Effect of Building Height on the Seismic Behavior of Steel Framed Structures

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ABSTRACT

Northridge-USA and Kobe-Japan earthquakes in mid 1990s caused numerous structural damages to 3, 6 and 12 story buildings, in relation to structural design and framing type. Hence, this research was aimed at studying the effect of structural framing type and building height on seismic behavior of steel structures. Equivalent Static Analysis (ESA) were carried out using ETABS software to analyze 6, 12 and 20 story Moment Resisting Frame (MRF) and Concentric Braced Frame (CBF) buildings, with regular and irregular plan and elevations. Eurocodes 3 and 8 were used for the design of 77 different building models considering soil and earthquake parameters for Lebanon. In addition selective models of both frame types were also analyzed using Response Spectrum (RS) and Nonlinear Static Pushover Analysis (NSPA). Considering the lateral displacements obtained it was found that generally up to story 15 moment frames have more displacements than braced frames with similar structure. However, for taller structures the situation was reversed and braced frames achieved more displacements than moment frames. Introducing belts at top and middle or top story only of 20 story braced framed structure generally reduced its lateral displacement in both directions except in y-direction only up to 14 floors. Pushover analysis results showed that moment framed 6 and 12 story regular buildings performed better than similar braced frame ones, and the case was vice versa for 20 story regular buildings.

Keywords: Earthquake, Moment Resisting Frame, Concentric Braced Frame, Irregularity, Displacement, Height Effect, Equivalent Static, Response Spectrum, Nonlinear Static Pushover.

ÖZ

Çelik karkas yapıların birçok avantajları vardır. Bunlardan birisi depreme dayanıklılık için gerekli olan süneklikti̇r. 1990 yılı ortalarında meydana gelen Northridge-ABD ve Kobe-Japonya depremleri 3, 6 ve 12 katlı yapılarda bir dizi yapısal tasarım ve taşıyıcı çerçeve çeşidi alakalı zararlara neden olmuştur. Bu araştırma yapısal çerçeve çeşidinin ve bina yüksekliğinin çelik yapıların depremsel davranışına etkilerini araştırmayı amaçlamıştır. ETABS yazılımı kullanılarak 6, 12 ve 20 katlı, düzenli ve düzensiz plan ve görünüşe sahip, rijit ve çarpraz çerçeveli binalar Eşdeğer Statik yöntemle analiz edilmişlerdir. Çelik ve deprem tasarım standardları, Eurocode 3 ve 8, Lübnan deprem ve zemin parametreleri kullanılarak 77 farklı bina tasarımı yapılmıştır. İlaveten her iki çerçeve tasarımlarından seçilmiş modeller davranış spektrumu ve doğrusal olmayan statik itme yöntemleriyle analiz edilmişlerdir. Analiz sonuçlarında elde edilen veriler 15 kata kadar olan yüksekliklerde ayni tip binalarda rijit çerçeve binaların çarprazlı binalardan daha fazla yatay yer değiştirmeye maruz kaldığını göstermiştir. Diğer yandan 15 kat sonrası yüksekliklerde durumun tam ters olduğu not edildi. 20 katlı çarprazlı binaların en üst ve orta veya sadece en üst katlarına makas tipi kemer yerleştirildi. Binanın yatay yer değiştirmesi, her iki yönde, tüm katlarda rijit çerçeve binadan daha az olurken y yönünde azalma sadece 14 üncü kata kadar oldu. Doğrusal olmayan statik itme analiz sonuçları 6 ve 12 kat düzenli rijit çerçeve yapıların çapraz çerçeveli yapılardan daha iyi performansı olduğunu göstermiştir. 20 kat düzenli yapılarda ise durum tam tersidir.

Keywords: Deprem, Rijit Çerçeve, Merkezi Çarpraz Çerçeve, Düzensizlik, Yer değiştirme, Yütkseklik Etkisi, Eşdeğer Statik, Davranış Spektrum, Doğrusal Olmayan Statik İtme

DEDICATION

Dedicated to

My lovely Father and Mother

To my dearest Brothers and Sisters

To my dear Fiancée

To my Friends

For their Love, Endless Support and

Encouragement

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First of all, I would like to thank God the Almighty for his blessing, good health and special opportunity to obtain higher education.

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LIST OF ABREVIATIONS

1Rx1L	1 Number of Bayes Removed from Extreme Right and 1 Number of Bayes Removed from Extreme Left
1Rx1L D E	1 Number of Bayes Removed from Extreme Right and 1 Number of Bayes Removed from Extreme Left with 2 Different Elevation
15 B 14	15 Story Building with the Same Cross Bracing Steel Sections Used in 14 Story Braced Building
15 B 16	15 Story Building with the Same Cross Bracing Steel Sections Used in 16 Story Braced Building
2Rx1L	2 Number of Bayes Removed from Extreme Right and 1 Number of Bayes Removed from Extreme Left
3D1	First Type of 3D Irregularity
3D2	Second Type of 3D Irregularity
3D3	Third Type of 3D Irregularity
3D4	Fourth Type of 3D Irregularity
B1	Braced Frame Type One
B2	Braced Frame Type Two
B (20)	Braced Frame with Cross-Bracings Belt at the 20th Story

B (10, 20)	Braced Frame with Cross-Bracings Belt at the 20th and 10th Story
B (x dir)	Braced Frame at x Direction
B (y dir)	Braced Frame at Y direction
M (x dir)	Moment Frame at x Direction
M (y dir)	Moment Frame at y Direction

Chapter 1

INTRODUCTION

1.1 Introduction

Steel structures offer many advantages, such as, lower cost, easy installation, quality and sustainability. Nowadays, earthquake resistance of buildings is an important factor for design and steel structures offer high resistance against seismic forces. Steel structures have several structural typologies, some of which are listed below, according to their connection and lateral bracing methods.

- Moment Resisting Frames
- Frames with Concentric Bracings
- Frames with Eccentric Bracings
- Inverted Pendulum Structures

Over the years there has been numerous research on the behavior of steel framed buildings with the above mentioned lateral bracing methods [1]. However, according to the literature review, so far there has not been a comprehensive study looking into the behavioral changes of the same building when it is moment and braced frame. Furthermore, possible behavioral changes when these buildings are regular and irregular in plan, elevation and 3D were also not investigated.

This thesis tried to carry out static and dynamic linear analysis for 77 designs, and pushover analysis for some selected regular buildings to try to see the changes in base shear, lateral displacement of such buildings and also to find their performance point. All these analysis also considered the effect of changes in height of these buildings, 6, 12, and 20 story, on their seismic behavior.

1.2 Earthquake Phenomenon

Despite the accumulated knowledge on seismic activity and effects on buildings still earthquakes happen without warning and the seismic actions are often unexpected. It cannot be determined when and where the earthquakes will happen. For that reason the resulting damages may be disastrous on both humans and nature [2]. After 1945, Japan used steel, which gained huge reputation in the construction of its buildings, more specifically in the 1980’s when construction was mainly with cold-formed steel columns an wide-flange beams to minimize the effect of motions coming from earthquakes, strong construction materials were needed, thus the demand for steel increased to reach its optimal point in 1990 [3] (Fig 1).

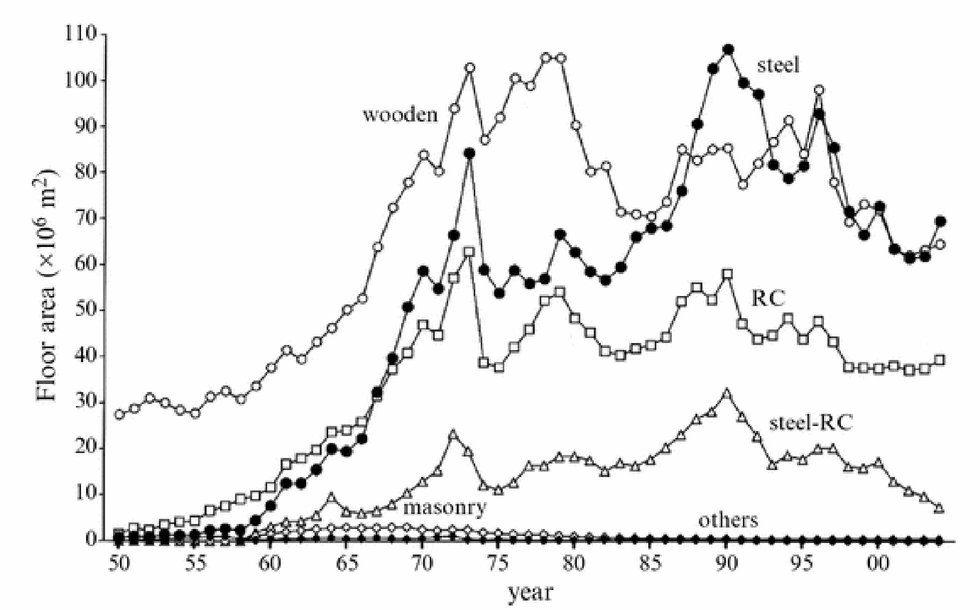


Figure 1.1: Building construction in the latter half of the 20th century of Japan

Two of the well-known earthquakes with relevance to this research are the Northridge and the Kobe earthquakes. Northridge earthquake damages were due to the propagation of seismic waves lasted effectively for 8 seconds but according to citizens it lasted for 30 seconds. This earthquake anticipated the destruction of almost 449,000 houses, and 9,000 buildings. Whereas the Kobe earthquake in Japan resulted in the destruction of over 100,000 buildings and damaged about 80,000 buildings ranging from 3, 6, and 12 stories height. The damages were mainly due to structural problems, for example, type of soil and the design of buildings [4]. The damages of the Northridge earthquake were mainly on buildings with steel moment-resisting frames with no diagonal braces [5]. These results of the earthquakes were shocking for engineers who anticipated better performance from steel-framed buildings than other types of structure [4]. Due to its geographical location, Japan gained quite an interesting reputation as being the country where high magnitude earthquakes happen. Approximately 1500 earthquakes are reported every year some of which leave behind tragedies from physical destruction to biological disasters [6]. One of the most recent earthquake is 9.0 magnitude that hit Tohoko in 2011 resulting the death of nearly 29,000 thousand lives. The reason behind such a loss was not due to building destruction but rather it was due to tsunami that accompanied the earthquake [7].

The effective search for earthquake resistant building designs took place after the Kobe earthquake in 1995 where millions of dollars were spent in research and research equipment like shake tables and 3-D buildings samples to actually know how buildings react to different ground motions [8].

From 2009 to 2013, four agencies grouped together to implement measures that minimizes the risks of earthquakes. The Federal Emergency Management Agency

(FEMA), the National Institute of Standards and Technology (NEHRP), the National Science Foundation and the United States Geological Survey (USGS) had three goals in mind one of which was the improvement of building structures by either rehabilitation of the existing ones to resist risks or constructing new ones in a cost-effective way [9]. With the help of engineers and researchers, FEMA had studied the effect of earthquakes on steel MRF buildings and published many guide lines on how these buildings should be fabricated and constructed to achieve buildings that are more resistant to earthquakes [10].

Placing the importance on improving building construction, UNESCO had highlighted some of the ways in which civil engineers can look at and put in mind when implementing such buildings. Points to be taken into consideration are as follows:

1- Separation joints: separate the joints of the building to let each part move independently avoiding its collusion.
2- Flexible joints: isolate windows from the walls and implement control joints to avoid its breakage.
3- Isolate foundation: ensure that the foundation columns of the building are isolate so that it can move simultaneously during an earthquake.
4- Building sites: pay attention to the quality of the soil and its capacity to hold a building during earthquake.
5- Weight of the construction: construct light buildings especially regarding the roof and floors.
6- Building form: avoid complex building by constructing simple and symmetrical structures.

1.3 Definition of Terms

Earthquake: When rocks deep under the ground rub against each other releasing waves or energy called seismic waves causing the earth to shake and vibrate [11].

EuroCode: Eurocodes are a set of standards for civil engineers concerning design standards in terms of building and other works. These standards are set by the European Committee for Standardization, CEN [12].

Regularities: building structure that has no physical discontinuities.

Irregularities: buildings that has physical discontinuities. It is of two types, vertical or horizontal [13].

Moment frames: A construction design summarized by the way columns and beams are linked together with the use of moment connections allowing its flexibility during wind and earthquakes [14].

1.4 The Objective of the Study

Since avoiding earthquake is not an option, worldwide committees are seeking to find ways to reduce the impact of an earthquake through developing methods and approaches to achieve earthquake-proof countries [15]. Through research different theoretical and experimental cases are considered and still under consideration to learn more about seismic effect on structures so as to reduce the risk of damages to structures.

This research study was aimed at filling a gap with regards to the effect of buildings height on the seismic behavior of different structural systems. For this reason numerous moment resisting and concentrically braced frames of 6, 12 and 20 stories high with regular and irregular plan, elevation and 3D were investigated. Lateral displacements of the buildings at the top story, in both x and y direction, were recorded and compared for MRF and CBF by using Equivalent Static and Response Spectrum analysis. Furthermore, Nonlinear Static Pushover analysis were also carried out on selective models to compare the performance of the two types of framing methods.

1.5 Outline of Thesis

This thesis consists of eight chapters as follows:

Chapter 1 contains a brief introduction to earthquakes and their effects on buildings and hence states the significance and the main objectives of this study.

Chapter 2 presents a literature review about earthquakes, types of buildings used, moment and braced designs, and earthquakes in Lebanon.

Chapter 3 gives details on the methodology used to develop the structural models for analysis. Design parameters, steel standards, analysis methods and steel section properties are also provided.

Chapter 4 contains the results of ES analysis, namely top story displacements for the buildings considered.

Chapter 5 presents the results of RS analysis, namely top story displacements for the buildings considered.

Chapter 6 is the heart of this research where discussions of all the results are presented.

Chapter 7 presents the results of non-linear static pushover analysis.

Chapter 8 gives the conclusions drawn from this research along with the recommendations for future work.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

When a wave hits any building, it creates a natural period under which the building vibrates. This period is studied through careful analysis of the height of a structure because these two happen to be proportional [16]. Higher buildings have low stiffness since they are heavier in mass. Having everything the same, the more stories added, the larger the fundamental natural period becomes [17]. Limited literature is provided on the 6th, 12th and the 20th stories heights.

This research was aimed at investigating numerous MRF and CBF buildings with 6, 12 and 20 stories high with regular and irregular plan, elevation and 3D, by using Equivalent Static and Response Spectrum analysis. Later both framing types and analysis methods were compared to see which method gives less lateral displacement at the top story of the case buildings and the change in behavior with increase in height. There has been limited research into this subject.

Studying ground motion during earthquake is especially important for engineers since they need to understand this behavior and hence construct earthquake resistant structures [11]. These waves can cause damages to buildings that neither have the ability to sway nor to resist the wave, especially the after-shock wave, which may lead to its collapse [18]. In other words the buildings need to behave in a ductile manner so that they have enough strength to resist the earthquake forces and at the same time enough flexibility without collapse. Furthermore, soft soils act as good conductors of seismic waves. It usually multiplies the shaking up to six times. Therefore, as far as practically possible such soils are avoided when trying to build a structure in earthquake prone zone. If there is no other option then soft soils can be replaced by rocky soils [16].

2.2 Factors Affecting Seismic Design

The philosophy of an earthquake resistant structure states that a building must not have any damage to its structural and non-structural elements when facing a minor shake little damages when subject to a moderate shake and severe damages with no collapse when it is exposed to severe shake [17].

Energy released from seismic waves builds up in a structure initiating internal force, which is calculated by multiplying the mass of the building by the acceleration of the wave. Naturally the bigger the mass the greater the internal force is, thus higher the probability of damages to the building. Therefore, seismic-resistant buildings tend to be lighter in weight [16].

When planning for the design of a structure, engineers must take the following factors into consideration:

a) Torsion: the act of twisting an object when a force is exerted on it. Hence, the twist will occur to one end while the other end remains stable, cause deformation to the object. Therefore, engineers should try as much as possible to balance the masses to be able to match the geometric center of the earth to the center of mass.

b) Damping: damping allows the building to have an outstanding performance during earthquake and that is done due to its absorption of energy [19].

c) Ductility: b it is important for engineers to apply flexible materials in their designs so as to achieve earthquake resistant buildings [16].

d) Strength and stiffness: strength indicates the extent to which building can sustain loads before it collapses. Stiffness is measured by the relocation of an element when it is subjected to a force [16].

e) Building configuration: the design of a building in terms of shape, size and elements used. Regular and Irregular building configurations are further discussed and detailed in section 2.3 [16].

2.3 Regular and Irregular Building Configurations

As can be seen from section 2.2 building configuration is one of the important factors that affect seismic behavior. The following sections provide details about the geometrical configurations [20].

2.3.1 Regularity

There are two types of regularities, in plan and in elevation.

2.3.1.1 Regularity in Plan

- A building structure is symmetrical around two orthogonal axes.
- Each story should have a compact outline. However a 5% of its area can be ignored maintaining the stiffness of the plan.
- Stiffness of each floor must be well examined and individually they must be larger than the overall stiffness of the structure.
- The slenderness ratio should remain less than 4
- Two conditions must be maintained: $e_{0x} \leq 0.3\, r_x \;\; and \;\; r_x \geq 1s$

2.3.1.2 Regularity in Elevation

- Elements of structure should operate independently from the entire building.
- Each floor should have its own stiffness studied and it should not be part of the whole structure.

2.4 Irregularity

There are two types of irregularities, in plan and in elevation.

2.4.1 Irregularity in Plan [21]

- Torsional Irregularity: when the maximum drift is higher than 1.2 times the average drift. In addition, extreme torsion irregularities having a drift higher than 1.4 times the average drift.
- Reentrant corner irregularity: when the plan of the structure’s outside reentrant corner is bigger than 15% of its plan size (Fig. 2.1).
- Diaphragm Discontinuity irregularity: summarized by having diaphragm stiffness variations greater than 50% moving from one floor to another (Fig. 2.2).
- Out-of-order offsets irregularities: when the vertical lateral force-resistance elements are not symmetrical to the seismic force-resistance system.

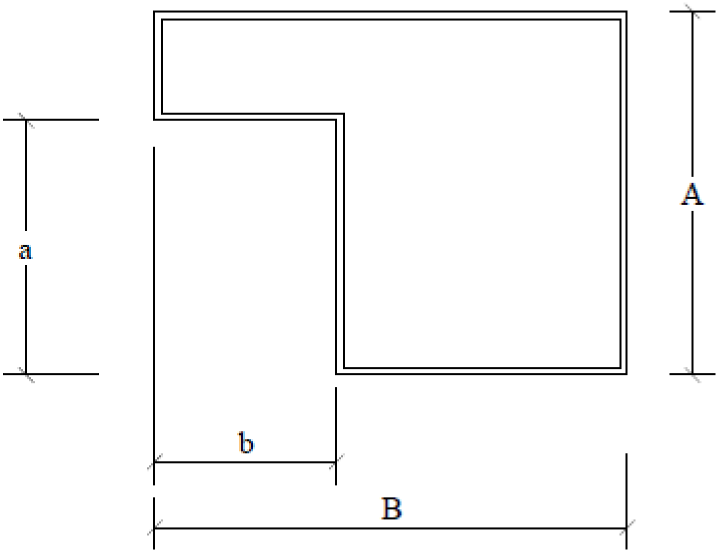


Figure 2.1: Reentrant Corner Irregularity [20]

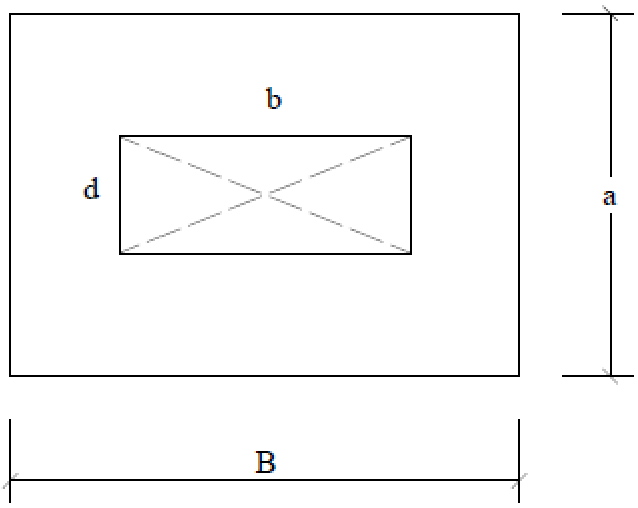


Figure 2.2: Diaphragm Discontinuity Irregularity [20]

2.4.2 Irregularities in Elevation [21]

- Stiffness-soft irregularities: when stiffness of the floor is less than 70% of the floor above or less than 80% of the average stiffness of the three floor levels above. It is called extreme when it is less than 60% or less than 70% respectively (Fig.2.3).

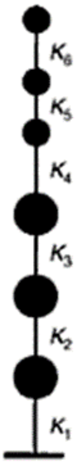


Figure 2.3: Stiffness Irregularities [21]

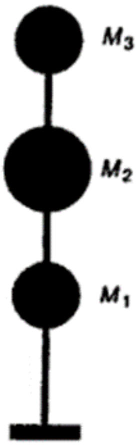


Figure 2.4: Mass Irregularity [21]

- Weight-mass irregularities: effective mass of a floor is bigger than 150% of the effective mass of an adjacent floor (Fig 2.4).
- Vertical geometric irregularities: when the seismic force resistance system has a horizontal dimension exceeding 130% of the adjacent story (Figure 2.5).

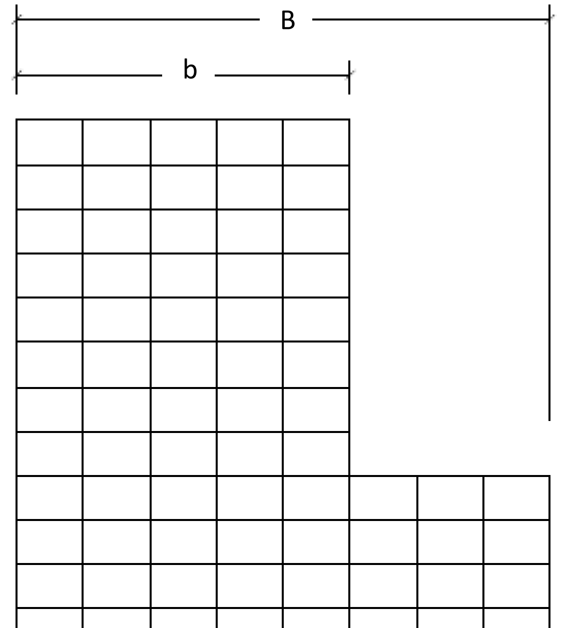


Figure 2.5: Vertical Geometric Irregularities [20]

- In-plane discontinuity in vertical lateral force-resisting element irregularity: simplified as a reduction in stiffness of the element in floor below (Figure 2.6).

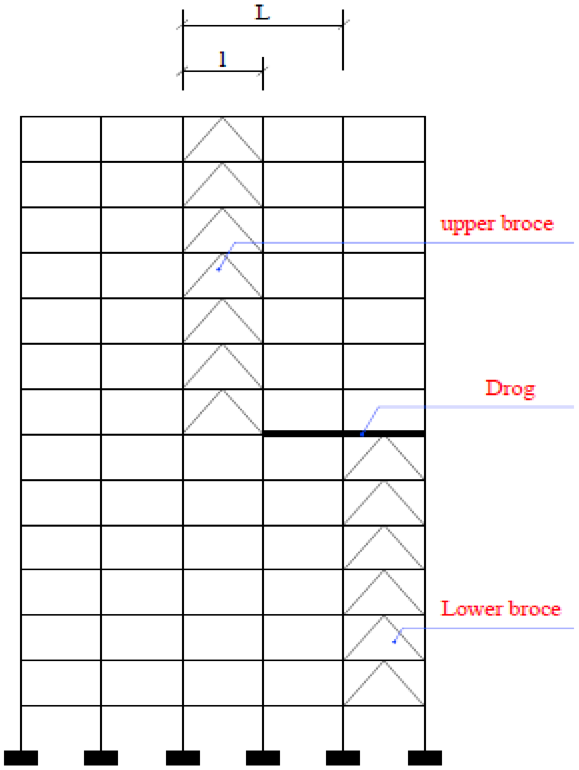


Figure 2.6: In-plane discontinuity irregularity [21]

- Discontinuity in lateral strength-weak story irregularity: when the floor lateral strength is 80% less than the floor above. It is extreme when it is less than 65% (Figure 2.7).

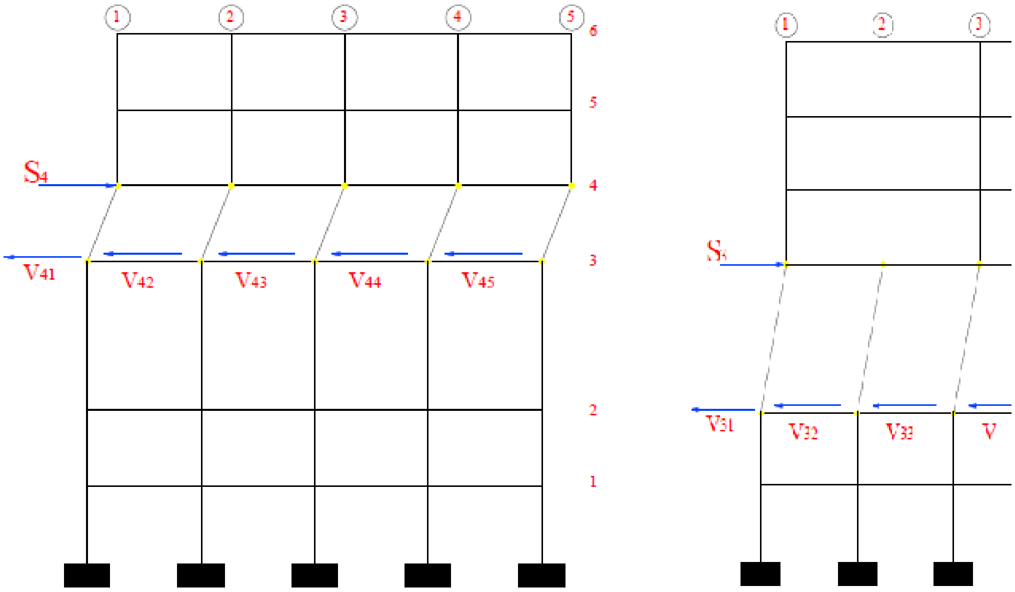


Figure 2.7: Discontinuity in Capacity [21]

2.5 Moment and Braced Frames

Lateral Load Resisting Systems (LLRC) are important to understand when dealing with steel designs. These systems are called moment frames or unbraced frames and braced frames [22].

Braced frames have high strength and stiffness (more rigid), are efficient since they require the use of little material and are easily connected, are of economic benefit since they are compact thus have lower heights between floors. Nevertheless, braced frames may have conflict with the architectural design, location of doors and windows in addition to having low ductility which is the most important criteria to look at when dealing with seismic designs, but it can be solved with the use of structural sleeves [23]. Braced frames in general are advised when dealing with steel and when having a maximum of eight stories buildings, due to its ability to be stable [24].

In steel structure braced frames use additional diagonal elements to overcome any load. They come in many forms, X braced uses small space and it is great in bending, other forms of bracing, like K-braced and knee brace, are not to be discussed in this paper [25].

Moment frames are known for their flexibility due to the lack of braces and have good ductility. On the other hand, it is expensive because of the amount of material used and labor required, plus it has low stiffness leading to damages of non-structural elements during earthquakes [16].

Moment-resisting connections (to stabilize the structure): Unlike concrete, steel structures lack moment resisting joints. This beam and column engagement is all about using shear connection to transfer horizontal loads to column extensions with the help of stiffener plates [25].

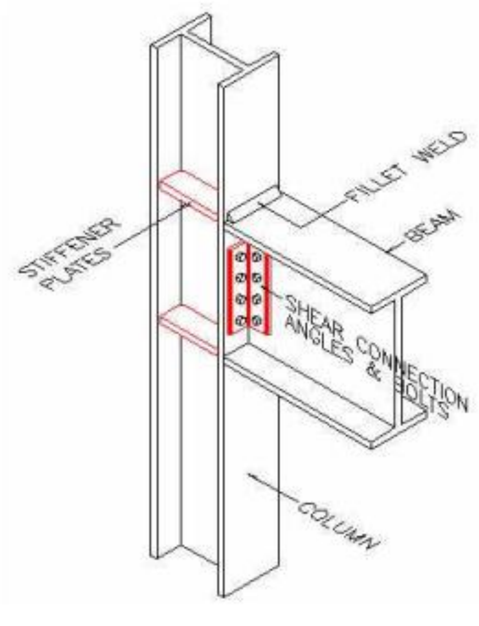


Figure 2.8: Steel Connection [24]

2.6 Seismic Analysis Methods

2.6.1 Equivalent Static Analysis

Equivalent static analysis comes handy when dealing with a displacement controlled structure which causes the natural frequencies of variation to be higher than the usual. Its use allows fast development of foundation loading and it also gives information about the final stiffness of the structure. [26]

2.6.2 Linear Dynamic (Response Spectrum) Analysis

For design purposes, response spectra serve as a common seismic analysis. It has ability to cut through time and provide only the maximum response without really explaining it. It is determined by the formula of motion q (t) after submitting an appropriate SDOF system. A response spectra is simply the diagram resulting from the independent variable as the natural variation frequencies of the SDOF and the dependent variable as the equivalent maximum response values [27].

2.6.3 Non-Linear Static (Pushover) Analysis

Non-linear analysis was first developed in Slovenia more specifically by Tomazevic during the late seventies, which is mainly based on the “story-mechanism” approach studying and analyzing shear displacement for each story [28]. Pushover analysis helps study the behavior of buildings during earthquakes. It is the act of pushing in a horizontal form while exercising some force to a structure until it reaches its limit states, hence the name pushover. While conducting a pushover analysis, it is advised to look at the performance point of the structure being analyzed. A performance point is simply the intersection between the capacity spectrum curve and the demand spectrum curve [29].

By applying this method, engineers will be able to compare the load and the deformation behavior of a structure. The displacement studied is analyzed by looking at the pushover curve, which is basically plot of the values of base shear and roof displacement. It offers information about lateral strength, stiffness and drift of the building [30], and the performance levels which are divided as structural and non-structural: (31)

- Immediate occupancy performance level: the damage occurring after the earthquake took place resulting a low damage i.e: cracks.
- Life safety performance level: the damage occurring after the earthquake took place resulting a noticeable damage. i.e: intensive damage in the beams, and destruction of concrete cover.
- Collapse prevention level: when the structure is about to experience partial or total collapse. i.e: hinges formed in the ductile.

2.6.4 Non-Linear Dynamic (Time-History) Analysis

Modern engineering believes that response spectra may have misleading information and consideration of the motion duration an earthquake. Therefore, the assessment of seismic analysis is unrealistic. Hence, the non-linear dynamic structural analysis provides more details which enable engineers to have more information about the procedure in hand. It has three- components; ground motion time history: the seismic sources, regional ground motion attenuation and the essential geotechnical characteristics of the target. It is advised to use this technique when dealing with low seismic motions [32].

2.7 Earthquakes in Lebanon

According to Ata Elias, assistant professor of Geology at AUB, Israel, Palestine, Jordan, Syria and Lebanon are sitting on a fault line that recently became active [33].

This line stretches from Aqaba to Turkey. Robert Watkins, UN resident coordinator in Lebanon, expressed his grief and concern not only to the earthquake but to its consequences on the buildings. As a result of the collapse of Ashrafieh building, public and the professionals demanded a study of all the buildings in Beirut and assess if they can resist an earthquake [33]. Watkins stressed on that fact and called for a conference under the name “Assessing and managing risks in Lebanon” Natural disasters caused a loss of over 1.5Billion USD for Lebanon, between the years of 1980 and 2012 [34].

Lebanon has a history of earthquakes with magnitudes up to 7.0. However, during the last five years, the highest magnitude of earthquake reported in Lebanon by the National Center for Geological Research of Bhanes is 4.0 which followed by aftershock tremor of 3.6 in magnitude [35].

Mouin Hamze, secretary general of the national council for scientific research (CNRS), claimed that in 2008, thousands of earthquakes occurred in Srifa and the Litani basin indicating huge seismic activity and for that he urged the Lebanese government to be prepared and ready for future with more powerful earthquakes by having seismic-resistant structures [36].

Lebanon is divided into two zones, zone 1 of moderate earthquake hazards, ground acceleration of 20% g (gravitational acceleration) and zone 2 of high earthquake hazards, ground acceleration of 30% g (Figure 2.11) [37].

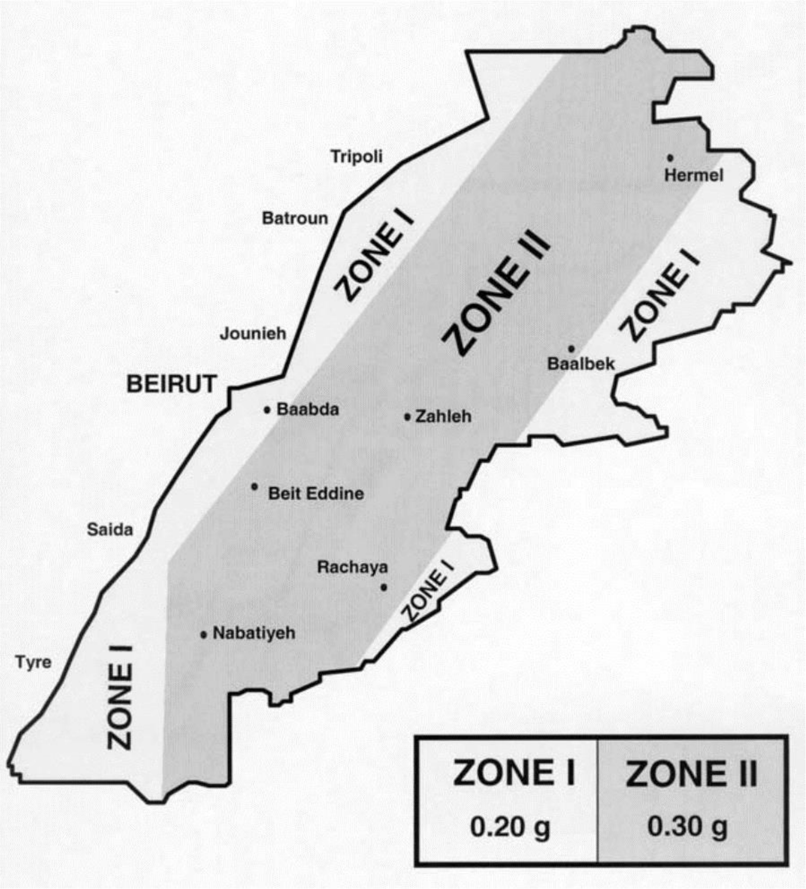


Figure 2.9: Earthquake Lebanon zone [37]

Chapter 3

METHODOLOGY

3.1 Introduction

This research thoroughly investigates the behavior of Moment Resisting Frames (MRF) and Concentric Bracing Frames (CBF) that are subjected to seismic loads. For this purpose, 77 regular and irregular buildings with three different building heights and number of floors, 19m (6 Story), 37m (12 Story) and 61m (20 Story), with same steel column and beam sections , except in few occasion when columns failed, were considered. General analysis software ETABS version 2013 [38] was used to carry out the linear dynamic analysis with different load combinations.

3.1.1 Steel Sections and Weight of Regular Design MRF and CBF:

Table 3.1: section and weight of 6 story regular geometry MRF

Section	Element Type	Piece No	Weight (kN)
HE200B	Column	12	21.6417
HE240B	Column	60	146.8642
HE320B	Column	48	198.2821
HE450B-1	Column	24	134.2407
IPE330	Beam	186	597.4749
IPE400	Beam	132	528.5579
Total			1627.0615

Table 3.2: Section and weight of 6 story regular geometry CBF

Section	Element Type	Piece No	Weight (kN)
HE200B	Column	12	21.6417
HE240B	Column	60	146.8642
HE320B	Column	24	99.141
HE400B	Column	24	121.925
HE450B-1	Column	24	134.2407
IPE330	Beam	186	597.0123
IPE400	Beam	132	528.2457
TUBO180X126X14.2	Brace	12	48.8508
TUBO180X180X10	Brace	36	139.7909
Total			1837.7123

Table 3.3: Section and weight of 12 story regular geometry MRF

Section	Element Type	Pieces No	Weight (kN)
H400X262	Column	24	205.6715
H400X314	Column	24	246.3132
HE200B	Column	12	21.6417
HE260B	Column	12	32.6981
HE280B	Column	36	108.9012
HE300B	Column	36	123.8647
HE320B	Column	12	44.6135
HE400B	Column	48	219.465
HE450B-1	Column	36	181.2249
HE550B-1	Column	24	140.768
HE600B-1	Column	12	83.1307
HE650B-1	Column	12	88.057
IPE330	Beam	204	673.4916
IPE360	Beam	40	150.1275
IPE400	Beam	152	614.4915
IPE450	Beam	77	346.8756
IPE500	Beam	163	901.2676
Total			4182.6033

Table 3.4: Section and weight of 12 story regular geometry CBF

Section	Element Type	Pieces No	Weight (kN)
H400X262	Column	12	102.8357
H400X314	Column	24	246.3132
H400X340	Column	12	133.317
H400X383	Column	12	150.251
HE200B	Column	12	21.6417
HE260B	Column	12	32.6981
HE280B	Column	36	108.9012
HE300B	Column	36	123.8647
HE320B	Column	12	44.6135
HE400B	Column	48	219.465
HE450B-1	Column	12	60.4083
HE550B-1	Column	36	211.152
HE600B-1	Column	12	83.1307
HE700B-1	Column	12	84.7933
IPE330	Beam	204	673.4916
IPE360	Beam	40	150.1275
IPE400	Beam	152	614.4915
IPE450	Beam	84	386.8227
IPE500	Beam	156	852.4429
TUBO180X126X14.2	Brace	32	139.081
TUBO180X180X10	Brace	32	119.9583
TUBO180X180X20	Brace	32	229.5453
Total			4789.3462

Table 3.5: Section and weight of 20 story regular geometry MRF

Section	Element Type	Pieces No	Weight (kN)
H400X237	Column	36	251.0547
H400X288	Column	24	203.3931
H400X340	Column	24	239.9706
H400X347	Column	36	380.1844
H400X383	Column	12	150.251
H400X463	Column	24	362.6961
H400X467	Column	24	366.3908
HE300B	Column	20	68.8137
HE320B	Column	100	371.7789
HE340B	Column	12	47.3845
HE360B	Column	12	50.1555
HE400B	Column	12	54.8663
HE450B-1	Column	24	120.8166
HE500B	Column	24	132.4549
HE550B-1	Column	24	140.768
HE600B-1	Column	36	224.4529
HE650B-1	Column	36	237.7538
IPE330	Beam	300	1011.8853
IPE360	Beam	60	224.1057
IPE400	Beam	120	443.2916
IPE500	Beam	129	704.8838
IPE550	Beam	140	949.9508
IPE600	Beam	143	1127.7034
IPE750X137	Beam	168	1262.273
Total			9127.2794

Table 3.6: Section and weight of 20 story regular geometry CBF

Section	Element Type	Pieces No	Weight (kN)
H400X237	Column	24	167.3698
H400X288	Column	24	203.3931
H400X340	Column	36	359.9559
H400X347	Column	24	244.4042
H400X383	Column	12	150.251
H400X422	Column	12	148.8039
H400X463	Column	12	181.3481
H400X467	Column	24	366.3908
H400X509	Column	12	179.5623
H400X593	Column	12	209.2122
H400X678	Column	12	239.4164
H400X900	Column	12	353.7673
H400X990	Column	12	388.559
HE300B	Column	20	68.8137
HE320B	Column	100	371.7789
HE360B	Column	12	50.1555
HE450B-1	Column	12	60.4083
HE500B	Column	24	132.4549
HE550B-1	Column	36	211.152
HE600B-1	Column	12	74.8176
HE650B-1	Column	36	237.7538
IPE330	Beam	300	1011.8853
IPE360	Beam	60	224.1057
IPE400	Beam	120	440.2477
IPE500	Beam	129	704.5088
IPE550	Beam	140	947.9086
IPE600	Beam	143	1126.493
IPE750X137	Beam	168	1262.2326
TUBO180X180X10	Brace	48	179.9374
TUBO180X180X20	Brace	48	338.7057
TUBO180X180X30	Brace	64	640.3347
Total			11276.1282

3.2 Moment Resisting Frames

In Moment Resisting Frames the members act in a flexural manner, which means that the horizontal forces are mainly resisted by these members.

3.2.1 Regular Building Designs

As mentioned earlier, three different elevations were considered with a plan layout having a 5 x 3 bays: The first floor having a height of 4m, while the others having 3m height. Each of the 5 bays has a span of 7m which can be seen through 4 typical elevation views in x direction (Fig 3.1a), and each of the 3 bays has a span of 6m which can be viewed through 6 typical elevation views in y direction (Fig 3.1b). A secondary beam is placed at every 3m of the 6m span bays (Fig 3.1c).

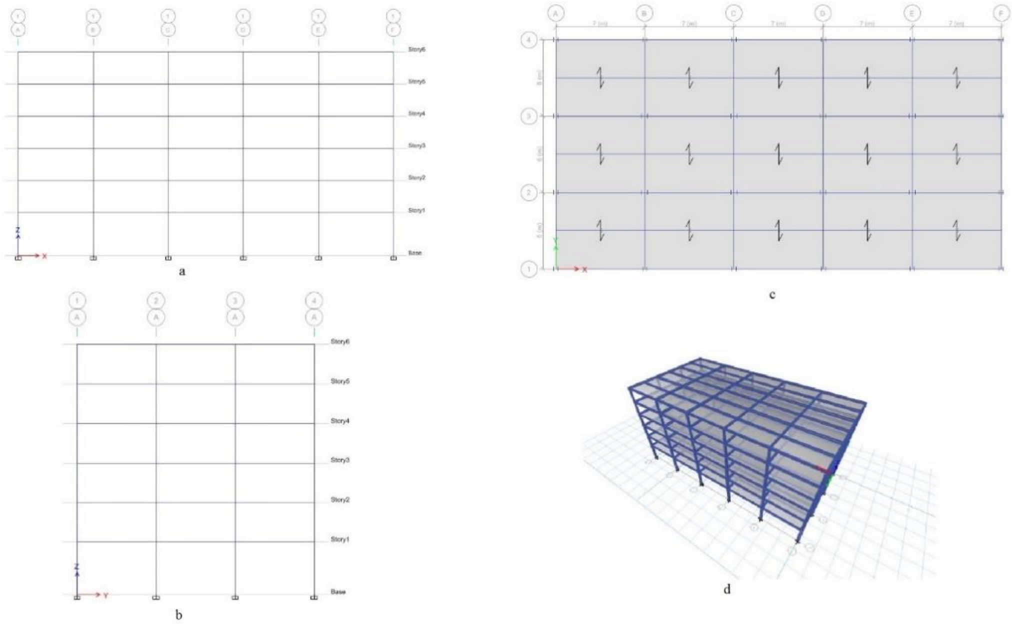


Figure 3.1: typical view of regular building

3.2.2 MRF Irregular Building Designs

Three types of irregularities were considered: Plan, elevation and 3D. Several designs of the aforementioned were studied: 1 plan irregularity design, 3 elevation irregularity designs and 4 3D irregularity designs.

3.2.2.1 MRF Plan Irregularity

To conduct the study of seismic loads, 26.6% of the members in original design was removed in all three building types investigated (6, 12, and 20 floors) (Fig 3.2).

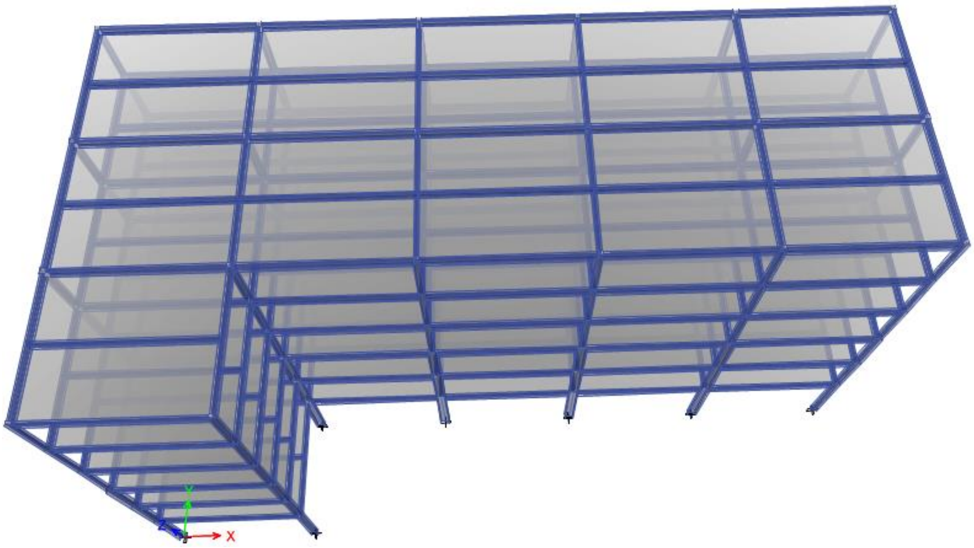


Figure 3.2: Typical 3D view of plan irregularity

3.2.2.2 MRF Elevation Irregularity

(1Rx1L) is the first elevation irregularity where 2/3 of the structural members from the original design, which are located at the extreme left and right of the 5 bays, were removed from the elevations on gridlines 1 to 4.

