2 | IV-brace | ✓ | | | |
| Concentric | Case 2 | V-brace | ✓ | | | |
| Concentric | Case 3 | Diagonal brace | | ✓ | | |
| Concentric | Case 3 | IV-brace | | ✓ | | |
| Concentric | Case 3 | V-brace | | ✓ | | |
| Eccentric | Case 1 | Diagonal brace | | ✓ | | |
| Eccentric | Case 1 | IV-brace | | | ✓ | |
| Eccentric | Case 1 | V-brace | | ✓ | | |
| Eccentric | Case 2 | Diagonal brace | | ✓ | | |
| Eccentric | Case 2 | IV-brace | | ✓ | | |
| Eccentric | Case 2 | V-brace | | ✓ | | |
| Eccentric | Case 3 | Diagonal brace | | ✓ | | |
| Eccentric | Case 3 | IV-brace | | ✓ | | |
| Eccentric | Case 3 | V-brace | | ✓ | | |

### 5.3.4 Fifteen Story Building

Table 4: Performance level of Fifteen story building.

| Plastic hinges for Four story building | | | | | | |
|---|---|---|---|---|---|---|
| Type of braces | | | CO | LD | CD | CP |
| unbraced | | | | | | ✓ |
| Concentric | Case 1 | Diagonal brace | | | ✓ | |
| | | IV-brace | | | ✓ | |
| | | V-brace | | ✓ | | |
| | Case 2 | Diagonal brace | | | ✓ | |
| | | IV-brace | | ✓ | | |
| | | V-brace | ✓ | | | |
| | Case 3 | Diagonal brace | | ✓ | | |
| | | IV-brace | | ✓ | | |
| | | V-brace | ✓ | | | |
| Eccentric | Case 1 | Diagonal brace | | ✓ | | |
| | | IV-brace | | | ✓ | |
| | | V-brace | | | ✓ | |
| | Case 2 | Diagonal brace | | ✓ | | |
| | | IV-brace | | ✓ | | |
| | | V-brace | | ✓ | | |
| | Case 3 | Diagonal brace | | ✓ | | |
| | | IV-brace | | ✓ | | |
| | | V-brace | | ✓ | | |

A comparison of the performance levels of concentric and eccentric BRB is shown in Tables 1 to 4 for every story height. In addition, it shows that unbraced buildings have Collapse Prevention Performance (CP), whereas when braces are added, the performance improves to Continued Operation Performance (CO), Controlled Damage Performance (CD), and Limited Damage Performance (LD). Additionally, concentric braces perform better than eccentric braces.

## 5.4 Target displacement

Building displacement targets are used to estimate the damage pattern and deformation patterns of a structure. In this part the target displacement and target point will be considered according to Turkish Earthquake Code.

### 5.4.1 Performance for Four Story Building

Table 5: Target displacements of four-story building.

| Target displacements for Four story building (m) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Type of braces | | | LD | CD | CP | Target point |
| unbraced | | | 0.0453 | 0.1234 | 0.2099 | 0.1248 |
| Concentric | Case 1 | Diagonal brace | 0.0112 | 0.0306 | 0.0521 | 0.0312 |
| | | IV-brace | 0.0166 | 0.0427 | 0.0743 | 0.0432 |
| | | V-brace | 0.0193 | 0.0526 | 0.0896 | 0.0528 |
| | Case 2 | Diagonal brace | 0.0115 | 0.0313 | 0.0533 | 0.0336 |
| | | IV-brace | 0.0084 | 0.0205 | 0.0357 | 0.0216 |
| | | V-brace | 0.0088 | 0.0223 | 0.0389 | 0.0240 |
| | Case 3 | Diagonal brace | 0.0111 | 0.0302 | 0.0514 | 0.0312 |
| | | IV-brace | 0.0087 | 0.0208 | 0.0362 | 0.0216 |
| | | V-brace | 0.0091 | 0.0217 | 0.0379 | 0.0240 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Eccentric | Case 1 | Diagonal brace | 0.0110 | 0.0300 | 0.0510 | 0.0120 |
| | | IV-brace | 0.0173 | 0.0472 | 0.0804 | 0.0472 |
| | | V-brace | 0.0112 | 0.0305 | 0.0519 | 0.0312 |
| | Case 2 | Diagonal brace | 0.0115 | 0.0312 | 0.0531 | 0.0336 |
| | | IV-brace | 0.0099 | 0.0265 | 0.0458 | 0.0288 |
| | | V-brace | 0.0096 | 0.0263 | 0.0447 | 0.0264 |
| | Case 3 | Diagonal brace | 0.0107 | 0.0291 | 0.0495 | 0.0312 |
| | | IV-brace | 0.0105 | 0.0274 | 0.0478 | 0.0288 |
| | | V-brace | 0.0098 | 0.0261 | 0.0453 | 0.0264 |

Table 5 shows the target displacement performance of buildings with different patterns and braces, the unbraced building performance found as Collapse Prevention Performance (CP) with the highest target displacement as 0.1248 m. The best performance system was concentric Inverted-V brace (IV-brace) for all the Cases, Case 2 and 3 of concentric V-brace as well as Case 3 of concentric diagonal brace of the as Continued Operation Performance (CO) at the displacement target points. The inverted-V brace (Case 2, and 3) has the highest performance (CO) at 0.0216m displacement.  Most of the eccentric braces were at Limited Damage Performance (LD). Concentrically braced frames (CBF) performance level was more efficient than the eccentric braces (EBF).

