The Weight Efficiency of Steel Framed Buildings with Various Wind Bracing Systems

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ABSTRACT

This research is about the efficiency of using different types of wind bracing and with different steel profiles for bracing members for multi-storey steel frames. ETABS software was used to obtain the design of frames and bracing systems with the least weight and appropriate steel section selection for beams, columns and bracing members from the standard set of steel sections. The design loads are specified in BS 5950 (2000). The serviceability limit state included in the design problem is achieved by limiting the overall and intermediate storey lateral displacement in the building to height/300 as specified by the code. Bracing members are considered to be made of Universal Angle section [Equal Angle (EA) and Unequal Angle (UA)], Rectangular Hollow section (RHHF), Circular Hollow section (CHHF) and I section [Universal Column (UC)]. This research presents the design of steel structure subjected to wind loading for buildings up to 5, 10, 15 and 20 stories with symmetrical plan and section, asymmetrical plan and section, symmetrical plan and asymmetrical section and asymmetrical plan and symmetrical section steel frame buildings with different bracing systems such as cross, zipper and knee bracing at the core and central bay of the structure. From this research it is concluded that Rectangular Hollow Section zipper bracing produces the lightest frame among the others.

Keywords: Braced steel frames; Bracing systems; Wind loads; Weight of steel elements; Lateral displacement.

ÖZET

Bu araştırma çok katlı çelik çerçevelerde hangi tip rüzgar bağ sisteminin daha etkili çalışabileceğini ve bu bağ sistemlerinde kullanılan çelik profilleri incelemek için yapılmıştır.

Bu amaçla çelik çerçeve tasarımı için ETABS programı kullanılmış ve tasarıma en uygun profiller programda yer alan standard tablolardan seçilmiştir. Kiriş kolon ve bağ sistem elemanları için seçilmiştir. Tasarımda kullanılan yükler ingiliz çelik standardı BS5950 (2000)'den alınmıştır.

Bu kodun önerdiği her kat için yatay öteleme limiti olan kat yüksekliği / 300 her bir katın ve tüm binanın yatay ötelemesini kısıtlamak için kullanılmıştır. Böylece yatay yönde gerekli sağlanmıştır. Bağ sistem elemanları için köşebend, dikdörtgen ve daire profil ve I-profil kolon kullanılmıştır.

Bu araştırmada 5, 10, 15 ve 20 katlı simetrik plan ve kesiti, asimetrik plan ve kesiti simetrik plan ve asimetrik kesiti, asimetrik plan ve simetrik kesiti olan, çelik yapılar tasarlanmıştır. Göbeğinde ve orta açıklıklarında farklı bağ sistemleri kullanılmış, örneğin çapraz, ters V ve dışmerkezli bağlanmış çelik yapılar tasarlanmıştır.

Elde edilen sonuçlar doğrultusunda dikdörtgen profil kullanılan ters V bağ sisteminin tüm sistemler arasında en hafif çerçeveyi verdiği görülmüştür.

Anahtar kelimeler: bağlanmış çelik çereçeve, bağ sistemleri, rüzgar yükleri, çelik elemanların ağırlıkları; yatay öteleme

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I am tempted to individually thank all of my friends which have joined me in this department. However, because the list might be too long and by fear of leaving someone out, I will simply say *thank you very much to you all*.

DEDICATION

This thesis is dedicated to my beloved mother Rana Riahi and brother Milad K. Abbassi for their constant encouragement, support and love through these years to pursue my goals. Also, this thesis is dedicated to my supportive fiancé, Alireza Sarrafi who has been a great source of motivation and inspiration and I would also like to appreciate the love and support from my future mother, father and brother in law.

Finally, this thesis is dedicated to the memory of my father Mohammad K. Abbassi who had made all these possible and if he was still alive, he would have been incredibly happy.

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F =force

x =distance from the end of the knee bracing to the connection over the width or height of the frame

B_2 = width from the end of the knee bracing to the beam-column connection of the frame

B =width of beam

H_2 =length from the end of the knee bracing to the column-beam connection of the frame

H =height above ground

V_s =site wind speed

V_b =basic wind speed

V_e= effective wind speed

S_a =altitude factor

S_d =direction factor

S_s =seasonal factor

S_p =probability factor

S_b=terrain and building factor

q_s =dynamic pressure of wind (stagnation pressure)

k =a constant

$MaxD$ =maximum horizontal displacement

C_{pe} =external pressure coefficient

TABLE OF EQUATIONS

CHAPTER 1

INTRODUCTION

Most of the tallest buildings in the world have steel structural system, due to its high strength-to-weight ratio, ease of assembly and field installation, economy in transport to the site, availability of various strength levels, and wider selection of sections. Innovative framing systems and modern design methods, improved fire protection, corrosion resistance, fabrication, and erection techniques combined with the advanced analytical techniques made possible by the use of computers.