- 6 story building design: 4 floors were removed from extreme left and right bays (Fig 3.3)
- 12 story building design: 8 floors were removed from extreme left and right bays (Fig 3.4)
- 20 story building design: 13 floor were removed from extreme left and right bays (Fig 3.5)

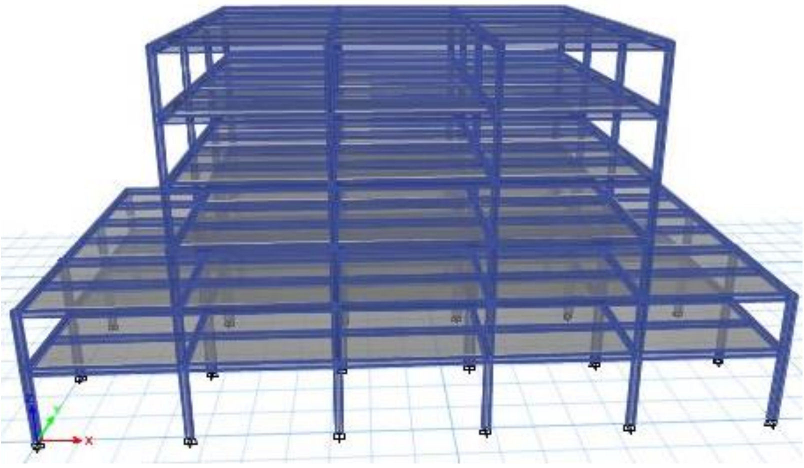


Figure 3.3: 3D view of (1Rx1L) 6 story elevation

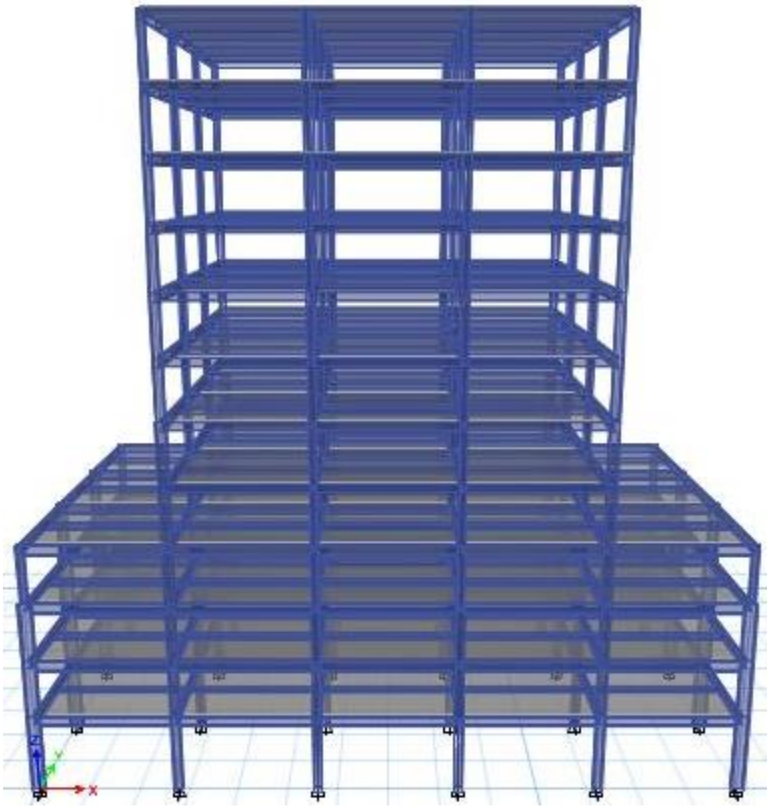


Figure 3.4: 3D view of (1Rx1L) 12 story elevation

Figure 3.5: 3D view of (1Rx1L) 20 story elevation

(2Rx1L) is the second elevation irregularity, which is same as the (1Rx1L) irregularity except that 2 bays from the right were removed along with the extreme left bay in all three building heights at the elevations on gridlines 1 to 4.

- 6 story building design: 4 floor were removed from the left bay and 4 floor were removed from the extreme 2 right bays (Fig 3.6)
- 12 story building design: 8 floor were removed from the left bay and 8 floor were removed from the extreme 2 right bays (Fig 3.7)
- 20 story building design: 13 floor were removed from the left bay and 4 floor were removed from the extreme 2 right bays (Fig 3.8)

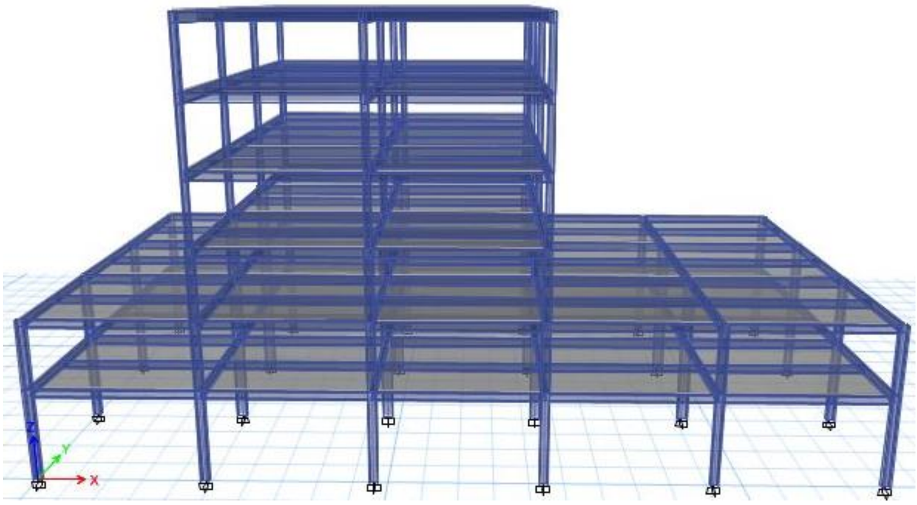


Figure 3.6: 3D view of (2Rx1L) 6 story elevation

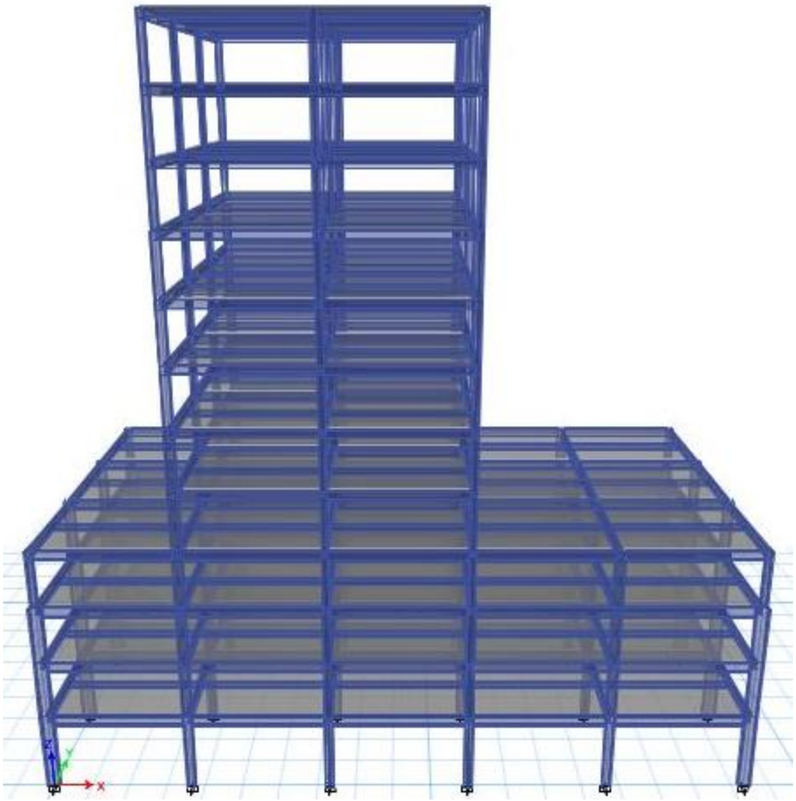


Figure 3.7: 3D view of (2Rx1L) 12 story elevation

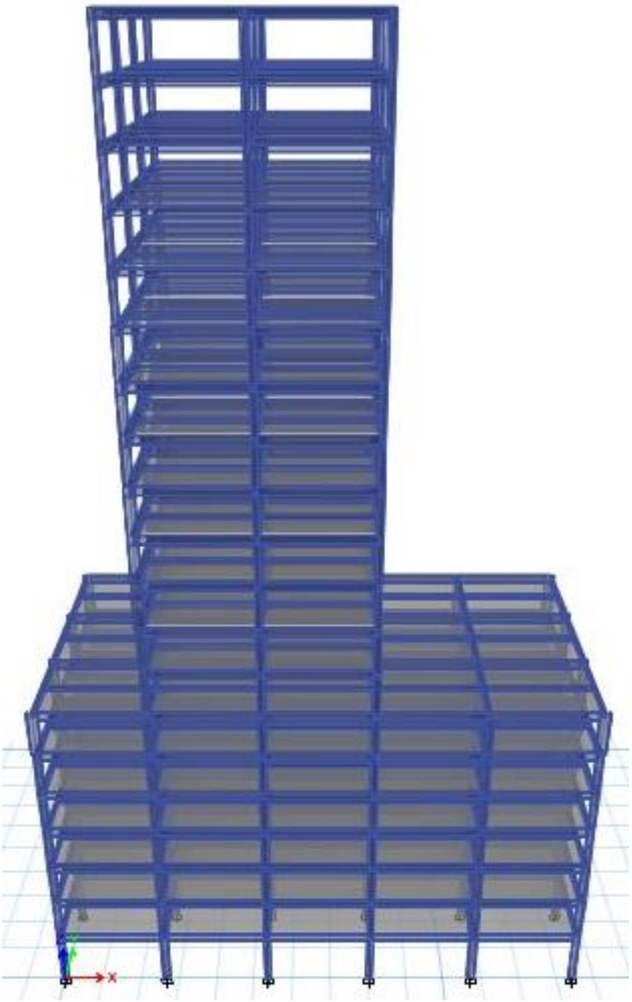


Figure 3.8: 3D view of (2Rx1L) 20 story elevation

(1Rx1L) different elevation is the third elevation irregularity which consisted of removing 2/3rd of the original design members on one extreme of the horizontal bays while removing 1/3rd of the original design members on the other extreme bay in all the elevations at gridlines 1 to 4. In other words,

- 6 story building design: 4 floors were removed from left side and 2 floors were removed from the right side (Fig 3.9)
- 12 story building design: 8 floors were removed from left and 4 floors were removed from the right side (Fig 3.10)
- 20 story building design: 13 floors were removed from the left span, and 7 floors were removed from the right span (Fig 3.11).

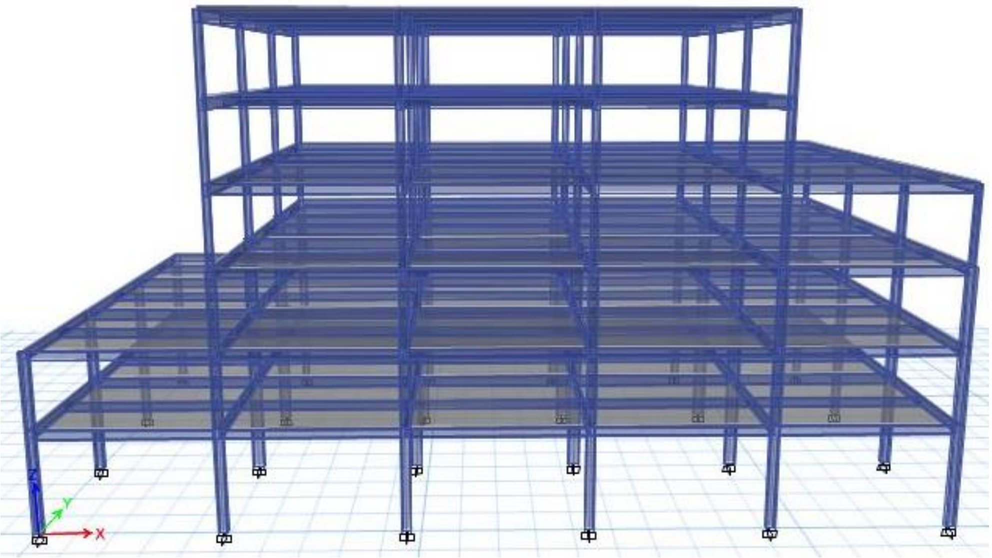


Figure 3.9: 3D view of (1Rx1L) D E 6 story elevation

Figure 3.10: 3D view of (1Rx1L) D E 12 story elevation

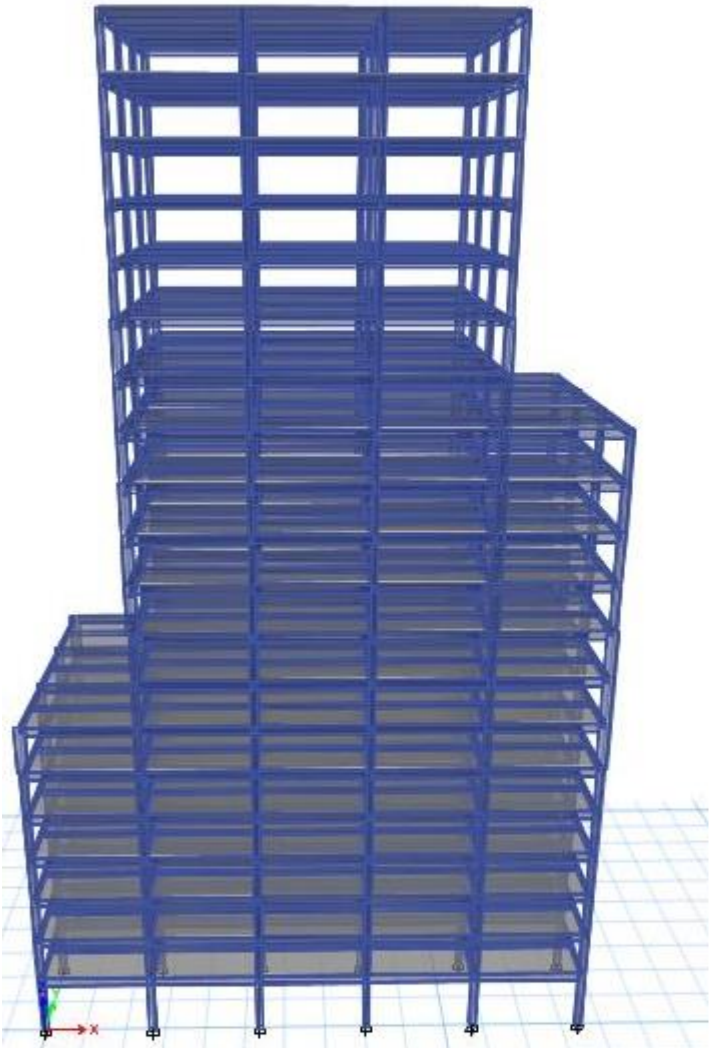


Figure 3.11: 3D view of (1Rx1L) D E 20 story elevation

3.2.2.3 MRF 3D Irregularity

The first 3D irregularity considered is the 3D1 which consisted of removing two thirds of the original design members from the far 2 right bays then removing one third of the members from the middle bay in all elevations. In other words,

- 6 story building design: 4 floors were removed from the right bay and 2 floors were removed from the middle bay (Fig 3.12).
- 12 story building design: 8 floors were removed from the right bay and 4 floors were removed from the middle bay (Fig 3.13).

- 20 story design: 14 floors were removed from the right bay and 7 floors were removed from the middle bay (Fig 3.14).

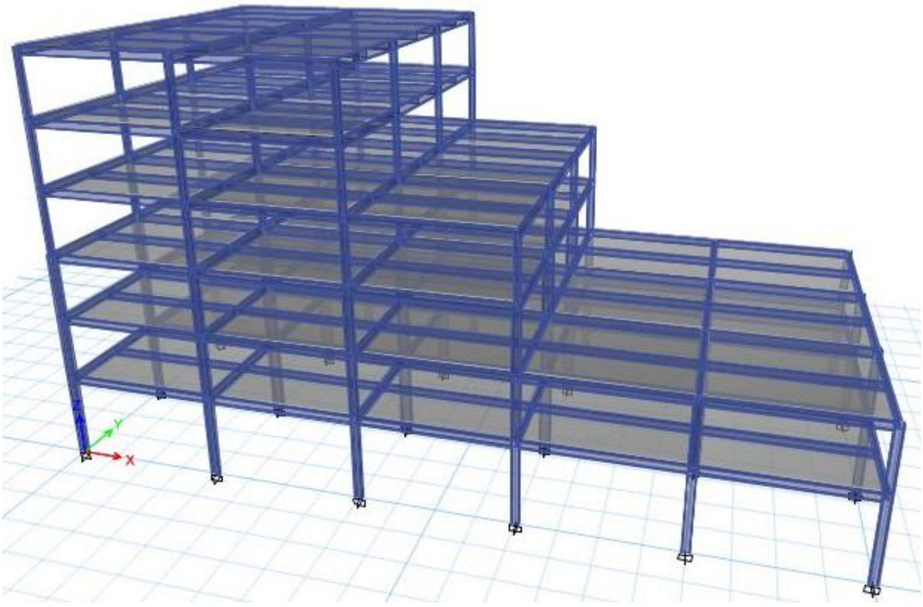


Figure 3.12: 3D view of 3D1 irregularity 6 story elevation

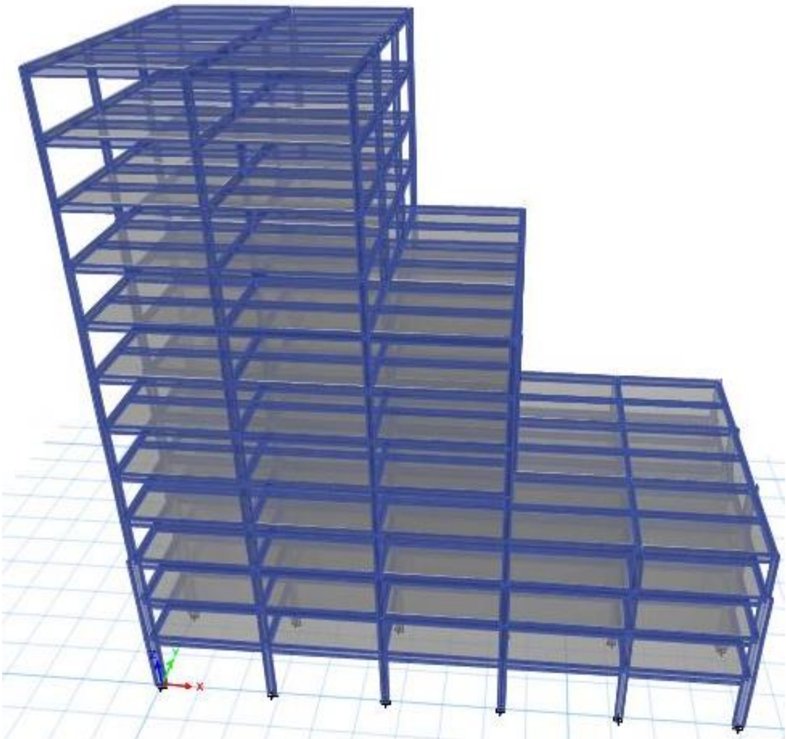


Figure 3.13: 3D view of 3D1 irregularity 12 story elevation

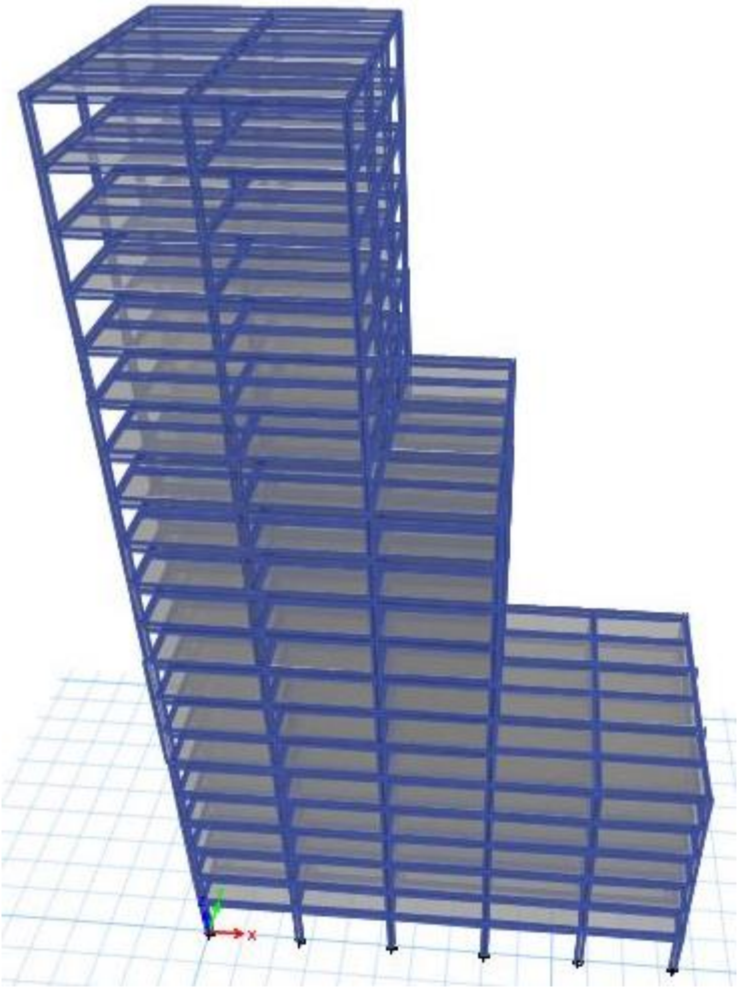
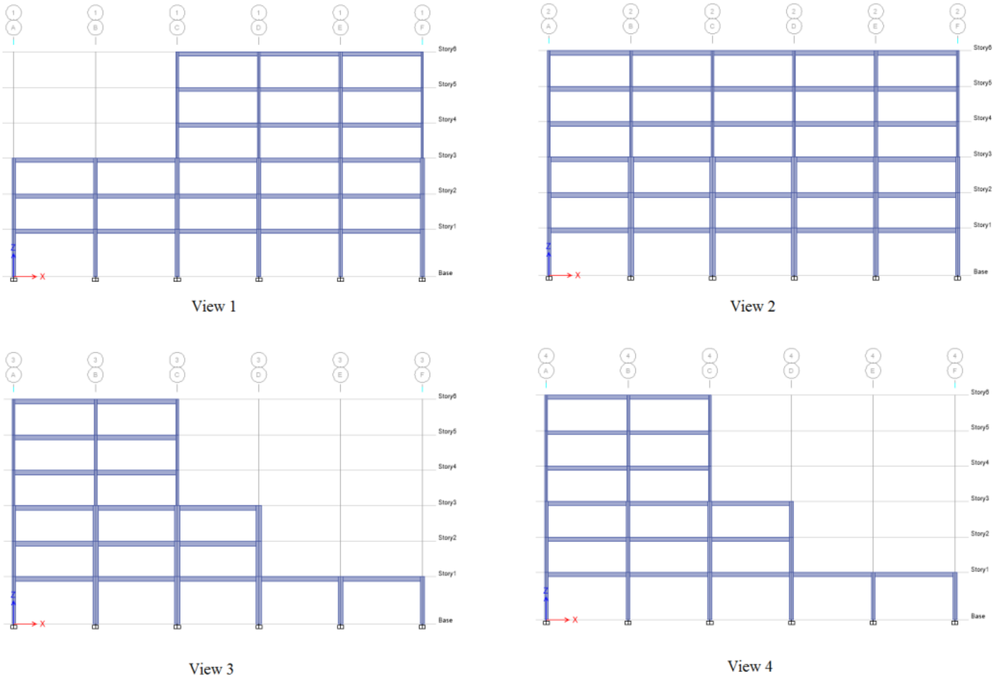


Figure 3.14: 3D view of 3D1 irregularity 20 story elevation

The second 3D irregularity considered was 3D2 which consisted of removing 5/6 of the original design from the far 2 right bays and then removing 1/2 from the middle bay from the gridlines 3 and 4, and 1/2 from the left 2 bays from gridline 1. This means that

- 6 story building design: 5 floors were removed from the right bay and 3 floors were removed from the middle bay on gridlines 3 and 4, and 3 floors were removed from the left bays on gridline 1 (Fig 3.15 - 3.16).
- 12 story building design: 10 floors were removed from the right bay, 6 floors were removed from the middle bay on gridlines3 and 4, 6 floors were removed from the left bay on gridline 1 (Fig 3.17 - 3.18).

- 20 story building design: 17 floors were removed from the right bay, and 10 floors were removed from the middle bay on gridlines 3 and 4, and 10 floors were removed from the left bays on gridline 1 (Fig 3.19 – 3.20).



View 1

View 2

View 3

View 4

Figure 3.15: 3D2 irregularity at 6 story

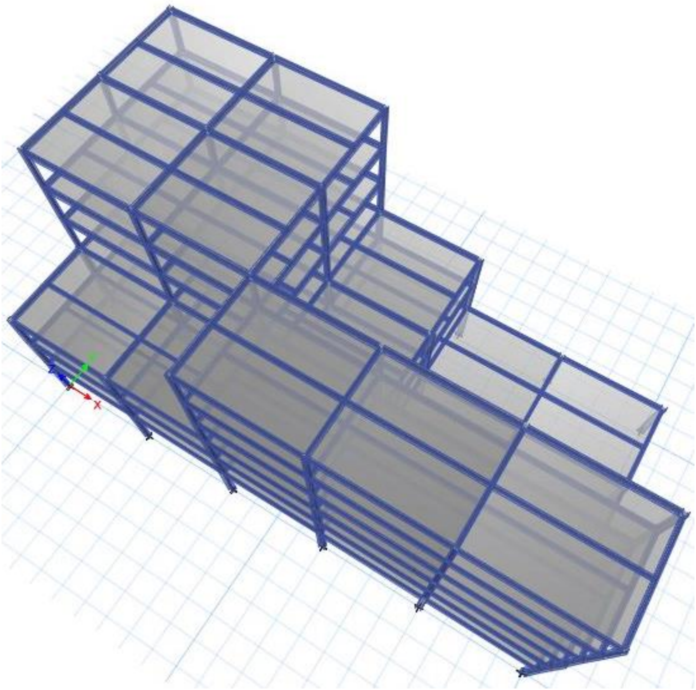
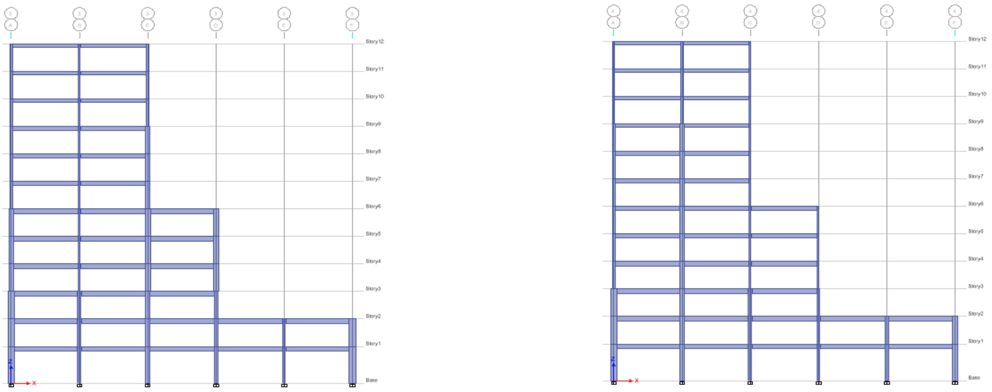


Figure 3.16: 3D view of 3D2 irregularity 6 story elevation

View 1

View 2



View 3

View 4

Figure 3.17: 3D2 irregularity at 12 story

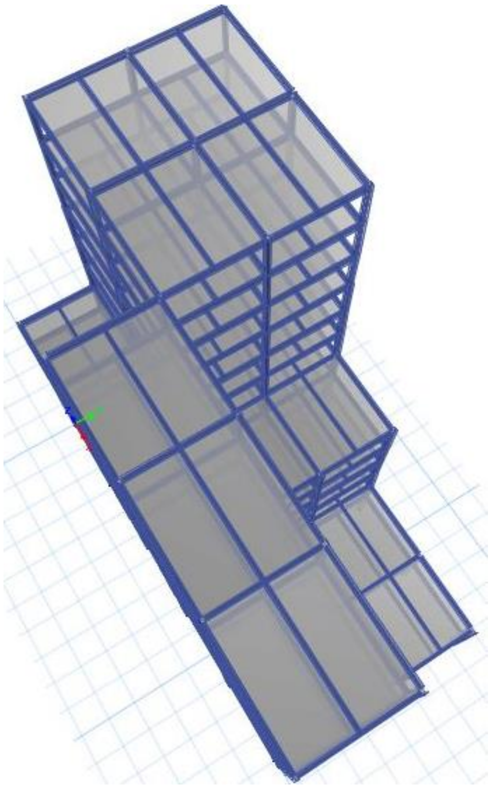
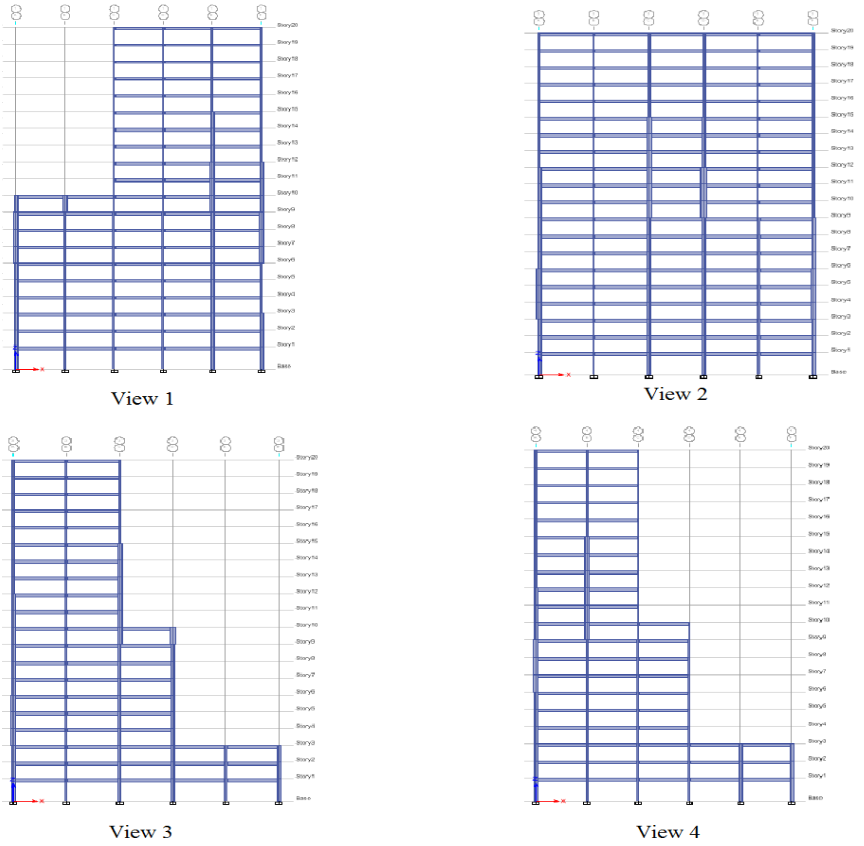


Figure 3.18: 3D view of 3D2 irregularity12 story elevation


View 1

View 2

View 3

View 4

Figure 3.19: 3D2 irregularity at 20 story

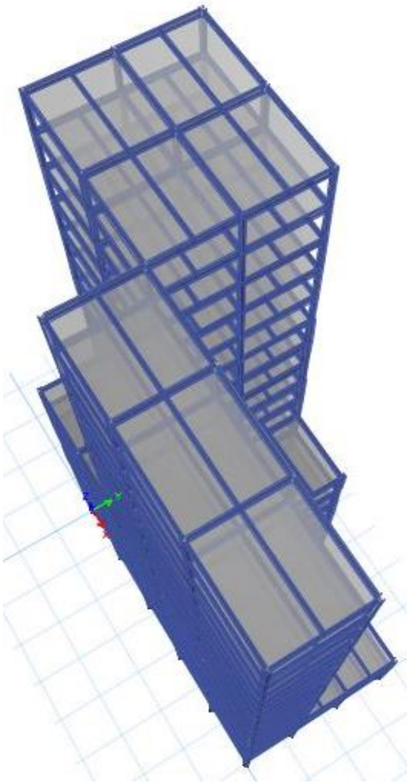


Figure 3.20: 3D view of 3D2 irregularity 20 story elevation

The third 3D irregularity considered was 3D3 which is same as 3D2 with a bay added in the middle as shown in Figures 3.21 and 3.22. 3D view for 3D3 in 3 different elevation was shown in Figures 3.23, 3.24 and 3.25.

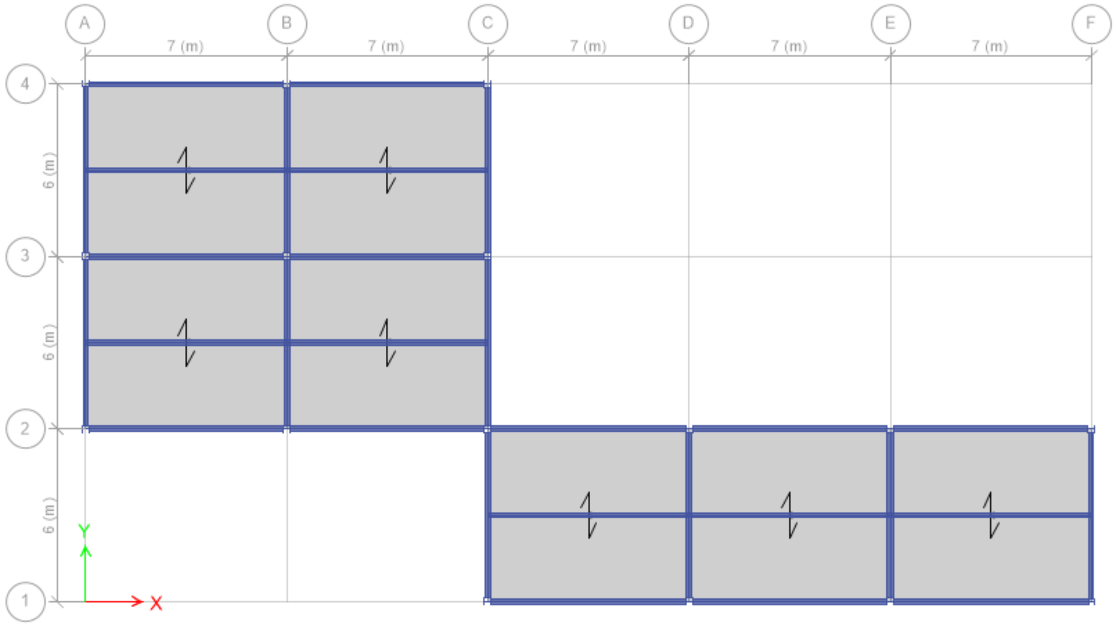


Figure 3.21: Plan view of 3D2 irregularity

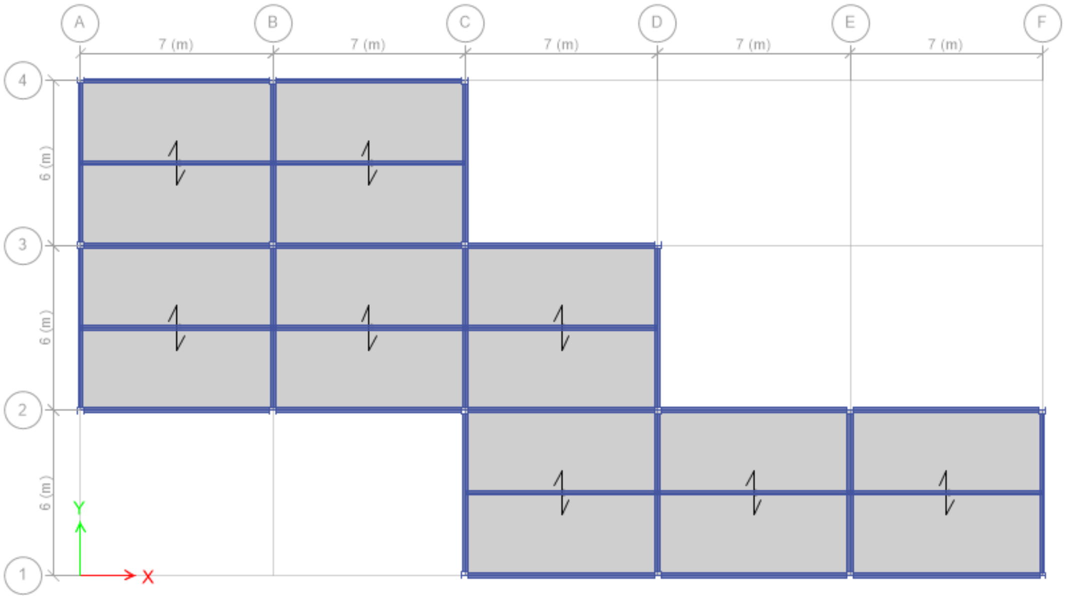


Figure 3.22: Plan view of 3D3 irregularity

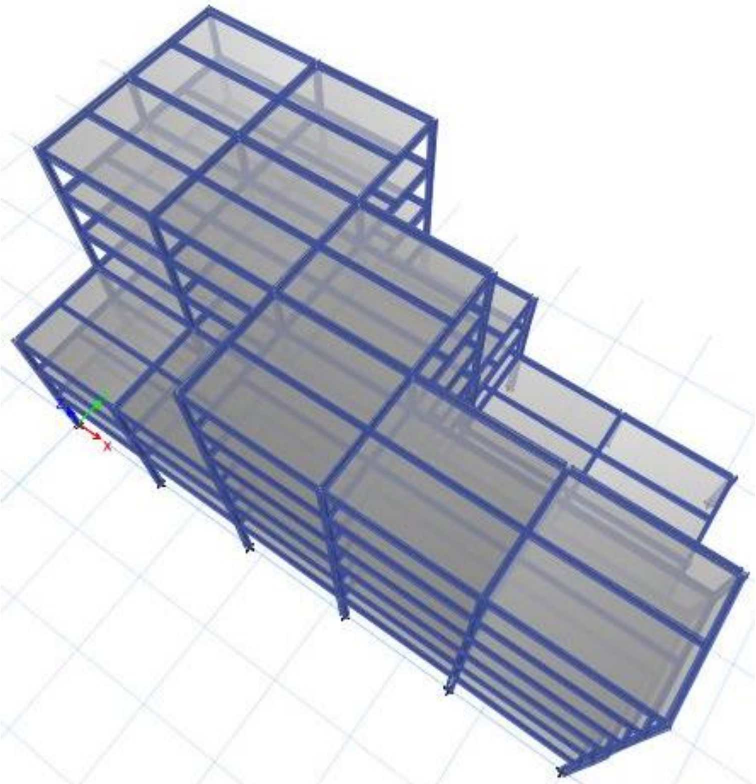


Figure 3.23: 3D view of 3D3 irregularity 6 story elevation

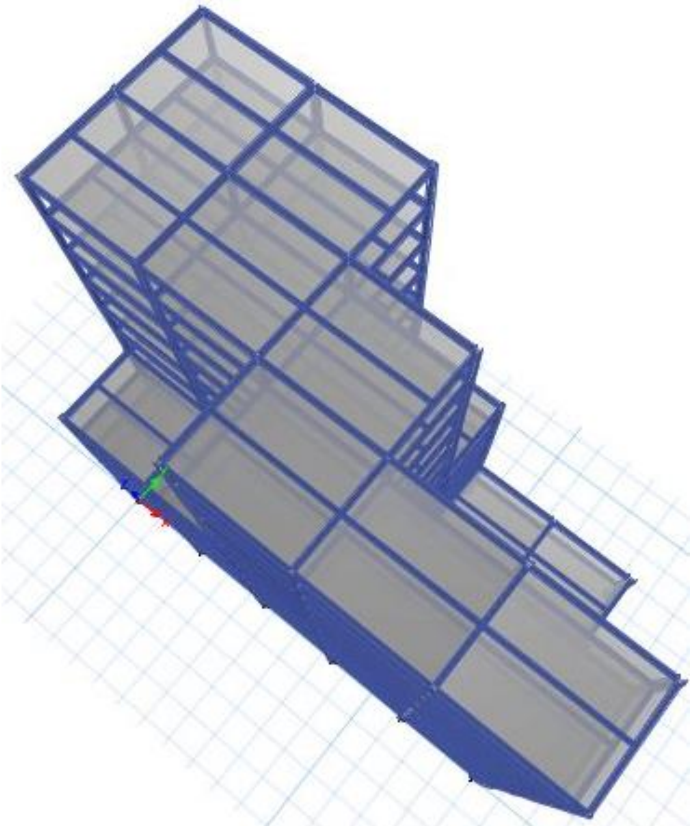


Figure 3.24: 3D view of 3D3 irregularity 12 story elevation

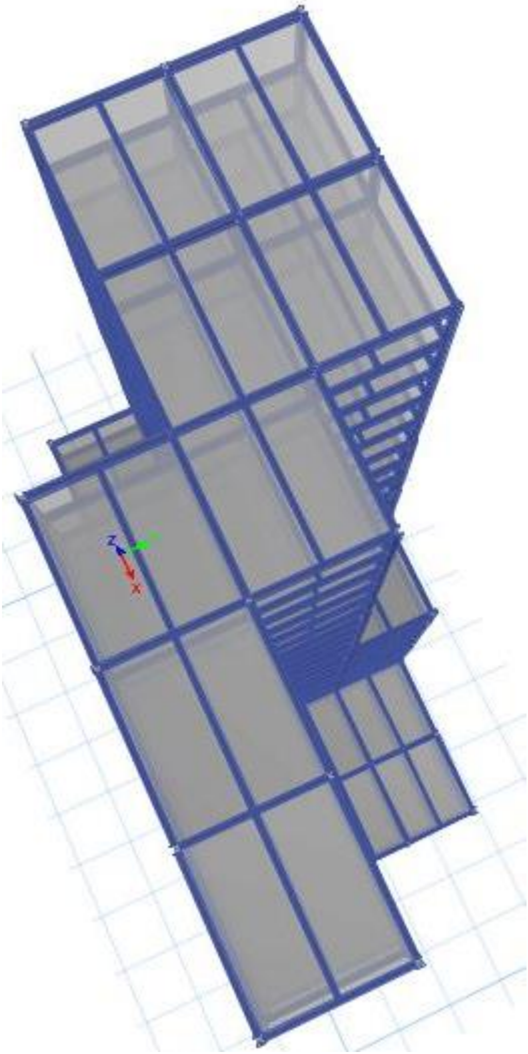


Figure 3.25: 3D view of 3D3 irregularity 20 story elevation

The fourth 3D irregularity considered was 3D4 which consisted of removing 2/3 of the original design members from the 3 middle bays on gridline 1 and 1/3 from the 3 middle bays on gridline 2. In other words

- 6 story building design: 4 floors were removed from gridline 1 and 2 floors were removed from gridline 2 (Fig 3.26).
- 12 story building design: 8 floors were removed from gridline 1 and 4 floors were removed from gridline 2 (Fig 3.27).

- 20 story building design: 14 floors were removed from grid line 1 and 7 floors were removed from gridline 2 (Fig 3.28).