### 5.4.2 Performance for Six Story Building

Table 6: Target displacements of six story building.

| Target displacements for Six story building | | | | | | | |
|---|---|---|---|---|---|---|---|
| Type of braces | | | LD | CD | CP | Target point |
| unbraced | | | 0.0435 | 0.1186 | 0.2018 | 0.1188 |
| Concentric | Case 1 | Diagonal brace | 0.0177 | 0.0483 | 0.0822 | 0.0504 |
| | | IV-brace | 0.0234 | 0.0639 | 0.1086 | 0.0648 |
| | | V-brace | 0.0281 | 0.0766 | 0.1303 | 0.0792 |
| | Case 2 | Diagonal brace | 0.0179 | 0.0488 | 0.0829 | 0.0504 |
| | | IV-brace | 0.0141 | 0.0384 | 0.0654 | 0.0396 |
| | | V-brace | 0.0127 | 0.0347 | 0.0591 | 0.0360 |
| | Case 3 | Diagonal brace | 0.0311 | 0.0848 | 0.1443 | 0.0864 |
| | | IV-brace | 0.0243 | 0.0663 | 0.1127 | 0.0684 |
| | | V-brace | 0.0137 | 0.0374 | 0.0636 | 0.0396 |
| Eccentric | Case 1 | Diagonal brace | 0.0163 | 0.0444 | 0.0755 | 0.0468 |
| | | IV-brace | 0.0277 | 0.075 | 0.1283 | 0.0754 |
| | | V-brace | 0.0296 | 0.0806 | 0.1371 | 0.0828 |
| | Case 2 | Diagonal brace | 0.0236 | 0.0642 | 0.1092 | 0.0648 |
| | | IV-brace | 0.0194 | 0.0528 | 0.0899 | 0.0528 |
| | | V-brace | 0.0179 | 0.0488 | 0.0830 | 0.0504 |
| | Case 3 | Diagonal brace | 0.0227 | 0.0618 | 0.1051 | 0.0648 |
| | | IV-brace | 0.0279 | 0.0759 | 0.1292 | 0.0759 |
| | | V-brace | 0.0257 | 0.0700 | 0.1191 | 0.0720 |

Table 6 shows the target displacement performance of buildings with different patterns and braces, the unbraced building performance is found as Collapse Prevention Performance (CP) with the highest target displacement as 0.1188 m. The best eccentric performance system was a Case 1 of diagonal brace as Continued Operation Performance (CO) at the displacement target points. For concentric brace V-brace and IV-brace of Case 2 are best performance as CO. Eccentric braces show more plasticity than concentric braces.

### 5.4.3 Performance for Eight Story Building

Table 7: Target displacements of eight story building.

| Target displacements for Eight story building | | | | | | |
|---|---|---|---|---|---|---|
| Type of braces | | | LD | CD | CP | Target point |
| unbraced | | | 0.0653 | 0.1781 | 0.3029 | 0.1824 |
| Concentric | Case 1 | Diagonal brace | 0.0394 | 0.1074 | 0.1827 | 0.1104 |
| | | IV-brace | 0.0332 | 0.0905 | 0.1540 | 0.0912 |
| | | V-brace | 0.0266 | 0.0725 | 0.1234 | 0.0768 |
| | Case 2 | Diagonal brace | 0.0261 | 0.0711 | 0.1209 | 0.0720 |
| | | IV-brace | 0.0208 | 0.0567 | 0.0964 | 0.0576 |
| | | V-brace | 0.0187 | 0.0509 | 0.0867 | 0.0528 |
| | Case 3 | Diagonal brace | 0.0304 | 0.0827 | 0.1407 | 0.0864 |
| | | IV-brace | 0.0248 | 0.0675 | 0.1148 | 0.0720 |
| | | V-brace | 0.0178 | 0.0486 | 0.0826 | 0.0528 |
| Eccentric | Case 1 | Diagonal brace | 0.0211 | 0.0576 | 0.0980 | 0.0576 |
| | | IV-brace | 0.0307 | 0.0836 | 0.1423 | 0.0864 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | V-brace | 0.0272 | 0.0741 | 0.1261 | 0.0768 |
| | Case 2 | Diagonal brace | 0.0202 | 0.0549 | 0.0935 | 0.0576 |
| | | IV-brace | 0.0177 | 0.0481 | 0.0819 | 0.0481 |
| | | V-brace | 0.0176 | 0.0479 | 0.0815 | 0.0480 |
| | Case 3 | Diagonal brace | 0.0206 | 0.0560 | 0.0953 | 0.0576 |
| | | IV-brace | 0.0180 | 0.0490 | 0.0834 | 0.0528 |
| | | V-brace | 0.0185 | 0.0505 | 0.0859 | 0.0528 |

Table 7 shows the target displacement performance of buildings with different patterns and braces, the unbraced building performance is found as Collapse Prevention Performance (CP) with the highest target displacement of 0.1824 m. The best performance systems were concentric Case 2 of IV, and V-braces as Continued Operation Performance (CO) at the displacement target points. Most of eccentric brace's building were Limited Damage Performance (LD).