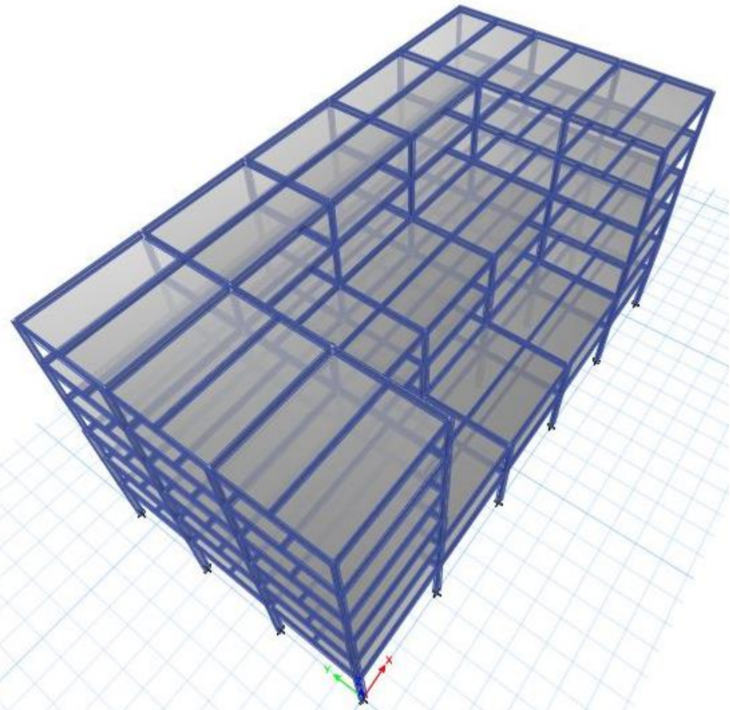


Figure 3.26: 3D view of 3D4 irregularity 6 story elevation

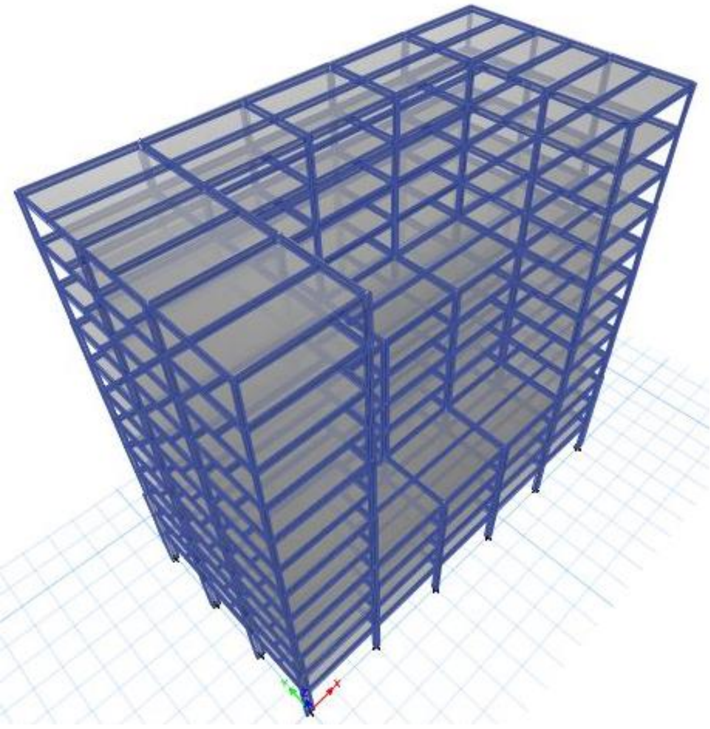


Figure 3.27: 3D view of 3D4 irregularity 12 story elevation

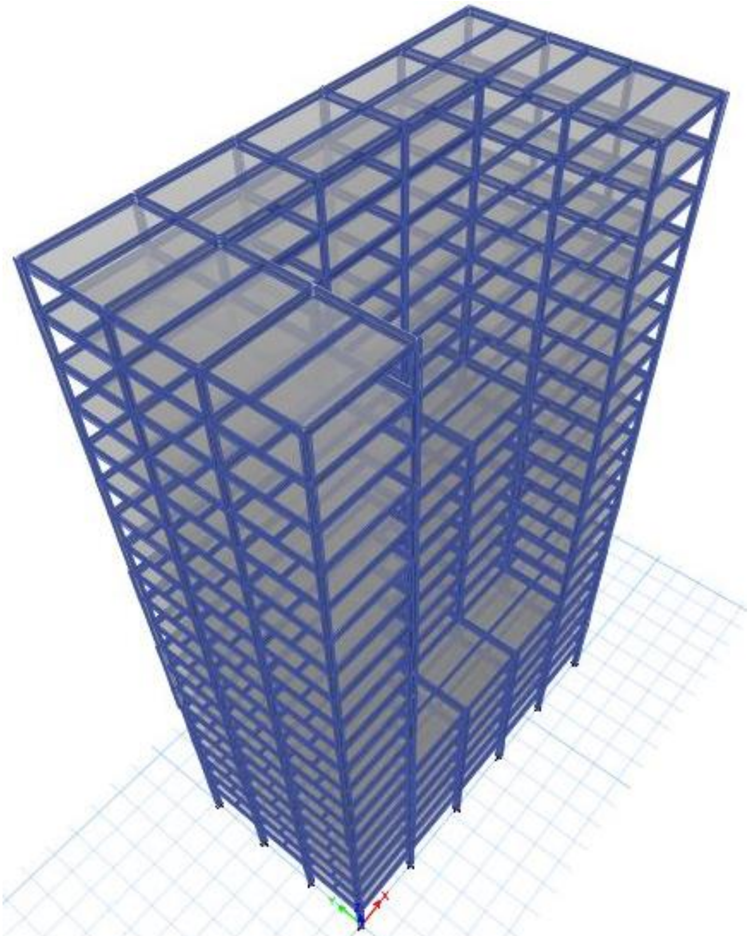


Figure 3.28: 3D view of 3D4 irregularity 20 story elevation

3.3 Frames with Concentric Bracings

Frames with concentric bracings known to have the ability to reach the yielding stage before the failure of connections and before the yielding or buckling of the beams or columns [39]. Simple beam to column connections were used instead of moment connections and bracing members were introduced for stability.

3.3.1 CBF Regular Designs

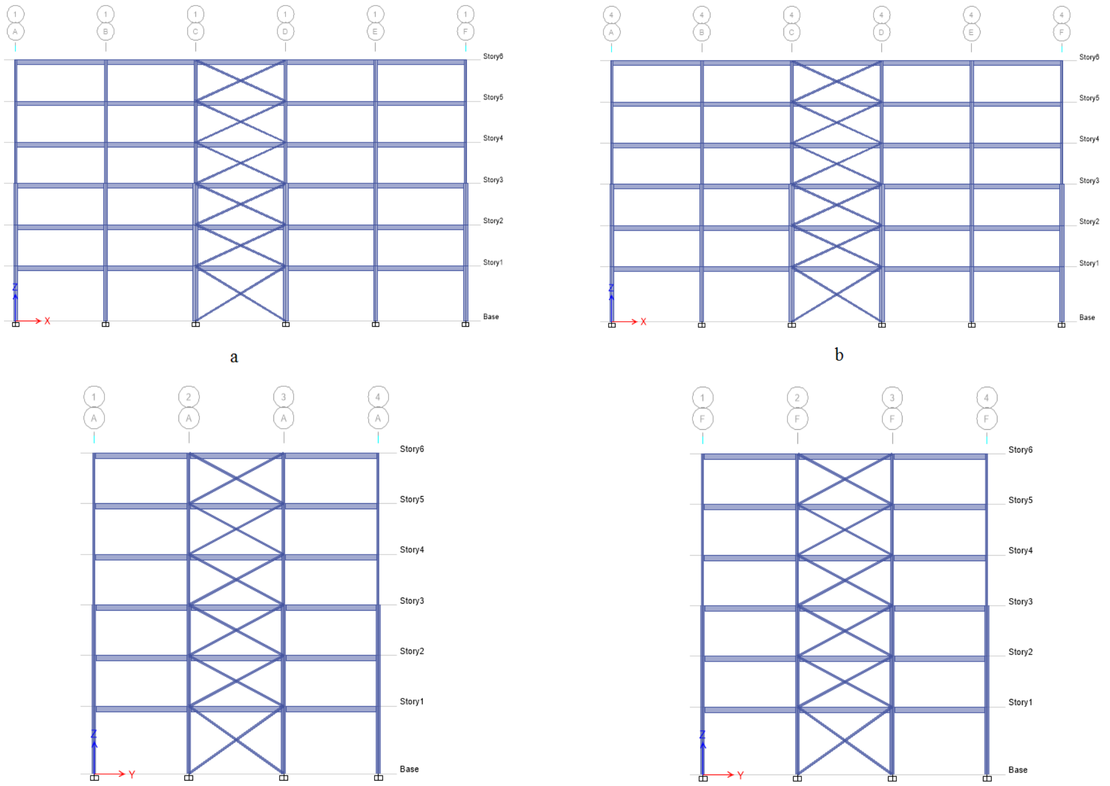
Same designs of regular MRF are used here with bracings introduced in all 6, 12, and 20 story-structures as follow:

- Gridline 1/C-D (Fig 3.29a)

- Gridline 4/C-D (Fig 3.29b)

- Gridline A/2-3 (Fig 3.29c)

- Gridline F/2-3 (Fig 3.29d)



a

b

c

d

Figure 3.29: Braced location in regular frame

3.3.2 CBF Irregular Designs

Same types of irregularity designs in Moment Resisting Frames were considered: Plan, elevation, and 3D. Several designs of the aforementioned were studied: 1 plan irregularity design, 3 elevation irregularity designs, and 4 3D irregularity designs.

3.3.2.1 CBF Plan Irregularity

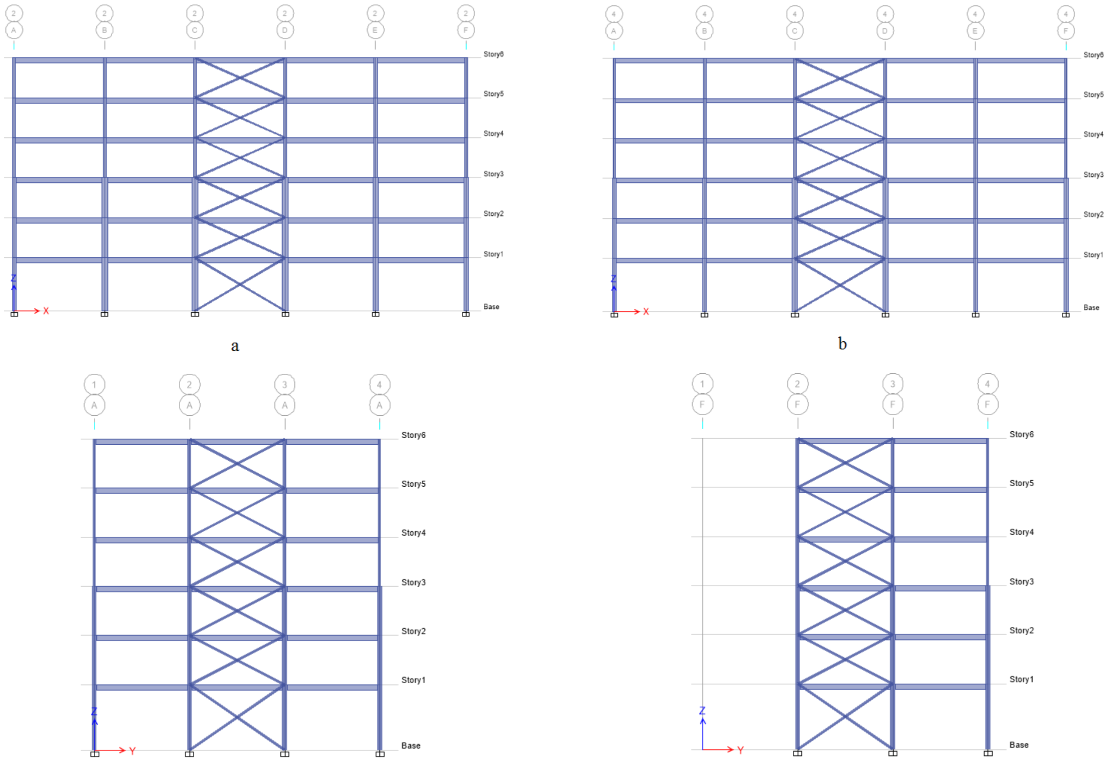
Same designs of MRF plan irregularity were used while introducing bracings in 6, 12, and 20 story-structures as follow:

- Gridline 2/C-D (Fig 3.30a)

- Gridline 4/C-D (Fig 3.30b)

- Gridline A/2-3 (Fig 3.30c)

- Gridline F/2-3 (Fig 3.30d)



a b c d

Figure 3.30: Braced location in irregular plane frame

3.3.2.2 CBF Elevation Irregularity

1Rx1L, 2Rx1L, and 1Rx1L Different Elevations when introducing bracings in 6, 12, and 20 of same designs as MRF story-structures differing in location and explained in the following tables:

Table 3.7: Location of x-bracing for the 6 story with different elevation irregularities

1Rx1L	2Rx1L	1Rx1L Different Elevation
Gridline 1/C-D	Gridline 1/C-D	Gridline 1/C-D
Gridline 4/C-D	Gridline 4/C-D	Gridline 4/C-D
Gridline A/2-3 (Base till Story2)	Gridline A/2-3 (Base till Story2)	Gridline A/2-3 (Base till Story2)
Gridline B/2-3 (From Story 2 till 6)	Gridline B/2-3 (From Story 2 till 6)	Gridline B/2-3 (From Story 2 till 6)
Gridline E/2-3(From Story 2 till 6)	Gridline D/2-3(From Story 2 till 6)	Gridline E/2-3(From Story 4 till 6)
Gridline F/2-3 (Base till Story 2)	Gridline F/2-3 (Base till Story 2)	Gridline F/2-3 (Base till Story 4)

Table 3.8: Location of x-bracing for the 12 story with different elevation irregularities

1Rx1L	2Rx1L	1Rx1L Different Elevation
Gridline 1/C-D	Gridline 1/C-D	Gridline 1/C-D
Gridline 4/C-D	Gridline 4/C-D	Gridline 4/C-D
Gridline A/2-3(Base till 4)	Gridline A/2-3(Base till 4)	Gridline A/2-3 (Base till 4)
Gridline B/2-3(From Story 4 till 12)	Gridline B/2-3(From Story 4 till 12)	Gridline B/2-3(From Story 4 till 12)
Gridline E/2-3(From Story 4 till 12)	Gridline D/2-3(From Story 4 till 12)	Gridline E/2-3(From Story 8 till 12)
Gridline F/2-3(Base till 4)	Gridline F/2-3(Base till 4)	Gridline F/2-3(Base till 8)

Table 3.9: Location of x-bracing for the 20 story with different elevation irregularities

1Rx1L	2Rx1L	1Rx1L Different Elevation
Gridline 1/C-D Gridline 4/C-D Gridline A/2-3(Base till 7) Gridline B/2-3(Story 7 till 20) Gridline E/2-3(Story 7 till 20) Gridline F/2-3(Base till 7)	Gridline 1/C-D Gridline 4/C-D Gridline A/2-3(Base till 7) Gridline B/2-3(Story 7 till 20) Gridline D/2-3(Story 7 till 20) Gridline F/2-3(Base till 7)	Gridline 1/C-D Gridline 4/C-D Gridline A/2-3(Base till 7) Gridline B/2-3(Story 7 till 20) Gridline E/2-3(Story 13 till 20) Gridline F/2-3(Base till 13)

3.3.2.3 CBF 3D Irregularity

Same designs as Moment Resisting Frames: 3D1, 3D2, 3D3, and 3D4 with introducing bracings in 2 different ways “Braced 1, Braced 2” in 6, 12, and 20 story-structures differing in location and explained in the wing tables:

Table 3.10: Location of x-bracing for the 6 story 3D1 irregularity in 2 different ways

Braced 1	Braced 2
Gridline 1/C-D (Base till 4)	Gridline 1/B-C
Gridline 1/B-C (Story4 till 6)	Gridline 4/B-C
Gridline 4/C-D (Base till 4)	Gridline A/2-3
Gridline 4/B-C (Story4 till 6)	Gridline C/2-3 (Story 4 till 6)
Gridline A/2-3	Gridline D/2-3(Story 2 till 4)
Gridline C/2-3 (Story 4 till 6)	Gridline F/2-3(Base till story 2)
Gridline D/2-3 (Story 2 till 4)	
Gridline F/2-3 (Base till story 2)	

Table 3.11: Location of x-bracing for the 12 story 3D1 irregularity in 2 different ways

Braced 1	Braced 2
Gridline 1/C-D (Base till 8)	Gridline 1/B-C
Gridline 1/B-C (Story8 till 12)	Gridline 4/B-C
Gridline 4/C-D (Base till 8)	Gridline A/2-3
Gridline 4/B-C (Story8 till 12)	Gridline C/2-3 (Story 8 till 12)
Gridline A/2-3	Gridline D/2-3 (Story 4 till 8)
Gridline C/2-3 (Story 8 till 12)	Gridline F/2-3 (Base till 4)
Gridline D/2-3(Story 4 till 8)	
Gridline F/2-3 (Base till 4)	

Table 3.12: Location of x-bracing for the 20 story 3D1 irregularity in 2 different ways

Braced 1	Braced 2
Gridline 1/C-D (Base till 13)	Gridline 1/B-C
Gridline 1/B-C (Story13 till 20)	Gridline 4/B-C
Gridline 4/C-D (Base till 13)	Gridline A/2-3
Gridline 4/B-C (Story13 till 20)	Gridline C/2-3 (From Story 13 till 20)
Gridline A/2-3	Gridline D/2-3 (From Story 6 till 13)
Gridline C/2-3 (Story 13 till 20)	Gridline F/2-3 (Base till 6)
Gridline D/2-3 (Story 6 till 13)	
Gridline F/2-3 (Base till 6)	

Table 3.13: Location of x-bracing for the 6 story 3D2 irregularity in 2 different ways

Braced 1	Braced 2
Gridline 1/C-D	Gridline 1/C-D
Gridline 4/C-D (Base till 3)	Gridline 4/B-C
Gridline 4/B-C (Story3 till 6)	Gridline A/2-3
Gridline A/2-3	Gridline C/2-3 (Story 3 till 6)
Gridline C/2-3(Story 3 till 6)	Gridline D/2-3 (Story 1 till 3)
Gridline D/2-3 (Story 1 till 3)	Gridline F/2-3 (Base)
Gridline F/2-3 (Base)	

Table 3.14: Location of x-bracing for the 12 story 3D2 irregularity in 2 different ways

Braced 1	Braced 2
Gridline 1/C-D Gridline 4/C-D (Base till 6) Gridline 4/B-C (Story 6 till 12) Gridline A/2-3 Gridline C/2-3(Story 6 till 12) Gridline D/2-3 (Story 2 till 6) Gridline F/2-3 (Base till Story 2)	Gridline 1/C-D Gridline 4/B-C Gridline A/2-3 Gridline C/2-3 (Story 6 till 12) Gridline D/2-3 (Story 2 till 6) Gridline F/2-3 (Base till Story 2)

Table 3.15: Location of x-bracing for the 20 story 3D2 irregularity in 2 different ways

Braced 1	Braced 2
Gridline 1/C-D Gridline 4/C-D (Base till 10) Gridline 4/B-C (Story 10 till 20) Gridline A/2-3 Gridline C/2-3(Story 10 till 20) Gridline D/2-3 (Story 3 till 10) Gridline F/2-3 (Base till Story 3)	Gridline 1/C-D Gridline 4/B-C Gridline A/2-3 Gridline C/2-3 (Story 10 till 20) Gridline D/2-3 (Story 3 till 10) Gridline F/2-3 (Base till Story 3)

Table 3.16: Location of x-bracing for the 6 story 3D3 irregularity in 2 different ways

Braced 1	Braced 2
Gridline 1/C-D Gridline 4/C-D (Base till Story 3) Gridline 4/B-C (Story 3 till 6) Gridline A/2-3 Gridline D/2-3 (Story 1 till 6) Gridline F/2-3 (Base)	Gridline 1/C-D Gridline 4/B-C Gridline A/2-3 Gridline D/2-3 (Story 1 till 6) Gridline F/2-3 (Base)

Table 3.17: Location of x-bracing for the 12 story 3D3 irregularity in 2 different ways

Braced 1	Braced 2
Gridline 1/C-D Gridline 4/C-D (Base till Story 6) Gridline 4/B-C (Story 6 till 12) Gridline A/2-3 Gridline D/2-3 (Story 2 till 12) Gridline F/2-3 (Base till Story 2)	Gridline 1/C-D Gridline 4/B-C Gridline A/2-3 Gridline D/2-3 (Story 2 till 12) Gridline F/2-3 (Base till Story 2)

Table 3.18: Location of x-bracing for the 20 story 3D3 irregularity in 2 different ways

Braced 1	Braced 2
Gridline 1/C-D Gridline 4/C-D (Base till Story 10) Gridline 4/B-C (Story 10 till 20) Gridline A/2-3 Gridline D/2-3 (Story 3 till 20) Gridline F/2-3 (Base till Story 3)	Gridline 1/C-D Gridline 4/B-C Gridline A/2-3 Gridline D/2-3 (Story 3 till 20) Gridline F/2-3 (Base till Story 3)

Table 3.19: Location of x-bracing for the 6 story 3D4 irregularity in 2 different ways

Braced 1	Braced 2
Gridline 1/C-D (Base till Story 2) Gridline 4/C-D Gridline A/2-3 Gridline F/2-3	Gridline 1/C-D (Base till Story 2) Gridline 2/C-D (Story 2 till 4) Gridline 3/C-D (Story 4 till 6) Gridline 4/C-D Gridline A/2-3 Gridline F/2-3

Table 3.20: Location of x-bracing for the 12 story 3D4 irregularity in 2 different ways

Braced 1	Braced 2
Gridline 1/C-D (Base till Story 4) Gridline 4/C-D Gridline A/2-3 Gridline F/2-3	Gridline 1/C-D (Base till Story 4) Gridline 2/C-D (Story 4 till 8) Gridline 3/C-D (Story 8 till 12) Gridline 4/C-D Gridline A/2-3 Gridline F/2-3

Table 3.21: Location of x-bracing for the 20 story 3D4 irregularity in 2 different ways

Braced 1	Braced 2
Gridline 1/C-D (Base till Story 6) Gridline 4/C-D Gridline A/2-3 Gridline F/2-3	Gridline 1/C-D (Base till Story 6) Gridline 2/C-D (Story 6 till 13) Gridline 3/C-D (Story 13 till 20) Gridline 4/C-D Gridline A/2-3 Gridline F/2-3

3.4 Seismic Load

Earthquakes cause dynamic motions to buildings. This is due to the inertia forces that act in the opposite direction of earthquake acceleration towards the building. These forces are called seismic loads and are usually opposed by assuming external forces to the building. Moreover, earthquake motions and seismic loads vary with time and direction while noting that these loads aren’t constant in time and space. Designers take into consideration many factors that may help in counteracting such phenomena.

3.4.1 Equivalent Static Analysis

Factors considered in these designs are:

- Ground Acceleration (ag/g): 0.2

- Ground Type: B (regarding the soil in Lebanon)
- Behavior Factor q: 4
- Class Section: Ductility Class Medium (DCM) was chosen because it provides high ductility levels since the behavior factor that is 4. DCM is also easier to be used on the work site and provides better results against medium seismic loads.

The core load combinations of this study are:

- 1 Dead Load + 0.3 Live Load + 1 Seismic Load X+
- 1 Dead Load + 0.3 Live Load + 1 Seismic Load Y+

3.4.2 Response Spectrum Analysis

The following factors were considered in the design and analysis of frames:

- Ground acceleration (ag/g): 0.2
- Spectrum type: 1
- Ground type: B
- Soil factor, S: 1.2
- Spectrum period, Tb: 0.15 sec
- Spectrum period, Tc: 0.5 sec
- Spectrum period, Td: 2
- Lower bound factor, Beta: 0.2
- Behavior factor, q: 4
- Damping ratio: 0.05

3.4.3 Pushover Analysis

To apply pushover analysis, nonlinear static dead load case were with Pushover was applied as horizontal acceleration load by an initial condition which was continue from state at end of nonlinear case.

3.5 Use of Computer Software ETABS

ETABS is a computer software which is widely used by researchers for simple to complex building analysis and design through its easy interface.

Based on a vast number of building codes in ETABS, designers can choose between automated results of static loads for earthquakes or wind. In this study, EUROCODE 3 was selected for the designs and EUROCODE 8 is selected for the seismic loads.

Chapter 4

EQUIVALENT STATIC ANALYSIS

4.1 Introduction

The aim of this chapter is to investigate and try to understand behavior of structures against an earthquake with 0.2 ground acceleration, type B soil and a behavior factor of q=4.

This types of structures considered in this study have six, twelve and twenty stories. They have either moment or braced frame with regular and irregular elevation, plan and 3D view. More detail about the types of structures can be found in Chapter 3.

4.2 Six-Story Building Structures

Regular building design consists of 5 bays (each with 7m span) in x-direction and 3 bays (each with 6m span) in y-direction and a total building height of 19m. Secondary beams are connected to mid points of 6m long main beams. Therefore, secondary beams have a spacing of 3m between them. Cross-bracing is used for the braced frame. The irregular building design has 8 different types of irregularity, 1 on plan, 3 on elevations and 4 on 3D views.

4.2.1 Regular Building Analysis

Two types of regular buildings were studied: moment frame and braced frame. Braced frames were placed at the middle bay in x- and y-directions of the building. Moment frame lateral displacement is more than the braced frame (Fig.4.1) and the percentage difference is given in Table 4.1.

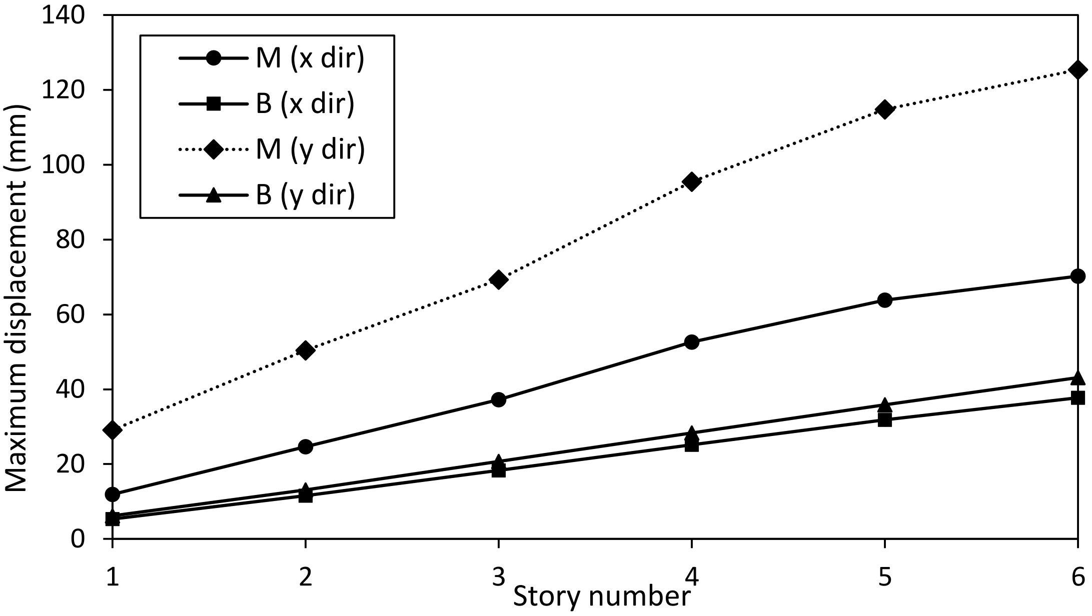


Figure 4.1: 6 story regular frame displacements in x and y directions

Table 4.1: Percentage difference of displacement between moment and braced frames for 6 story regular building design

Story	x-dir	y-dir
Base	0	0
Story 1	124.5	369.4
Story 2	112.9	284.7
Story 3	103.3	234.8
Story 4	108.7	237.5
Story 5	100.6	219.8
Story 6	86.2	191.0

In x-direction, the moment frame displacement is 86% to 124% more than the braced frame at different stories. In y-direction, the difference is even more with moment frame displacement being 191% to 369% more than the braced frame at different stories. This was due to greater lateral stiffness provided by the braced frame and thus considerable reduction in lateral displacements achieved. However, it should be noted that the lateral displacement rate reduces as the story number increases.

4.2.2 Irregular Plan Analysis

One irregular design was studied which consisted of removing 26.67% of the floors from the regular design, as shown in Fig.4.2.

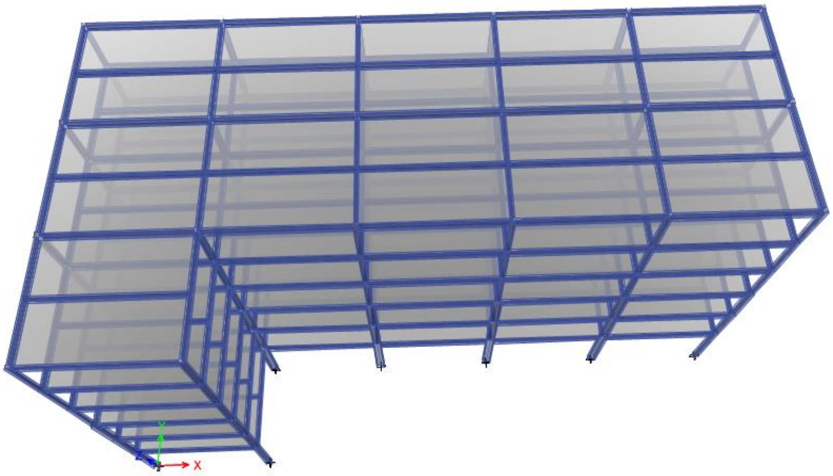


Figure 4.2: Building design with plan irregularity

As in the case of regular building, moment frame achieved higher lateral displacements when compared to the braced fame (Fig.4.3) and the percentage difference is given in Table 4.2.

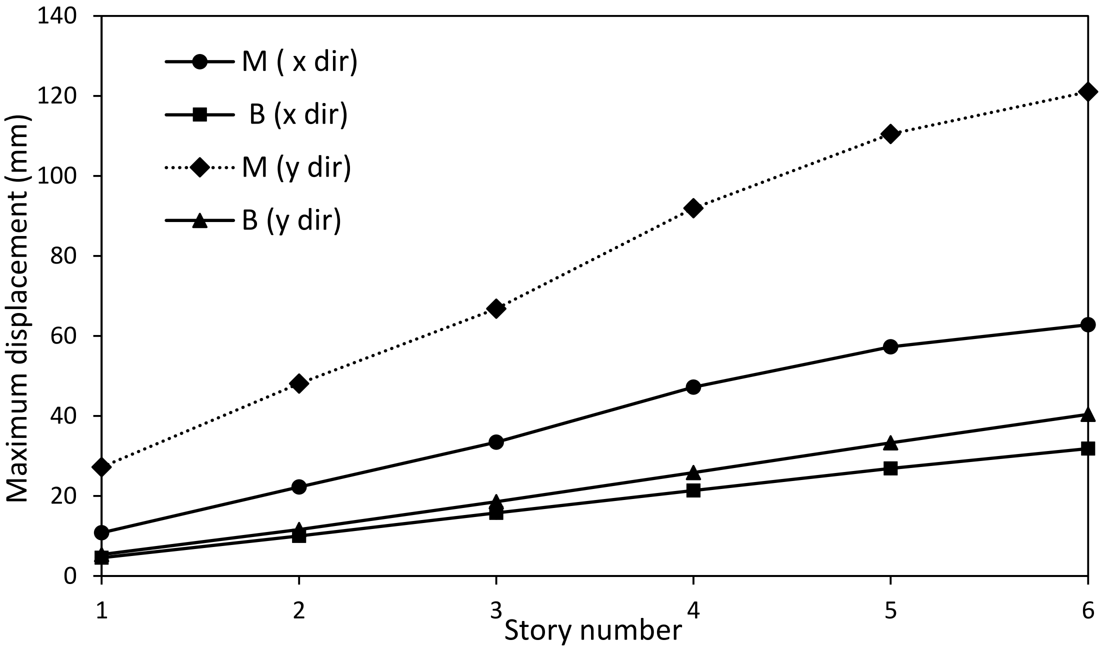


Figure 4.3: 6 story irregular plan frame displacements in x and y directions

Table 4.2: Percentage difference of displacement between moment and braced frames for 6 story irregular plan building design

Story	x-dir	y-dir
Base	0	0
Story 1	134.8	403.7
Story 2	123.0	314.7
Story 3	112.0	259.1
Story 4	120.6	254.8
Story 5	113.0	231.8
Story 6	96.9	199.5

In x-direction, the moment frame displacements are 96.9% to 134.8% higher than the braced frame ones at different stories. In y- direction, the moment frame displacements are 199.5%-403.7% higher than the braced frame ones. So despite the irregularity in plan of the building still bracings provided greater lateral stiffness to the braced frame and thus displacements reduced considerably. However, it should be noted that the lateral displacement rate increases at story 4 in x-direction and then continues to decrease for the following floors.

4.2.2.1 Irregular Elevation Building Analysis

Three types of irregular elevation designs were studied: They are labeled as 1Rx1L, 2Rx1L, and 1Rx1L at different elevation. The irregular height 1Rx1L building design consisted of removing 4 floors from each side of the building at the remote bays, as shown in the Fig 4.4.

Figure 4.4: Irregular height 1Rx1L building design

The irregular height 2Rx1L design is same as the 1Rx1Lexcept that 4 floors were removed from two bays on one side of the building as illustrated in the Fig 4.5.

Figure 4.5: Irregular height 2Rx1L building design

The irregular height 1Rx1L different elevation design was about removing 2 floors from one side extreme bay and 4 floors from the other, as shown in Fig. 4.6.

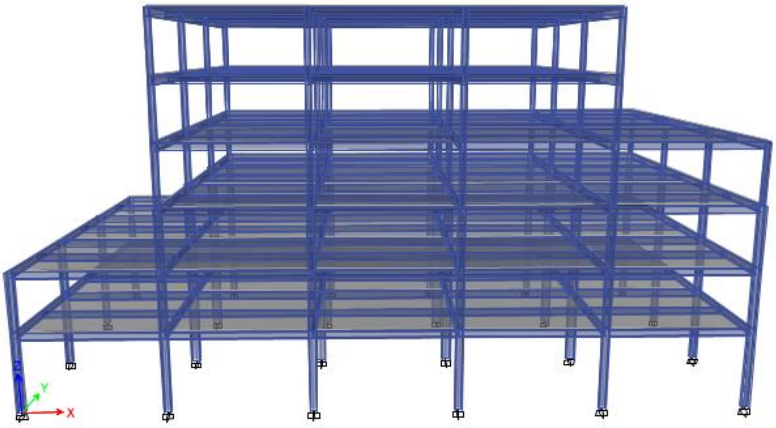


Figure 4.6: Irregular height 1Rx1L different elevation building design

4.2.2.1.1 Irregular Height 1Rx1L Building Analysis

Fig. 4.7 shows the lateral displacements for the 6 story irregular height (1Rx1L) braced and moment frames. As in the design cases given so far this case also indicates moment frame achieving more lateral displacement than the braced frame in both x and y directions (Table 4.3).

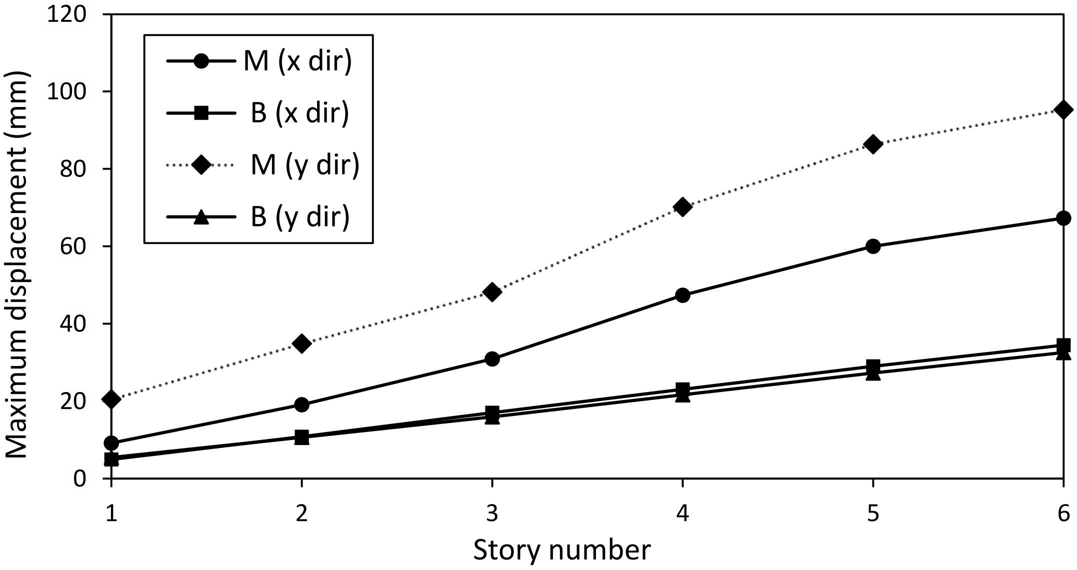


Figure 4.7: 6 story irregular height 1Rx1L frame displacements in x and y directions

Table 4.3: Percentage difference of displacement between moment and braced frames for 6 story irregular height (1Rx1L) building design.

Story	x-dir	y-dir
Base	0	0
Story 1	84.0	272.7
Story 2	76.9	226.2
Story 3	81.8	201.3
Story 4	105.2	223.5
Story 5	106.9	216.5
Story 6	95.1	192.3

In x-direction, the moment frame displacements are 76.9% to 106.9% higher than the braced frame ones at different stories. In y- direction, the moment frame displacements are 192.3%-272.7% higher than the braced frame ones. So despite the irregularity in elevation of the building still bracings provided greater lateral stiffness to the braced frame and thus displacements reduced considerably. It should be noted that the lateral displacement rate increases at stories 3 to 5 possible due to removal of one bay and then reduces again in x-direction whilst there is an increase at story 4 for y-direction and then continues to reduce.

4.2.2.1.2 Irregular Height 2Rx1L Building Analysis

Fig. 4.8 shows the lateral displacements for the 6 story irregular height (2Rx1L) braced and moment frames. As in the design cases given so far this case also indicates moment frame achieving more lateral displacement than the braced frame in both x and y directions (Table 4.4). However, it must be noted that both x and y direction displacement of the moment frame further increased for this design case.

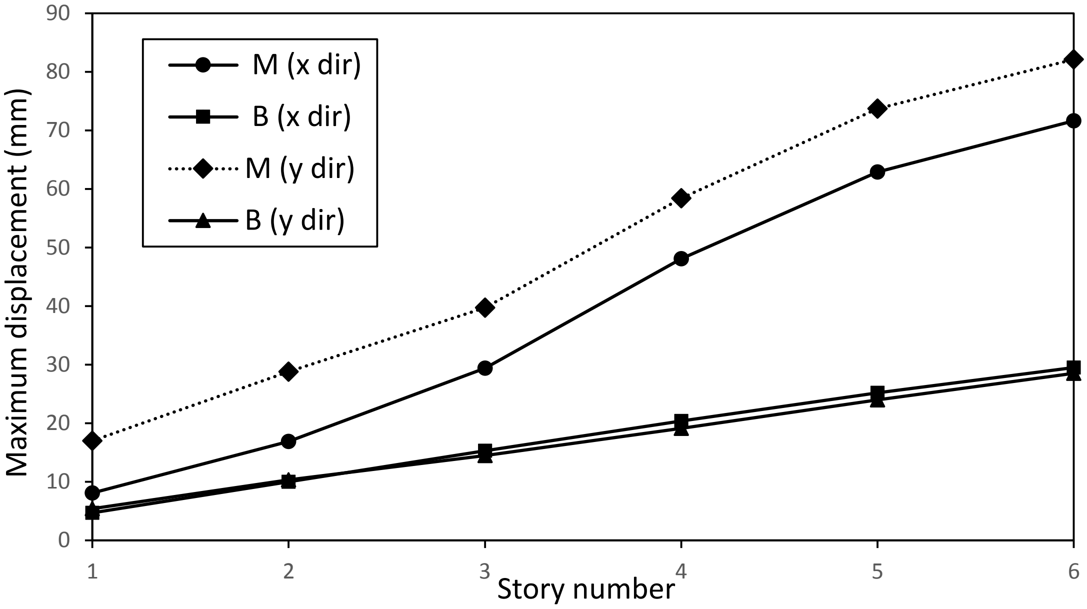


Figure 4.8: 6 story irregular height 2Rx1L frame displacements in x and y directions

Table 4.4: Percentage difference of displacement between moment and braced frames for 6 story irregular height (2Rx1L) building design

Story	x-dir	y-dir
Base	0	0
Story 1	72.3	214.8
Story 2	69.0	179.6
Story 3	92.2	173.8
Story 4	135.8	205.8
Story 5	149.6	207.1
Story 6	142.7	188.1

As in earlier cases, for irregular height (2Rx1L) building design braced frame managed to better laterally stiffen the building and limited the lateral displacement. In x-direction, the moment frame displacements are 69.0% to 149.6% and in y- direction, 173.8%-214.8% higher than the braced frame, respectively. There has been fluctuations in the lateral displacement rate of moment frame over braced frame at story 2 and 6 in x-direction and story 4 and 5 in y-direction.

4.2.2.1.3 Irregular Height 1Rx1L Different Elevation Building Analysis

Fig. 4.9 shows the lateral displacements for the 6 story irregular height (1Rx1L) different elevation braced and moment frames. Moment frame achieving more lateral displacement than the braced frame in both x and y directions (Table 4.5).

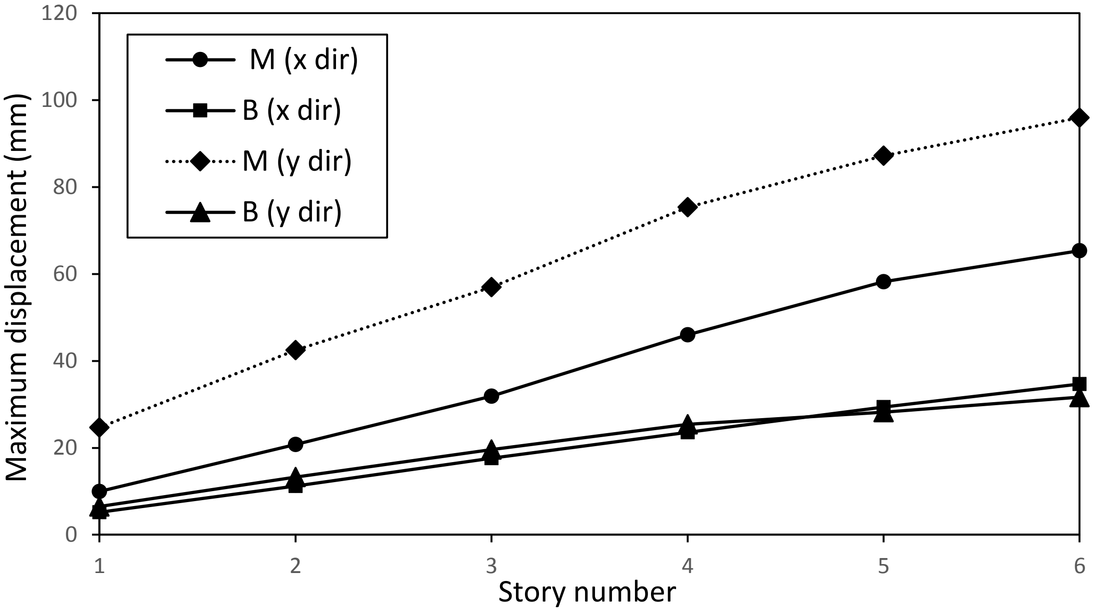


Figure 4.9: 6 story irregular height 1Rx1L different elevation frame displacements in x and y directions

Table 4.5: Percentage difference of displacement between moment and braced frames for 6 story irregular height (1Rx1L) different elevation building design.

Story	x-dir	y-dir
Base	0	0
Story 1	92.3	280.0
Story 2	85.7	219.5
Story 3	81.3	190.8
Story 4	94.9	196.9
Story 5	98.0	209.2
Story 6	88.5	202.8

For irregular height (1Rx1L) different elevation building design, braced frame also had lower lateral displacement than moment frame. In x-direction, the moment frame displacements are 81.3% to 98.0% higher than the braced frame ones at different stories. In y- direction, the moment frame displacements are 190.8%-280.0% higher than the braced frame ones.

4.2.2.2 Irregular 3D Building Analysis

12 types of irregular 3D designs of 4 moment frames and 8 braced frames were studied: 3D1, 3D2, 3D3, 3D4. Each design is different from the other with respect to the location of the bracing and variations in building plan design. (Figs.4.10 to 4.17).