### 5.4.4 Performance for Fifteen Story Building

Table 8: Target displacements of fifteen story building

| Target displacements for fifteen story building | | | | | | |
|---|---|---|---|---|---|---|
| Type of braces | | | LD | CD | CP | Target point |
| unbraced | | | 0.1153 | 0.3141 | 0.5345 | 0.3150 |
| Concentric | Case 1 | Diagonal brace | 0.0732 | 0.1995 | 0.3394 | 0.1995 |
| | | IV-brace | 0.0625 | 0.1704 | 0.2898 | 0.1710 |
| | | V-brace | 0.0394 | 0.1073 | 0.1826 | 0.1140 |
| | Case 2 | Diagonal brace | 0.0489 | 0.1333 | 0.2268 | 0.1425 |
| | | IV-brace | 0.0386 | 0.1051 | 0.1789 | 0.1140 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | V-brace | 0.0334 | 0.0911 | 0.1551 | 0.0950 |
| | Case 3 | Diagonal brace | 0.0530 | 0.1444 | 0.2456 | 0.1520 |
| | | IV-brace | 0.0398 | 0.1084 | 0.1845 | 0.1140 |
| | | V-brace | 0.0333 | 0.0907 | 0.1543 | 0.0950 |
| Eccentric | Case 1 | Diagonal brace | 0.0463 | 0.1262 | 0.2147 | 0.1330 |
| | | IV-brace | 0.0713 | 0.1942 | 0.3304 | 0.1995 |
| | | V-brace | 0.0670 | 0.1906 | 0.3243 | 0.1995 |
| | Case 2 | Diagonal brace | 0.0384 | 0.1045 | 0.1779 | 0.1045 |
| | | IV-brace | 0.0334 | 0.0909 | 0.1547 | 0.0950 |
| | | V-brace | 0.0316 | 0.0861 | 0.1465 | 0.0950 |
| | Case 3 | Diagonal brace | 0.0414 | 0.1129 | 0.1920 | 0.1140 |
| | | IV-brace | 0.0351 | 0.0956 | 0.1626 | 0.1045 |
| | | V-brace | 0.0323 | 0.0881 | 0.1499 | 0.0950 |

Table 8 shows the target displacement performance of buildings with different patterns and braces, the unbraced building performance found as Collapse Prevention Performance (CP) with the highest target displacement as 0.3150 m. The best performance systems were concentric V-brace of Case 2 and 3 as Continued Operation Performance (CO) at the displacement target points. Case 2 and 3 for all the eccentric braces are considered as Limited Damage Performance (LD).

## 5.5 Elastic Stiffness

To achieve the best resistance to earthquake, the elastic stiffness should be high to increase the building's strength. This part compares the different elastic stiffness of the buildings braced and unbraced to find the best resisting building.

### 5.5.1 Four Story Building

Table 9: Elastic stiffness of braced and unbraced Four story building.

| Type of braces | | | Elastic stiffness (kN) for Four story building |
|---|---|---|---|
| unbraced | | | 93125.35 |
| Concentric | Case 1 | Diagonal brace | 342286.57 |
| | | IV-brace | 545625.26 |
| | | V-brace | 451865.47 |
| | Case 2 | Diagonal brace | 375953.17 |
| | | IV-brace | 620913.22 |
| | | V-brace | 542964.29 |
| | Case 3 | Diagonal brace | 363871.44 |
| | | IV-brace | 569379.88 |
| | | V-brace | 539820.25 |
| Eccentric | Case 1 | Diagonal brace | 338452.07 |
| | | IV-brace | 480013.98 |
| | | V-brace | 391112.98 |
| | Case 2 | Diagonal brace | 373931.76 |
| | | IV-brace | 514911.75 |
| | | V-brace | 454878.43 |
| | Case 3 | Diagonal brace | 350868.07 |
| | | IV-brace | 468471.55 |
| | | V-brace | 426283.23 |

Stiffness is important to resist the lateral loads of the earthquake, bracing system increases the stiffness of the structure. The unbraced building has the lowest stiffness at 93125.35 kN, which it can be increased by adding a bracing system. The concentrically braced system has mostly higher stiffness than the eccentrically braced as shown in Table 9. The highest elastic stiffness brace is the Inverted V-brace in all the Cases (Case 1, Case 2, and Case 3) as 545625.26 kN, 620913.22 kN, and 569379.88 kN, respectively; which the elastic stiffness increased by 82.93 %, 85%, and 83.64%, respectively, when compared with unbraced system.

### 5.5.2 Six Story Building

Table 10: Elastic stiffness of braced and unbraced Six story building.

| Type of braces | | | Elastic stiffness (kN) for Six story building |
|---|---|---|---|
| unbraced | | | 73275.50 |
| Concentric | Case 1 | Diagonal brace | 256639.88 |
| | | IV-brace | 376981.00 |
| | | V-brace | 325280.65 |
| | Case 2 | Diagonal brace | 289189.94 |
| | | IV-brace | 452847.27 |
| | | V-brace | 420487.20 |
| | Case 3 | Diagonal brace | 262388.34 |
| | | IV-brace | 383129.26 |
| | | V-brace | 367618.34 |
| Eccentric | Case 1 | Diagonal brace | 257034.53 |
| | | IV-brace | 335833.70 |
| | | V-brace | 291589.92 |

| | | | |
|---|---|---|---|
| | Case 2 | Diagonal brace | 283314.44 |
| | | IV-brace | 379163.65 |
| | | V-brace | 355431.79 |
| | Case 3 | Diagonal brace | 253560.01 |
| | | IV-brace | 317912.90 |
| | | V-brace | 300705.33 |

Table 10 shows the elastic stiffness of the structure in which the unbraced has the lowest load at 73275.50 kN. The concentric Inverted V-brace (Case 2) stiffness increases by 83.82% compared with unbraced structure, the increase in the stiffness will increase the strength of the structure to resist the lateral load.