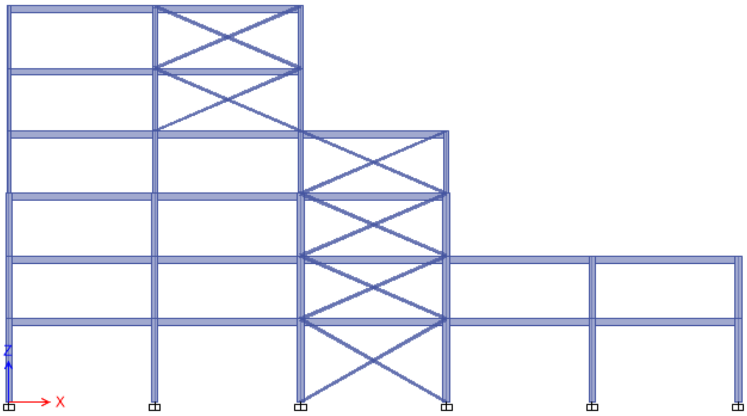


Figure 4.10: Irregular 3D1 B1 design

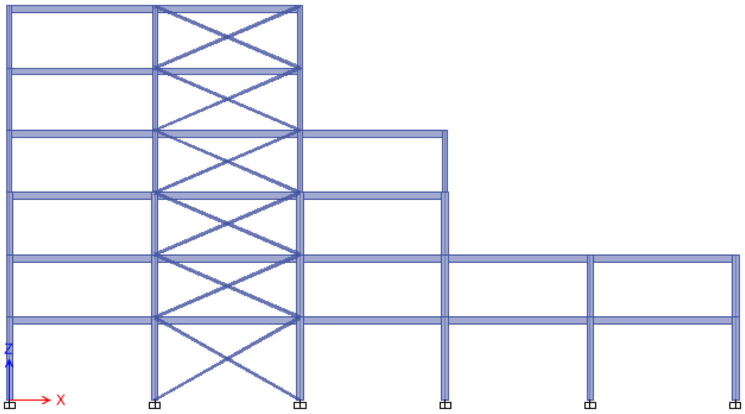


Figure 4.11: Irregular 3D1 B2 design

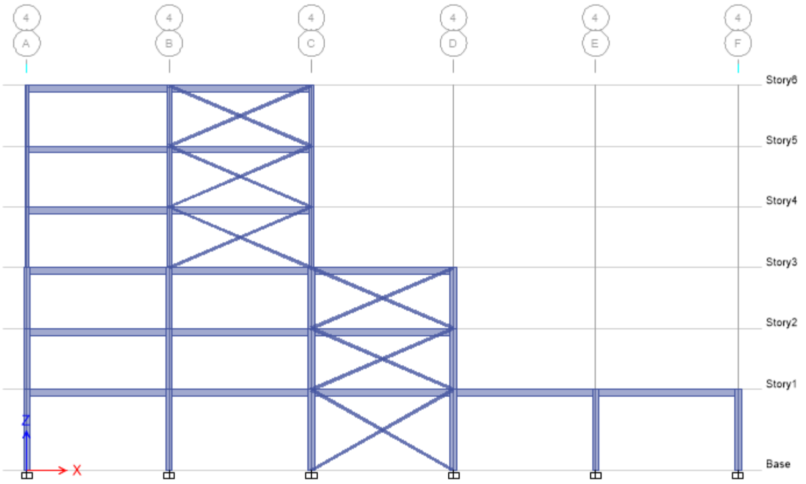


Figure 4.12: Irregular 3D2 B1 design

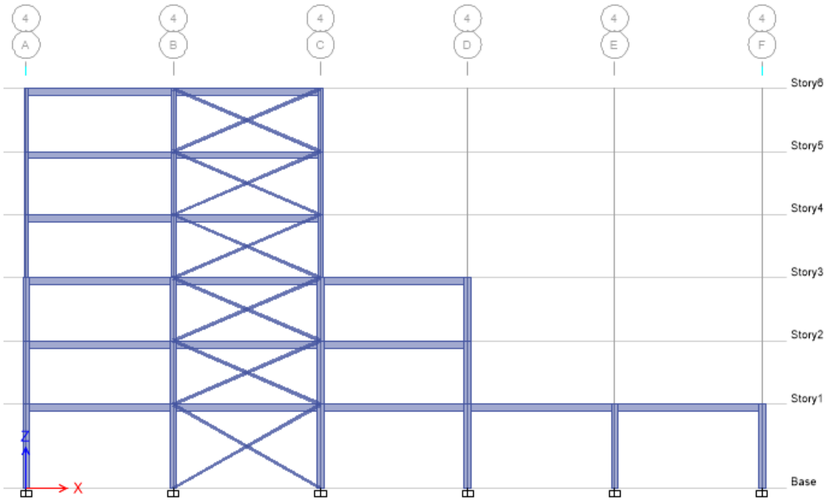


Figure 4.13: Irregular 3D2 B2 design

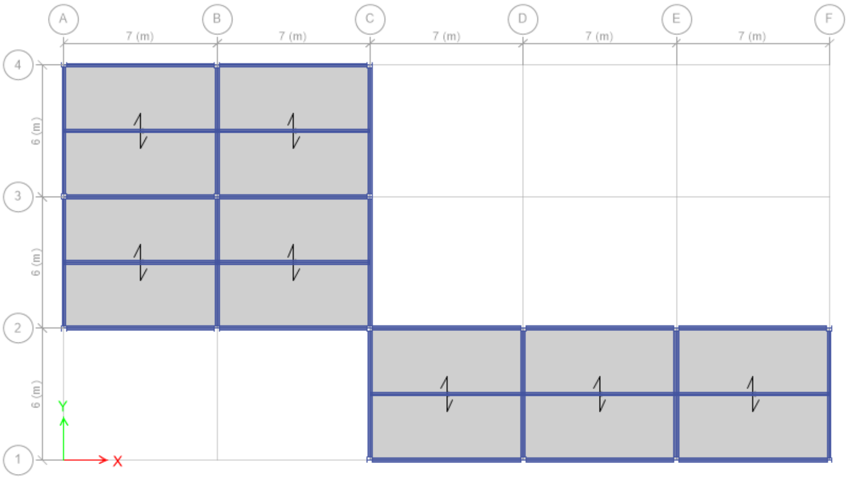


Figure 4.14: Plan view for irregular 3D2 design

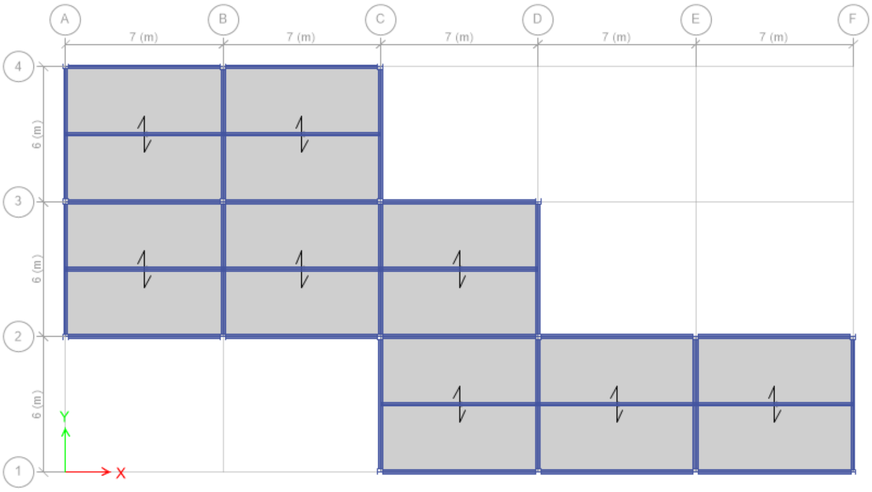


Figure 4.15: Plan view for irregular 3D3 design

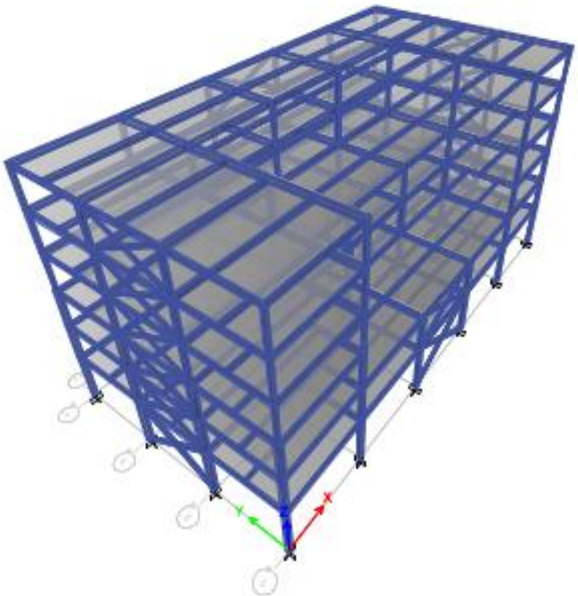


Figure 4.16: Irregular 3D4 B1 design

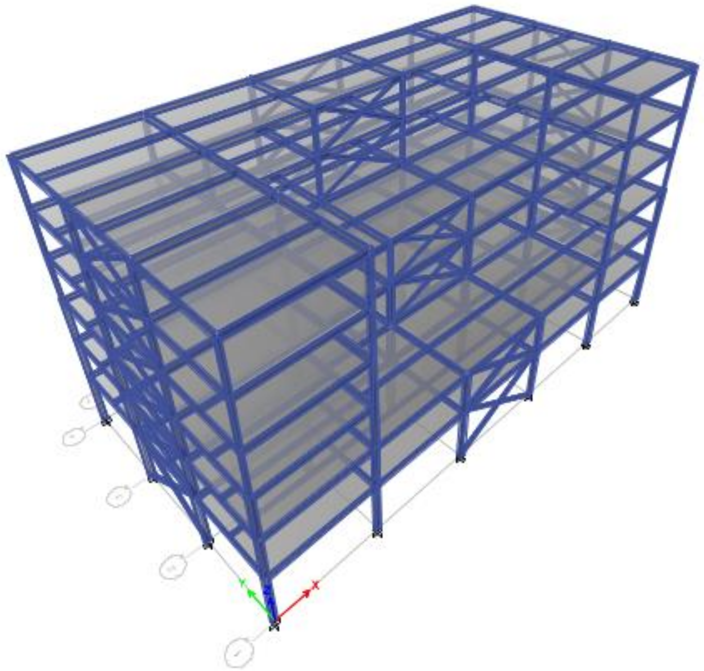


Figure 4.17: Irregular 3D4 B2 design

4.2.2.2.1 Irregular 3D1 Building Analysis

Fig. 4.18 shows the lateral displacements for the 6 story irregular 3D1 braced and moment frames. As in the design cases given so far this case also indicates moment frame achieving more lateral displacement than the braced frame in both x and y directions (Table 4.6).

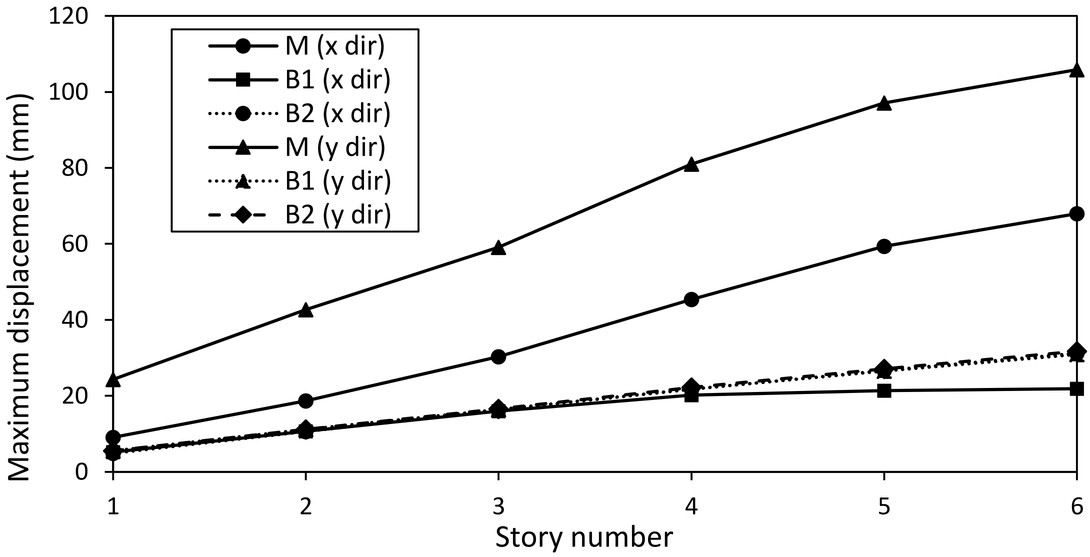


Figure 4.18: 6 story irregular 3D1 frame displacements in x and y directions

Table 4.6: Percentage difference of displacement between moment and braced frames for 6 story irregular 3D1building design.

	Braced 1		Braced 2	
Story	x-dir	y-dir	x-dir	y-dir
Base	0	0	0	0
Story 1	75.0	341.8	85.7	341.8
Story 2	74.8	281.3	76.4	281.3
Story 3	89.4	260.4	85.9	256.0
Story 4	124.8	271.6	109.2	264.9
Story 5	177.6	266.4	122.5	258.3
Story 6	210.5	242.7	117.9	234.1

In x-direction, the moment frame displacement is 74.8% to 210.5% more than the braced 1, and 76.4% to 122.5% more than the braced 2 frame at different stories. In y-direction, the difference is even more with moment frame displacement being 242.7% to 341.8% more than the braced 1, and 234.1% to 341.8% more than the braced 2 frame at different stories. The percentage difference in displacement gradually increases in x-direction and decreases for y-direction for both braced case 1 and 2.

4.2.2.2.2 Irregular 3D2 Building Analysis

Fig. 4.19 shows the lateral displacements for the 6 story irregular 3D2 braced and moment frames. As in the design cases given so far this case also indicates moment frame achieving more lateral displacement than the braced frame in both x and y directions (Table 4.7).

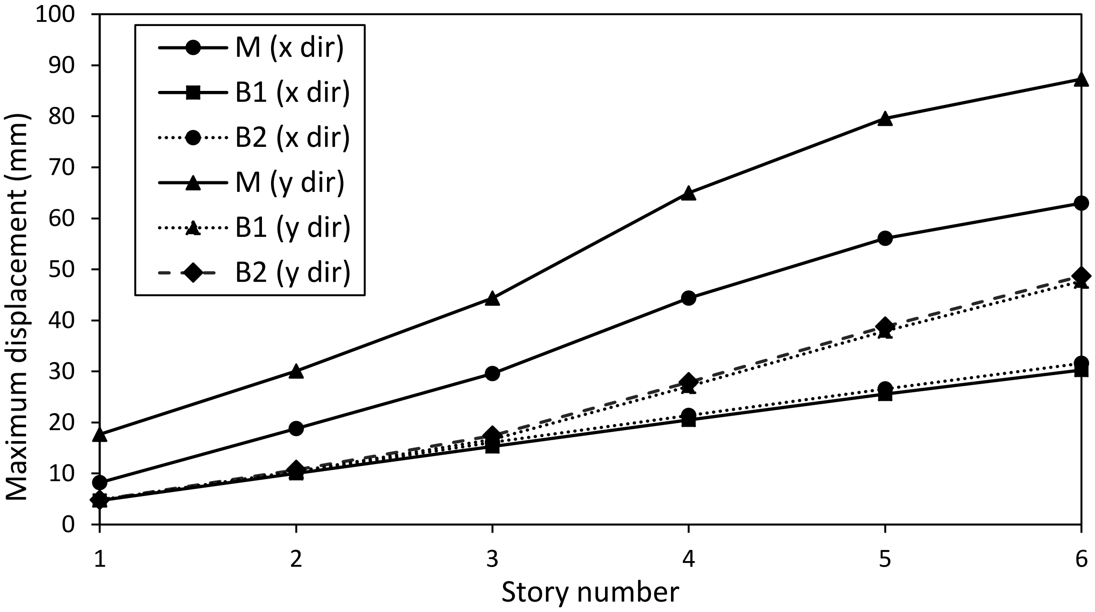


Figure 4.19: 6 story irregular 3D2 frame displacements in x and y directions

Table 4.7: Percentage difference of displacement between moment and braced frames for 6 story irregular 3D2building design.

	Braced 1		Braced 2	
Story	x-dir	y-dir	x-dir	y-dir
Base	0	0	0	0
Story 1	74.5	268.8	74.5	268.8
Story 2	88.0	189.4	82.5	181.3
Story 3	93.5	165.9	83.9	155.2
Story 4	116.6	139.9	107.5	133.0
Story 5	119.1	110.0	110.9	105.2
Story 6	107.9	83.0	99.4	79.3

In x-direction, the moment frame displacement is 74.5% to 119.1% more than the braced 1, and 74.5% to 110.9% more than the braced 2 frame at different stories. In y-direction, the difference is even more with moment frame displacement being 83.0% to 268.8% more than the braced 1, and 79.3% to 268.8% more than the braced 2 frame at different stories. The percentage difference in displacement gradually increases in x-direction except at story 5 and decreases for y-direction for both braced case 1 and 2.

4.2.2.2.3 Irregular 3D3 Building Analysis

Fig. 4.20 shows the lateral displacements for the 6 story irregular 3D3 braced and moment frames. As in the design cases given so far this case also indicates moment frame achieving more lateral displacement than the braced frame in both x and y directions (Table 4.8).

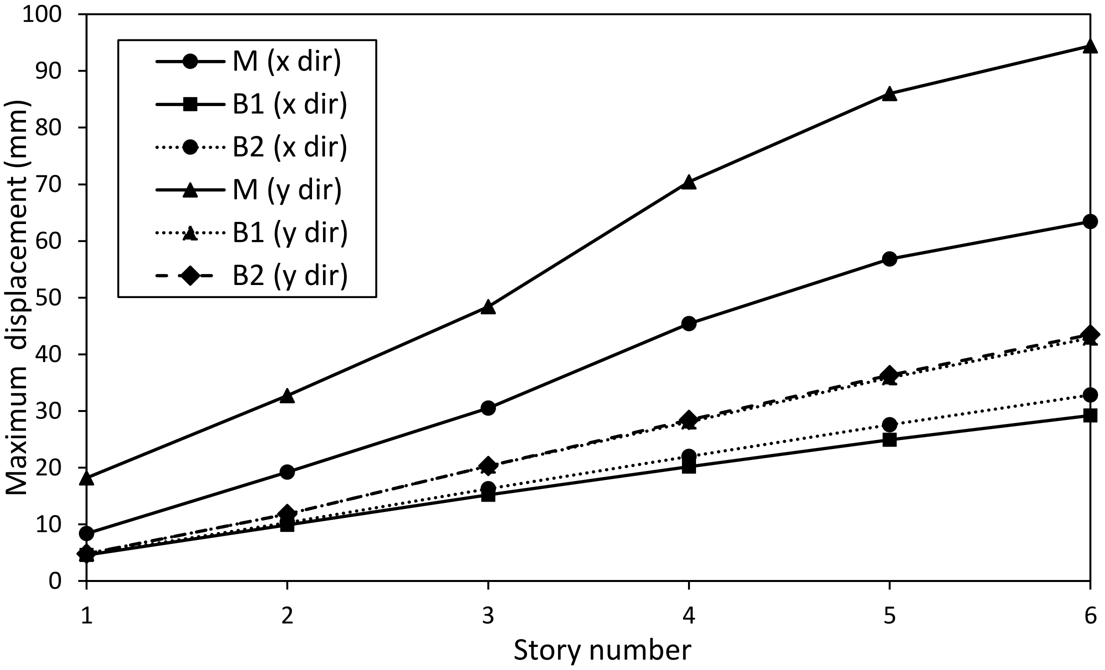


Figure 4.20: 6 story irregular 3D3 frame displacements in x and y directions

Table 4.8: Percentage difference of displacement between moment and braced frames for 6 story irregular 3D3 building design.

	Braced 1		Braced 2	
Story	x-dir	y-dir	x-dir	y-dir
Base	0	0	0	0
Story 1	82.6	279.2	78.7	279.2
Story 2	93.9	177.1	86.4	177.1
Story 3	100.7	138.4	87.1	138.4
Story 4	124.8	150.5	106.4	147.9
Story 5	128.1	139.6	105.8	136.9
Story 6	117.1	120.0	93.3	117.0

In x-direction, the moment frame displacement is 82.6% to 128.1% more than the braced 1, and 78.7% to 106.4% more than the braced 2 frame at different stories. In y-direction, the difference is even more with moment frame displacement being 120.0% to 279.2% more than the braced 1, and 117.0% to 279.2% more than the braced 2 frame at different stories. The percentage difference in displacement has similar pattern as in irregular 3D3 building design case.

4.2.2.2.4 Irregular 3D4 Building Analysis

Fig. 4.21 shows the lateral displacements for the 6 story irregular 3D4 braced and moment frames. As in the design cases given so far this case also indicates moment frame achieving more lateral displacement than the braced frame in both x and y directions (Table 4.9).

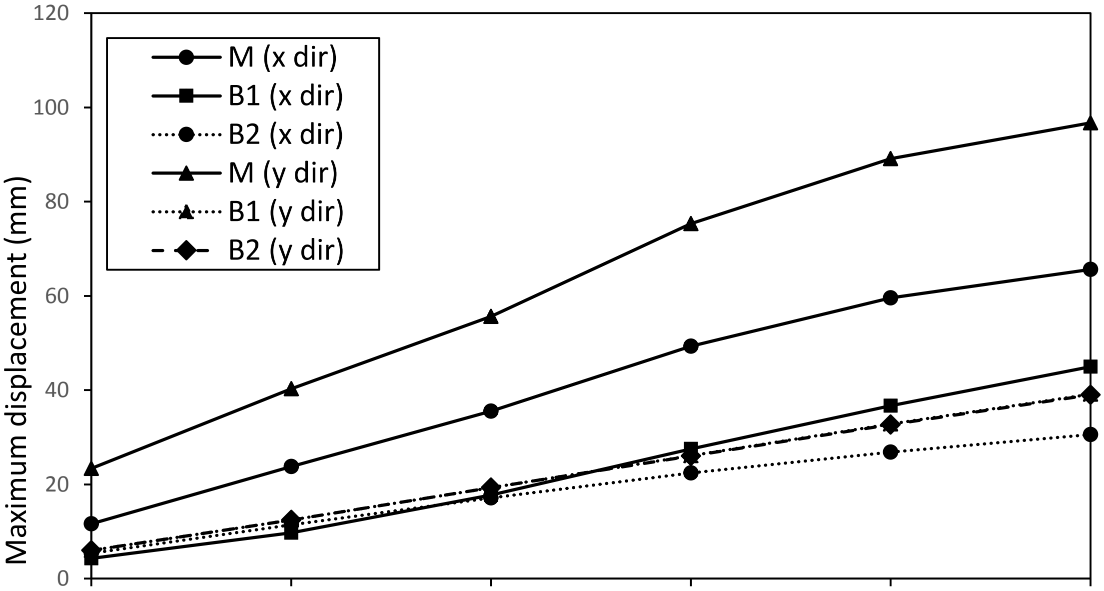


Figure 4.21: 6 story irregular 3D4 frame displacements in x and y directions

Table 4.9: Percentage difference of displacement between moment and braced frames for 6 story irregular 3D4 building design.

	Braced 1		Braced 2	
Story	x-dir	y-dir	x-dir	y-dir
Base	0	0	0	0
Story 1	169.8	290.0	114.8	290.0
Story 2	145.4	225.0	108.8	225.0
Story 3	100.6	188.1	107.6	188.1
Story 4	79.3	188.5	120.1	189.6
Story 5	62.4	171.6	122.4	172.5
Story 6	45.8	147.3	114.4	147.9

In x-direction, the moment frame displacement is 45.8% to 169.8% more than the braced 1, and 107.6% to 1122.4% more than the braced 2 frame at different stories. In y-direction, the difference is even more with moment frame displacement being 147.3% to 290.0% more than the braced 1, and 147.9% to 290.0% more than the braced 2 frame at different stories. The trend changes in this case where displacement percentage reduces for x-direction for both braced 1 and 2, y-direction for braced 1 but for braced 2 x-direction there is increase at story 4 and 5 and then reduction again.

4.3 Twelve-Story Building Structures

The regular building design consists of 5 bays (each with 7m span) in x-direction and 3 bays (each with 6m span) in y-direction and a total building height of 37m. Cross-bracing is used for the braced frame. The irregular building design has 8 different types of irregularity, 1 on plan, 3 on elevations and 4 on 3D views.

4.3.1 Regular Building Analysis

Two types of regular buildings were studied: moment frame and braced frame. Braced frames were placed at the middle bay in x- and y-directions of the building. Moment frame lateral displacement is more than the braced frame (Fig.4.22) and the percentage difference is given in Table 4.10.

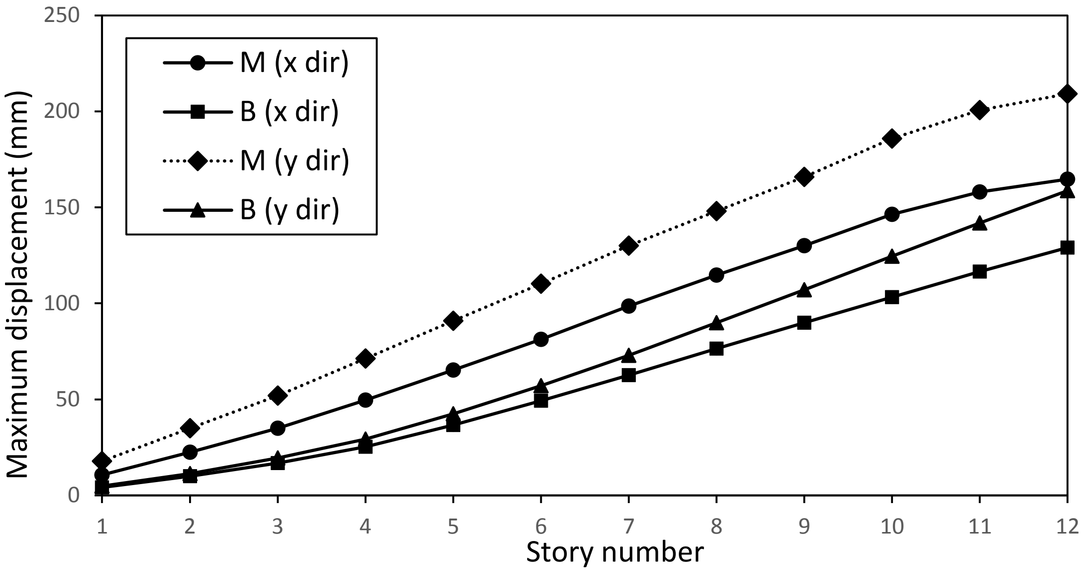


Figure 4.22: 12 story regular frame displacement in x and y direction

Table 4.10: Percentage difference of displacement between moment and braced frames for 12 story regular building design

Story	x-dir	y-dir
Base	0	0
Story 1	154.8	265.3
Story 2	125.0	206.1
Story 3	106.5	166.7
Story 4	95.7	143.3
Story 5	77.9	114.1
Story 6	64.7	92.7
Story 7	57.3	78.2
Story 8	50.3	64.7
Story 9	44.7	54.8
Story 10	41.6	49.3
Story 11	35.6	41.5
Story 12	27.5	31.9

In x-direction, the moment frame displacement is 27.5% to 154.8% more than the braced frame at different stories. In y-direction, the difference is even more with moment frame displacement being 31.9% to 265.3% more than the braced frame at different stories. Generally the lateral displacement of moment frame reduces with the increase in the number of floors. However, y-direction displacements are higher than those of x-direction.

4.3.2 Irregular Plan Analysis

One irregular design was studied which consisted of removing 26.67% of the floors from the regular design.

As in the case of regular building, moment frame achieved higher lateral displacements when compared to the braced frame (Fig 4.23) and the percentage difference is given in Table 4.11.

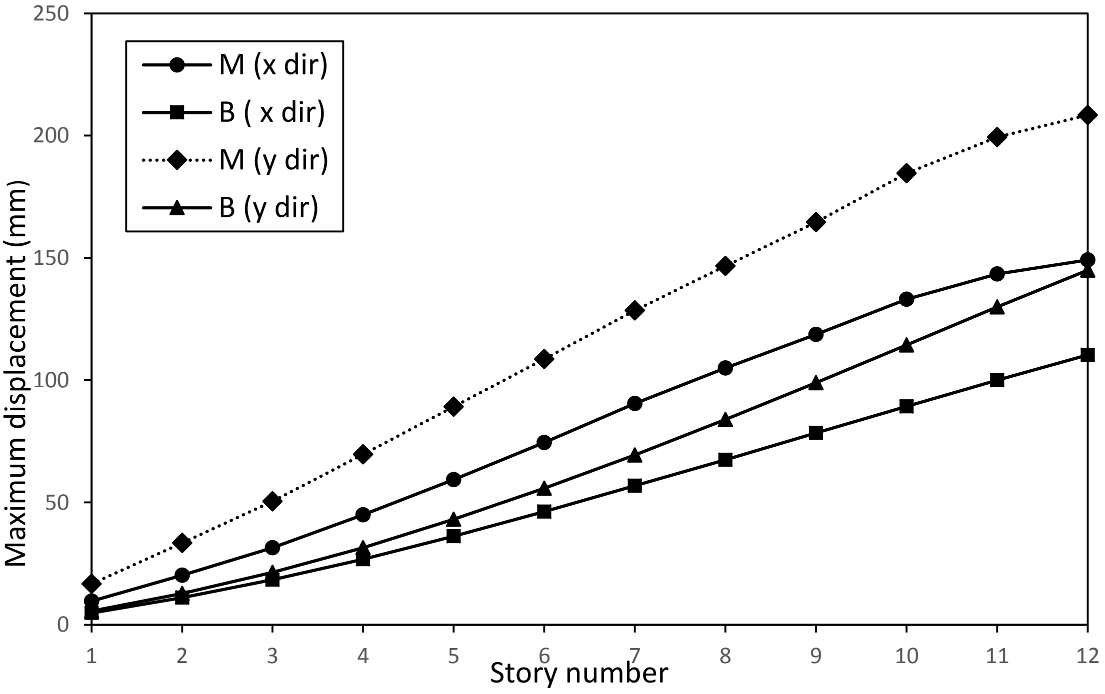


Figure 4.23: 12 story irregular plan frame displacements in x and y directions

Table 4.11: Percentage difference of displacement between moment and braced frames for 12 story irregular plan design.

Story	x-dir	y-dir
Base	0	0
Story 1	100.0	198.2
Story 2	82.9	160.9
Story 3	71.2	136.0
Story 4	67.5	121.3
Story 5	64.1	107.0
Story 6	60.9	94.6
Story 7	59.3	85.2
Story 8	55.6	74.9
Story 9	51.4	66.3
Story 10	49.0	61.4
Story 11	43.4	53.5
Story 12	35.3	43.7

In x-direction, the moment frame displacements are 35.3% to 100% higher than the braced frame ones at different stories. In y-direction, the moment frame displacements are 43.7%-198.2% higher than the braced frame ones. So despite the irregularity in plan of the building still bracings provided greater lateral stiffness to the braced frame and thus displacements reduced considerably.

4.3.2.1 Irregular Elevation Building Analysis

Three types of irregular elevation designs were studied: They are labeled as 1Rx1L, 2Rx1L, and 1Rx1L at different elevation. The irregular height 1Rx1L design consisted of removing 8 floors from each side of the building at the remote bays, as shown in the Fig 4.24.

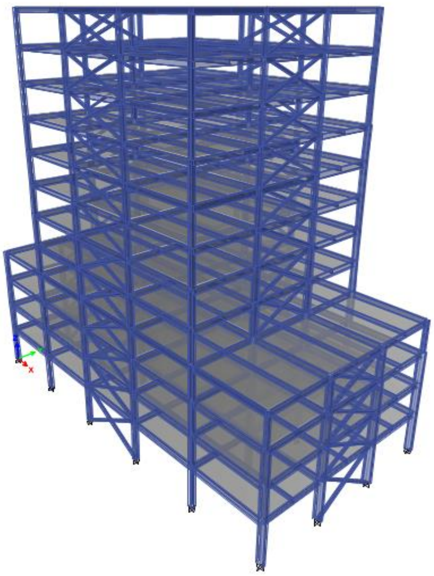


Figure 4.24: Irregular Height 1Rx1L building design

The irregular height 2Rx1L design is same as the 1Rx1L except that 8 floors were removed from two bays on one side of the buildings as illustrated in the Fig 4.25.

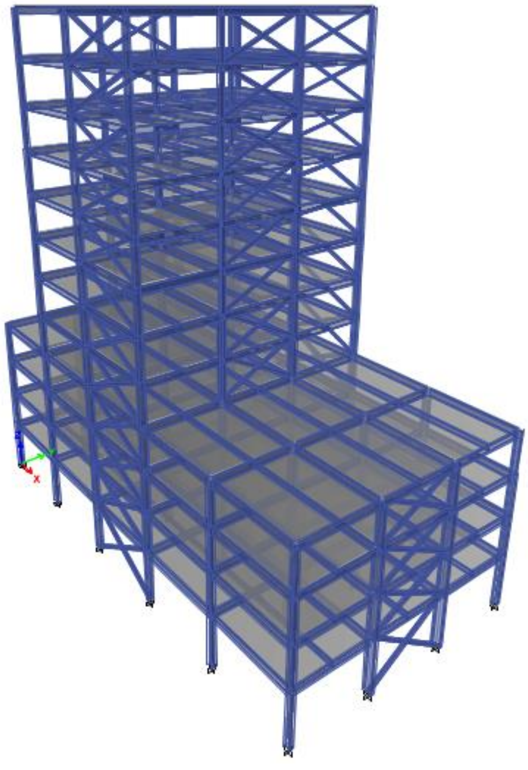


Figure 4.25: Irregular Height 2Rx1L building design

The irregular height 1Rx1L different elevation design was about removing 4 floors from one side extreme bay and 8 floors from the other, as shown in Fig. 4.26:

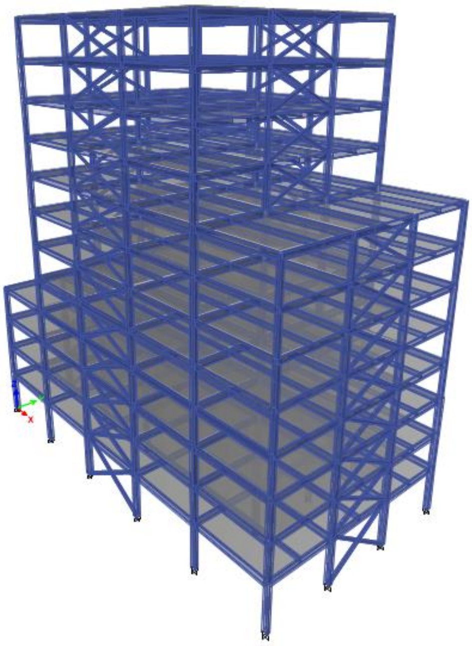


Figure 4.26: Irregular Height 1Rx1L different elevation building design

4.3.2.1.1 Irregular Height 1Rx1L Building Analysis

Fig. 4.27 shows the lateral displacements for the 12 story irregular height (1Rx1L) braced and moment frames. As in the design cases given so far this case also indicates moment frame achieving more lateral displacement than the braced frame in both x and y directions (Table 4.12).

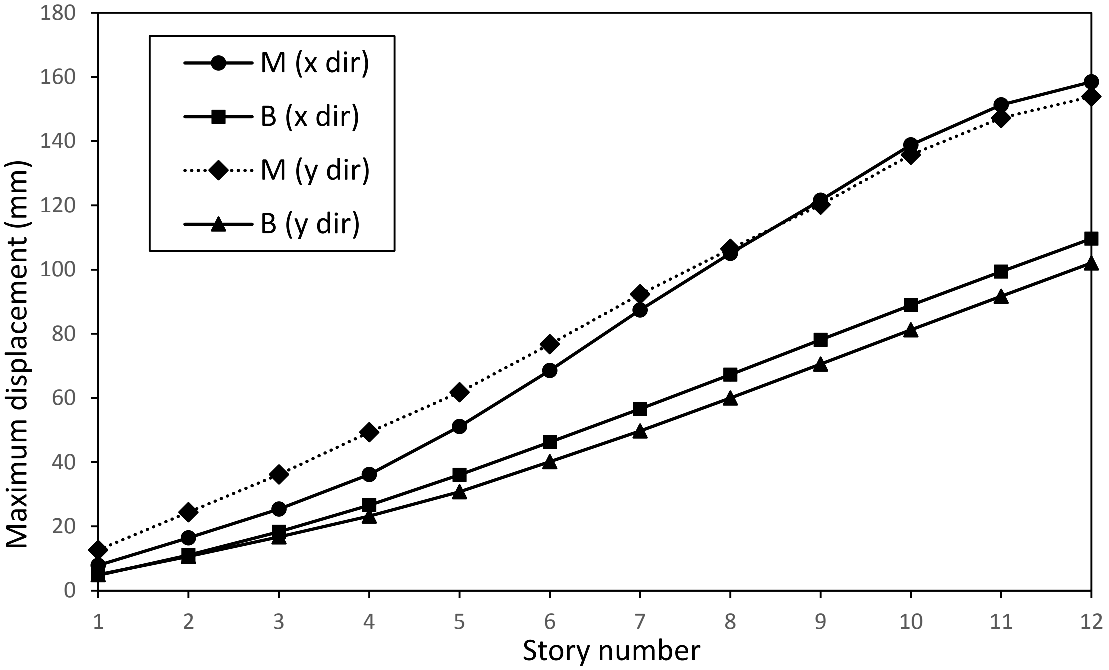


Figure 4.27: 12 story irregular height 1Rx1L frame displacements in x and y directions

Table 4.12: Percentage difference of displacement between moment and braced frames for 12 story irregular height (1Rx1L) building design.

Story	x-dir	y-dir
Base	0	0
Story 1	66.0	157.1
Story 2	49.1	130.2
Story 3	38.8	116.2
Story 4	35.7	112.5
Story 5	41.9	100.6
Story 6	48.3	91.3
Story 7	54.4	85.7
Story 8	56.0	77.3
Story 9	55.7	70.5
Story 10	56.1	67.1
Story 11	52.2	60.5
Story 12	44.6	50.9

In the x-direction, the moment frame displacements are 35.7% to 66.0% higher than the braced frame ones at different stories. In y-direction, the moment frame displacements are 50.9%-157.1% higher than the braced frame ones. So despite the irregularity in elevation of the building still bracings provided greater lateral stiffness to the braced frame and thus displacements reduced considerably.

4.3.2.1.2 Irregular Height 2Rx1L Building Analysis

Fig. 4.28 shows the lateral displacements for the 12 story irregular height (2Rx1L) braced and moment frames. As in the design cases given so far this case also indicates moment frame achieving more lateral displacement than the braced frame in both x and y directions (Table 4.13).

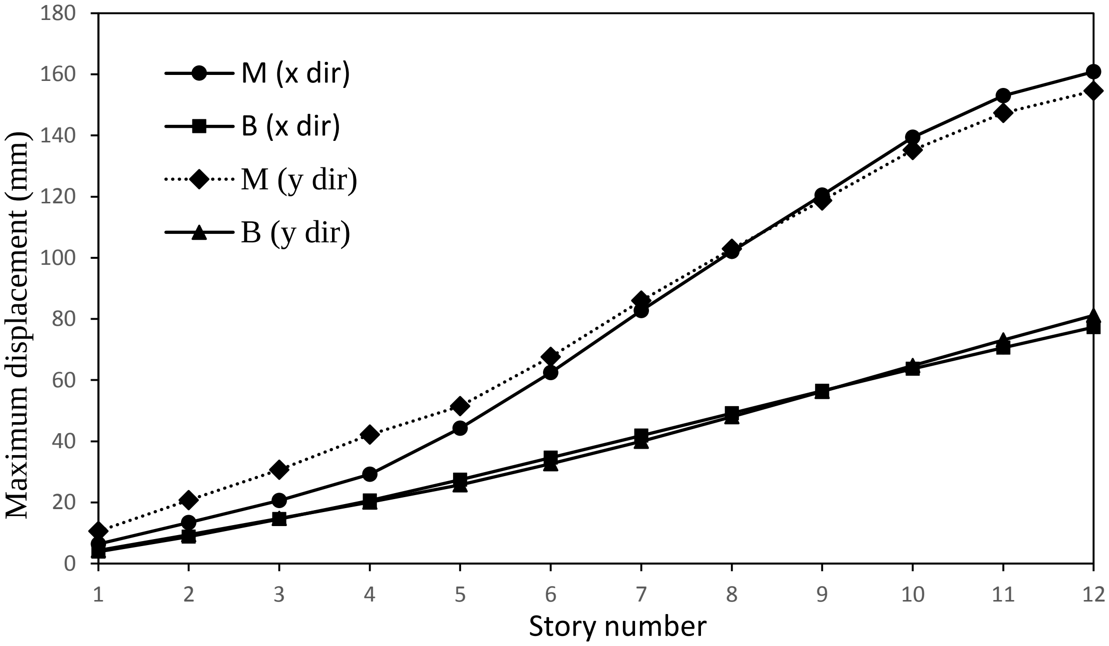


Figure 4.28: 12 story irregular height 2Rx1L frame displacements in x and y directions

Table 4.13: Percentage difference of displacement between moment and braced frames for 12 story irregular height (2Rx1L) building design.

Story	x-dir	y-dir
Base	0	0
Story 1	64.1	146.5
Story 2	52.3	120.2
Story 3	42.1	108.2
Story 4	41.7	109.5
Story 5	61.3	100.0
Story 6	80.3	107.4
Story 7	97.8	115.5
Story 8	107.5	114.4
Story 9	113.3	110.8
Story 10	118.8	109.0
Story 11	116.7	101.5
Story 12	108.0	90.6

As in earlier cases, for irregular height (2Rx1L) building design braced frame managed to better laterally stiffen the building and limited the lateral displacement. In x-direction, the moment frame displacements are 41.7% to 118.8% higher than the braced frame ones at different stories. In y- direction, the moment frame displacements are 90.6%-146.5% higher than the braced frame ones.

4.3.2.1.3 Irregular Height 1Rx1L Different Elevation Building Analysis

Fig. 4.29 shows the lateral displacements for the 12 story irregular height (2Rx1L) braced and moment frames. As in the design cases given so far this case also indicates moment frame achieving more lateral displacement than the braced frame in both x and y directions (Table 4.14).

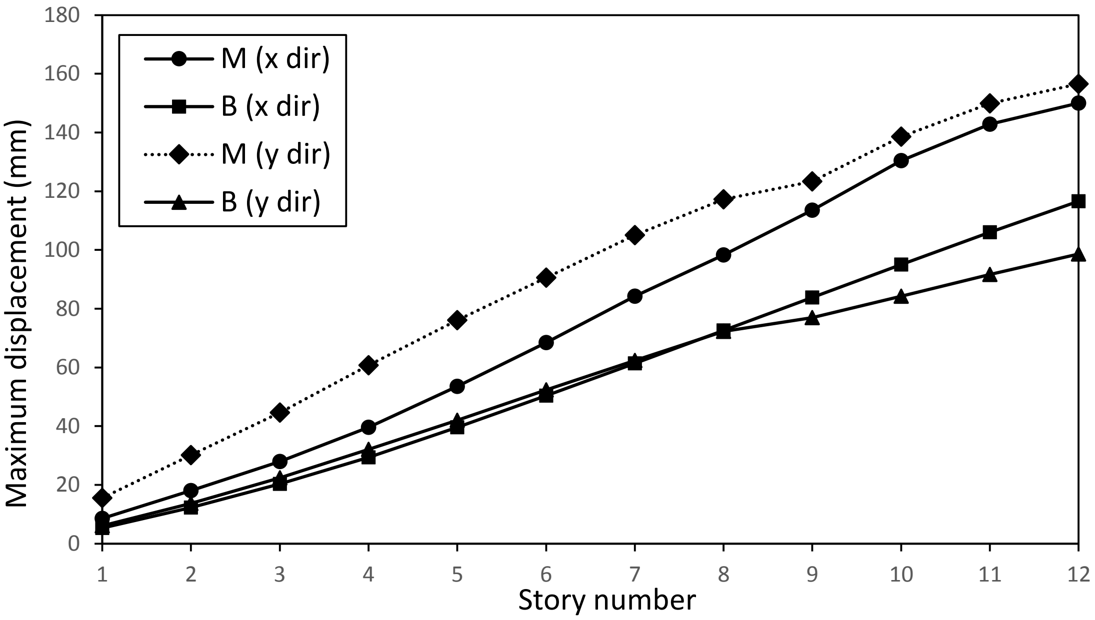


Figure 4.29: 12 story irregular height 1Rx1L different elevation frame displacements in x and y directions

Table 4.14: Percentage difference of displacement between moment and braced frames for 12 story irregular height (1Rx1L) different elevation building design.

Story	x-dir	y-dir
Base	0	0
Story 1	62.3	154.1
Story 2	46.3	119.7
Story 3	37.4	99.1
Story 4	34.7	89.1
Story 5	35.1	81.2
Story 6	35.9	73.2
Story 7	37.1	68.3
Story 8	35.4	62.1
Story 9	35.4	60.1
Story 10	37.3	64.4
Story 11	34.7	63.6
Story 12	28.6	58.8

For irregular height 1Rx1L different elevation building design, braced frame also had lower lateral displacement than moment frame. In x-direction, the moment frame displacements are 28.6% to 62.3% higher than the braced frame ones at different stories. In y-direction, the moment frame displacements are 58.8%-154.1% higher than the braced frame ones.

4.3.2.2 Irregular 3D Building Analysis

12 types of irregular 3D designs of 4 moment and 8 braced frames were studied: 3D1, 3D2, 3D3, 3D4. Each design is different from the other with respect to the location of the bracing and variations in building plan design (Fig 4.30 to 4.35).