**5.5.3 Eight Story Building**

Table 11: Elastic stiffness of braced and unbraced Eight story building.

| Type of braces | | | Elastic stiffness (kN) for Eight story building |
|---|---|---|---|
| unbraced | | | 75689.43 |
| Concentric | Case 1 | Diagonal brace | 224445.55 |
| | | IV-brace | 310288.43 |
| | | V-brace | 278554.43 |
| | Case 2 | Diagonal brace | 253664.99 |
| | | IV-brace | 378472.78 |
| | | V-brace | 356775.79 |
| | Case 3 | Diagonal brace | 234033.72 |
| | | IV-brace | 339688.90 |

| | | | |
|---|---|---|---|
| | | V-brace | 324357.89 |
| Eccentric | Case 1 | Diagonal brace | 223421.45 |
| | | IV-brace | 277876.93 |
| | | V-brace | 260362.37 |
| | Case 2 | Diagonal brace | 252935.41 |
| | | IV-brace | 317658.10 |
| | | V-brace | 320771.67 |
| | Case 3 | Diagonal brace | 231026.27 |
| | | IV-brace | 281408.02 |
| | | V-brace | 280582.34 |

In eight story building Inverted-V brace was the highest elastic stiffness in all the case, in Case 1 the increasing in the stiffness was 75.61%, as for Case 2 and Case 3 the stiffness increased by 80% and 77.72%, respectively, as shown in Table 11.

### 5.5.4 Fifteen Story Building

Table 12: Elastic stiffness of braced and unbraced Fifteen story building.

| Type of braces | | | Elastic stiffness (kN) for Fifteen story building |
|---|---|---|---|
| unbraced | | | 41160.97 |
| Concentric | Case 1 | Diagonal brace | 116118.89 |
| | | IV-brace | 144260.17 |
| | | V-brace | 134418.28 |
| | Case 2 | Diagonal brace | 137944.95 |
| | | IV-brace | 189177.54 |

| | | | |
|---|---|---|---|
| | | V-brace | 179753.50 |
| | Case 3 | Diagonal brace | 132691.45 |
| | | IV-brace | 179009.42 |
| | | V-brace | 171840.46 |
| Eccentric | Case 1 | Diagonal brace | 117993.67 |
| | | IV-brace | 133946.33 |
| | | V-brace | 129269.26 |
| | Case 2 | Diagonal brace | 138253.59 |
| | | IV-brace | 163106.55 |
| | | V-brace | 169892.89 |
| | Case 3 | Diagonal brace | 129253.18 |
| | | IV-brace | 153057.50 |
| | | V-brace | 156892.68 |

To increase the strength to resist the lateral load, the stiffness should be increased. For the unbraced system the stiffness was 41160.97 kN but when the braced system was added the stiffness increased as in concentric Inverted-V brace; Case 1, 2, and 3 increased by 71.47%, 78.24%, and 77%.

## 5.6 Lateral load and displacement

Structures exposed to lateral loads like earthquakes so it's needed to take into consideration their lateral displacement. The slenderness and height of the structure determine the lateral displacement. Due to their increased flexibility under lateral loads, structures become more vulnerable as they get higher.

### 5.6.1 Four Story Building

Table 13: lateral load and displacement of four-story building.

| Type of braces | | | Lateral load capacity (KN) | Lateral displacement (m) |
|---|---|---|---|---|
| unbraced | | | 2214.56 | 0.0608 |
| Concentric | Case 1 | Diagonal brace | 11766.52 | 0.0590 |
| | | IV-brace | 16757.07 | 0.0766 |
| | | V-brace | 12503.27 | 0.0581 |
| | Case 2 | Diagonal brace | 11962.30 | 0.0494 |
| | | IV-brace | 17187.46 | 0.0454 |
| | | V-brace | 13929.60 | 0.0375 |
| | Case 3 | Diagonal brace | 14904.71 | 0.0873 |
| | | IV-brace | 17075.77 | 0.0601 |
| | | V-brace | 15444.84 | 0.0650 |
| Eccentric | Case 1 | Diagonal brace | 9234.78 | 0.0415 |
| | | IV-brace | 9451.64 | 0.0257 |
| | | V-brace | 8444.38 | 0.0363 |
| | Case 2 | Diagonal brace | 9874.35 | 0.0398 |
| | | IV-brace | 10874.37 | 0.0272 |
| | | V-brace | 9586.83 | 0.0359 |

| | | | | |
|---|---|---|---|---|
| | Case 3 | Diagonal brace | 10131.81 | 0.0475 |
| | | IV-brace | 10424.87 | 0.0300 |
| | | V-brace | 9223.24 | 0.0370 |

The structure should stand the lateral load to prevent the formation of stresses. The unbraced building has the lowest lateral load capacity as 2214.56 kN at 0.0608 m displacement as shown in Table 13. The highest lateral load is for concentric IV-brace (Case 2), the percentage of the increasing load compare to unbraced is 87.12%.