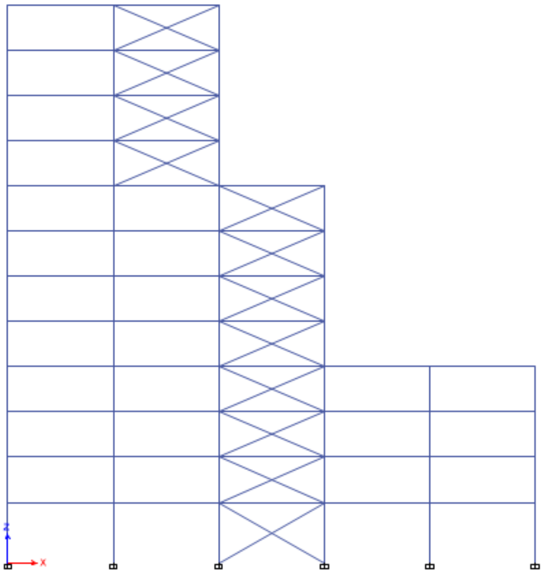


Figure 4.30: Irregular 3D1 B1 design

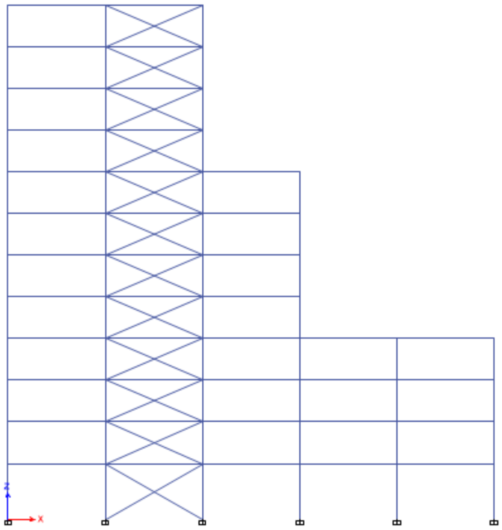


Figure 4.31: Irregular 3D1 B2 design

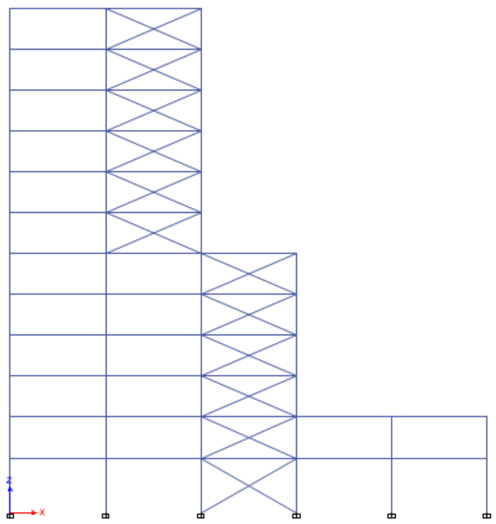


Figure 4.32: Irregular 3D2 B1 design

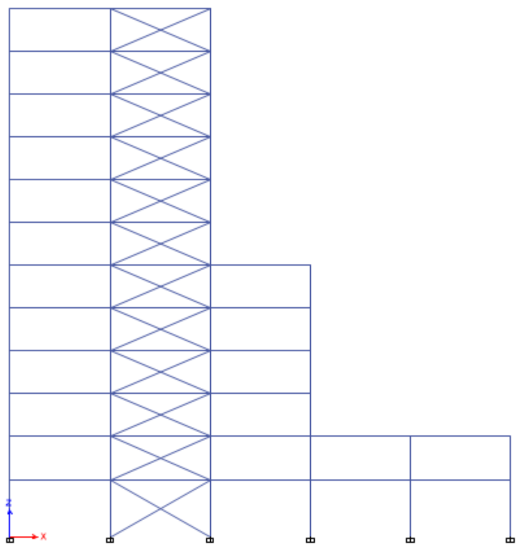


Figure 4.33: Irregular 3D2 B2 design

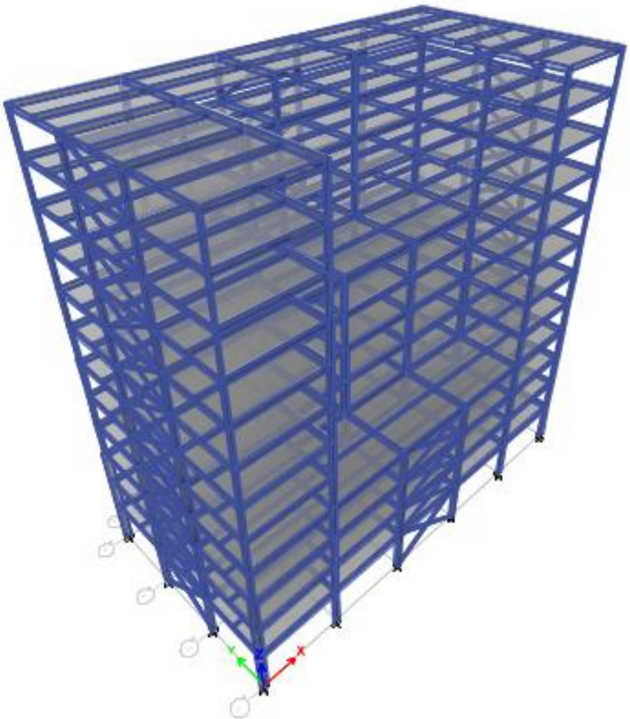


Figure 4.34: Irregular 3D4 B1 design

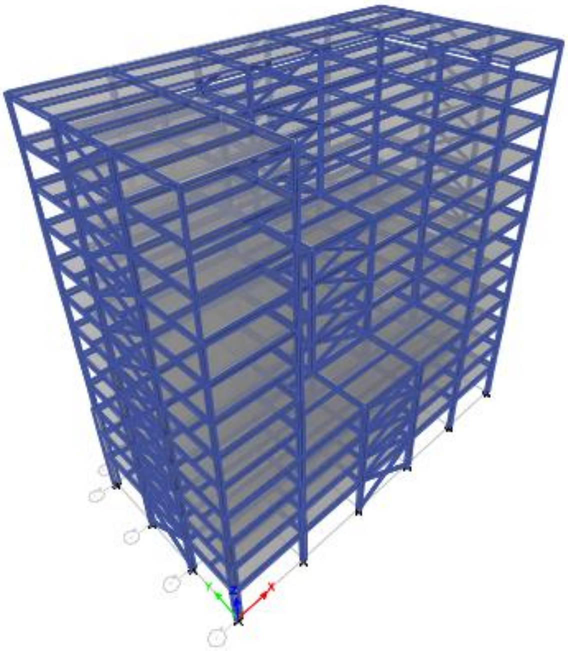


Figure 4.35: Irregular 3D4 B2 design

4.3.2.2.1 Irregular 3D1 Building Analysis

Fig. 4.36 shows the lateral displacements for the 12 story irregular 3D1 braced and moment frames. As in the design cases given so far this case also indicates moment frame achieving more lateral displacement than the braced frame in both x and y directions (Table 4.15).

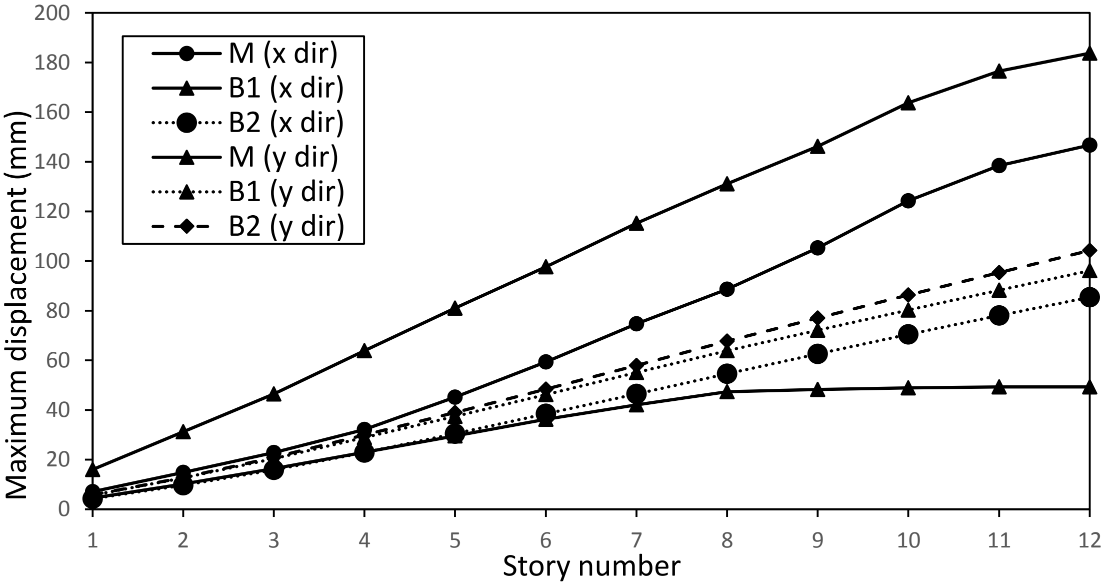


Figure 4.36: 12 story irregular 3D1 frame displacements in x and y directions

Table 4.15: Percentage difference of displacement between moment and braced frames for 12 story irregular 3D1 building design.

	Braced 1		Braced 2	
Story	x-dir	y-dir	x-dir	y-dir
Base	0	0	0	0
Story 1	57.8	180.7	69.0	175.9
Story 2	45.1	147.6	52.6	143.8
Story 3	39.0	127.9	43.4	122.5
Story 4	40.2	121.1	40.8	113.7
Story 5	52.4	116.6	47.9	108.2
Story 6	63.8	111.5	54.0	101.9
Story 7	77.4	109.3	60.6	98.8
Story 8	87.5	105.2	62.5	93.4
Story 9	118.0	102.8	68.2	89.9
Story 10	154.2	104.0	76.3	89.8
Story 11	180.9	100.0	77.3	85.1
Story 12	197.6	91.1	71.8	76.2

In x-direction, the moment frame displacement is 40.2% to 197.6% more than the braced 1, and 40.8% to 77.3% more than the braced 2 frame at different stories. In y-direction, the difference is even more with moment frame displacement being 91.1% to 180.7% more than the braced 1, and 76.2% to 175.9% more than the braced 2 frame at different stories.

4.3.2.2.2 Irregular 3D2 Building Analysis

Fig. 4.37 shows the lateral displacements for the 12 story irregular 3D2 braced and moment frames. As in the design cases given so far this case also indicates moment frame achieving more lateral displacement than the braced frame in both x and y directions (Table 4.16).

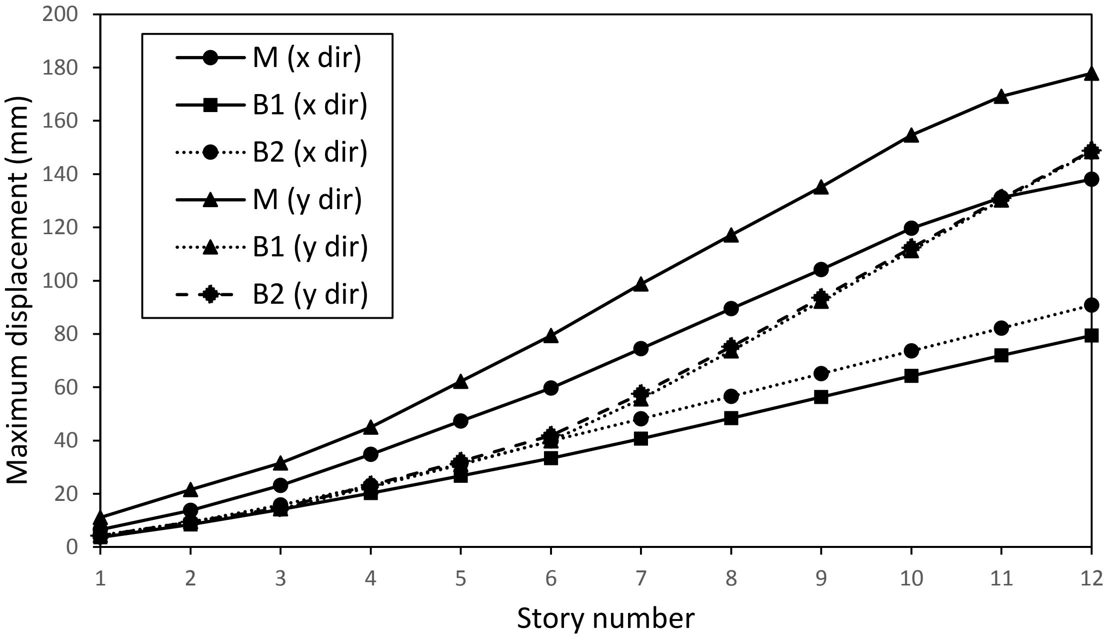


Figure 4.37: 12 story irregular 3D2 frame displacements in x and y directions

Table 4.16: Percentage difference of displacement between moment and braced frames for 12 story irregular 3D2 building design.

	Braced 1		Braced 2	
Story	x-dir	y-dir	x-dir	y-dir
Base	0	0	0	0
Story 1	75.7	152.3	62.5	158.1
Story 2	62.4	127.4	46.8	129.8
Story 3	63.8	120.3	46.2	114.3
Story 4	72.3	100.0	50.6	94.0
Story 5	77.2	101.3	51.6	93.2
Story 6	78.7	99.5	50.0	89.5
Story 7	83.0	77.5	54.9	71.7
Story 8	84.9	59.1	58.1	55.7
Story 9	85.1	46.5	60.1	44.4
Story 10	86.4	39.0	62.6	37.8
Story 11	82.5	30.0	59.6	29.4
Story 12	73.9	19.9	52.1	19.6

In x-direction, the moment frame displacement is 62.4% to 86.4% more than the braced 1 and 46.2% to 62.6% more than the braced 2 frame at different stories. In y-direction, the difference is even more with moment frame displacement being 19.9% to 152.3% more than the braced 1, and 19.6% to 158.1% more than the braced 2 frame at different stories. After story 6 the displacement of braced 1 and 2 in y-direction increases and approaches to those of moment frame in y-direction. So building with cross bracing in two different bays caused more displacement percentage in x-direction than the one having bracing in one bay.

4.3.2.2.3 Irregular 3D3 Building Analysis

Fig. 4.38 shows the lateral displacements for the 12 story irregular 3D3 braced and moment frames. As in the design cases given so far this case also indicates moment frame achieving more lateral displacement than the braced frame in both x and y directions (Table 4.17).

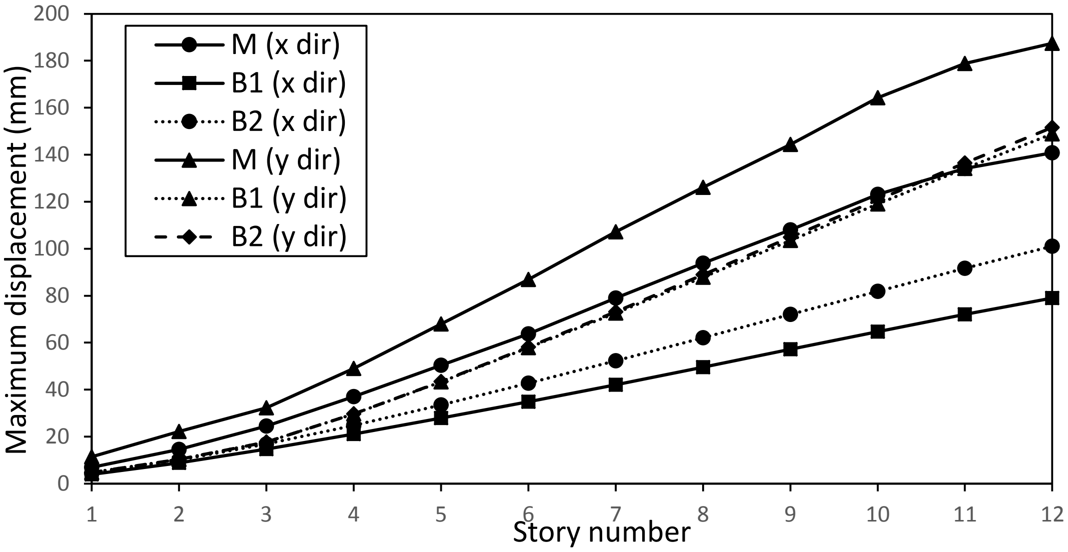


Figure 4.38: 12 story irregular 3D3 frame displacements in x and y directions.

Table 4.17: Percentage difference of displacement between moment and braced frames for 12 story irregular 3D3 building design.

	Braced 1		Braced 2	
Story	x-dir	y-dir	x-dir	y-dir
Base	0	0	0	0
Story 1	76.9	142.6	60.5	142.6
Story 2	64.0	113.5	44.6	113.5
Story 3	66.7	82.5	45.0	82.5
Story 4	75.8	65.0	49.6	65.0
Story 5	80.6	56.8	50.4	56.5
Story 6	82.8	50.1	49.1	49.6
Story 7	87.6	47.7	51.1	46.4
Story 8	89.1	43.5	51.0	41.8
Story 9	88.8	39.5	50.0	37.7
Story 10	90.3	38.0	50.3	35.9
Story 11	86.4	33.2	46.3	31.0
Story 12	78.2	25.9	39.3	23.6

In x-direction, the moment frame displacement is 64.0% to 90.3% more than the braced 1, and 39.3% to 60.5% more than the braced 2 frame at different stories. In y-direction, the difference is even more with moment frame displacement being 25.9% to 142.6% more than the braced 1, and 23.6% to 142.6% more than the braced 2 frame at different stories. Behavior is similar to 12 story irregular 3D2 building design.

4.3.2.2.4 Irregular 3D4 Building Analysis

Fig. 4.39 shows the lateral displacements for the 12 story irregular 3D4 braced and moment frames. As in the design cases given so far this case also indicates moment frame achieving more lateral displacement than the braced frame in both x and y directions (Table 4.18).

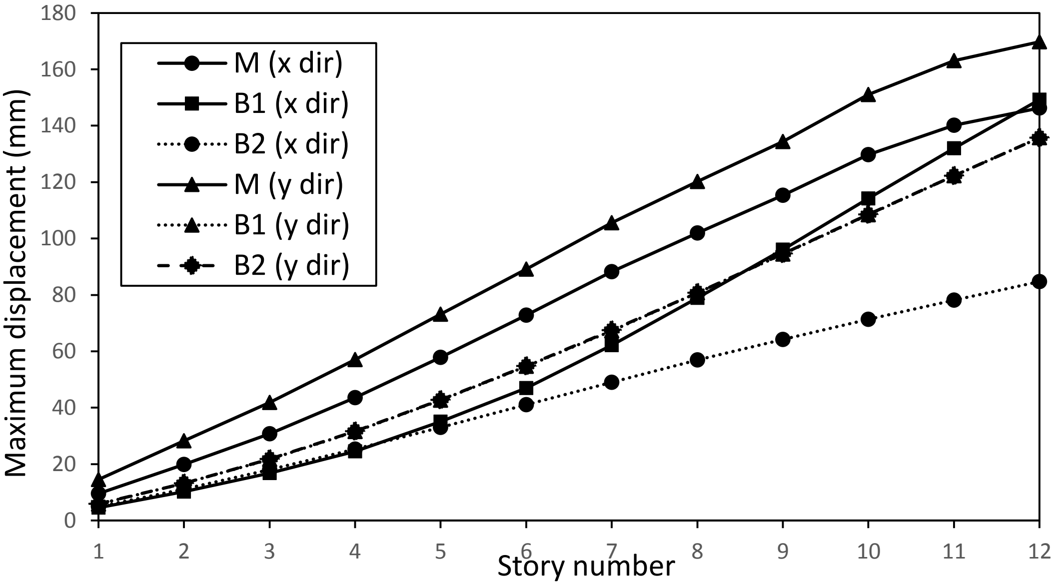


Figure 4.39: 12 story irregular 3D4 frame displacement in x and y direction

Table 4.18: Percentage difference of displacement between moment and braced frames for 12 story irregular 3D4 building design.

	Braced 1		Braced 2	
Story	x-dir	y-dir	x-dir	y-dir
Base	0	0	0	0
Story 1	111.1	150.0	93.9	145.8
Story 2	95.1	113.6	79.3	113.6
Story 3	82.7	92.6	70.6	91.7
Story 4	77.6	81.3	71.9	80.7
Story 5	65.1	71.8	75.2	71.4
Story 6	54.9	62.9	77.6	62.6
Story 7	41.8	56.9	80.0	56.4
Story 8	29.2	48.9	79.1	48.8
Story 9	20.0	42.2	79.6	42.1
Story 10	13.6	39.3	81.9	39.2
Story 11	6.2	33.4	79.5	33.4
Story 12	-1.9	25.0	72.7	25.0

In x-direction, the moment frame displacement is 6.2% to 111.1% more than the braced 1, but in the last floor the displacement was 1.9% less than the braced 1, and 72.7% to 93.9% more than the braced 2 frame at different stories. In y-direction, the difference is even more with moment frame displacement being 25.0% to 150.0% more than the braced 1, and 25.0% to 145.6% more than the braced 2 frame at different stories. Braced 1 and 2 in y-direction had very similar displacements, however, after story 4 B1 had considerably higher lateral displacements.

4.4 Twenty-Story Building Structures

The regular building design consists of 5 bays (each with 7m span) in x-direction and 3 bays (each with 6m span) in y-direction and a total building height of 61m. Cross-bracing is used for the braced frame. The irregular building design has 8 different types of irregularity, 1 on plan, 3 on elevations and 4 on 3D views.

4.4.1 Regular Building Analysis

Two types of regular buildings were studied: moment frame and braced frame. Braced frames were placed at the middle bay in x- and y-directions of the building. Moment frame lateral displacement is more than the braced frame at some stories and less at others (Fig.4.40) and the percentage difference is given in Table 4.19.

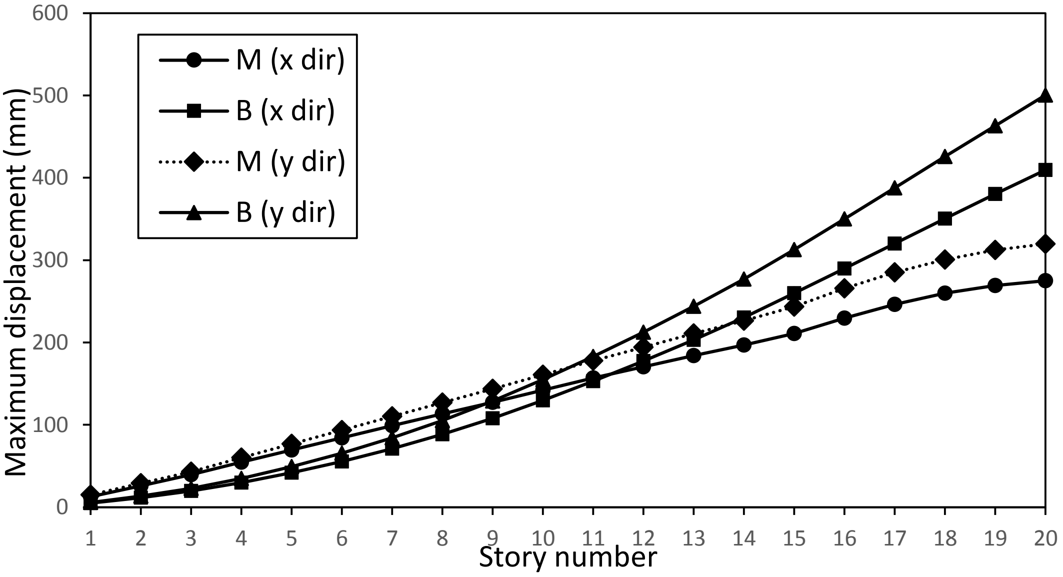


Figure 4.40: 20 story regular frame displacements in x and y directions.

Table 4.19: Percentage difference of displacement between moment and braced frames for 20 story regular building design

Story	x-dir	y-dir
Base	0	0
Story 1	164.6	169.6
Story 2	123.3	118.8
Story 3	99.5	88.6
Story 4	83.2	72.4
Story 5	66.3	56.4
Story 6	52.0	42.4
Story 7	39.6	31.0
Story 8	28.4	20.7
Story 9	17.9	11.2
Story 10	9.6	3.7
Story 11	2.4	-2.7
Story 12	-4.0	-8.6
Story 13	-9.4	-13.5
Story 14	-14.5	-18.2
Story 15	-18.8	-22.2
Story 16	-20.8	-24.1
Story 17	-23.1	-26.5
Story 18	-25.9	-29.4
Story 19	-29.2	-32.6
Story 20	-32.8	-36.1

In x-direction, the moment frame percentage displacement is 164.6% to 2.4% more than the braced frame from story 1 to story 11 and it is 4.0% to 32.8% less than the braced frame from story 12 to story 20. In y-direction, the lateral displacement trend is similarly to x-direction except that the change is at story 10 rather than story 11.

4.4.2 Irregular Plan Building Analysis

One irregular design was studied which consisted of removing 26.67% of the floors from the regular building design.

Fig. 4.41 shows the lateral displacements for the 20 story irregular plan braced and moment frames. This case also indicates moment frame achieving more lateral displacement up to some story height the less displacement in both x and y direction (Table 4.20).

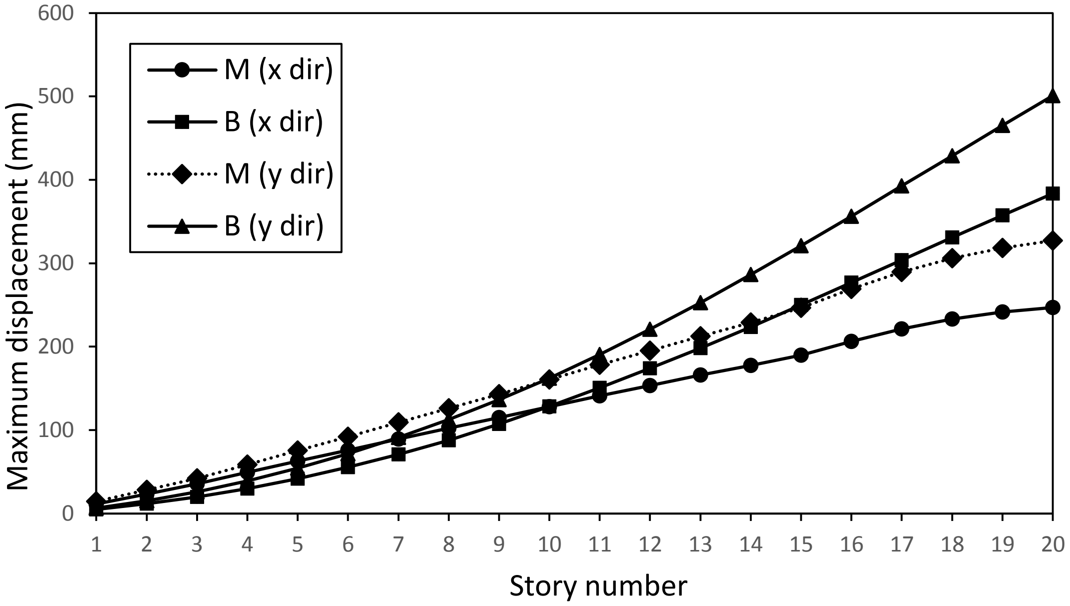


Figure 4.41: 20 story irregular plan frame displacements in x and y directions.

Table 4.20: Percentage difference of displacement between moment and braced frames for 20 story irregular plan building design.

Story	x-dir	y-dir
Base	0	0
Story 1	137.5	120.0
Story 2	100.9	83.7
Story 3	78.9	62.3
Story 4	64.5	50.9
Story 5	50.0	39.1
Story 6	36.9	28.7
Story 7	26.0	19.8
Story 8	16.3	11.8
Story 9	7.0	4.7
Story 10	-0.1	-0.9
Story 11	-6.2	-6.5
Story 12	-11.8	-11.6
Story 13	-16.3	-15.9
Story 14	-20.7	-20.0
Story 15	-24.1	-23.2
Story 16	-25.5	-24.4
Story 17	-27.2	-26.3
Story 18	-29.6	-28.7
Story 19	-32.4	-31.5
Story 20	-35.6	-34.7

In x-direction, the moment frame displacement is 7.0% to 137.5% more than the braced frame from story 1 to story 9, and it is 0.1% to 35.6% less than the braced frame from story 10 to story 20. In y-direction, the moment frame displacement is 4.7% to 120.0% more than the braced frame from story 1 to story 9 and it is 0.9% to 34.7% less than the braced frame from story 10 to story 20. The bracing locations along the structure height were the reasons for the displacements achieved and they follow similar trend as those of regular building design

4.4.2.1 Irregular Elevation Building Analysis

Three types of irregular elevation designs were studied: They are labeled as 1Rx1L, 2Rx1L, and 1Rx1L at different elevation. The irregular height 1Rx1L design consisted of removing 13 floors from each side of the building at the remote bays, as shown in the Fig 4.42.

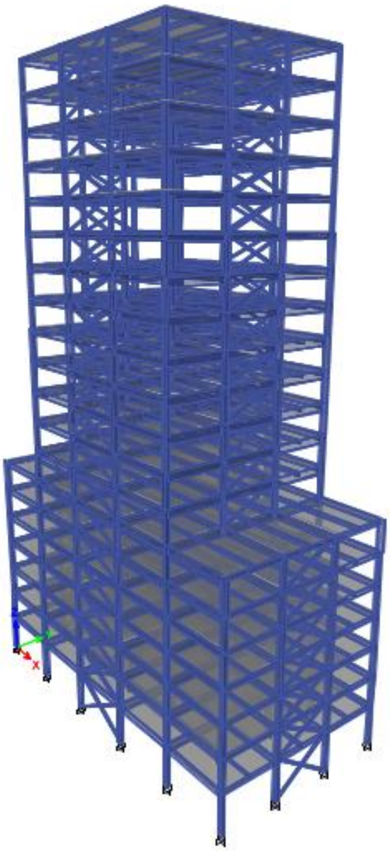


Figure 4.42: Irregular Height 1Rx1L building design

The irregular height 2Rx1L design is same as the 1Rx1L except that 13 floors were removed from two bays on one side of the building, as illustrated in Fig. 4.43.

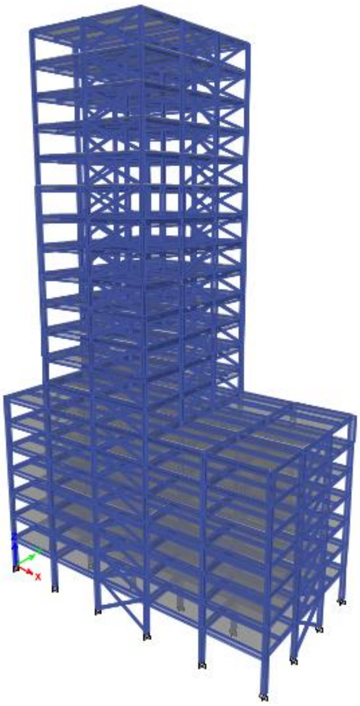


Figure 4.43: Irregular height 2Rx1L building design

The irregular height 1Rx1L different elevation design was about removing 13 floors from one side extreme bay and 7 floors from the other, as shown in figure 4.44.

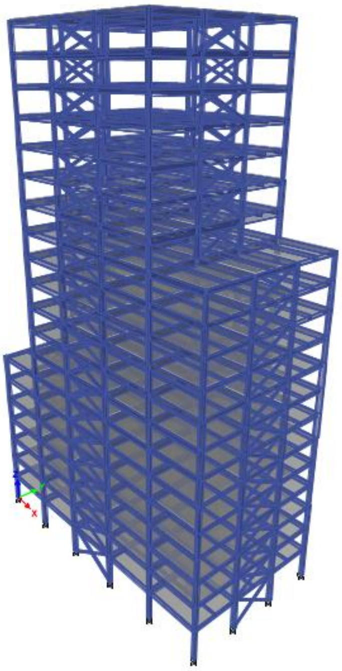


Figure 4.44: Irregular height 1Rx1L different elevation building design.

4.4.2.1.1 Irregular Height 1Rx1L Building Analysis

Fig. 4.45 shows the lateral displacements for the 20 story irregular height (1Rx1L) braced and moment frames. This case indicates braced frame achieving more lateral displacement than moment frame in both x and y directions (Table 4.21)

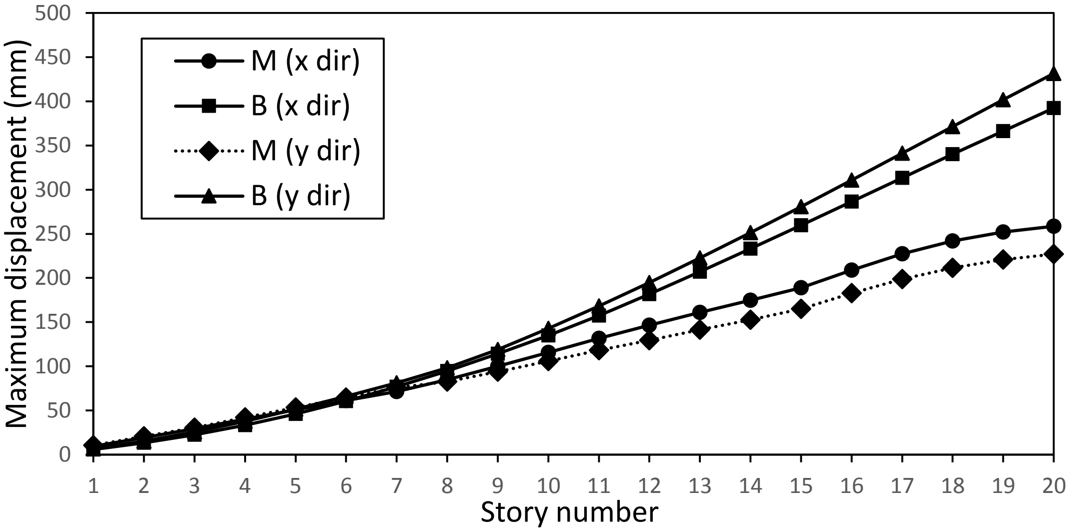


Figure 4.45: 20 story irregular height (1Rx1L) frame displacements in x and y directions.

Table 4.21: Percentage difference of displacement between moment and braced frames for 20 story irregular height (1Rx1L) building design.

Story	x-dir	y-dir
Base	0	0
Story 1	69.6	60.6
Story 2	45.1	34.0
Story 3	30.2	17.4
Story 4	20.4	10.8
Story 5	10.7	3.7
Story 6	1.0	-2.3
Story 7	-7.0	-7.0
Story 8	-10.4	-15.7
Story 9	-12.4	-21.0
Story 10	-14.2	-25.7
Story 11	-16.5	-29.7
Story 12	-19.5	-33.4
Story 13	-22.3	-36.5
Story 14	-25.1	-39.3
Story 15	-27.2	-41.3
Story 16	-27.1	-41.2
Story 17	-27.5	-41.8
Story 18	-28.9	-43.1
Story 19	-31.2	-45.0
Story 20	-34.1	-47.4

In x-direction, the moment frame displacement is up to 69.6% more than the braced frame from story 1 to story 6, and it is 7% to 34.1% less than the braced frame from story 7 to story 20. In y-direction, the moment frame displacement is 3.7% to 60.0% more than the braced frame from story 1 to story 5 and it is 2.3% to 47.4% less than the braced frame from story 6 to story 20.

4.4.2.1.2 Irregular Height 2Rx1L Building Analysis

Fig 4.46 shows the lateral displacements for the 20 story irregular height (2Rx1L) braced and moment frames. Moment frame achieved marginally more lateral displacement up to story 6 in x-direction and story 7 in y-direction (Table 4.22). After these stories braced frame displacements continued to increase up to story 20.

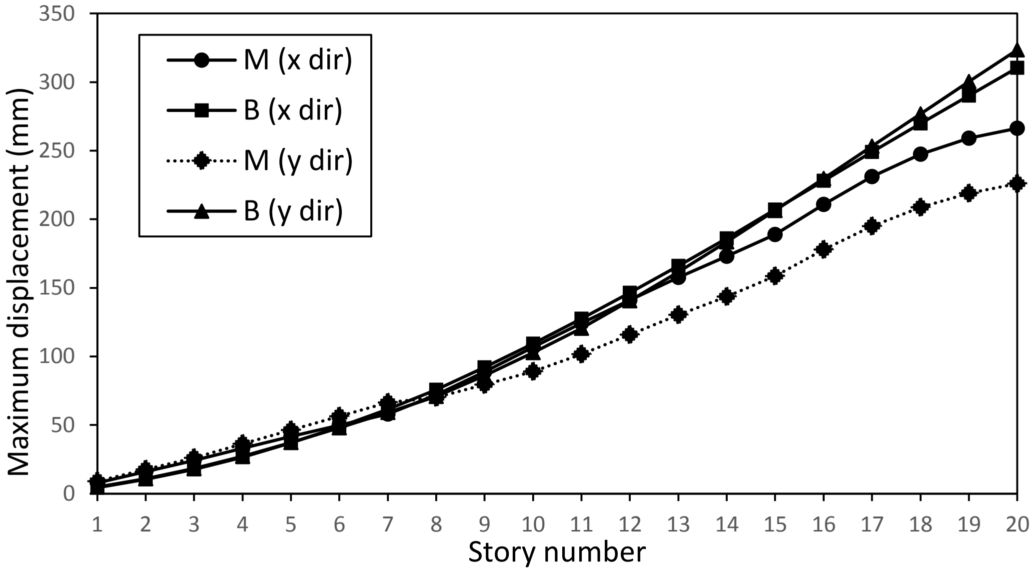


Figure 4.46: 20 story irregular height (2Rx1L) frame displacements in x and y directions.

Table 4.22: Percentage difference of displacement between moment and braced frames for 20 story irregular height (2Rx1L) building design.

Story	x-dir	y-dir
Base	0	0
Story 1	83.7	93.6
Story 2	54.4	61.5
Story 3	36.2	41.8
Story 4	24.5	32.6
Story 5	12.7	24.1
Story 6	2.5	17.5
Story 7	-5.7	12.4
Story 8	-5.0	-1.0
Story 9	-3.4	-7.8
Story 10	-2.4	-13.2
Story 11	-2.5	-15.7
Story 12	-3.8	-17.6
Story 13	-5.1	-19.4
Story 14	-7.0	-21.6
Story 15	-8.8	-23.2
Story 16	-7.6	-22.6
Story 17	-7.2	-23.0
Story 18	-8.3	-24.6
Story 19	-10.7	-27.1
Story 20	-14.1	-30.1

In x-direction, the moment frame displacement is up to 83.7% more than the braced frame from story 1 to story 6, and it is 5.7% to 14.1% less than the braced frame from story 7 to story 20. In y-direction, the moment frame displacement is 12.4% to 93.6% more than the braced frame from story 1 to story 7 and it is 1.0% to 30.1% less than the braced frame from story 8 to story 20.

4.4.2.1.3 Irregular Height 1Rx1L Different Elevation Building Analysis

Fig 4.47 and Table 4.23 show the lateral displacements for the 20 story irregular height (1Rx1L) different elevation braced and moment frames.

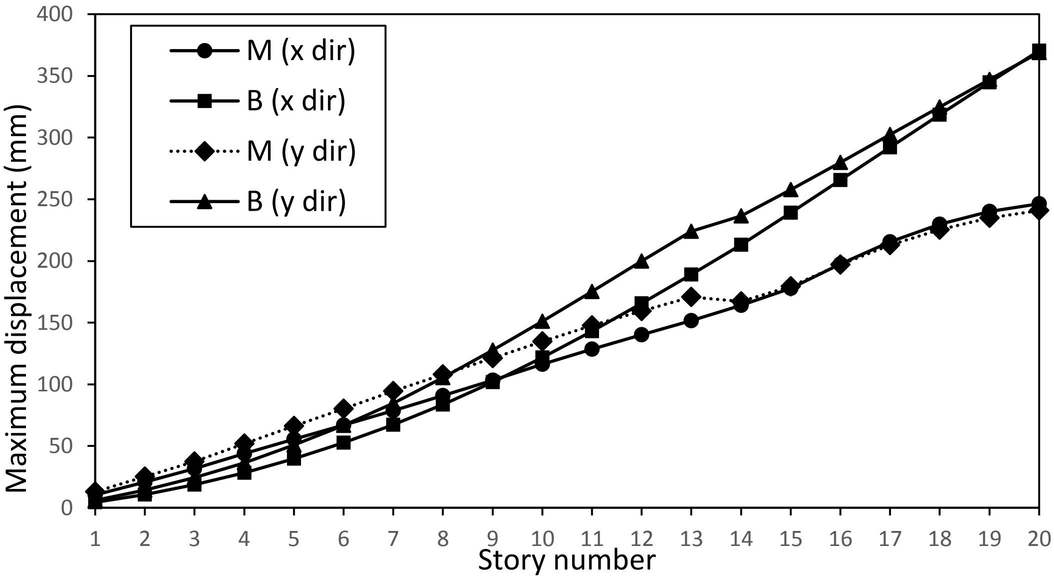


Figure 4.47: 20 story irregular height (1Rx1L) different elevation frame displacements in x and y directions

Table 4.23: Percentage difference of displacement between moment and braced frames for 20 story irregular height (1Rx1L) different elevation building design.

Story	x-dir	y-dir
Base	0	0
Story 1	128.9	113.1
Story 2	93.5	76.2
Story 3	70.1	53.3
Story 4	54.8	42.2
Story 5	40.1	30.3
Story 6	27.6	20.1
Story 7	17.0	11.5
Story 8	8.7	2.6
Story 9	1.3	-5.0
Story 10	-4.6	-10.9
Story 11	-10.1	-15.7
Story 12	-15.3	-20.2
Story 13	-19.7	-23.7
Story 14	-23.0	-29.3
Story 15	-25.6	-30.4
Story 16	-25.6	-29.6
Story 17	-26.2	-29.6
Story 18	-27.9	-30.6
Story 19	-30.3	-32.4
Story 20	-33.5	-34.7

In x-direction, up to story 9, the moment frame displacement was maximum 128.9% more than the braced frame and it is up to 33.5% less than the braced frame at story 20. In y-direction, up to story 8, the moment frame displacement was maximum 113.1% more than the braced frame and it was maximum 34.7% less than the braced frame at story 20.

4.4.2.2 Irregular 3D Building Analysis

12 types of irregular 3D designs of 4 moments and 8 braced were studied: 3D1, 3D2, 3D3, 3D4. Each design is different from the other with respect to the location of the bracing and variations in building plan design (Fig 4.48 to 4.52).

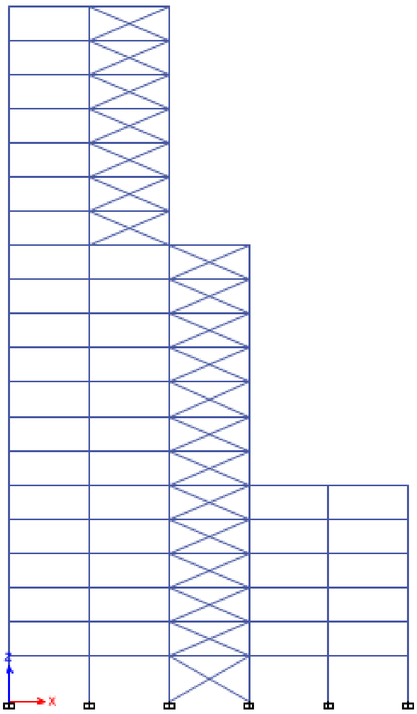


Figure 4.48: Irregular 3D1 B1 design

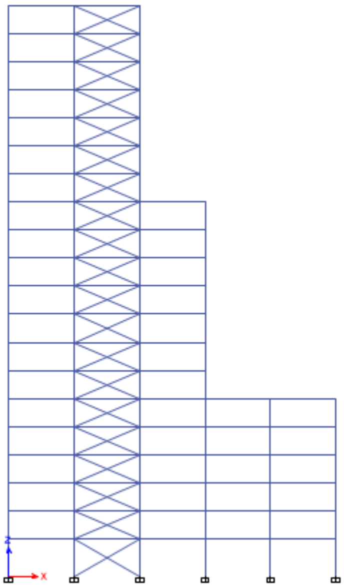


Figure 4.49: Irregular 3D1 B2 design

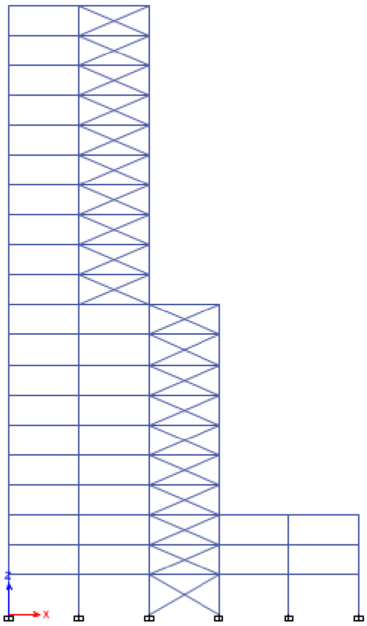


Figure 4.50: Irregular 3D2 B1 design

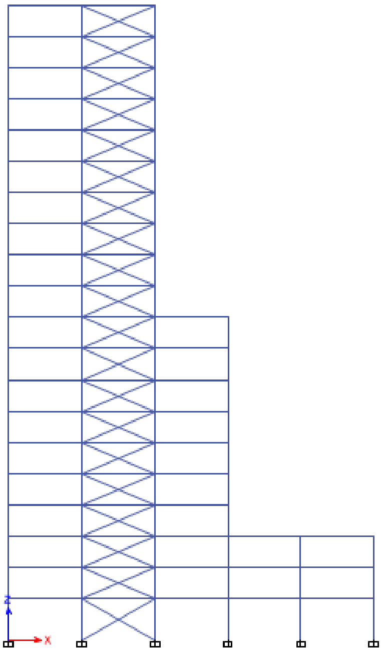


Figure 4.51: Irregular 3D2 B2 design

Figure 4.52: Irregular 3D4 B1 design

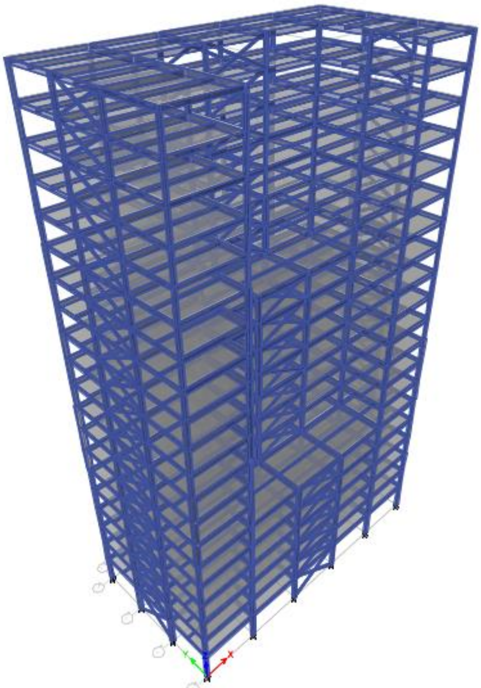


Figure 4.53: Irregular 3D4 B2 design

4.4.2.2.1 Irregular 3D1 Building Analysis

Fig. 4.53 shows the lateral displacements for the 20 story irregular 3D1 braced and moment frames. Moment frame achieved more lateral displacement up to some story elevation and then less displacement in both x and y directions (Table 4.24).