**5.6.2 Six Story Building**

Table 14: lateral load and displacement of six story building.

| Type of braces | | | Lateral load capacity (KN) | Lateral displacement (m) |
|---|---|---|---|---|
| unbraced | | | 3416.19 | 0.0885 |
| Concentric | Case 1 | Diagonal brace | 14113.65 | 0.1131 |
| | | IV-brace | 16776.59 | 0.1144 |
| | | V-brace | 14503.14 | 0.1093 |
| | Case 2 | Diagonal brace | 14609.61 | 0.0866 |
| | | IV-brace | 18479.53 | 0.0709 |
| | | V-brace | 15928.98 | 0.0636 |
| | Case 3 | Diagonal brace | 11763.64 | 0.0812 |
| | | IV-brace | 13295.60 | 0.0613 |
| | | V-brace | 13554.52 | 0.0881 |
| Eccentric | Case 1 | Diagonal brace | 11334.24 | 0.0733 |
| | | IV-brace | 10824.93 | 0.0466 |

| | | | | |
|---|---|---|---|---|
| | | V-brace | 10157.63 | 0.0624 |
| | Case 2 | Diagonal brace | 10779.64 | 0.0570 |
| | | IV-brace | 10705.93 | 0.0366 |
| | | V-brace | 11524.65 | 0.0573 |
| | Case 3 | Diagonal brace | 8640.17 | 0.0539 |
| | | IV-brace | 9753.07 | 0.0439 |
| | | V-brace | 8506.30 | 0.0498 |

The lateral load and displacement for the unbraced building are 3416.19 kN and 0.0885 m. The percentage of highest lateral load which is concentric IV- brace (Case 2) compared to the lowest load capacity is 81.51%.

### 5.6.3 Eight Story Building

Table 15: lateral load and displacement of eight story building.

| Type of braces | | | Lateral load capacity (KN) | Lateral displacement (m) |
|---|---|---|---|---|
| unbraced | | | 3855.65 | 0.1010 |
| Concentric | Case 1 | Diagonal brace | 17284.96 | 0.1871 |
| | | IV-brace | 17663.03 | 0.1318 |
| | | V-brace | 17034.14 | 0.1651 |
| | Case 2 | Diagonal brace | 18738.42 | 0.1505 |
| | | IV-brace | 21792.84 | 0.1113 |
| | | V-brace | 19329.36 | 0.1024 |
| | Case 3 | Diagonal brace | 14746.77 | 0.1132 |
| | | IV-brace | 18859.85 | 0.1156 |
| | | V-brace | 15485.18 | 0.0957 |

| | | | | |
|---|---|---|---|---|
| Eccentric | Case 1 | Diagonal brace | 13145.60 | 0.1002 |
| | | IV-brace | 12000.89 | 0.0645 |
| | | V-brace | 11943.53 | 0.0860 |
| | Case 2 | Diagonal brace | 12177.47 | 0.0743 |
| | | IV-brace | 12289.03 | 0.0520 |
| | | V-brace | 13393.59 | 0.0734 |
| | Case 3 | Diagonal brace | 10192.88 | 0.0691 |
| | | IV-brace | 11607.65 | 0.0556 |
| | | V-brace | 10094.66 | 0.0596 |

The lateral load capacity increases in the concentric IV-brace (Case 2) by 82.31% compared to the lowest lateral load of 3855.65 kN at lateral displacement of 0.1010 m.

### 5.6.4 Fifteen Story Building

Table 16: lateral load and displacement of fifteen story building.

| Type of braces | | | Lateral load capacity (KN) | Lateral displacement (m) |
|---|---|---|---|---|
| unbraced | | | 4657.06 | 0.1753 |
| Concentric | Case 1 | Diagonal brace | 16466.92 | 0.3220 |
| | | IV-brace | 17213.09 | 0.2989 |
| | | V-brace | 16544.30 | 0.3172 |
| | Case 2 | Diagonal brace | 18838.59 | 0.2676 |
| | | IV-brace | 19294.82 | 0.1825 |
| | | V-brace | 19219.48 | 0.2039 |

| | | | | |
|---|---|---|---|---|
| | Case 3 | Diagonal brace | 20812.38 | 0.3061 |
| | | IV-brace | 22362.55 | 0.2382 |
| | | V-brace | 21394.43 | 0.2440 |
| Eccentric | Case 1 | Diagonal brace | 15213.85 | 0.2588 |
| | | IV-brace | 12635.89 | 0.1559 |
| | | V-brace | 13503.33 | 0.2108 |
| | Case 2 | Diagonal brace | 12434.84 | 0.1400 |
| | | IV-brace | 12259.69 | 0.1025 |
| | | V-brace | 12865.70 | 0.1189 |
| | Case 3 | Diagonal brace | 12898.03 | 0.1540 |
| | | IV-brace | 12604.19 | 0.1104 |
| | | V-brace | 12939.17 | 0.1280 |

Compared to the lowest lateral load of 4657.06 kN at lateral displacement of 0.1753 m, the concentric IV-brace (Case 3) has 79.17% higher lateral load capacity.