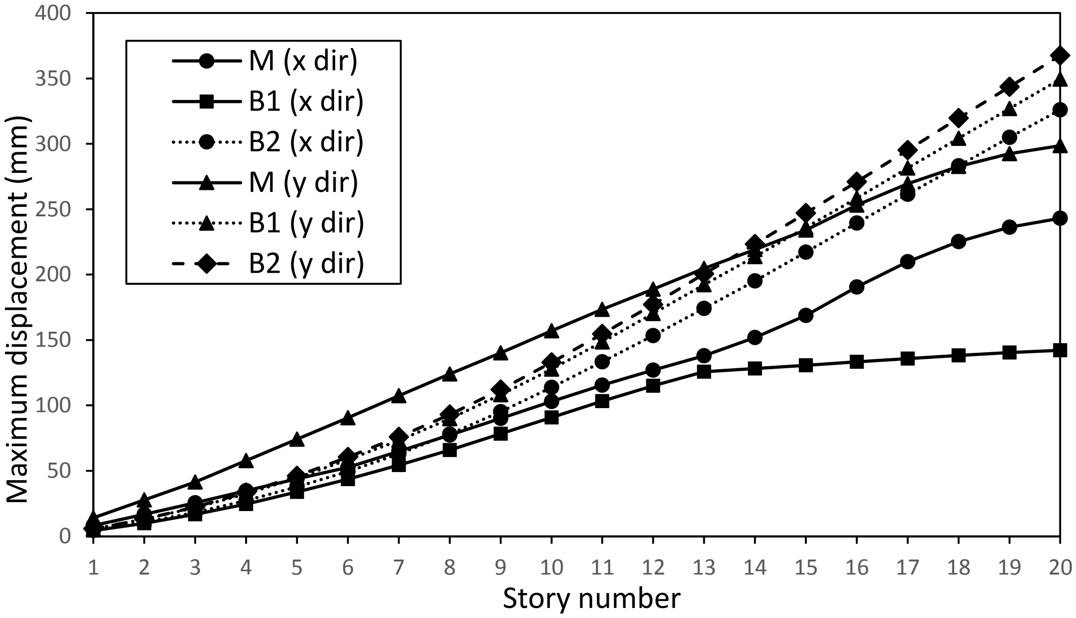


Figure 4.54: 20 story irregular 3D1 frame displacements in x and y directions

Table 4.24: Percentage difference of displacement between moment and braced frames for 20 story irregular 3D1 building design.

	Braced 1		Braced 2	
Story	x-dir	y-dir	x-dir	y-dir
Base	0	0	0	0
Story 1	93.0	153.6	84.4	149.1
Story 2	68.0	113.1	57.0	109.8
Story 3	51.8	89.5	40.1	85.3
Story 4	41.3	78.7	28.3	73.9
Story 5	30.2	66.2	16.7	61.2
Story 6	20.8	54.9	6.7	49.8
Story 7	18.9	46.5	3.0	41.5
Story 8	17.6	38.1	-0.8	33.2
Story 9	14.9	29.7	-5.6	25.0
Story 10	13.3	22.8	-9.6	18.2
Story 11	11.9	16.7	-13.4	12.2
Story 12	10.3	11.0	-17.3	6.6
Story 13	9.7	6.5	-20.8	2.1
Story 14	18.5	2.5	-22.2	-1.9
Story 15	29.2	-0.8	-22.3	-5.2
Story 16	43.0	-2.1	-20.4	-6.6
Story 17	54.5	-4.2	-19.7	-8.7
Story 18	62.8	-7.1	-20.5	-11.5
Story 19	68.3	-10.6	-22.5	-14.9
Story 20	71.1	-14.5	-25.4	-18.7

In the X direction, the moment frame displacement is 9.7% to 93.0% more than the braced 1. The moment frame displacement is 3.0% to 84.4% more than the braced 2 frame from story 1 to story 7, and it is 0.8% to 25.4% less than the braced 2 frame from story 8 to story 20. In y-direction, the moment frame displacement is 2.5% to 153.6% more than the braced 1 frame from story 1 to story 14 and it is 0.8% to 14.5% less than the braced 1 frame from story 15 to story 20. Moreover the moment frame displacement is 2.1% to 149.1% more than the braced 2 frame from story 1 to story 13 and it is 1.9% to 18.7% less than the braced 2 frame from story 14 to story 20. The bracing placed at two different gridlines, B1-C1 from story 13 to story 20 and C1-D1 from base to story 13 in bracing 1, and the bracing placed at one gridline B1-C1 all stories in bracing 2, also the irregularity of the building in elevation lead to the reduction in displacement or increase in displacement in x and y directions. So building with cross bracing in two different bays caused more displacement percentage in x-direction than the one having bracing in one bay.

4.4.2.2.2 Irregular 3D2 Building Analysis

Fig. 4.54 shows the lateral displacements for the 20 story irregular 3D2 braced and moment frames. As in the design cases given so far this case also indicates moment frame achieving more lateral displacement up to some story elevation then less displacement in both x and y direction (Table 4.25)

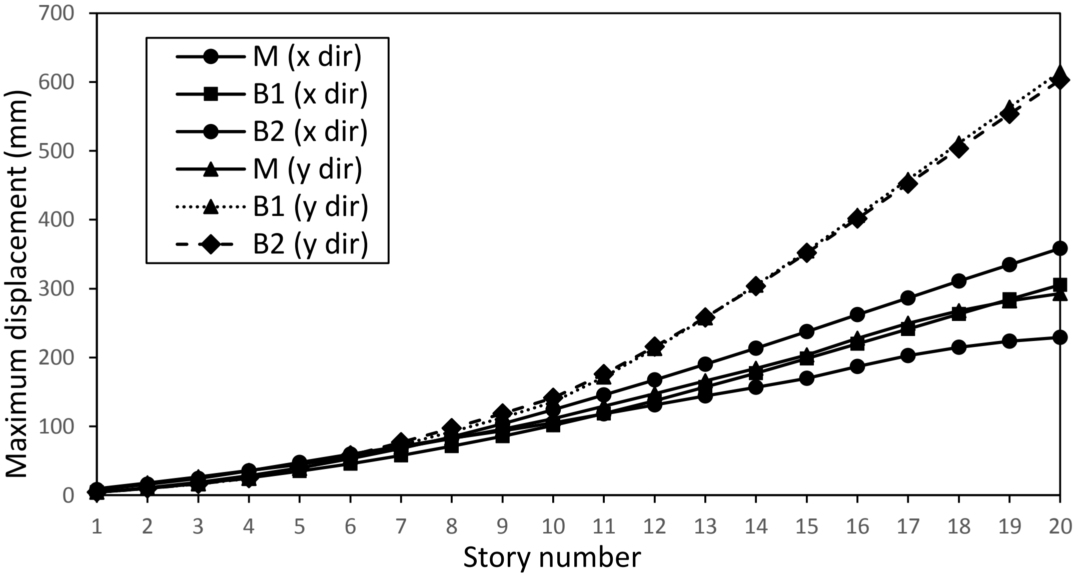


Figure 4.55: 20 story irregular 3D2 frame displacements in x and y directions

Table 4.25: Percentage difference of displacement between moment and braced frames for 20 story irregular 3D2 building design.

	Braced 1		Braced 2	
Story	x-dir	y-dir	x-dir	y-dir
Base	0	0	0	0
Story 1	88.1	118.6	75.6	113.6
Story 2	61.6	82.8	46.8	82.8
Story 3	45.2	62.8	30.5	60.8
Story 4	41.7	49.2	25.7	45.0
Story 5	36.7	15.1	19.5	10.9
Story 6	30.1	0.7	12.5	-3.6
Story 7	23.5	-5.3	5.3	-10.0
Story 8	16.6	-10.5	-2.2	-15.4
Story 9	9.3	-15.0	-9.6	-19.2
Story 10	3.7	-17.8	-15.4	-21.3
Story 11	-0.7	-24.6	-18.9	-26.5
Story 12	-4.7	-30.7	-21.8	-31.5
Story 13	-8.2	-35.5	-24.1	-35.6
Story 14	-11.7	-39.5	-26.6	-39.2
Story 15	-14.4	-42.5	-28.5	-42.0
Story 16	-14.8	-43.9	-28.6	-43.2
Story 17	-16.1	-45.5	-29.3	-44.8
Story 18	-18.3	-47.6	-30.8	-46.8
Story 19	-21.3	-49.9	-33.1	-49.0
Story 20	-24.9	-52.3	-36.0	-51.4

In the X direction, the moment frame displacement is 3.7% to 88.1% more than the braced 1 frame from story 1 to story 10, and it is 0.7% to 24.9% less than the braced 1 frame from story 11 to story 20. The moment frame displacement is 5.3% to 75.6% more than the braced 2 frame from story 1 to story 7, and it is 2.2% to 36.0% less than the braced 2 frame from story 8 to story 20. In y-direction, the moment frame displacement is 0.7% to 118.6% more than the braced 1 frame from story 1 to story 7 and it is 5.3% to 52.3% less than the braced 1 frame from story 7 to story 20. Moreover the moment frame displacement is 10.9% to 113.6% more than the braced 2 frame from story 1 to story 5 and it is 3.6% to 51.4% less than the braced 2 frame from story 6 to story 20. The bracing placed at two different gridlines, B1-C1 from story 10 to story 20 and C1-D1 from base to story 10 in bracing 1, and the bracing placed at one gridline B1-C1 all stories in bracing 2, also the irregularity of the building in elevation lead to the reduction in displacement or increase in displacement in x and y directions. So building with cross bracing in two different bays caused more displacement percentage in x-direction than the one having bracing in one bay.

4.4.2.2.3 Irregular 3D3 Building Analysis

Fig. 4.55 shows the lateral displacements for the 20 story irregular 3D3 braced and moment frames. As in the design cases given so far this case also indicates moment frame achieving more lateral displacement up to some story level and then less displacement in both x and y direction (Table 4.26)

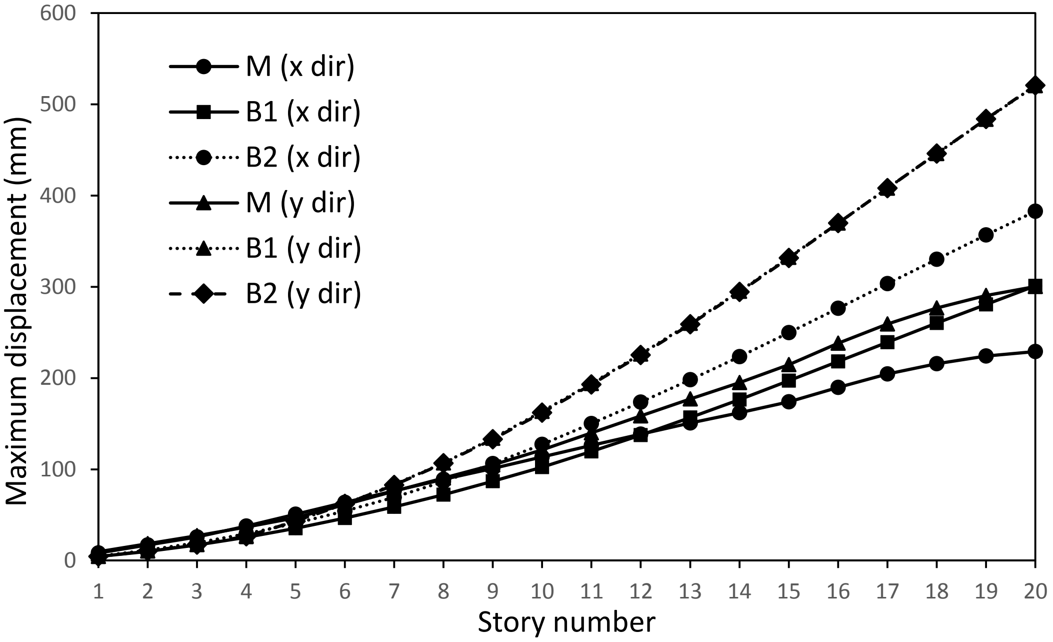


Figure 4.56: 20 story irregular 3D3 frame displacements in x and y directions

Table 4.26: Percentage difference of displacement between moment and braced frames for 20 story irregular 3D3 building design

	Braced 1		Braced 2	
Story	x-dir	y-dir	x-dir	y-dir
Base	0	0	0	0
Story 1	93.0	113.3	80.4	113.3
Story 2	69.0	78.6	50.9	78.6
Story 3	52.7	57.2	33.0	57.2
Story 4	48.8	38.5	29.5	39.0
Story 5	43.6	8.3	24.3	8.8
Story 6	36.9	-1.5	17.4	-1.1
Story 7	30.4	-8.9	10.2	-8.5
Story 8	23.2	-15.7	2.7	-15.2
Story 9	16.4	-21.9	-4.9	-21.3
Story 10	11.0	-25.8	-10.8	-25.2
Story 11	5.8	-27.9	-15.7	-27.5
Story 12	0.7	-30.0	-20.2	-29.7
Story 13	-3.8	-31.9	-23.9	-31.6
Story 14	-8.1	-33.9	-27.4	-33.7
Story 15	-11.7	-35.4	-30.4	-35.3
Story 16	-12.9	-35.6	-31.4	-35.6
Story 17	-14.6	-36.4	-32.7	-36.4
Story 18	-17.0	-37.9	-34.6	-37.9
Story 19	-20.2	-39.9	-37.2	-39.9
Story 20	-23.9	-42.3	-40.2	-42.4

In the X direction, the moment frame displacement is 0.7% to 93.0% more than the braced 1 frame from story 1 to story 12, and it is 3.8% to 23.9% less than the braced 1 frame from story 13 to story 20. The moment frame displacement is 2.7% to 80.4% more than the braced 2 frame from story 1 to story 8, and it is 4.9% to 40.2% less than the braced 2 frame from story 9 to story 20. In y-direction, the moment frame displacement is 8.3% to 113.3% more than the braced 1 frame from story 1 to story 5, and it is 1.5% to 42.3% less than the braced 1 frame from story 6 to story 20. Moreover the moment frame displacement is 8.8% to 113.3% more than the braced 2 frame from story 1 to story 5 and it is 1.1% to 42.44% less than the braced 2 frame from story 6 to story 20. Behavior is similar to 20 story irregular 3D2 design.

4.4.2.2.4 Irregular 3D4 Building Analysis

Fig. 4.56 shows the lateral displacements for the 20 story irregular 3D4 braced and moment frames. As in the earlier cases in this case also indicates moment frame achieving more lateral displacement up to some story level and then less displacement in both x and y directions (Table 4.27).

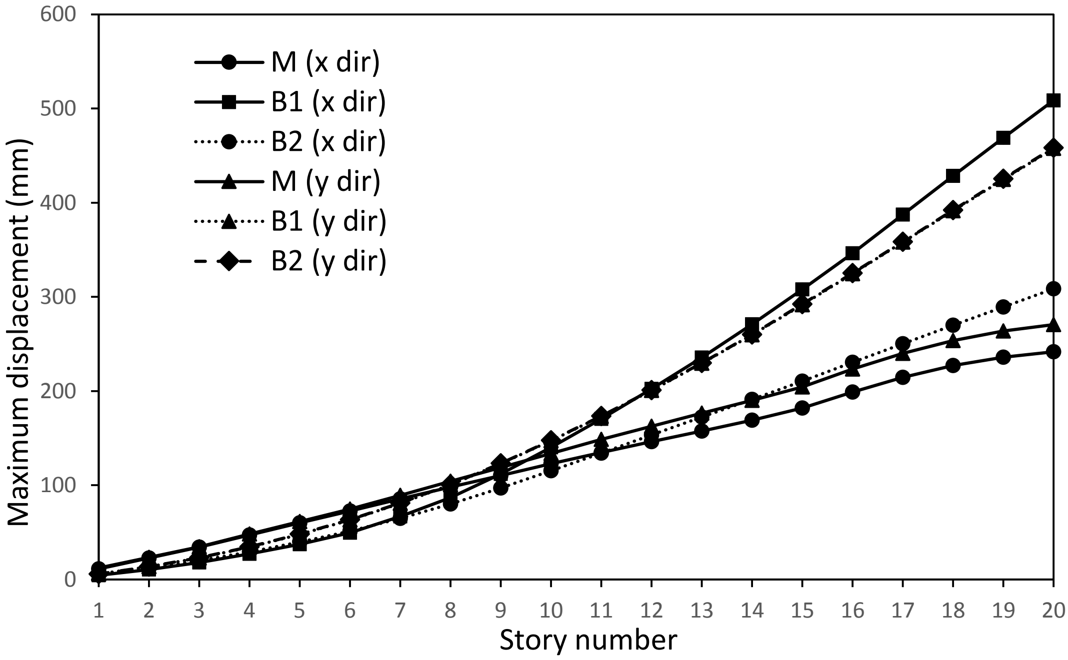


Figure 4.57: 20 story irregular 3D4 frame displacements in x and y directions

Table 4.27: Percentage difference of displacement between moment and braced frames for 20 story irregular 3D4 building design.

	Braced 1		Braced 2	
Story	x-dir	y-dir	x-dir	y-dir
Base	0	0	0	0
Story 1	152.3	112.3	122.0	108.6
Story 2	113.2	74.6	91.5	73.3
Story 3	90.6	52.2	72.4	50.9
Story 4	75.2	40.5	62.0	39.7
Story 5	61.4	28.9	51.3	28.1
Story 6	47.4	18.2	41.9	17.8
Story 7	28.3	10.6	32.1	10.2
Story 8	13.0	3.6	22.5	3.4
Story 9	-1.6	-3.3	13.4	-3.6
Story 10	-12.4	-9.0	6.5	-9.3
Story 11	-20.8	-14.2	0.5	-14.4
Story 12	-27.6	-18.9	-4.6	-19.1
Story 13	-33.2	-23.0	-8.7	-23.2
Story 14	-37.7	-26.9	-11.6	-27.0
Story 15	-40.9	-29.9	-13.6	-30.0
Story 16	-42.5	-31.2	-13.6	-31.3
Story 17	-44.6	-33.0	-14.3	-33.1
Story 18	-47.0	-35.2	-15.9	-35.3
Story 19	-49.6	-37.9	-18.4	-38.0
Story 20	-52.4	-40.9	-21.6	-41.0

In the X direction, the moment frame displacement is 13.0% to 152.3% more than the braced 1 frame from story 1 to story 8, and it is 1.6% to 52.4% less than the braced 1 frame from story 9 to story 20. The moment frame displacement is 0.5% to 122.0% more than the braced 2 frame from story 1 to story 11, and it is 4.6% to 21.6% less than the braced 2 frame from story 12 to story 20. In y-direction, the moment frame displacement is 3.6% to 112.3% more than the braced 1 frame from story 1 to story 8, and it is 3.3% to 40.9% less than the braced 1 frame from story 9 to story 20. Moreover the moment frame displacement is 3.4% to 108.6% more than the braced 2 frame from story 1 to story 8 and it is 3.6% to 41.0% less than the braced 2 frame from story 9 to story 20. Braced 1 and 2 in y-direction had very similar displacement, however after story 9 B1 has considerably higher lateral displacement.

4.5 Summary of the Analysis Results

- In 6 story buildings, adding bracing helped in reducing the displacements by approximately 50% when compared to MRF.
- In 12 story buildings, adding bracing helped in reducing the displacements by approximately 25% when compared to MRF.
- In 20 story buildings, adding bracing helped in reducing the displacements at lower stories while in the higher stories, the displacement were increased when compared to MRF.
- Types of irregularity introduced in the buildings played a major role in the final displacements achieved, particularly when 3D irregularities are considered.
- The location of bracing played a major role in the displacements achieved, especially for 3D irregularities. It was observed that when the bracing was split into 2 gridlines, there was decrease in displacements when compared to the case where the bracings were used in only one gridline.

Chapter 5

RESPONSE SPECTRUM ANALYSIS

5.1 Introduction

The aim of this chapter is to investigate and try to understand the behavior of structures against an earthquake. Response spectrum analysis with 0.2 ground acceleration, spectrum type 1, soil type B, and behavior factor q=4 were used to analyze and collect all the data by using response spectrum analysis.

Results of a set of six story building models, including irregular ones, and a set of regular buildings six, twelve and twenty stories have been added in this chapter.

5.2 Six-Story Building Structures

5.2.1 Regular Building Analysis

It is clear that the Moment frame lateral displacement is more than the braced frame (Fig.5.1)

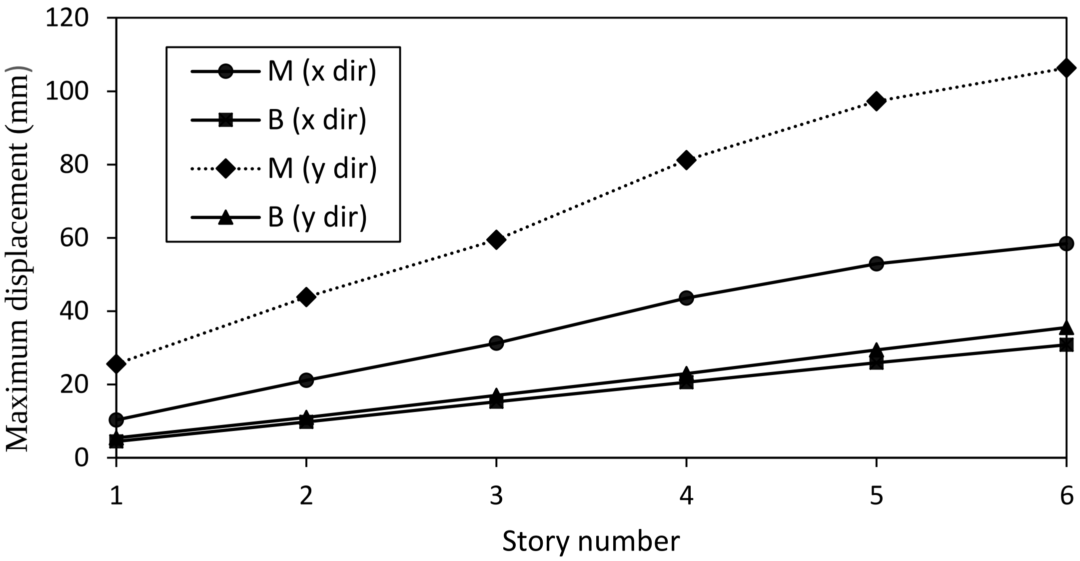


Figure 5.1: 6 story regular frame displacements in x and y directions.

In x-direction, the moment frame displacement is 89.6% to 128.9% more than the braced frame at different stories. In y-direction, the difference is even more with moment frame displacement being 199.4% to 374.1% more than the braced frame at different stories. It should be noted that the lateral displacement rate reduces as the story number increases.

5.2.2 Irregular Plan Analysis

Moment frame achieved higher lateral displacements when compared to the braced frame (Fig.5.2)

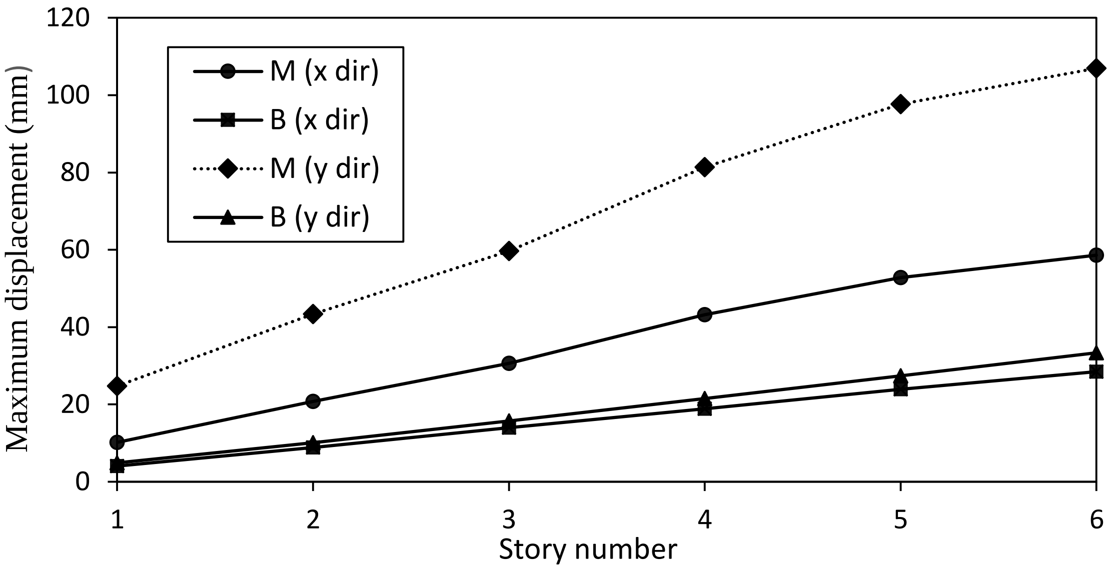


Figure 5.2: 6 story irregular plan frame displacements in x and y directions.

In x-direction, the moment frame displacements are 105.6% to 148.8% higher than the braced frames ones at different stories. In y-direction, the moment frame displacements are 220.4% to 406.1% higher than the braced frame ones.

5.2.2.1 Irregular Elevation Building Analysis

5.2.2.1.1 Irregular Height 1Rx1L Building Analysis

Moment frame achieved more lateral displacement than the braced frame in both x and y directions (Fig.5.3).

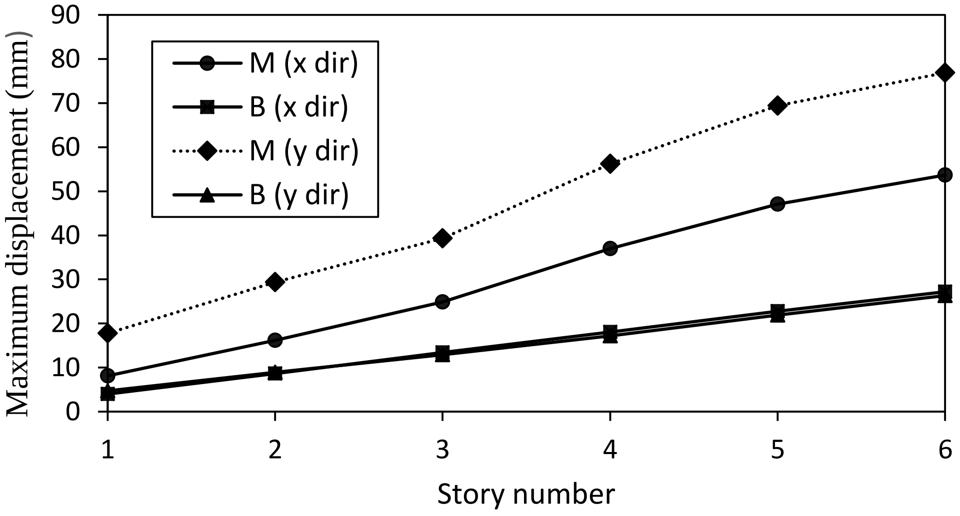


Figure 5.3: 6 story irregular height 1Rx1L, frame displacements in x and y directions

In x-direction, the moment frame displacements are 85.8% to 106.6% higher than the braced frame ones at different stories. In y-direction, the moment frame displacements are 192.4% to 278.7% higher than the braced frame ones.

5.2.2.1.2 Irregular Height 2Rx1L Building Analysis

As in the design case given so far this case also indicates moment frame achieving more lateral displacement than the braced frame in both x and y direction (Fig.5.4).

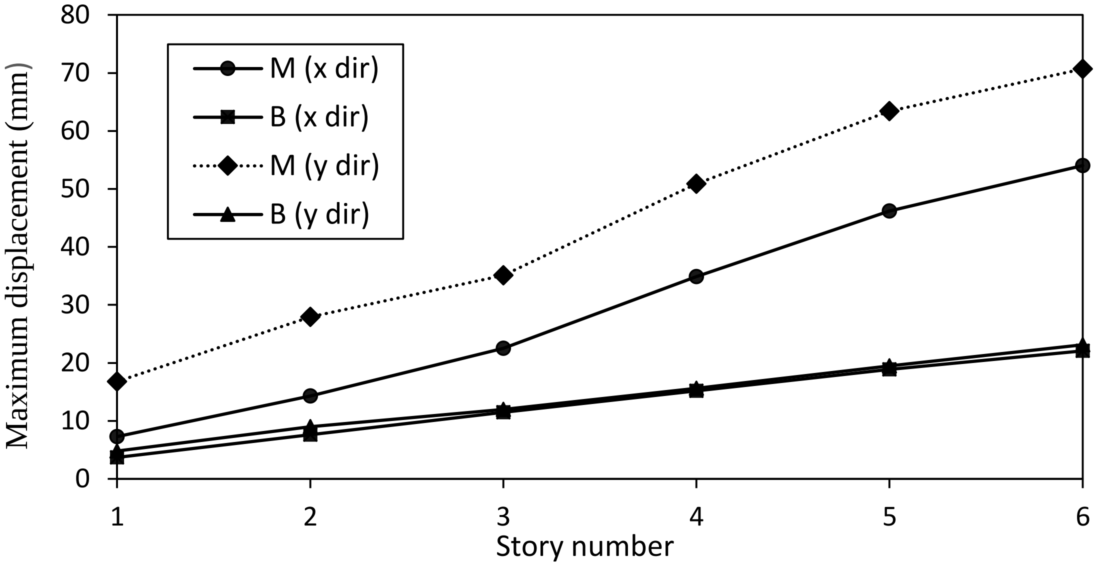


Figure 5.4: 6 story irregular height 2Rx1L frame displacements in x and y directions.

In x-direction, the moment frame displacements were 88.2% to 144.4% and in y-direction, 192.5% to 250.0% higher than the braced frame, respectively.

5.2.2.1.3 Irregular Height 1Rx1L Different Elevation Building Analysis

Fig. 5.5 shows the lateral displacements for the 6 story irregular height (1Rx1L) different elevation braced and moment frames.

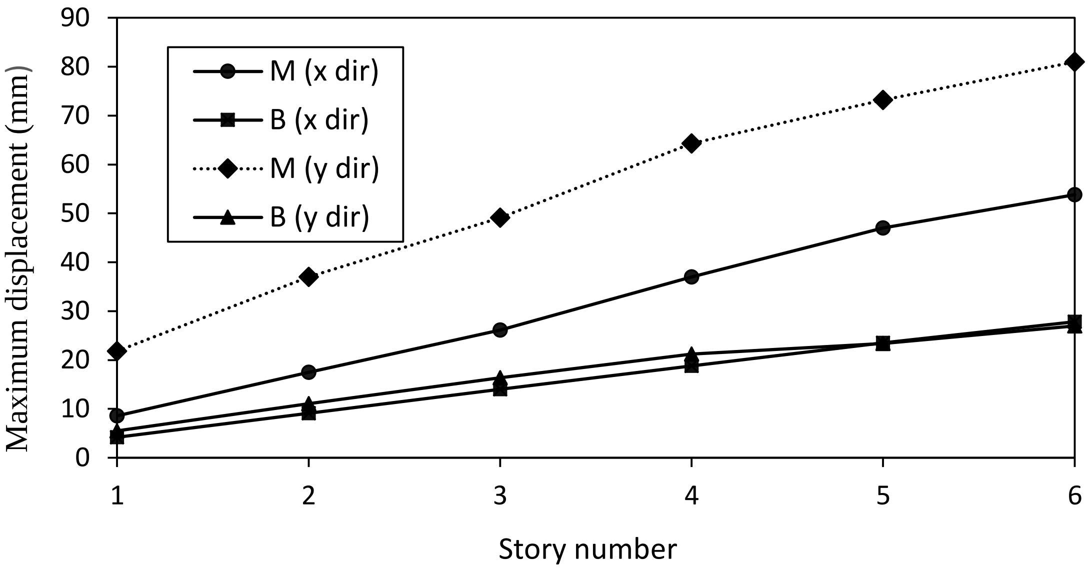


Figure 5.5: 6 story irregular height 1Rx1L different elevation frame displacements in x and y directions.

Moment frame achieving more lateral displacement than the braced frame in both x and y directions. In x-direction, the moment frame displacements are 86.4% to 104.8% higher than the braced frames ones at different stories. In y-direction, the moment frame displacements are 199.4% to 296.4% higher than the braced frame ones.

5.2.2.2 Irregular 3D Building Analysis

5.2.2.2.1 Irregular 3D1 Building Analysis

Moment frame achieving more lateral displacement than the braced frame in both x and y directions. Fig. 5.6 shows the lateral displacement for the 6 story irregular 3D1 braced and moment frames.

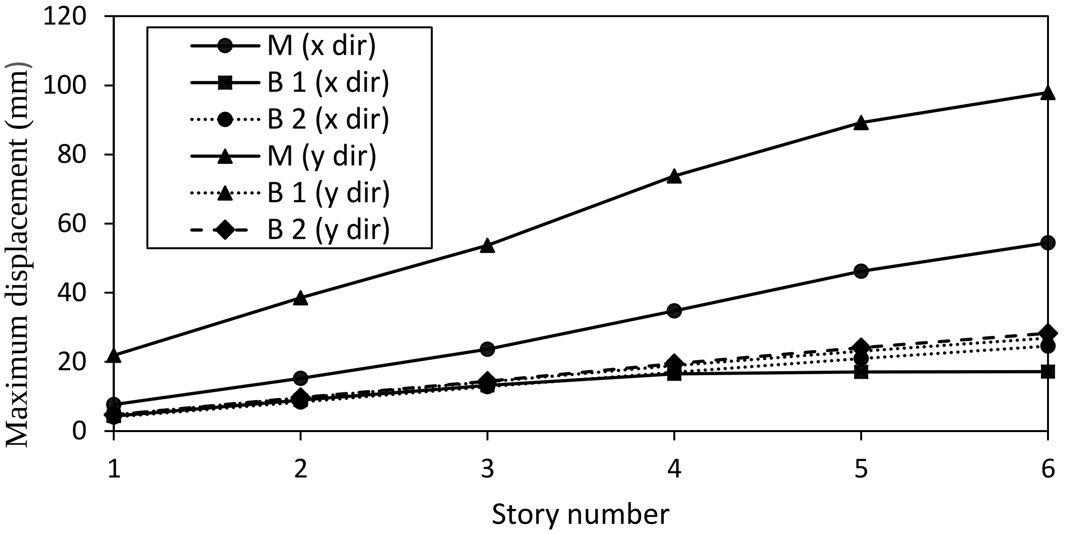


Figure 5.6: 6 story irregular 3D1 frame displacements in x and y directions.

In x-direction, the moment frame displacements are 70.8% to 216.3% more than the braced 1 frame and 81.0% to 121.1% more than the braced 2 frame at different stories. In y-direction, the difference is even more with moment frame displacement being 263.9% to 366.0% more than the braced 1 and 245.9% to 366.0% more than the braced 2 at different stories.

5.2.2.2.2 Irregular 3D2 Building Analysis

Fig. 5.7 shows the lateral displacement for the 6 story irregular 3D2 braced and moment frames. Moment frame achieving more lateral displacement than the braced frame in both x and y directions.

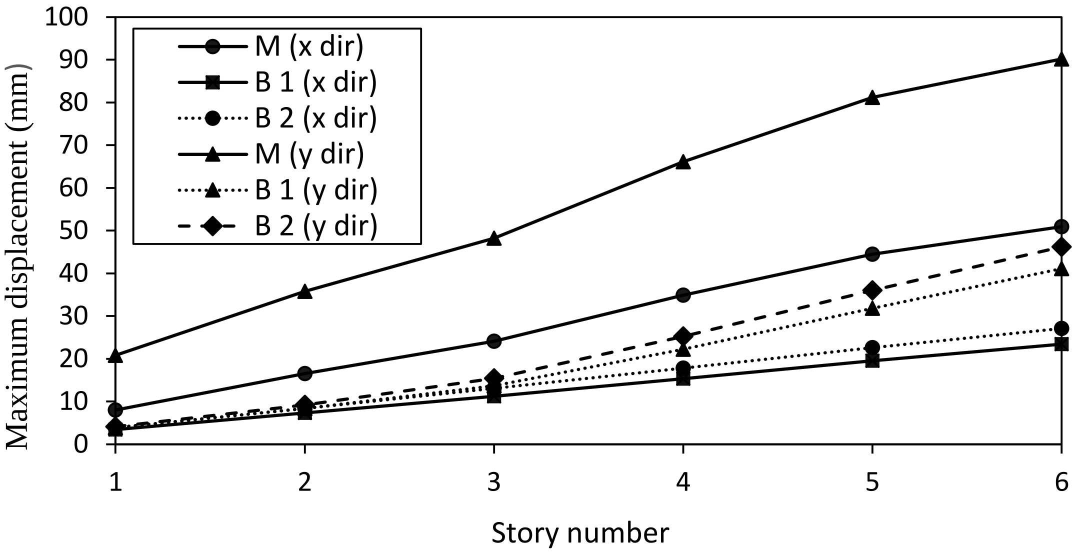


Figure 5.7: 6 story irregular 3D2 frame displacements in x and y directions

In x-direction, the moment frame displacements are 115.2% to 135.3% more than braced 1, and 84.0% to 105.1% more than braced 2. In y-direction, the difference is even more with moment frame displacement being 119.5% to 430.8% more than braced 1 and 95.2% to 404.9% more than braced 2.

5.2.2.2.3 Irregular 3D3 Building Analysis

Fig. 5.8 shows the lateral displacement for the 6 story irregular 3D2 braced and moment frames. Moment frame achieving more lateral displacement than the braced frame in both x and y directions.

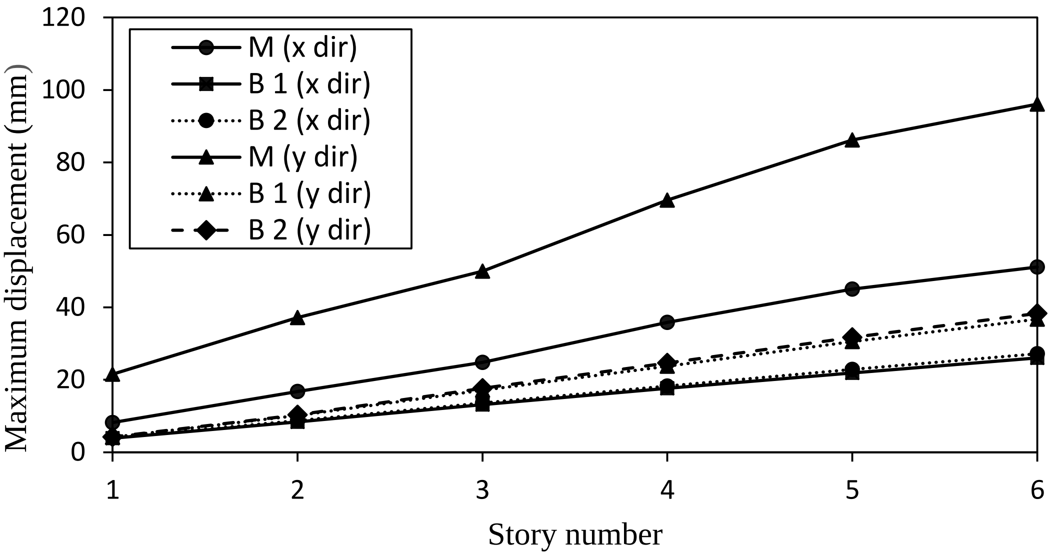


Figure 5.8: 6 story irregular 3D3 frame displacements in x and y directions

In x-direction, the moment frame displacements are 89.3% to 110.3% more than braced 1 and 82.4% to 105.0% more than braced 2. In y-direction, the difference is more with moment frame displacements being 161.9% to 424.4% more than the braced 1 and 150.9% to 411.9% more than the braced 2.

5.2.2.2.4 Irregular 3D4 Building Analysis

Fig. 5.9 shows the lateral displacement for the 6 story irregular 3D2 braced and moment frames. Moment frame achieving more lateral displacement than the braced frame in both x and y directions.

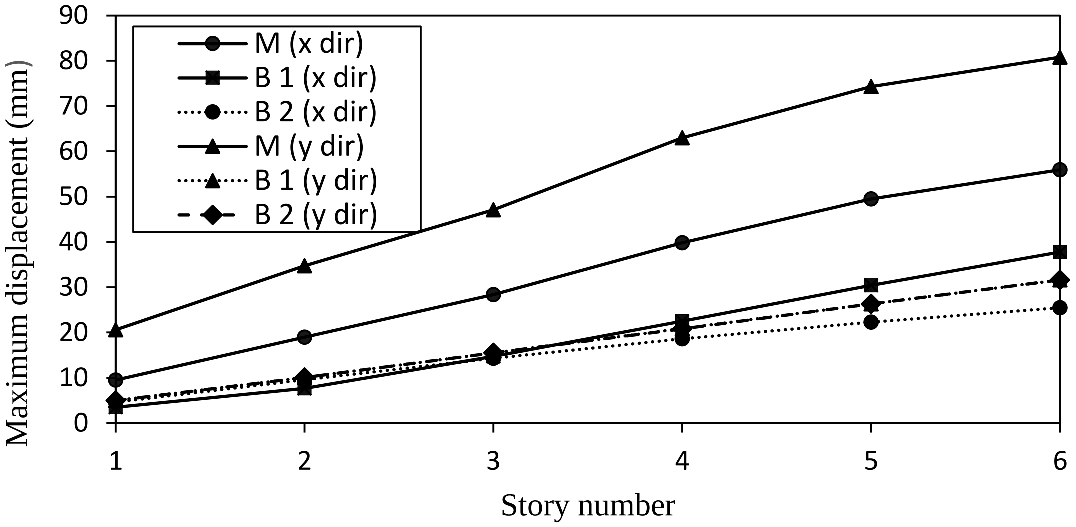


Figure 5.9: 6 story irregular 3D4 frame displacements in x and y directions

In x-direction, the moment frame displacement is 47.9% to 171.4% more than braced 1 and 97.9% to 122.4% more than braced 2. In y-direction, moment frame displacements are 155.7% to 312.0% more than braced 1 and 155.7% to 312.0% more than braced 2.

5.3 Twelve-story Building Structure

5.3.1 Regular Building Analysis

Moment frame lateral displacement is more than the braced frame (Fig.5.10)

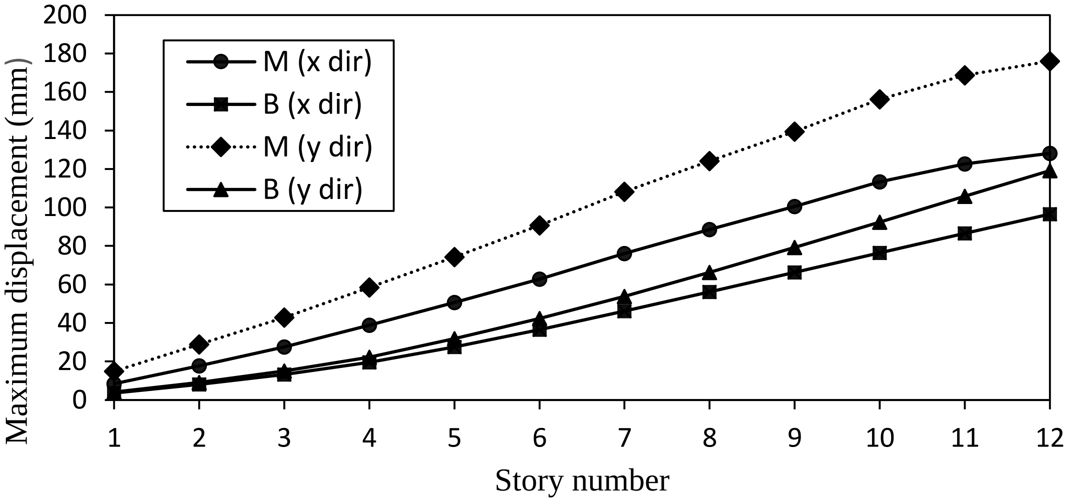


Figure 5.10: 12 story regular frame displacements in x and y directions.

In x-direction, the moment frame displacements are 32.8% to 136.1% more than the braced frame at different stories. In y-direction, the difference is more where the moment frame displacements were 47.8% to 263.4% more than the braced frame at different stories.

5.4 Twenty-Story Building Structure

5.4.1 Regular Building Analysis

Moment frame lateral displacement is more than the braced frame at some stories and less at others (Fig.5.11).