## 5.7 Comparison Between Conventional Steel Bracing System and Buckling-Restrained Bracing System

This part considers the comparison of the performance of steel bracing system and buckling-restrained bracing system. The best bracing type and the case for concentric and eccentric braces was considered to achieve these data. Same section and design data for BRB building was taken to design the Conventional Steel Braces.

### 5.7.1 Capacity Curve

All the capacity curve below shows that the BRB system has higher base shear load the conventional steel brace.

1) Four Building Story

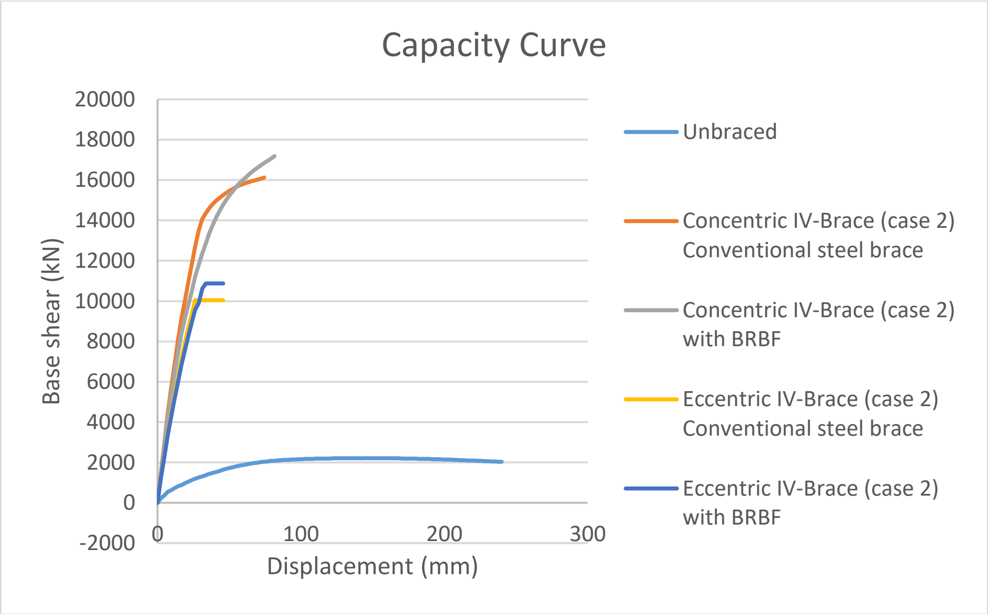



Figure 95: The base shear vs displacement (capacity curve) for concentric and eccentric conventional steel brace and BRBF of the four-story building.

2) Six Story Building

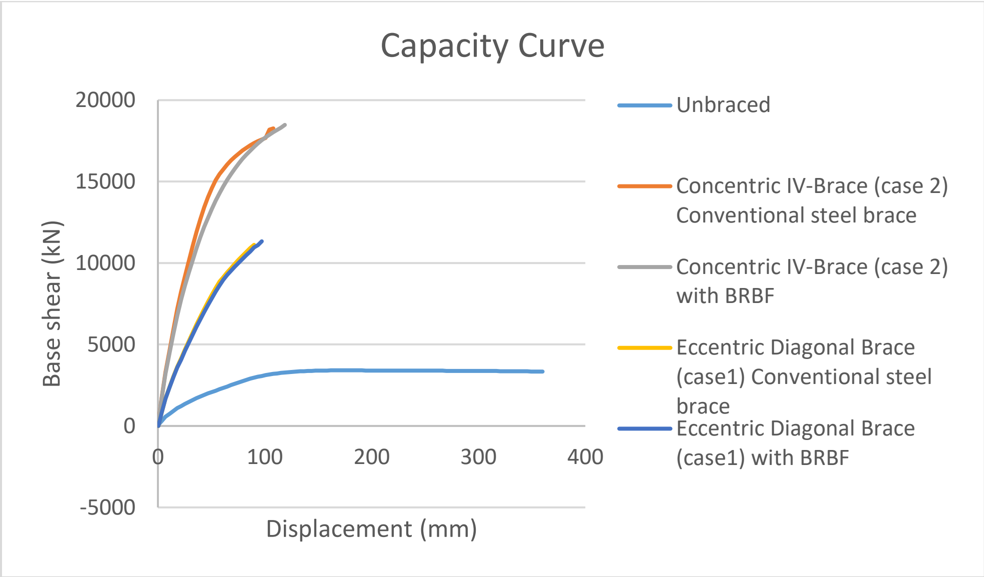



Figure 96: The base shear vs displacement (capacity curve) for concentric and eccentric conventional steel brace and BRBF of the six-story building.

3) Eight Story Building

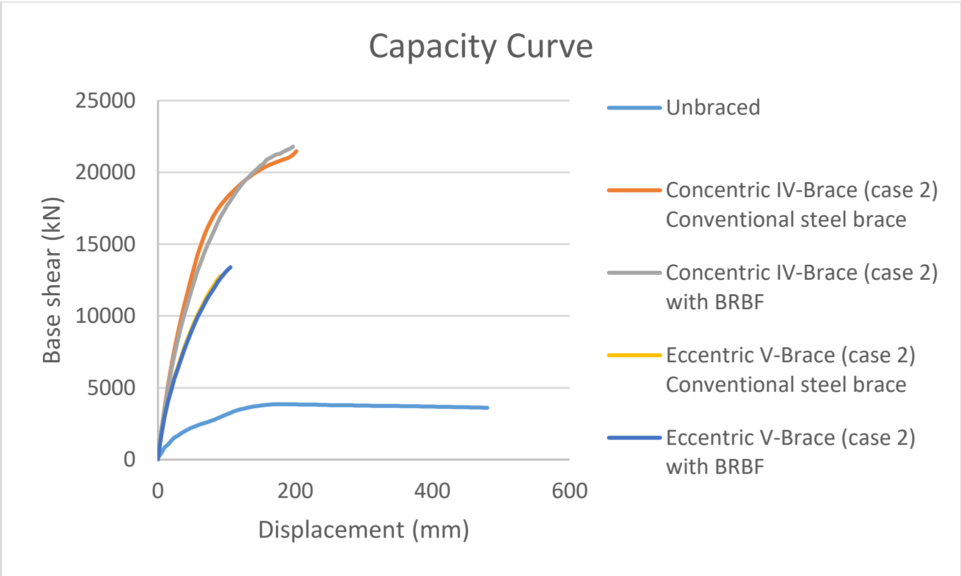



Figure 97: The base shear vs displacement (capacity curve) for concentric and eccentric conventional steel brace and BRBF of the eight-story building.

4) Fifteen Story Building

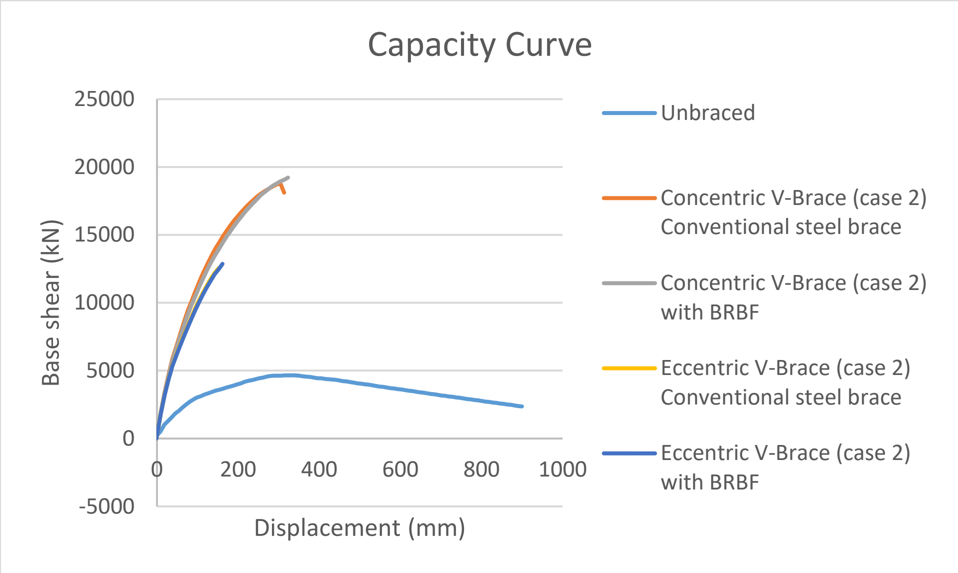



Figure 98: The base shear vs displacement (capacity curve) for concentric and eccentric conventional steel brace and BRBF of the fifteen-story building.

### 5.7.2 Elastic Stiffness

Table 17: Comparison of stiffness between steel brace and BRB system.

| Elastic stiffness (KN) | | | | |
|---|---|---|---|---|
| | | | BRB | Steel brace |
| Four story | Concentric | IV-brace (Case 2) | 620913.22 | 635706.50 |
| | Eccentric | IV-brace (Case 2) | 514911.75 | 521221.20 |
| Six story | Concentric | IV-brace (Case 2) | 452847.27 | 461673.46 |
| | Eccentric | Diagonal brace (Case 1) | 257034.53 | 257901.47 |
| Eight story | Concentric | IV-brace (Case 2) | 378472.78 | 384464.37 |
| | Eccentric | V- brace (Case 2) | 320771.67 | 322961.03 |

| | | | | |
|---|---|---|---|---|
| Fifteen story | Concentric | V-brace (Case 2) | 179753.50 | 181247.55 |
| | Eccentric | V-brace (Case 2) | 169892.89 | 170768 |

This show that the steel bracing that designed without using BRB (conventional steel brace) have slightly higher stiffness load.