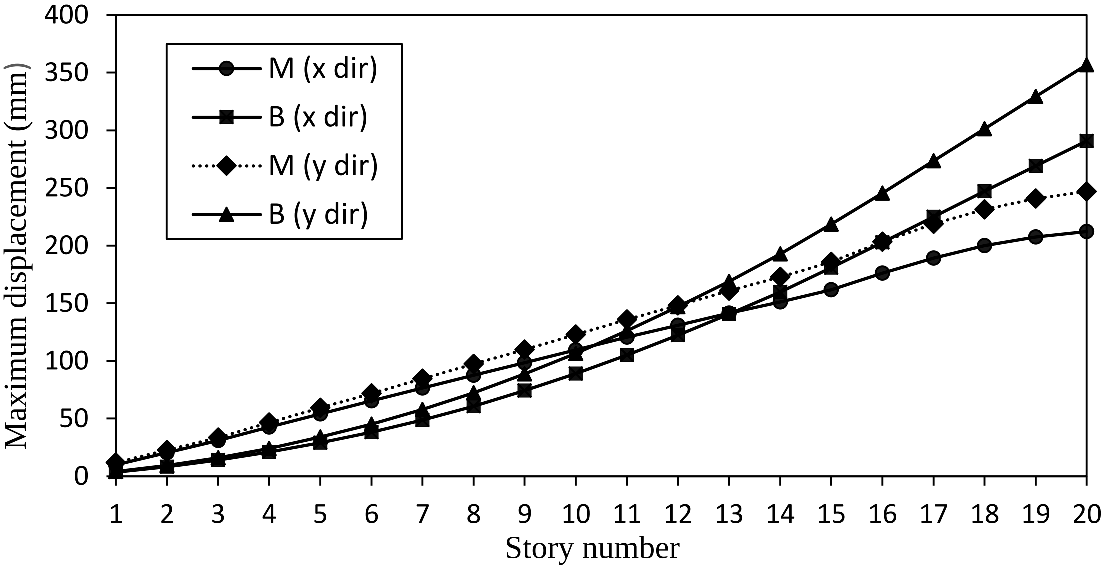


Figure 5.11: 20 story regular frame displacements in x and y directions.

In x-direction, the moment frame percentage displacement is 185.7% to 0.6% more than the braced frame from story 1 to story 13 and it is 5.4% to 27.0% less than the braced frame from story 14 to story 20. In y-direction, the lateral displacement trend is similarly to x-direction except that the change is at story 12 rather than story 13.

5.5 Summary

- In 6 story buildings, adding bracing to the structural frame helped in reducing the braced frame displacements by 45 to 65 percent when compared to moment resisting frames.
- In twelve story buildings, adding bracing to the structural frame helped in reducing the displacements by approximately 20% to 40% when compared to moment resisting frames.
- In twenty story buildings, adding bracing to the structural system helped in reducing the displacements at lower stories while in the higher stories, the displacement were increased when compared to moment resisting frames.

Chapter 6

DISCUSSION AND RESULTS FOR EQUIVALENT STATIC AND RESPONSE SPECTRUM ANALYSIS

6.1 Introduction

Equivalent static and response spectrum analysis are the two analysis methods used in chapters 4 and 5 respectively and the results obtained from these analysis are discussed in this chapter. Section 6.2 gives the discussion of results between moment and braced frame using equivalent static analysis and section 6.3 gives discussion of results between moment and braced frame using the response spectrum analysis. Where section 6.4 gives a comparison of the results of 2 different analysis.

6.2 Discussion of Results Using Equivalent Static Analysis

Looking deeper into the data collected in this study, the relationship between the height of buildings and different irregularities introduced to the moment framed and concentrically braced framed structures can be better realized. Since there are numerous combinations in this study, to simplify the discussion, one can consider lateral displacements at the top of 6, 12 and 20 story buildings, separately in x and y directions for regular, irregular plan, irregular height, 3D1, 3D2, 3D3 and 3D4.

Table 6.1: Percentage difference of displacement between moment and braced frame at the top of each building, in x and y direction.

	X-direction													
Story	Regular	Irr P	Irr H			3D1		3D2		3D3		3D4	
			(1RX1L)	(2RX1L)	(1RX1L) D E	B1	B2	B1	B2	B1	B2	B1	B2
6	86.2	96.9	95.1	142.7	88.5	211	118	108	99.4	117.1	93.3	45.8	114
12	27.5	35.3	44.6	108	28.6	198	71.8	73.9	52.1	78.2	39.3	-1.9	72.7
20	-32.8	-35.6	-34.1	-14.1	-33.5	71.1	-25.4	-24.9	-36	-23.9	-40.2	-52.4	-21.6
	Y-direction												
6	191	200	192.3	188.1	202.8	243	234	83	79.3	120.7	117	147	148
12	31.9	43.7	50.9	90.6	58.8	91.1	76.2	19.9	19.6	25.9	23.6	25	25
20	-36.1	-34.7	-47.4	-30.1	-34.7	-14.5	-18.7	-52.3	-51	-42.3	-42.4	-40.9	-41

From table 6.1, the role of x braces become less beneficial when building height changes from 6 to 12 and 12 to 20 story. That is to say, for 6 story buildings lateral displacements of buildings with moment frame is more than the braced frames. This is particularly more serious with irregular frames. When irregularities in 3-D are considered the trend is even more serious. As 12 story moment frames are compared with the braced ones, despite the fact that moment frames have more displacements than the braced frames, still displacements are considerably less than the 6 story buildings. Only for 3D4 B1 achieved displacements more than moment frame. The reduction in lateral displacement of moment frames with respect to braced frames continue with the increase in number of stories. For 20 story buildings it can be seen from Table 6.1 that all moment framed buildings, except 3D1-B1, achieved displacements that are less than the braced frames. Furthermore, if one considers the variation in displacements between the two types of braced frames, then it can be noted that frame B1 generally have less displacements, except for building 3D4, where B2 has less displacement. The differences between B1 and B2 at 3D4 are due to the location of cross bracing. B1 has discontinuity in bracing while B2 has more continuous bracing which helps to reduce lateral displacement. It should be noted that for 20-story building, the condition reversed and B1 had more displacement than B2.

The observations in y-direction differs from those of x-direction since the building has 3 bays in this direction and therefore the cross bracings are placed at the middle bay. Looking at percentage displacements of moment frames over braced frames for 3D2 and 3D3 6, 12 and 20 stories it can be noted that the bay added in 3D3 at story 6 caused a decrease in the displacement of story 6 by about 37.7% and story 20 by about 10%. The importance of x bracing becomes less when 20 story building is concerned where displacement of moment frame became about 40% less for braced frame.

While investigating the resultant data of this study, especially those that belong to 20-story buildings, something great importance was observed. To clarify and better understand this observation further analysis were carried out to study and investigate the problem regarding the changes recorded from 12 to 20 story buildings, more specifically further information was needed for 14 and 16 story buildings. In general moment frames had more displacements in y-direction than x-direction for 6 and 12 story buildings. For 20 story buildings moment frames had less displacement in y-direction than x-direction, except for building 3D1.

Table 6.2: 14 and 16 story regular frame displacements in x-direction.

	14 STORY (mm)		16 STORY(mm)	
	M	B	M	B
Base	0	0	0	0
story 1	M	4.8	57	6.2
story 2	28.9	11.4	82.8	13.3
story 3	45.1	19.3	104.1	22.4
story 4	62.8	28.9	125.1	34.6
story 5	80.2	40.1	145.5	50.3
story 6	97.0	52.7	165.3	68.9
story 7	113.7	66.9	185.5	90.1
story 8	129.6	83.8	205.3	113.8
story 9	145.6	101.8	225.4	140.9
story 10	162.5	120.3	247.5	169.8
story 11	176.7	138.9	267.7	199.6
story 12	188.1	157.1	285.5	230.0
story 13	196.8	174.9	302.2	260.2
story 14	201.9	192.2	315.3	290.3
story 15			324.5	320.0
story 16			329.9	349.3

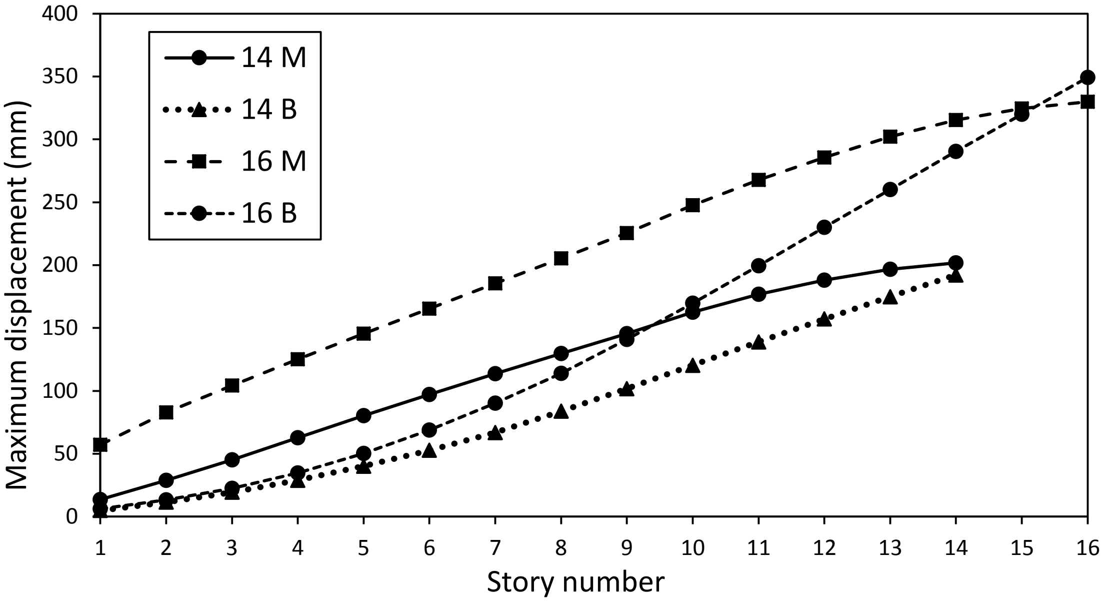


Figure 6.1: 14 and 16 story regular frame displacements in x direction

In Table 6.1 it was observed that stories 14 to 16 can be critical for high rise buildings. Both Table 6.2 and Fig.6.1 clearly show that generally braced frame displacements are less than those of moment frame, except just after story 15 when moment frames displacement become less than braced frame. Thus, 15th story appears to be a critical level for high rise structures. On the other hand adding two floors to 14 story building shows considerable increase in the displacements both for moment frame and braced frame. The displacements for 16 story moment frame is around 4 times higher than the 14 story moment frame at story 1. This rate continuous to decrease up to story 7 where it is 1.6 times higher than 14 story. From story 7 to 14 this rate stays almost constant. As for the braced frame, the rate is almost constant from story 1 to 6 and then starts to increase reaching to 1.5 at 14 story. So if high rise building construction is considered building 14 story as oppose to 16 story building would result in about 36% and 33.8% less lateral displacements for moment frame and braced frame buildings, respectively. This would mean more economical design.

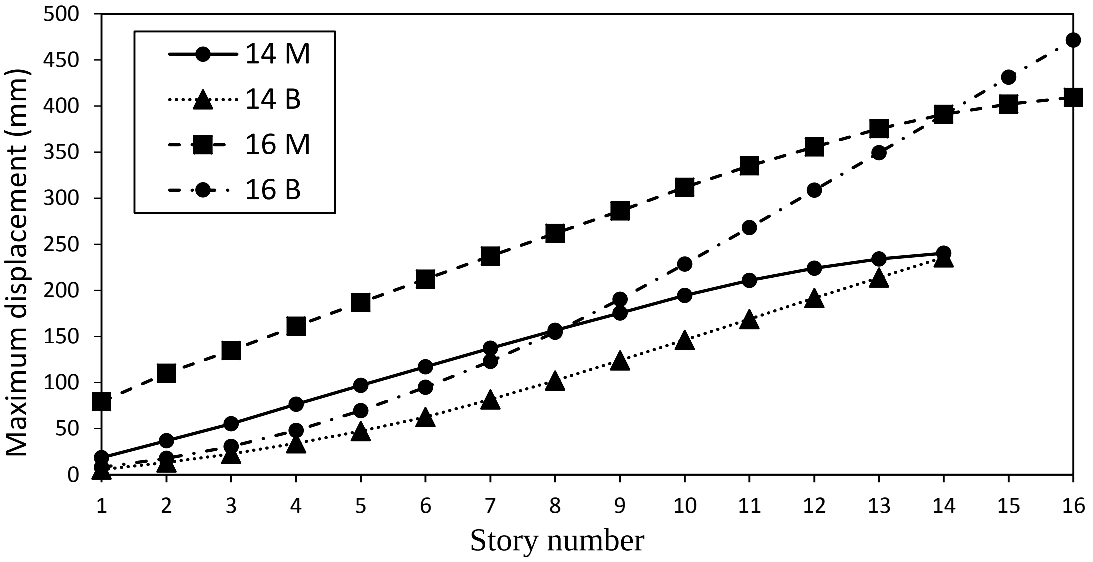


Figure 6.2: 14 and 16 story regular frame displacements in y direction.

Considering displacements in y-direction, Fig.6.2 14 story braced frame displacements are less than the moment frame up to the highest story, but in 16 story building the intersection of braced and moment frame displacements is at 14 story. Thus, it can be concluded that the 14th story could be taken as the critical level in y direction for buildings up to or may be above 16 story. For further clarification, a 15 story building was modelled and analyzed and displacement results were obtained by using Fig.6.3.

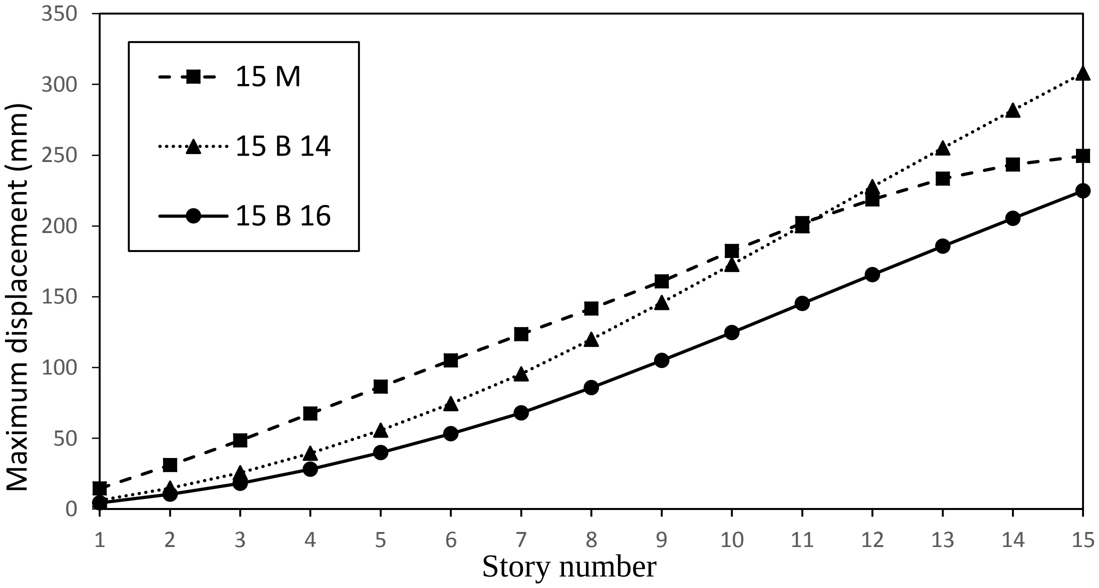


Figure 6.3: 15 story regular frame displacements in x direction

In Fig 6.3, 15 B14 means 15 story building with the same cross bracing steel sections used in 14 story braced building and 15 B16 means 15 story building with the same cross bracing steel sections used in 16 story braced building. The displacements of 15B14 exceed the displacements of moment frame at story 11, but when 15 B16 was used the braced frame displacement decreased for all the floor levels of this building.

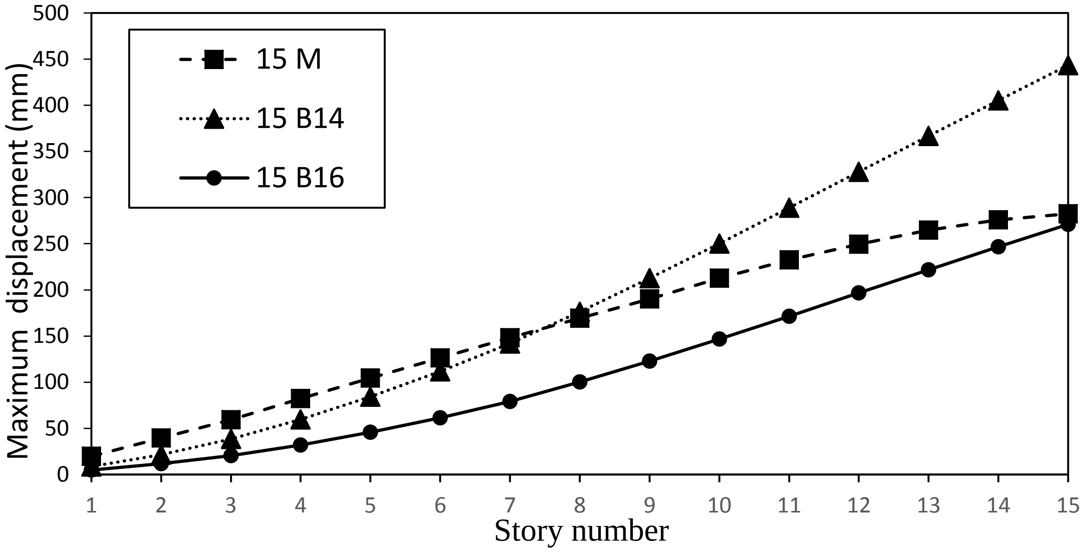


Figure 6.4: 15 story regular frame displacement in y direction

In Fig 6.4, the braced frame displacements exceed the displacements of moment frame at story 8, but when 15 B16 was used the braced frame displacement decreased for all the floor levels of this building.

To decrease the displacements of 20 story braced frame, a series of cross bracings like a belt was installed at the top of 20 story building. Then in another case diagonal bracings were installed in all the bays forming a belt at the top and at the middle of the building. The analysis results are given in Tables 6.3 and 6.4.

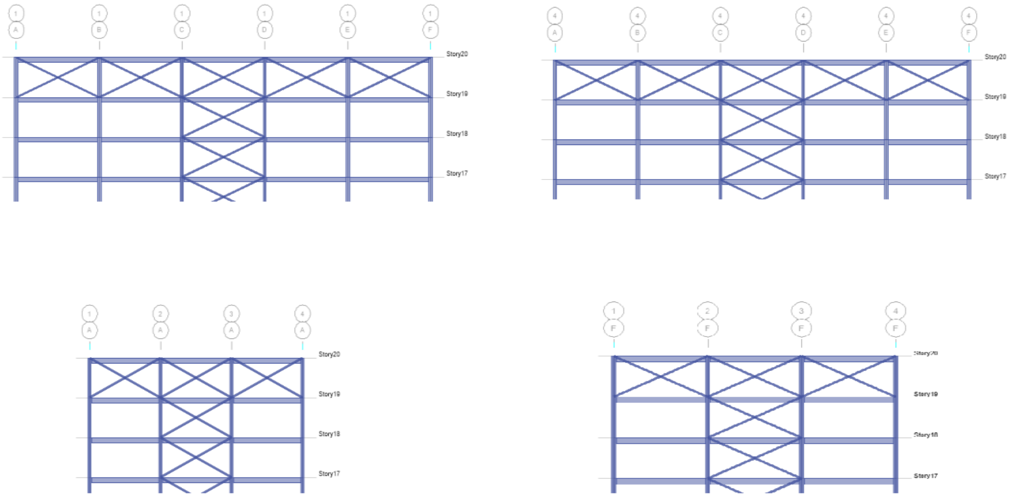


Figure 6.5: Bracing location at 20 story

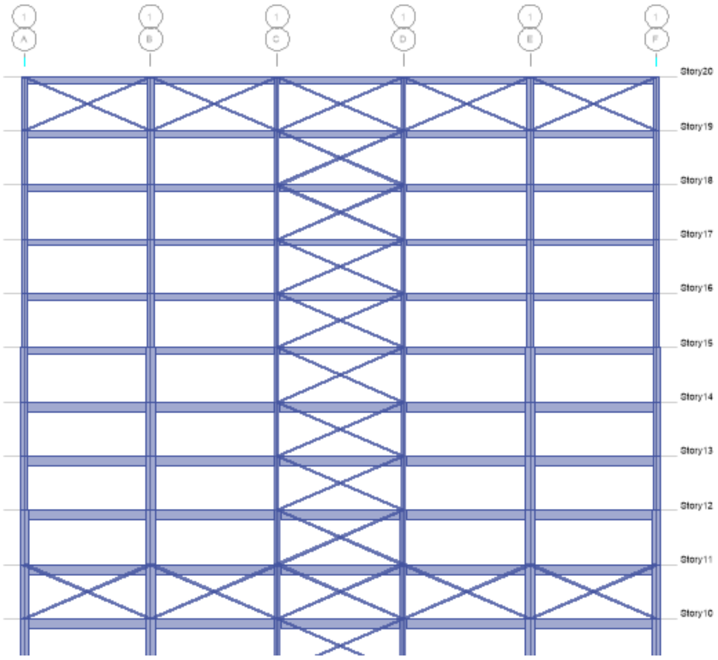


Figure 6.6: Bracing location at 10 and 20 story

Table 6.3: Displacements of regular framed 20 story building with cross–bracings forming a belt at the top, and belt at both top and middle of the 20 story building.

	x direction (mm)			y direction (mm)		
	M	B(20)	B(10,20)	M	B(20)	B(10,20)
Base	0.0	0.0	0.0	0.0	0.0	0.0
story 1	12.7	4.6	4.3	15.1	5.3	4.8
story 2	25.9	10.8	9.8	29.1	12.4	11.0
story 3	39.5	18.2	16.2	43.2	21.2	18.3
story 4	54.6	27.0	23.5	60.0	31.8	26.8
story 5	69.5	37.3	31.7	76.8	44.4	36.5
story 6	84.2	48.9	40.6	93.4	58.6	47.1
story 7	99.0	61.7	50.1	110.4	74.5	58.5
story 8	113.4	75.9	60.1	127.1	92.1	70.5
story 9	127.4	91.8	71.1	143.5	111.9	83.8
story 10	142.2	108.8	80.4	160.9	133.1	95.9
story 11	156.7	126.4	82.3	178.0	155.3	100.3
story 12	170.3	144.4	91.8	194.3	178.2	112.8
story 13	184.1	162.4	103.4	210.9	201.5	127.3
story 14	197.0	180.5	115.5	226.5	225.1	142.5
story 15	210.8	199.5	129.0	243.4	250.0	159.4
story 16	229.5	217.6	142.1	265.6	273.9	175.8
story 17	246.3	233.6	154.0	285.0	295.6	190.9
story 18	259.7	247.4	164.2	300.6	314.9	204.1
story 19	269.3	257.9	172.0	312.2	330.3	214.7
story 20	275.2	259.6	173.5	319.6	333.2	218.8

From table 6.3 it can be seen that providing a belt of x bracing at the 20th story (Fig 6.5) of the building led to reduction in lateral displacements x direction at story 20 by about 5.6%. In y direction generally all the displacements are more than the x-direction. After story 14 the braced frame displacements become more than moment frame and they reached around 4.25% more at story 20. For this reason another design was introduced where two belts, one at the middle of building (story 10) and the other one at the top of the building (story 20) were introduced (Fig 6.6). This design led to 37.1% decrease in displacements in x direction and 31.5% in y direction. Therefore, this approach can be considered as a possible solution to the displacement increase of buildings above 16 stories. Braced frame B (20) had more displacement than the Moment and B (10, 20) frame in y direction, after story 14.

The approach detailed above was repeated by using diagonal bracing instead of cross-bracing. The results of the analysis can be found in Table 6.4.

Table 6.4: Displacements of regular framed 20 story building with diagonal–bracings forming a belt at the top, and belt at both top and middle of the 20 story building

	x direction (mm)			y direction (mm)		
	M	B(20)	B(10,20)	M	B(20)	B(10,20)
Base	0.0	0.0	0.0	0.0	0.0	0.0
story 1	12.7	4.6	4.4	15.1	5.3	5.0
story 2	25.9	11.0	10.1	29.1	12.5	11.5
story 3	39.5	18.6	16.9	43.2	21.3	19.3
story 4	54.6	27.7	24.7	60.0	32.1	28.6
story 5	69.5	38.4	33.6	76.8	44.8	39.3
story 6	84.2	50.4	43.4	93.4	59.3	51.2
story 7	99.0	63.9	54.0	110.4	75.5	64.1
story 8	113.4	78.8	65.4	127.1	93.5	78.2
story 9	127.4	95.7	78.0	143.5	113.7	93.8
story 10	142.2	113.8	89.8	160.9	135.4	109.1
story 11	156.7	132.7	96.8	178.0	158.1	119.8
story 12	170.3	152.2	109.1	194.3	181.7	136.0
story 13	184.1	172.1	122.9	210.9	205.9	153.6
story 14	197.0	192.4	137.1	226.5	230.5	171.8
story 15	210.8	213.9	152.6	243.4	256.6	191.5
story 16	229.5	234.9	167.5	265.6	281.9	210.5
story 17	246.3	254.4	180.9	285.0	305.4	227.8
story 18	259.7	272.2	192.5	300.6	326.6	243.0
story 19	269.3	286.8	201.5	312.2	344.4	255.2
story 20	275.2	290.0	203.6	319.6	351.0	260.1

In general, provision of belt bracing at 20 story and 10 and 20 story led to reduction in lateral displacements up to 14 and 13 story, respectively. After these stories braced frame B (20) displacements continued to increase with respect to moment frame reaching to displacement 5.4% in x direction and 9.8% in y direction at story 20.

However, when double belt at story 10 and story 20 were used, it caused a decrease in the displacements, 26% in x direction and 18.6% in y direction.

6.3 Discussion of Results Using Response Spectrum Analysis

As it is mentioned in the chapter 5 that all the data are reanalyse using response spectrum analysis but some of them was collected, so in this part of discussion a 15 story building was modelled and analyzed Fig 6.7 gives the displacement results obtained in x direction.

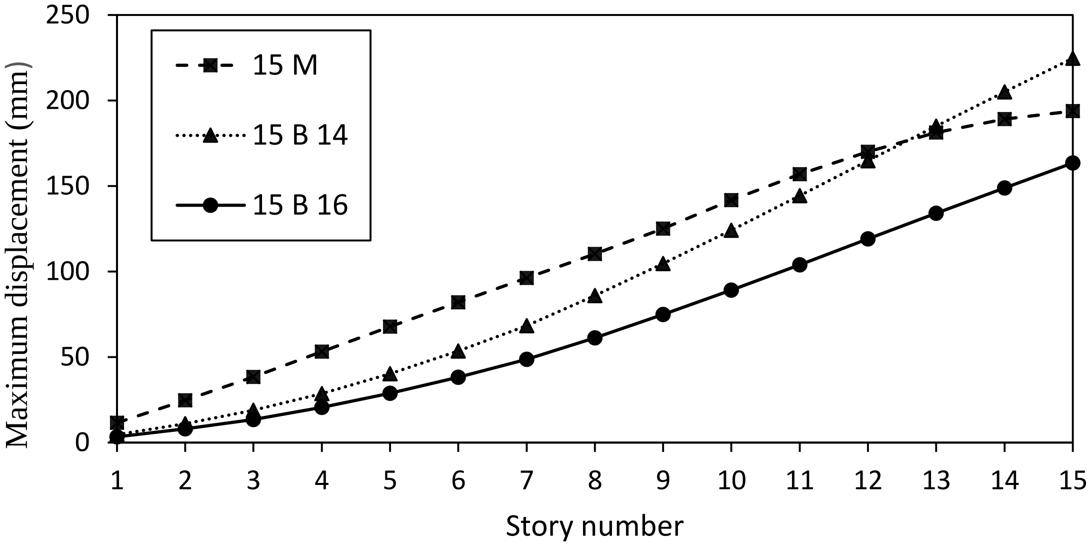


Figure 6.7: 15 story regular frame displacements in x direction.

In Fig 6.7, 15 B 14 means 15 story building with the same cross bracing steel sections used in 14 story braced building and 15 B 16 means 15 story building with the same cross bracing steel sections used in 16 story braced building. The displacements of 15 B 14 exceed the displacements of moment frame at story 13, but when 15 B 16 was used the braced frame displacement decreased for all the floor levels of this building.

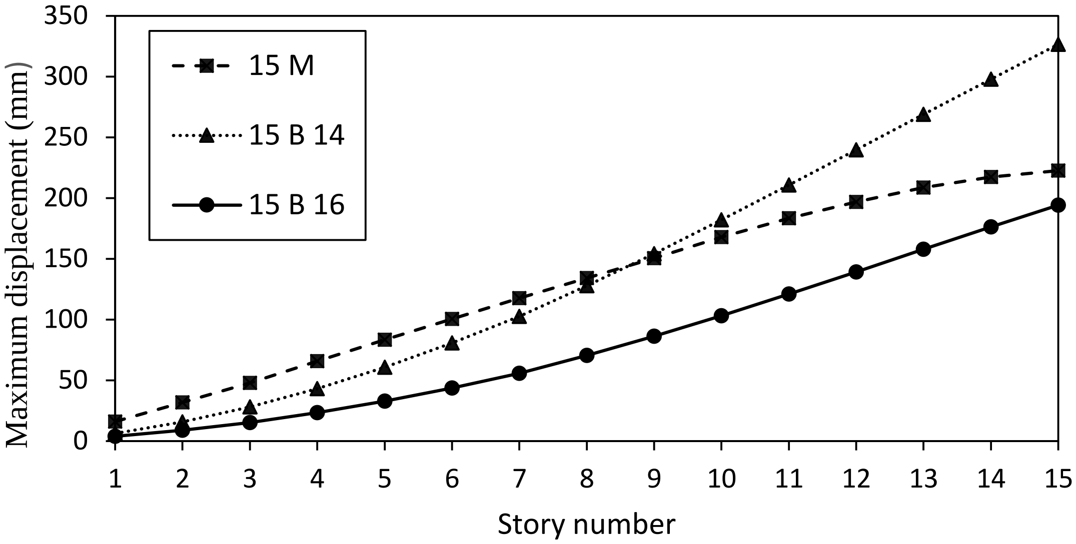


Figure 6.8: 15 story regular frame displacements in y direction.

In Fig 6.8, the braced frame displacements exceeded the displacements of moment frame at story 9, but when 15 B 16 was used the braced frame displacement decreased for all the floor levels of this building.

Same case on equivalent static analysis are repeated here for the 20 story braced frame with a series of cross bracing like a belt was installed at the top of 20 story building, and at the top and the middle of building. Then in other case diagonal bracings were installed replacing the x brace belt.

Table 6.5: Displacements of regular framed 20 story building with cross–bracings forming a belt at the top, and belt at both top and middle of the 20 story building.

	x direction (mm)			y direction (mm)		
	M	B(20)	B(10,20)	M	B(20)	B(10,20)
Base	0	0	0	0	0	0
story 1	10	3.5	3.3	11.7	4	3.7
story 2	20.3	8.1	7.5	22.6	9.2	8.3
story 3	30.9	13.5	12.3	33.5	15.4	13.7
story 4	42.6	19.8	17.6	46.4	22.9	19.8
story 5	54.1	27.1	23.5	59.2	31.6	26.6
story 6	65.4	35.3	29.8	71.7	41.5	34
story 7	76.6	44.3	36.4	84.6	52.6	41.8
story 8	87.6	54.3	43.4	97.2	64.8	50.1
story 9	98.3	65.6	51	109.7	78.6	59.3
story 10	109.5	77.7	57.4	122.8	93.3	67.5
story 11	120.5	90.2	58.4	135.8	108.8	70.3
story 12	130.9	103.1	64.9	148.2	124.8	78.8
story 13	141.4	116.1	72.9	160.9	141.1	88.8
story 14	151.2	129.2	81.4	172.9	157.5	99.5
story 15	161.8	143.1	91.2	185.9	174.9	111.7
story 16	176.2	156.3	100.8	203.3	191.5	123.8
story 17	189.3	168.1	109.6	218.8	206.4	135
story 18	199.9	178.2	117.4	231.3	219.3	145
story 19	207.5	185.9	123.4	240.8	229.5	153.2
story 20	212.2	187.4	124.5	246.8	232.5	156.3

From table 6.5 it can be seen that providing a belt of x bracing at the 20th story of the building led to reduction in lateral displacement in x direction at story 20 by about 11.6% and in y direction by about 5.8%. In case 2 where two belt was introduced at story 20 and story 10 the displacement in x direction reduce by about 41.3% and by 36.7% in y direction.

Therefore, this approach can be considered as a possible solution to the displacement increase if buildings above 16 stories.

The approach detailed above was repeated by using diagonal bracing instead of cross-bracing.

Table 6.6: Displacements of regular framed 20 story building with diagonal–bracings forming a belt at the top, and belt at both top and middle of the 20 story building

	x direction (mm)			y direction (mm)		
	M	B(20)	B(10,20)	M	B(20)	B(10,20)
Base	0	0	0	0	0	0
story 1	10	3.5	3.3	11.7	4	3.8
story 2	20.3	8.1	7.6	22.6	9.2	8.5
story 3	30.9	13.6	12.5	33.5	15.5	14
story 4	42.6	20.1	18	46.4	23.1	20.4
story 5	54.1	27.6	24.1	59.2	32.1	27.6
story 6	65.4	36	30.7	71.7	42.2	35.5
story 7	76.6	45.4	37.8	84.6	53.6	44
story 8	87.6	55.9	45.3	97.2	66.2	53.1
story 9	98.3	67.8	53.6	109.7	80.5	63.2
story 10	109.5	80.6	60.9	122.8	95.9	72.6
story 11	120.5	94	63.2	135.8	112.2	77.1
story 12	130.9	108	70.7	148.2	129.2	87.1
story 13	141.4	122.4	79.6	160.9	146.6	98.5
story 14	151.2	137.1	89.1	172.9	164.6	110.5
story 15	161.8	152.8	99.6	185.9	183.7	123.9
story 16	176.2	168.3	110.1	203.3	202.5	137.2
story 17	189.3	182.8	119.6	218.8	220	149.5
story 18	199.9	196.2	128.1	231.3	236	160.6
story 19	207.5	207.2	134.7	240.8	249.5	169.5
story 20	212.2	209.6	136.2	246.8	254.4	173.3

Providing a belt bracing at 20 story and 10 and 20 story led to reduction in lateral displacement up to story 20 by reaching 1.2% and 35.8% in x direction respectively. However in y direction inset a belt bracing at 20 story led to increase in displacement from story 17 to achieve 3.1% at story 20, when double belt cause a decrease in the displacements by 29.8%.

6.4 Comparison between Equivalent Static and Response Spectrum Analysis

- The displacement decreased using a response spectrum analysis compared to equivalent static analysis.
- Same response was obtained as the equivalent static analysis but with slightly lower displacements.
- At 20 story the displacement of braced frame increased from higher story than in equivalent static analysis
- In 15 story the displacement of braced increased from story 13 in x direction when a response spectrum analysis where used but when equivalent static analysis is used the braced gives more displacement from story 11. Same concept in the role of braced can be seen but the difference was the story numbers.
- Both x belt at 10, 10 and 20 gives less displacement using the response spectrum analysis in both directions.

Chapter 7

PUSHOVER ANALYSIS

7.1 Introduction

The aim of this chapter is to investigate the behavior and performance of selected steel framed buildings, regular six, twelve and twenty stories moment and braced frames, from this study against earthquake using pushover analysis. The following parameters were used with ETABS general analysis and design software for this study: short period spectral acceleration S_s= 0.68, long period spectral acceleration S_1= 0.23, site class C, and damping ratio of 0.05 as per FEMA 440. Assign hinge properties available in ETABS nonlinear as per ASCE 41-13 to the frame elements. For the beam default hinge that yields based upon the flexure (M3) and shear (V2) is assigned, for the column default hinge that yields based upon the interaction of the axial force and bending moment (P M2 M3) is assigned.

7.2 Comparison of Maximum Base Force and Displacement of Regular Building Using Pushover Analysis

7.2.1 Comparison of Results in x-Direction

Comparison of maximum base shear and displacement of 6, 12, 20 story braced and moment frames in the x direction were studied and reported in this section.

Table 7.1: Maximum values of base force (kN) and displacement (mm) in x direction

	Max Base Shear		Max Displacement	
Story	Moment	Braced	Moment	Braced
6	6855.7	6344.5	358.5	95.2
12	11602.4	8968.0	514.8	271.6
20	16405.8	13303.2	608.4	681.3

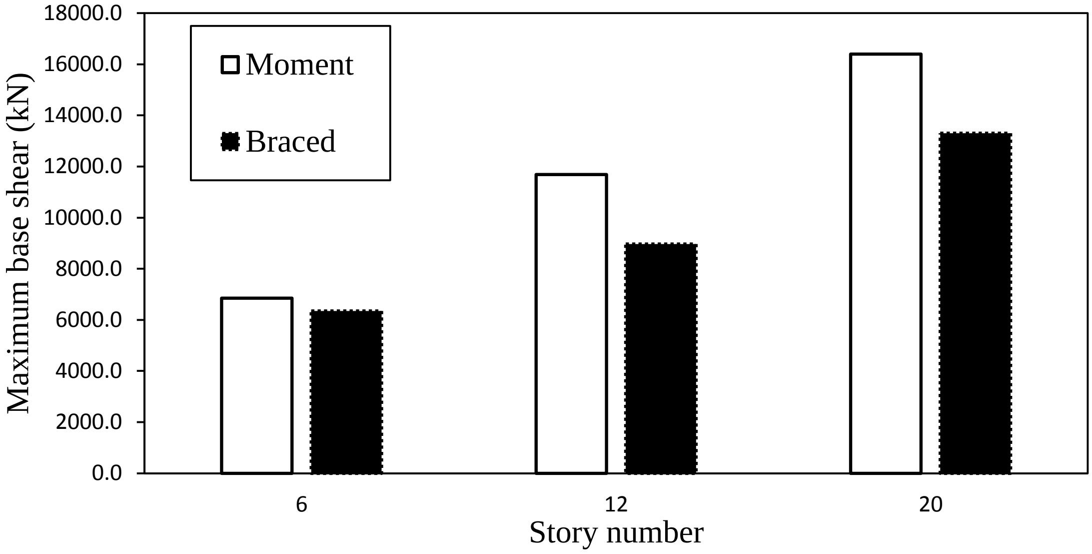


Figure 7.1: Comparison of maximum base force for 6, 12 and 20 story in x direction

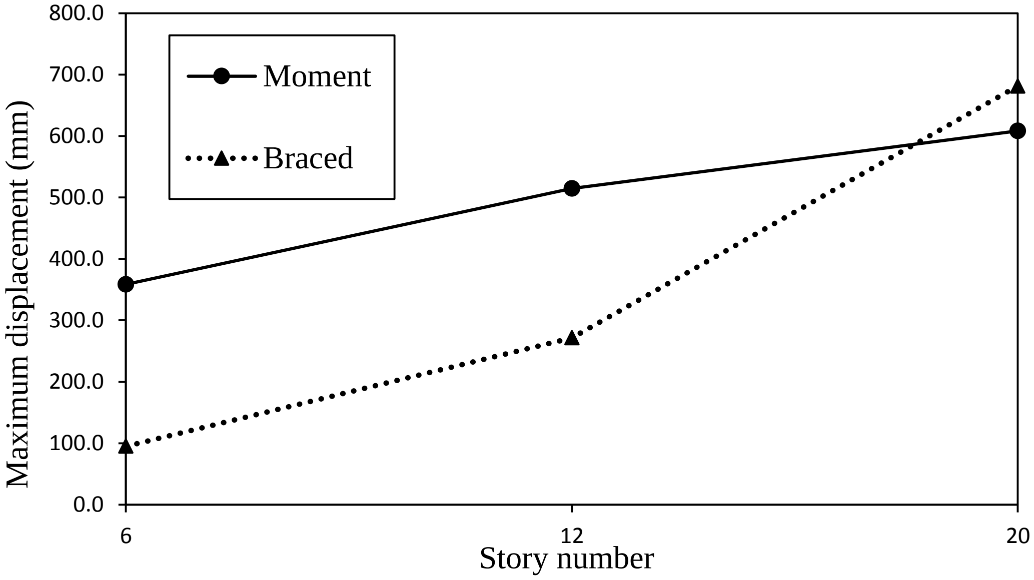


Figure 7.2: Comparison of maximum displacement for 6, 12, and 20 story in x direction

In x-direction, the moment frame max displacement was 276.6% more than the braced frame for 6 story and this percentage of difference between moment frame and braced frame is reduced to 89.5% for 12 story, but for 20 story the braced frame achieved 10.7% more displacement than the moment frame. As for maximum base force the moment frame achieve 8.1% more than the braced frame for 6 story and for 12 and 20 story moment frames the base shears were 30.3% and 23.3% more than the braced one, respectively. However, there was no performance point for 6 story braced frame. So for the first three floor of the building on two sides of the braced bay, the steel column cross section was changed to get the performance point. As a result both the base force and the displacement of the braced frame was increased and the percentage difference in the base force and displacement between moment and braced frame were reduced to -4.3% and 182.1%, respectively.

7.2.1.1 Six-Story Building Pushover Analysis

6 story moment frame structure's pushover analysis in x-direction was included 6 steps (Table 7.2). It has been observed that, on subsequent pushes to building, hinges started forming in columns at the base. Initially hinges were in A-IO and subsequently proceeded to IO-LS, LS-CP and >CP. At performance point, where the capacity and demands meets (Fig 7.3-7.4), out of 924 hinges 822 were in the A-IO stage and 76 and 26 hinges were in IO-LS and LS-CP stages respectively. As at performance point, hinges were in LS-CP range. Therefore, overall performance of building is said to be life safety to collapse prevention level.

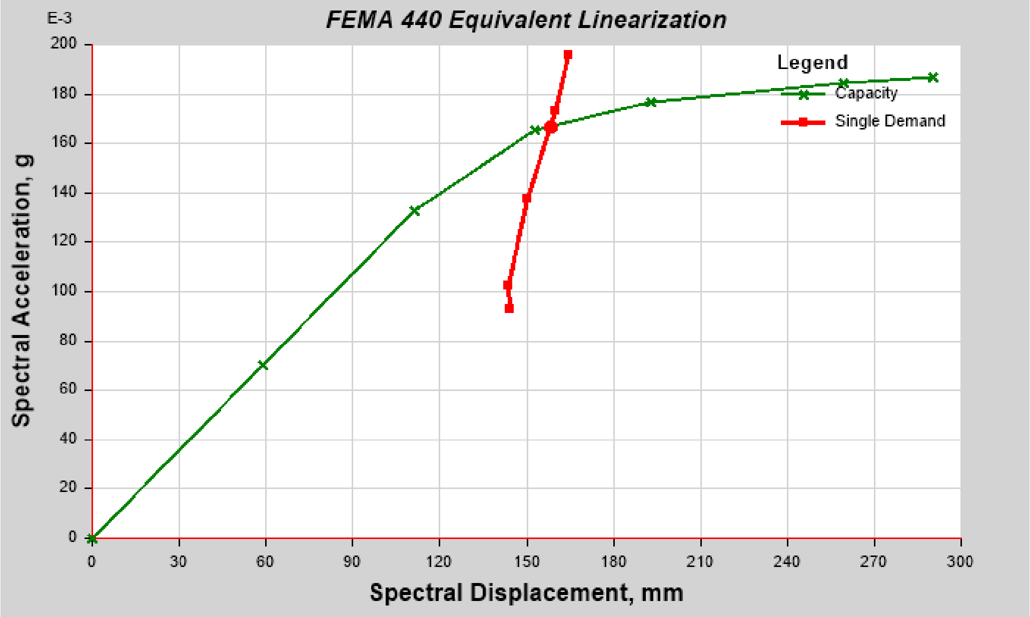
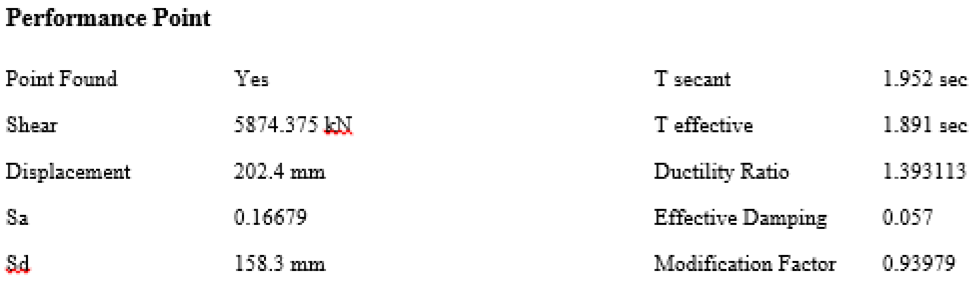


Figure 7.3: Performance point when the capacity and single demand intersect



Performance Point

Point Found	Yes	T secant	1.952 sec
Shear	5874.375 kN	T effective	1.891 sec
Displacement	202.4 mm	Ductility Ratio	1.393113
Sa	0.16679	Effective Damping	0.057
Sd	158.3 mm	Modification Factor	0.93979

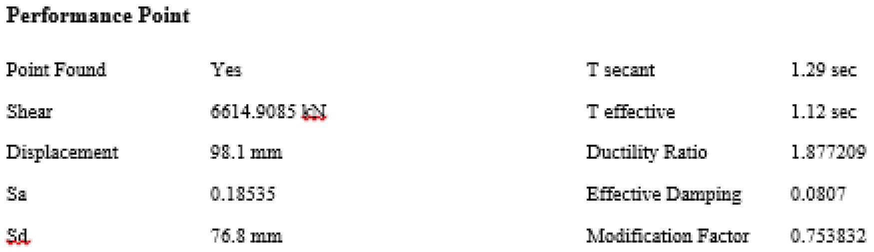
Figure 7.4: Performance point

Table 7.2: Base force versus monitored displacement for 6 story moment frame in x direction

Step	Monitored Displ mm	Base Force kN	A-IO	IO-LS	LS-CP	>CP	Total
0	0.0	0.0	924.0	0.0	0.0	0.0	924.0
1	143.6	4577.7	916.0	8.0	0.0	0.0	924.0
2	195.8	5801.2	862.0	52.0	10.0	0.0	924.0
3	244.0	6329.8	822.0	76.0	26.0	0.0	924.0
4	335.4	6786.2	772.0	68.0	84.0	0.0	924.0
5	358.5	6855.7	772.0	52.0	98.0	2.0	924.0
6	292.0	4406.3	772.0	50.0	94.0	8.0	924.0

6 story braced frame structure’s pushover analysis in x-direction was included 11 steps (Table 7.3). It has been observed that, on subsequent pushes to building, hinges started

forming in columns at the base where the bracing intersects with the column. Initially hinges were in A-IO and subsequently proceeded to IO-LS, LS-CP and >CP. At performance point (Fig 7.5), where the capacity and demand meets, out of 1020 hinges 984 were in the A-IO stage, 20, 8 and 8 hinges were in IO-LS, LS-CP and >CP stages, respectively. As at performance point, hinges were in >CP range and the overall performance of building is said to be collapse prevention level.