### 5.7.3 Target Displacement

Table 18: Performance level for steel bracing system without BRB.

| | | | LD | CD | CP | Target point |
|---|---|---|---|---|---|---|
| Four story | Concentric | IV-brace (Case 2) | 0.0084 | 0.0205 | 0.0357 | 0.0216 |
| | Eccentric | IV-brace (Case 2) | 0.0099 | 0.0264 | 0.0458 | 0.0264 |
| Six story | Concentric | IV-brace (Case 2) | 0.0141 | 0.0384 | 0.0654 | 0.0396 |
| | Eccentric | Diagonal brace (Case 1) | 0.0163 | 0.0444 | 0.0755 | 0.0468 |
| Eight story | Concentric | IV-brace (Case 2) | 0.0208 | 0.0567 | 0.0964 | 0.0576 |
| | Eccentric | V-brace (Case 2) | 0.0176 | 0.0479 | 0.0815 | 0.0480 |
| Fifteen story | Concentric | V-brace (Case 2) | 0.0334 | 0.0911 | 0.1551 | 0.0950 |
| | Eccentric | V-brace (Case 2) | 0.0316 | 0.0861 | 0.1465 | 0.0950 |

All of the braces in the BRB system and conventional steel brace shows similar performance level. In building 4 and 6 performance level was Continued Operation Performance (CO) and in building 8 and 15 it was Limited Damage Performance (LD).

### 5.7.4 Lateral Load Capacity

Table 19: Comparison of lateral load and displacement between steel brace and BRB system.

| | | | Lateral load | | Displacement | |
|---|---|---|---|---|---|---|
| | | | BRB | Conventional steel brace | BRB | Conventional steel brace |
| Four story | Concentric | IV-brace (Case 2) | 17187.46 | 16127.08 | 0.0454 | 0.0344 |
| | Eccentric | IV-brace (Case 2) | 10874.37 | 10045.94 | 0.0272 | 0.0231 |
| Six story | Concentric | IV-brace (Case 2) | 18479.53 | 18266.38 | 0.0709 | 0.0619 |
| | Eccentric | Diagonal brace (Case 1) | 11334.24 | 11115.77 | 0.0733 | 0.0688 |
| Eight story | Concentric | IV-brace (Case 2) | 21792.84 | 21477.07 | 0.1113 | 0.1023 |
| | Eccentric | V-brace (Case 2) | 13393.59 | 12855.24 | 0.0734 | 0.0664 |
| Fifteen story | Concentric | V-brace (Case 2) | 19219.48 | 18807.89 | 0.2039 | 0.1873 |
| | Eccentric | V-brace (Case 2) | 12865.70 | 12551.65 | 0.1189 | 0.1119 |

The lateral loads of BRB in all the buildings are higher than the conventional steel brace structure. Also, it shows the lateral load and displacement for concentric steel braces are higher than the eccentric braces.

# Chapter 6

# CONCLUSION AND RECOMMENDATION

## 6.1 Conclusion

A steel bracing system has been used for the strengthening of reinforced concrete buildings with inadequate seismic lateral resistance. In retrofitted RC frames, the bracing configuration plays a significant role in the response, since it controls the structure's actual lateral capacity. Consequently, there are many existing reinforced concrete frame structures that need seismic retrofitting because of their inadequate lateral resistance. As a result of poor design, changed usage, or changes in design loads following construction, the structure becomes inadequate. Recent studies have shown, however, that incorporating steel bracing into non-linear analysis significantly impacts a structure's stiffness, strength, and energy dispersal mechanisms. The purpose of this thesis, however, is to fill a significant research gap, which is to find the difference between different concentric and eccentric braces types as well as the comparison between BRB and Conventional Steel Braces in symmetrical buildings to find the best behavior braces by using the Seismostruct program.

To conclude, this thesis considered a comparison between the concentric braces and eccentric braces for different type of braces which are V-brace, IV-brace, and Diagonal brace as well as comparison between BRB and Conventional Steel Brace for various height stories as 4, 6, 8, and 15. The majority of the cases are concentric steel braces. There are very few studies concerning the behavior of RC frames with eccentricity bracing steel, so to fill the gap, a seismic investigation has been conducted to determine whether earthquake horizontal loads increase the structural stiffness and resist the horizontal loads for both types of bracing frames (eccentric and concentric). Furthermore, the non-linear pushover analysis for Turkish code 2018 has been applied, allowing for tracing of yielded as well as failed members, and determining the structural capacity.

Accordingly, this study has concluded that using the defined steel bracing in the RC building and by restrained a pushover analysis, assists to improve the structural capacity against the seismic load as it is stated in the following:

- The study analysis indicates that strengthening the system with steel braces enhances its structural integrity.
- It has been determined that existing RC buildings that designed without braces do not have the ability to resist and prevent collapse during moderate earthquakes.
- The pushover analysis shows that braced frames have higher base shear than unbraced frames.
- Concentric bracing frames (CBF) have higher lateral load and displacement than the eccentric bracing frames (EBF).
- As compared with Eccentric braces, Concentric braces show greater performance.
- The highest level of performance can be achieved with inverted V-braces.
- In general, the Case 2 pattern layout provides the best stiffness load.
- In story building 4, 6, and 8 Case 2 was the best performance.
- In high rise building fifteen story Case 3 was the best performance.

- BRB have higher base shear compare to conventional steel bracing. BRB building is heavier than the ordinary braced building.
- BRB have slightly higher lateral displacement than the conventional steel braced building. As well as its easier to fix the BRB when damage occur.

## 6.2 Further Research Stages and Remarks

Research into more types of braces that will enhance and stiffen the retrofitting efficiency of RC structural elements by laying out in various patterns. This is due to the unfavorable arrangement of bracings and their effects on existing members and foundations which result in retrofitting costs. The future research should focus on determining the stability of buildings with various bracing angles and cross-sectional members, and to investigate non-linearly unsymmetrical structures.

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