Performance Point

Point Found	Yes	T secant	1.29 sec
Shear	6614.9085 kN	T effective	1.12 sec
Displacement	98.1 mm	Ductility Ratio	1.877209
Sa	0.18535	Effective Damping	0.0807
Sd	76.8 mm	Modification Factor	0.753832

Figure 7.5: Performance point for 6 story braced in x-direction

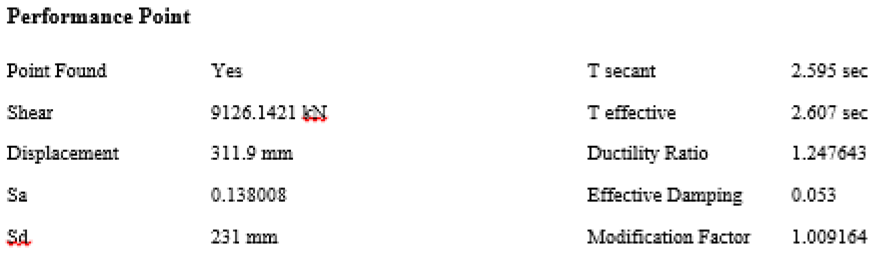
Table 7.3: Base force versus monitored displacement for 6 story braced frame in x direction

Step	Monitored Displ mm	Base Force kN	A-IO	IO-LS	LS-CP	>CP	Total
0	0.0	0.0	1020.0	0.0	0.0	0.0	1020.0
1	39.0	4030.6	1016.0	4.0	0.0	0.0	1020.0
2	69.8	6499.4	1002.0	14.0	2.0	2.0	1020.0
3	69.8	6240.2	1002.0	14.0	2.0	2.0	1020.0
4	74.1	6549.1	1002.0	12.0	2.0	4.0	1020.0
5	74.1	6195.2	998.0	16.0	2.0	4.0	1020.0
6	90.1	6880.4	990.0	22.0	2.0	6.0	1020.0
7	90.1	6377.6	986.0	26.0	2.0	6.0	1020.0
8	95.6	6568.4	986.0	26.0	2.0	6.0	1020.0
9	127.0	7166.2	984.0	20.0	8.0	8.0	1020.0
10	127.1	7134.4	984.0	20.0	8.0	8.0	1020.0
11	127.1	7134.1	984.0	20.0	8.0	8.0	1020.0

7.2.1.2 Twelve-Story Building Pushover Analysis

12 story moment frame structure's pushover analysis in x-direction was included 12 steps as shown in Table 7.4. It has been observed that, on subsequent pushes to

building, hinges started forming in Columns at the base and some joints at floor 3, 4 and 5. Initially hinges were in A-IO and subsequently proceeded to IO-LS, LS-CP and >CP. At performance point (Fig 7.6), where the capacity and demand meets, out of 1848 hinges 1820 were in the A-IO stage, 10 and 18 hinges were in IO-LS and LS-CP stages, respectively. As at performance point, hinges were in LS-CP range, overall performance of building is said to be life safety to collapse prevention level.



Performance Point

Point Found	Yes	T secant	2.595 sec
Shear	9126.1421 kN	T effective	2.607 sec
Displacement	311.9 mm	Ductility Ratio	1.247643
Sa	0.138008	Effective Damping	0.053
Sd	231 mm	Modification Factor	1.009164

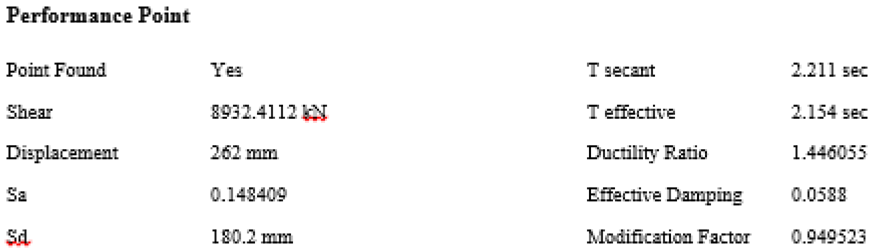
Figure 7.6: Performance point for 12 story moment in x-direction

Table 7.4: Base force versus monitored displacement for 12 story moment frame in x direction.

Step	Monitored Displ mm	Base Force kN	A-IO	IO-LS	LS-CP	>CP	Total
0	0.0	0.0	1848	0	0	0	1848
1	60.0	1778.6	1848	0	0	0	1848
2	120.0	3557.2	1848	0	0	0	1848
3	180.0	5335.8	1848	0	0	0	1848
4	240.0	7114.4	1846	2	0	0	1848
5	257.1	7612.7	1844	4	0	0	1848
6	318.0	9294.2	1820	10	18	0	1848
7	382.0	10717.8	1722	100	24	2	1848
8	423.5	11240.1	1642	156	48	2	1848
9	485.0	11627.2	1580	190	76	2	1848
10	496.7	11685.0	1574	184	86	4	1848
11	496.7	11455.4	1572	182	90	4	1848
12	514.8	11602.4	1572	166	106	4	1848

12 story braced frame structure’s pushover analysis in x-direction was included 7 steps as shown in Table 7.5. It has been observed that, on subsequent pushes to building,

hinges started forming in columns at the base where the bracing intersects with the column. Initially hinges were in A-IO and subsequently proceeded to IO-LS, LS-CP and >CP. At performance point (Fig 7.7), out of 2040 hinges 1992 were in the A-IO stage, 40 and 8 hinges were in IO-LS and >CP stages, respectively. As at performance point, hinges were in >CP range, overall performance of building is said to be collapse prevention level.



Performance Point

Point Found	Yes	T secant	2.211 sec
Shear	8932.4112 kN	T effective	2.154 sec
Displacement	262 mm	Ductility Ratio	1.446055
Sa	0.148409	Effective Damping	0.0588
Sd	180.2 mm	Modification Factor	0.949523

Figure 7.7: Performance point for 12 story braced in x-direction

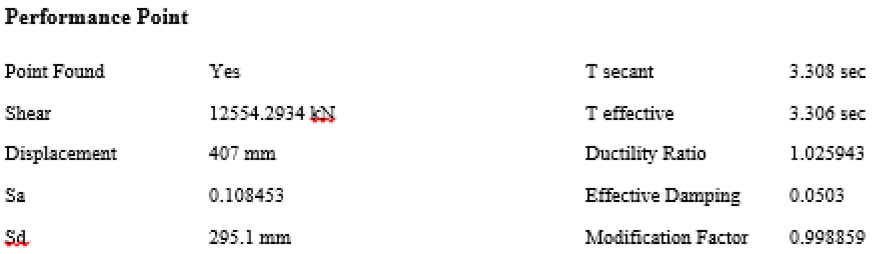
Table 7.5: Base force versus monitored displacement for 12 story braced frame in x direction.

Step	Monitored Displ mm	Base Force kN	A-IO	IO-LS	LS-CP	>CP	Total
0	0.0	0.0	2040	0	0	0	2040
1	60.0	2270.3	2040	0	0	0	2040
2	120.0	4540.5	2040	0	0	0	2040
3	158.4	5993.2	2032	8	0	0	2040
4	222.8	8078.3	1998	40	2	0	2040
5	254.3	8888.8	1992	40	0	8	2040
6	263.0	8937.5	1992	40	0	8	2040
7	271.6	8968.0	1992	38	0	10	2040

7.2.1.3 Twenty-Story Building Pushover Analysis

20 story moment frame structure’s pushover analysis in x-direction was included 5 steps, as shown in Table 7.6. It has been observed that, on subsequent pushes to building, hinges started forming in columns at the base and some joints at different stories. Initially hinges were in A-IO and subsequently proceeded to IO-LS, LS-CP

and >CP. At performance point (Fig 7.8), out of 3080 hinges 2926 were in the A-IO stage, 134 and 20 hinges were in IO-LS and LS-CP stages, respectively. As at performance point, hinges were in LS-CP range, overall performance of building is said to be life safety to collapse prevention level.



Performance Point

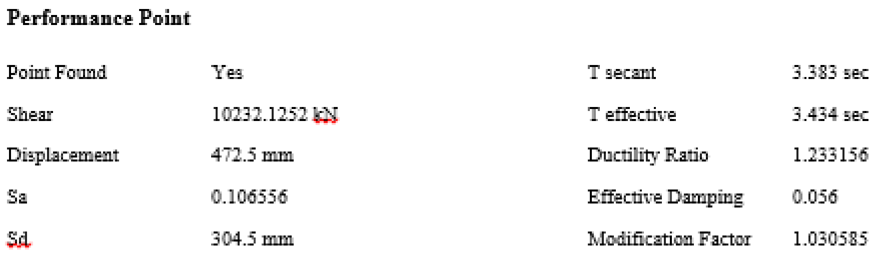
Point Found	Yes	T secant	3.308 sec
Shear	12554.2934 kN	T effective	3.306 sec
Displacement	407 mm	Ductility Ratio	1.025943
Sa	0.108453	Effective Damping	0.0503
Sd	295.1 mm	Modification Factor	0.998859

Figure 7.8: Performance point for 20 story moment in x-direction

Table 7.6: Base force versus monitored displacement for 20 story moment frame in x direction.

Step	Monitored Displ mm	Base Force kN	A-IO	IO-LS	LS-CP	>CP	Total
0	0.0	0.0	3080	0	0	0	3080
1	396.9	12282.7	3078	2	0	0	3080
2	512.0	15369.0	2926	134	20	0	3080
3	555.6	15986.5	2868	182	28	2	3080
4	608.4	16405.8	2830	152	96	2	3080
5	606.6	16223.3	2830	148	100	2	3080

20 story braced frame structure’s pushover analysis in x-direction was included 5 steps, as shown in Table 7.7. It has been observed that, on subsequent pushes to building, hinges started forming in columns at the base where the bracing intersects with the column and columns of third story. Initially hinges were in A-IO, and subsequently proceeded to IO-LS, LS-CP and >CP. At performance point (Fig 7.9), out of 3400 hinges 3350 were in the A-IO stage, 44, 4 and 2 hinges were in IO-LS, LS-CP and >CP stages, respectively. As at performance point, hinges were in >CP range, overall performance of building is said to be collapse prevention level.



Performance Point

Point Found	Yes	T secant	3.383 sec
Shear	10232.1252 kN	T effective	3.434 sec
Displacement	472.5 mm	Ductility Ratio	1.233156
Sa	0.106556	Effective Damping	0.056
Sd	304.5 mm	Modification Factor	1.030585

Figure 7.9: Performance point for 20 story braced in x-direction

Table 7.7: Base force versus monitored displacement for 20 story braced frame in x direction.

Step	Monitored Displ mm	Base Force kN	A-IO	IO-LS	LS-CP	>CP	Total
0	0.0	0.0	3400	0	0	0	3400
1	383.3	8412.7	3394	6	0	0	3400
2	614.4	13127.5	3350	44	4	2	3400
3	614.4	12839.7	3342	44	2	12	3400
4	642.6	13278.7	3336	48	4	12	3400
5	681.3	13303.2	3336	48	4	12	3400

7.2.2 Comparison of Results in y-Direction

Comparison of maximum base force and displacement for 6, 12, 20 story braced and moment frames in the y direction were studied and reported in this section.

Table 7.8: Maximum values of base force (kN) and displacement (mm) in x direction

	Max Base Shear		Max Displacement	
Story	Moment	Braced	Moment	Braced
6	4044.7	5675.4	333.8	103.1
12	9545.6	9040.7	565.5	292.8
20	14573.9	13210.9	497.9	711.5

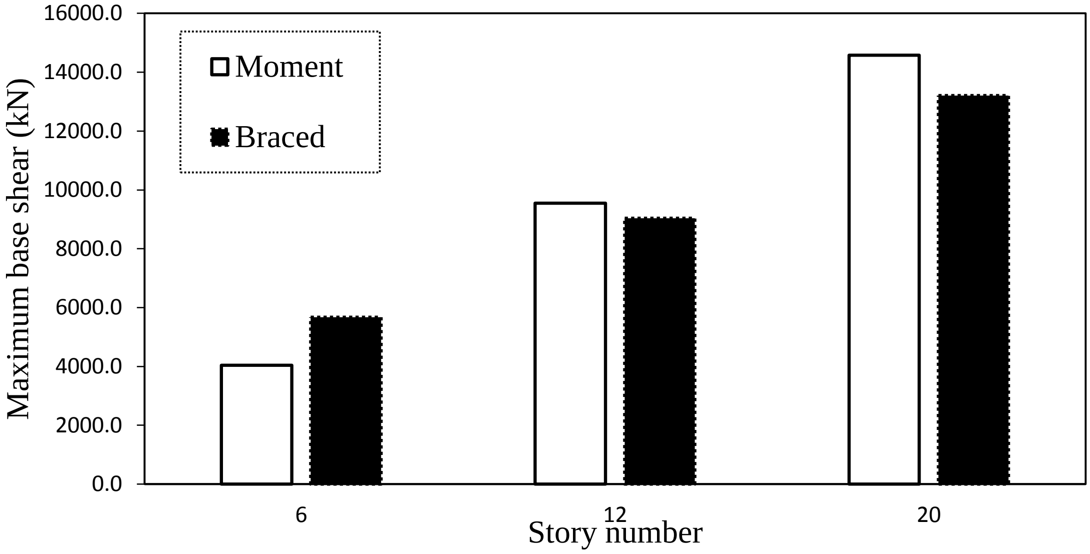


Figure 7.10: Comparison of maximum base shear for 6, 12, and 20 story in y direction

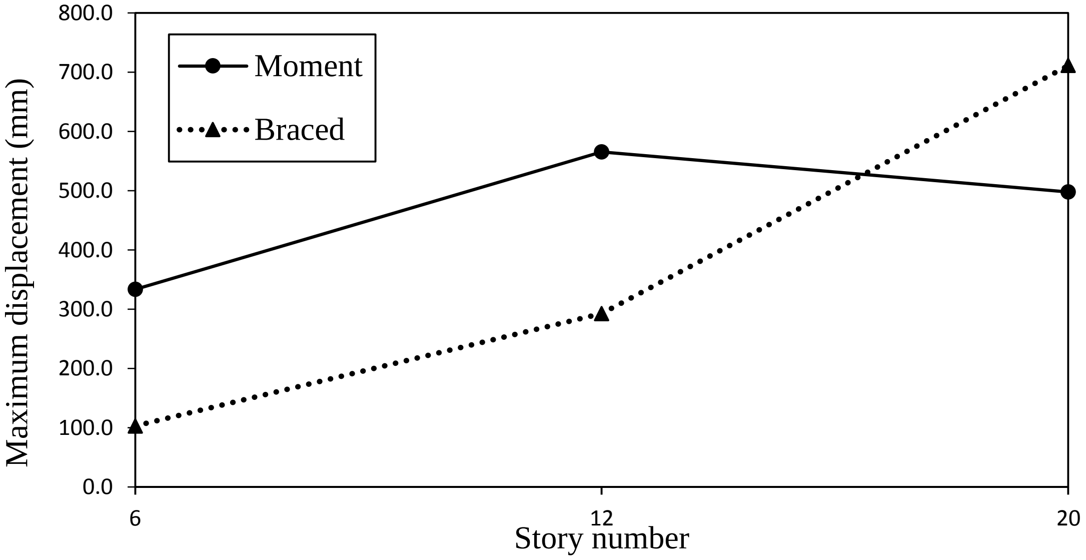
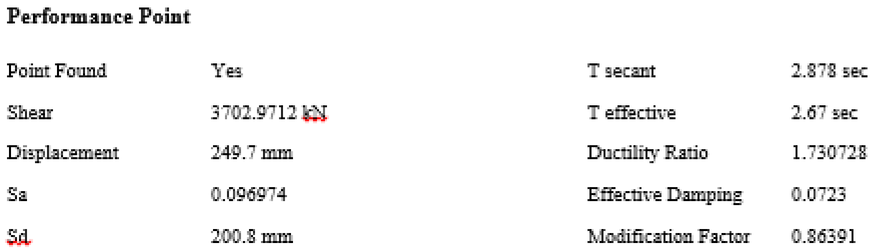


Figure 7.11: Comparison of maximum displacement for 6, 12, and 20 story in y direction

In y-direction, the moment frame max displacement was 223.8% more than the braced frame for 6 story, and this percentage of difference between moment frame and braced frame is reduced to 93.1% for 12 story, but for 20 story the braced frame achieved 30.2% more displacement than the moment frame. As for maximum base force the moment frame achieve 28.7% less than the braced frame for 6 story. At 12 and 20 story moment frames the base shears were 5.6% and 10.3% more than the braced one, respectively. However, there was no performance point for 6 story braced frame. So for the first three floor of the building on two sides of the braced bay, the steel column cross section was changed to get the performance point. As a result both the base force and the displacement of the braced frame was increased and the percentage difference in the base force and displacement between moment and braced frame were reduced to -32.0% and 126%, respectively.

7.2.2.1 Six-Story Building Pushover Analysis

6 story moment frame structure's pushover analysis in y-direction was included 7 steps as shown in Table 7.9. It has been observed that, on subsequent pushes to building, hinges started forming in columns at the base. Initially hinges were in A-IO, IO-LS and subsequently proceeded to IO-LS, LS-CP and >CP. At performance point (Fig 7.12), out of 924 hinges 844 were in the A-IO stage, 30 and 50 hinges were in IO-LS and LS-CP stages, respectively. As at performance point, hinges were in LS-CP range. Therefore, overall performance of building is said to be life safety to collapse prevention level.

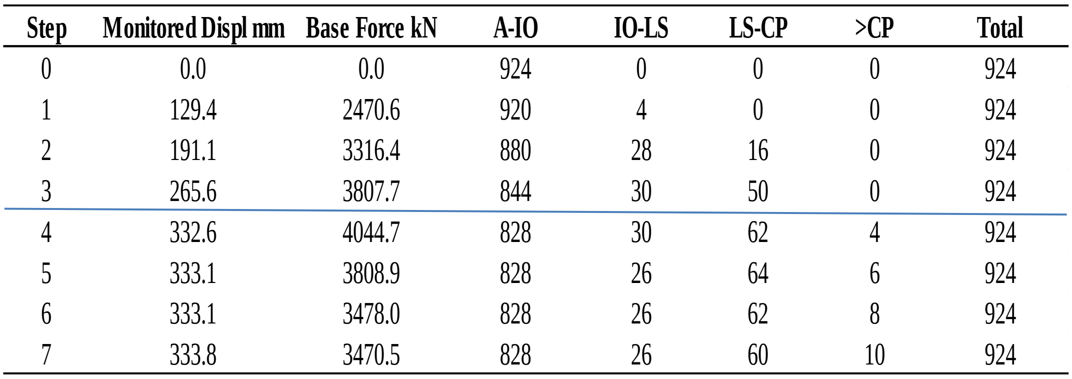


Performance Point

Point Found	Yes	T secant	2.878 sec
Shear	3702.9712 kN	T effective	2.67 sec
Displacement	249.7 mm	Ductility Ratio	1.730728
Sa	0.096974	Effective Damping	0.0723
Sd	200.8 mm	Modification Factor	0.86391

Figure 7.12: Performance point for 6 story moment in y-direction

Table 7.9: Base force versus monitored displacement for 6 story moment frame in y direction



Step	Monitored Displ mm	Base Force kN	A-IO	IO-LS	LS-CP	>CP	Total
0	0.0	0.0	924	0	0	0	924
1	129.4	2470.6	920	4	0	0	924
2	191.1	3316.4	880	28	16	0	924
3	265.6	3807.7	844	30	50	0	924
4	332.6	4044.7	828	30	62	4	924
5	333.1	3808.9	828	26	64	6	924
6	333.1	3478.0	828	26	62	8	924
7	333.8	3470.5	828	26	60	10	924

6 story braced frame structure pushover analysis in y-direction was included 9 steps, as shown in Table 7.10. It has been observed that, on subsequent pushes to building, hinges started forming in columns at the base where the bracing intersects with the column. Initially hinges were in A-IO and subsequently proceeded to IO-LS, LS-CP and >CP. At performance point (Fig 7.13), out of 1020 hinges 992 were in the A-IO stage, 16, 8 and 4 hinges were in IO-LS, LS-CP and >CP stages, respectively. As at performance point, hinges were in >CP range and the overall performance of building is said to be collapse prevention level.

Point Found	Yes	T secant	1.566 sec
Shear	5063.5853 kN	T effective	1.186 sec
Displacement	100.2 mm	Ductility Ratio	1.83439
Sa	0.130989	Effective Damping	0.0777
Sd	79.8 mm	Modification Factor	0.640206

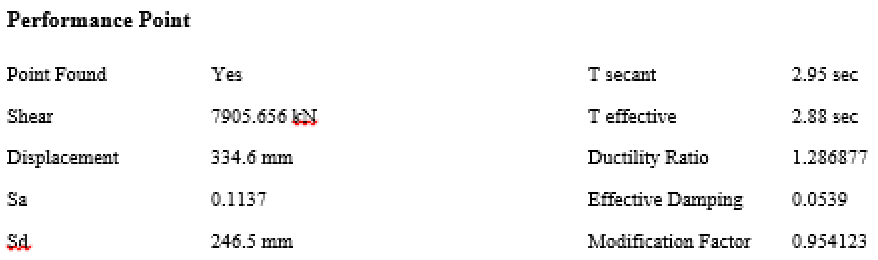
Figure 7.13: Performance point for 6 story braced in y-direction

Table 7.10: Base force versus monitored displacement for 6 story braced frame in y direction.

Step	Monitored Displ mm	Base Force kN	A-IO	IO-LS	LS-CP	>CP	Total
0	2.017E-08	0.0	1020	0	0	0	1020
1	40.0	3581.3	1016	4	0	0	1020
2	67.1	5590.0	1006	12	0	2	1020
3	67.1	4921.3	1002	16	0	2	1020
4	97.4	5910.2	996	16	6	2	1020
5	100.1	5950.0	996	14	6	4	1020
6	100.1	5059.3	996	14	6	4	1020
7	107.9	5407.3	992	16	8	4	1020
8	139.7	5862.4	990	16	8	6	1020
9	147.7	5930.9	990	16	8	6	1020

7.2.2.2 Twelve-Story Building Pushover Analysis

12 story moment frame structure's pushover analysis in y-direction was included 13 steps as shown in able 7.11. It has been observed that, on subsequent pushes to building, hinges started forming in columns at the base. Initially hinges were in A-IO, and subsequently proceeded to IO-LS, LS-CP and >CP. At performance point (Fig 7.14), out of 1848 hinges 1722 were in the A-IO stage, 87 and 39 hinges were in IO-LS and LS-CP stages, respectively. As at performance point, hinges were in LS-CP range and the overall performance of building is said to be life safety to collapse prevention level.



Performance Point

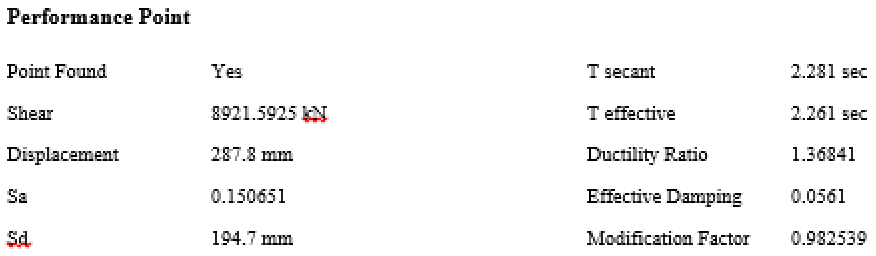
Point Found	Yes	T secant	2.95 sec
Shear	7905.656 kN	T effective	2.88 sec
Displacement	334.6 mm	Ductility Ratio	1.286877
Sa	0.1137	Effective Damping	0.0539
Sd	246.5 mm	Modification Factor	0.954123

Figure 7.14: Performance point for 12 story moment in y-direction

Table 7.11: Base force versus monitored displacement for 12 story moment in y direction.

Step	Monitored Displ mm	Base Force kN	A-IO	IO-LS	LS-CP	>CP	Total
0	-8.922E-12	0.0	1848	0	0	0	1848
1	60.0	1502.6	1848	0	0	0	1848
2	120.0	3005.2	1848	0	0	0	1848
3	180.0	4507.8	1848	0	0	0	1848
4	240.0	6010.4	1848	0	0	0	1848
5	252.2	6316.7	1844	4	0	0	1848
6	315.8	7653.2	1787	51	10	0	1848
7	377.9	8489.6	1722	87	39	0	1848
8	438.7	8935.7	1674	85	89	0	1848
9	504.0	9295.8	1643	69	136	0	1848
10	563.0	9545.6	1619	64	163	2	1848
11	563.0	9354.2	1619	64	163	2	1848
12	565.5	9382.8	1619	64	162	3	1848
13	545.2	8884.6	1619	64	162	3	1848

12 story braced frame structure’s pushover analysis in y-direction was included 6 steps as shown in Table 7.12. It has been observed that, on subsequent pushes to building, hinges started forming in columns at the base where the bracing intersects with the column and columns at first story. Initially hinges were in A-IO, and subsequently proceeded to IO-LS, LS-CP and >CP. At performance point (Fig 7.15), out of 2040 hinges 2000 were in the A-IO stage, 32, 4 and 4 hinges were in IO-LS, LS-CP and >CP stages, respectively. As at performance point, hinges were in >CP range, overall performance of building is said to be collapse prevention level.



Performance Point

Point Found	Yes	T secant	2.281 sec
Shear	8921.5925 kN	T effective	2.261 sec
Displacement	287.8 mm	Ductility Ratio	1.36841
Sa	0.150651	Effective Damping	0.0561
Sd	194.7 mm	Modification Factor	0.982539

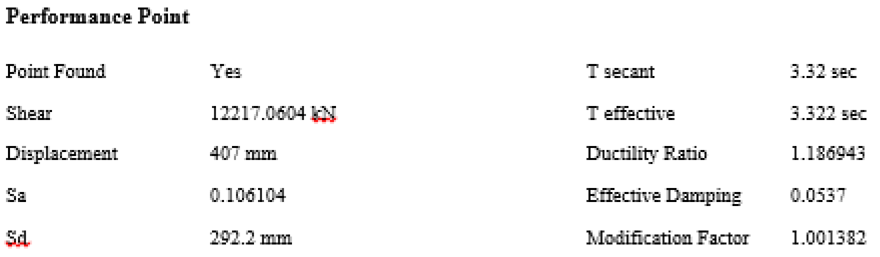
Figure 7.15: Performance point for 12 story braced in y-direction

Table 7.12: Base force versus monitored displacement for 12 story braced frame in y direction

Step	Monitored Displ mm	Base Force kN	A-IO	IO-LS	LS-CP	>CP	Total
0	0.0	0.0	2040	0	0	0	2040
1	60.0	1956.9	2040	0	0	0	2040
2	120.0	3913.7	2040	0	0	0	2040
3	180.0	5870.6	2040	0	0	0	2040
4	205.2	6692.4	2032	8	0	0	2040
5	273.0	8564.4	2002	34	4	0	2040
6	292.8	9040.7	2000	32	4	4	2040

7.2.2.3 Twenty-Story Building Pushover Analysis

20 story moment frame structure's pushover analysis in y-direction was included 3 steps, as shown in Table 7.13. It has been observed that, on subsequent pushes to building, hinges started forming in columns at the base and some joints at different stories. Initially hinges were in A-IO, IO-LS, LS-CP and >CP. At performance point (Fig 7.16), out of 3080 hinges 2944 were in the A-IO stage, 78, 54 and 4 hinges were in IO-LS, LS-CP and >CP stages, respectively. As at performance point, hinges were in >CP range and the overall performance of building is said to be collapse prevention level.



Performance Point

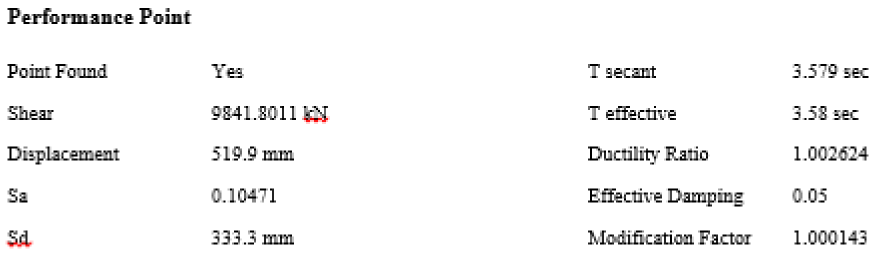
Point Found	Yes	T secant	3.32 sec
Shear	12217.0604 kN	T effective	3.322 sec
Displacement	407 mm	Ductility Ratio	1.186943
Sa	0.106104	Effective Damping	0.0537
Sd	292.2 mm	Modification Factor	1.001382

Figure 7.16: Performance point for 20 story moment in y-direction

Table 7.13: Base force versus monitored displacement for 20 story moment frame in y direction

Step	Monitored Displ mm	Base Force kN	A-IO	IO-LS	LS-CP	>CP	Total
0	0.0	0.0	3080	0	0	0	3080
1	343.8	10575.4	3078	2	0	0	3080
2	497.9	14573.9	2944	78	54	4	3080
3	496.6	14531.3	2944	78	54	4	3080

20 story braced frame structure's pushover analysis in y-direction was included 5 steps (Table 7.14). It has been observed that, on subsequent pushes to building, hinges started forming in columns at the base where the bracing intersects with the column and columns of first and third story. Initially hinges were in A-IO, and subsequently proceeded to IO-LS, LS-CP and >CP. At performance point (Fig 7.17), out of 3400 hinges 3360 were in the A-IO stage, 32 and 8 hinges were in IO-LS and LS-CP stages, respectively. As at performance point, hinges were in LS-CP range and the overall performance of building is said to be life safety to collapse prevention level.



Performance Point

Point Found	Yes	T secant	3.579 sec
Shear	9841.8011 kN	T effective	3.58 sec
Displacement	519.9 mm	Ductility Ratio	1.002624
Sa	0.10471	Effective Damping	0.05
Sd	333.3 mm	Modification Factor	1.000143

Figure 7.17: Performance point for 20 story braced in y-direction

Table 7.14: Base force versus monitored displacement for 20 story braced frame in y direction

Step	Monitored Displ mm	Base Force kN	A-IO	IO-LS	LS-CP	>CP	Total
0	0.0	0.0	3400	0	0	0	3400
1	500.0	9467.1	3400	0	0	0	3400
2	518.5	9817.5	3392	8	0	0	3400
3	706.1	13153.1	3360	32	8	0	3400
4	708.1	13156.4	3360	32	6	2	3400
5	711.5	13210.9	3360	32	4	4	3400

7.3 Performance Point

Table 7.15: Performance point of buildings in x direction

Story	Moment	Braced
6	1.9	1.1
12	2.6	2.2
20	3.3	3.4

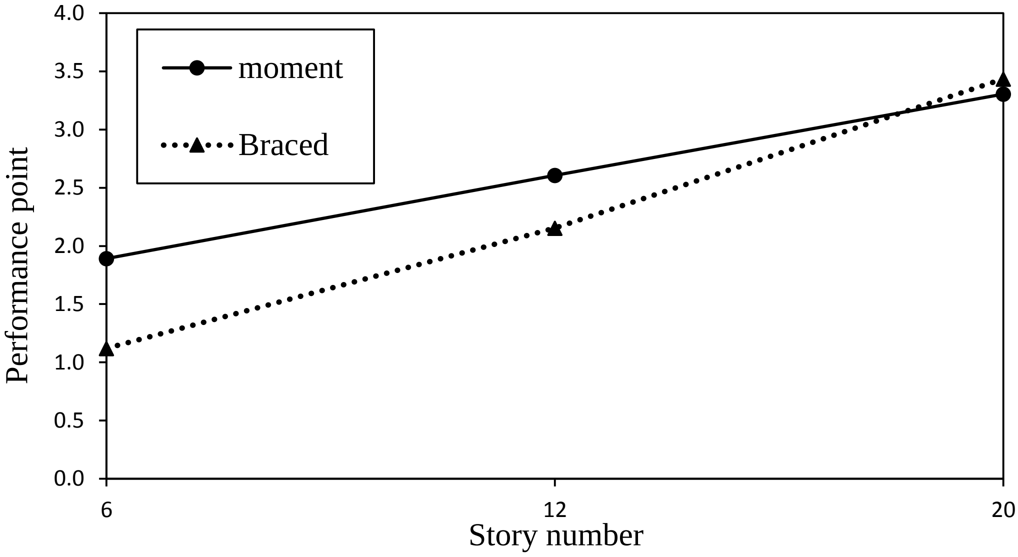


Figure 7.18: Comparison of building performance points in x direction

The performance in x direction of 6 and 12 story moment frame is better than the braced frame but for the 20 story building the performance of braced frame is better than the moment frame.

Table 7.16: Performances of buildings in y direction

Story	Moment	Braced
6	2.7	1.2
12	2.9	2.3
20	3.3	3.6

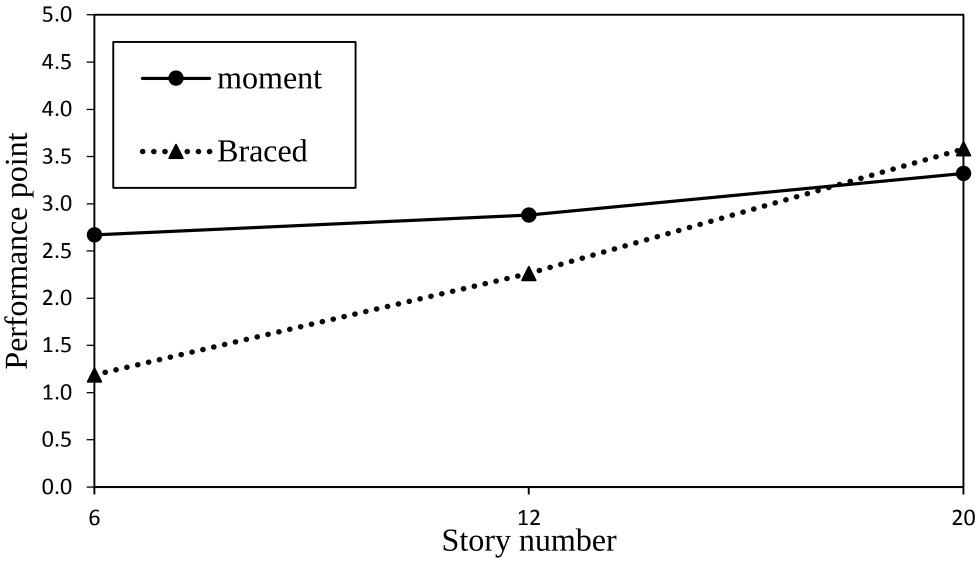


Figure 7.19: Comparison of building performance points in y direction

The performance in y direction of 6 and 12 story moment frame is better than the braced frame but for the 20 story building the performance of braced frame is better than the moment frame.

7.4 Comparison of Base Shear for Response Spectrum and Static Pushover Analysis

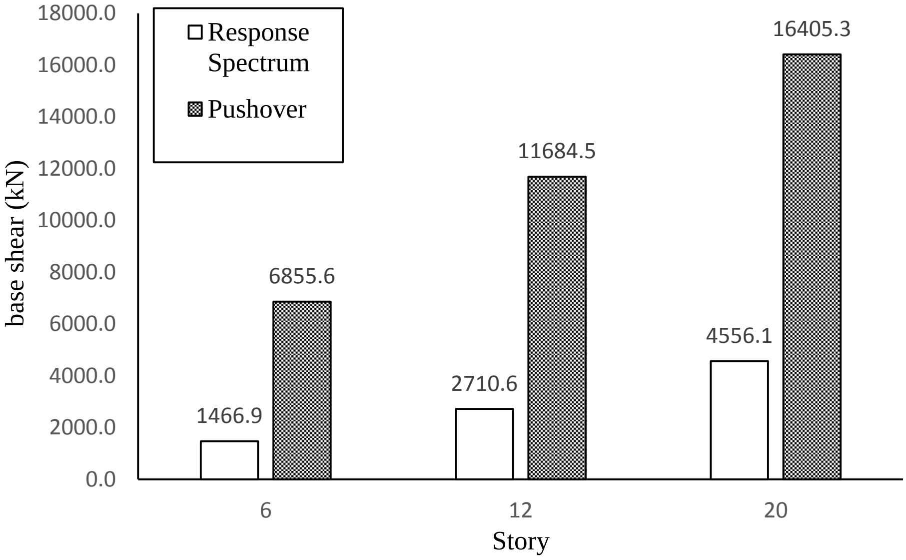


Figure 7.20: Comparison of base shear in x direction for 6, 12, and 20 regular moment frame for both response spectrum and pushover analysis

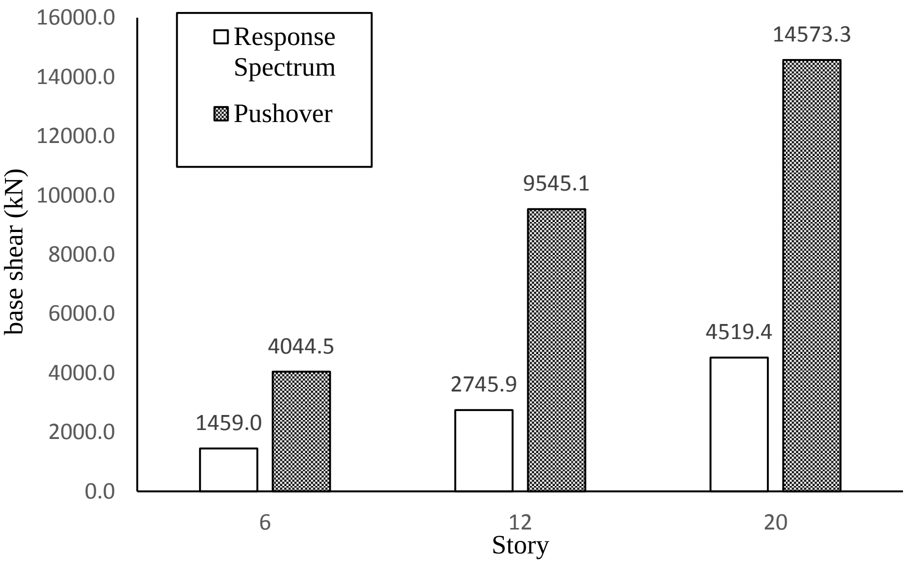


Figure 7.21: Comparison of base shear in y direction for 6, 12, and 20 regular moment frame for both response spectrum and pushover analysis

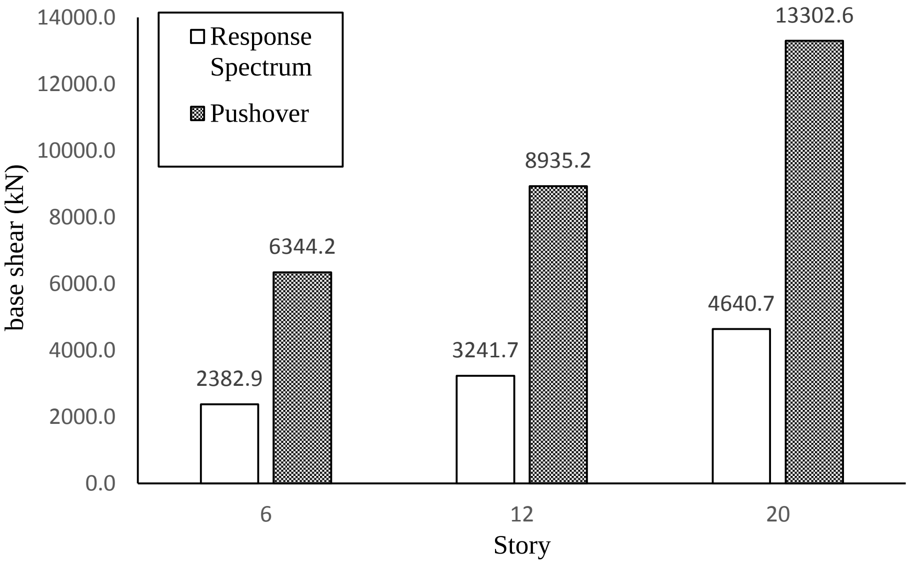


Figure 7.22: Comparison of base shear in x direction for 6, 12, and 20 regular braced frame for both response spectrum and pushover analysis

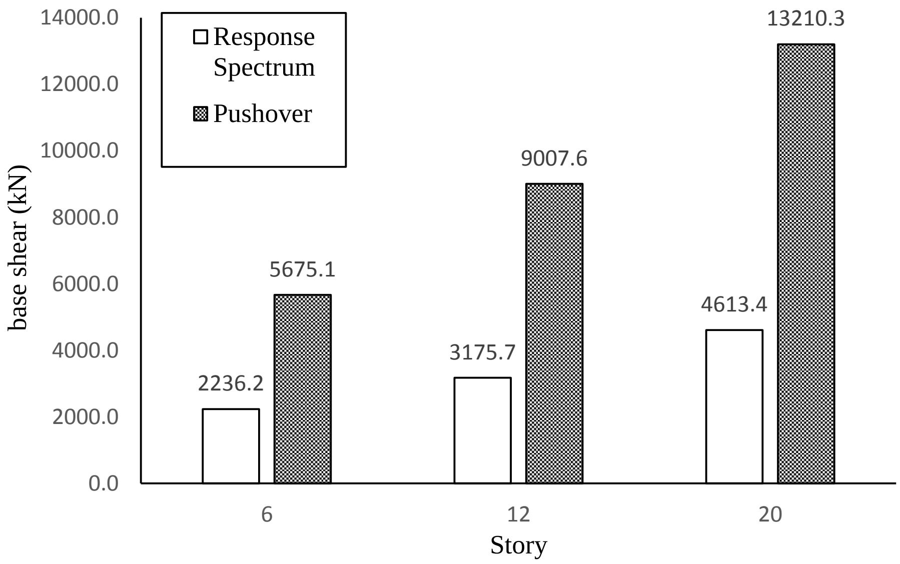


Figure 7.23: Comparison of base shear in y direction for 6, 12, and 20 regular braced frame for both response spectrum and pushover analysis

From figure 7.20 to 7.23 it can be seen that the base shear increases with the increase in mass and number of stories of building, and base shear obtained from pushover analysis is considerably higher than the base shear obtained from response spectrum analysis in both moment and braced frames.

Chapter 8

CONCLUSION AND RECOMMENDATION FOR FUTURE WORK

8.1 Conclusion

As eliminating earthquakes is not possible at the moment, it is important to minimize its drastic effects on life and structures. This study examines and compares different building heights using braced or moment frames with regular or irregular structure with 3 types of analysis equivalent static analysis. Response spectrum and Pushover analysis were used for selected number of buildings from this study.

Braced frames were used to resist the dangers of an earthquake by minimizing the displacements of steel buildings. The seismic movement of buildings differs according to building heights and irregularities. The heights studied in this thesis are the ones with 19 m (6-story), 37m (12-story), and 61m (20-story) in addition to eight forms of irregularities in each of these cases.

At the end of this research, several points were clarified:

- Bracing systems location at the middle of a building span reduces the displacement of 14-story building with different irregularities. Hence, irregularity plays an important role in the reduction of displacement due to the manner of putting braced frames at different irregularity form.

- Bracing systems causes a reverse action for 20-story building thus increasing the displacement of the building at its different heights and different irregularities.
- Bracing systems at the middle of a building is not beneficial for 14+ story buildings.
- Story 15 is considered to be the weak level of high rise buildings.
- To avoid any increase in the displacement, implementing a belt at the final, or at the final and at middle of a building can decrease the displacements.
- Results of the analysis from response spectrum and pushover analysis followed similar trend to those of equivalent static as far as lateral displacements are concerned.
- Pushover analysis results of 6, 12 story moment framed buildings produced better performance than the 6, 12 story brace framed buildings. On the other hand for 20 story brace framed building produced better performance than the 20 story moment framed.

8.2 Recommendation for Future Work

Considering the work done in this study and the results obtained the following are recommended for future research work:

1. Buildings with 14 story and more floors can be investigated by using non-linear analysis.
2. Different types of bracing can be used instead of x-bracing.
3. Different building irregularities which are not covered in this study can also be investigated.

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