1.1 Objectives and Research Approach

The study of wind has become an important issue for engineers and the most costly cause of damage to light weight steel-framed residential structures. In the US, wind is the most costly cause of damage to buildings. "From 1986 to 1993 extreme winds caused extensive damages cost $41 billion in insured catastrophe losses as compared to $6.8 billion for all other natural hazards combined" [1]. Keeping this problem in mind, the designer must design the structure so that it would neither fail nor deform under any possible loading conditions and have to consider all possible layouts in structural systems that might satisfy the requirements of the project. Structures must be designed with an adequate factor of safety to reduce the probability of failure. The design loads specified by the codes are generally satisfactory for most buildings. However, designers must decide whether these loads can be applied to the specific structure under consideration. Buildings have various types of plans, stories or heights, bracings, steel profiles for members and the braces can be in different locations due the varying direction and velocity of the wind. By considering these dissimilarities, dynamic loads that occur on the structures, then different designs and analysis may be required for buildings.

The floors of buildings are typically supported by beams which then are supported by columns. Under dead and live loads that act vertically downwards (gravity load), the columns are primarily subjected to axial compression forces. Since columns carry axial loads efficiently in direct stress, then they would have relatively small cross sections which are desirable condition since owners want to maximize usable floor space.

When lateral load, such as, wind load acts on a building, lateral displacements occur. These displacements are zero at the base of the building and increase with height. Since slender columns have relatively small cross sections, their bending stiffness is small. As a result, in a building with columns being the only supporting elements, large lateral displacements can occur. These lateral displacements can crack partition walls, damage utility lines, and produce motion sickness in occupants (particularly in the upper floors of multi-storey buildings where they have the greatest effect).

To limit lateral displacements, structural designers often insert, at appropriate locations within the building, structural walls of reinforced masonry or reinforced concrete (shear walls) or add different types of bracings between columns to form deep wind trusses which are very stiff in the plane of the truss. These bracings, together with the attached columns and horizontal floor beams in the plane of the bracings, forms a deep continuous, vertical truss that extends the full height of the building (from foundation to roof) and produces a stiff, lightweight structural element for transmitting lateral wind forces into the foundation.

It is very important to identify areas of the building where floor loads such as dead and live loads are lower (and material costs can be reduced) and areas where wind pressures on the cladding are higher (and the building's safety and reliability can be increased) in order to get optimal structural design and to design simple and diagonal members which are bracings, required lateral stability on the structure of the building.

The aim of this research is to compare the behavior and steel weights of 5, 10, 15 and 20 stories buildings with symmetrical/asymmetrical plans and sections subjected to wind loads in two different directions. These structures resist wind through concentric braces made of different steel profiles and located either at the core or central bay at the perimeter of the steel framed structure. Therefore, providing steel braces would increase the safety of buildings by resisting the wind loads. Steel braced frames are often economical way of providing lateral stability for buildings.

Use of different plans and storey heights for steel frame buildings was the method preferred for analysis and design. The computer software, ETABS was used to for the analysis and design to save time and minimize the errors.

1.2 Overview of Dissertation

This thesis is composed of five chapters and a list of references and appendices at the end. The present chapter has provided the motivation for this research. Chapter 2 summarizes current state of the art with regard to behavior of different concentric braced types with a broad literature review that describes the importance of wind loading performance assessment of multi-storey steel structures due to damages occurred on different buildings. Wind loads applied on different storey with different brace types and steel profiles at different locations in this study are described and discussed in Chapter 3. In Chapter 4, the representative model frames of the current steel building are described along with the details of each elements weight and structural displacements. Chapter 5 presents the main conclusions of this dissertation with suggestions for future research.

The Appendices A to D give all the necessary details of the column, beam and brace weights and their overall total weights. In addition lateral displacements in X and Y directions for structures with different storey levels, bracing types, steel profiles and different bracing locations on symmetrical/asymmetrical plans and sections are also given in these appendices.

Appendix E gives all the information needed on wind loading for factor S_d, external pressure coefficients C_{pe} for vertical walls and S_b terrain and building factor.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

The literature review revealed that, as expected, there was very few reported research on bracing systems for wind loading. Instead literature review indicated that eccentric and concentric bracing were mainly provided for earthquake loading.

Some countries are located in the earthquake zones where the buildings are designed to resist earthquake loads. Other countries, such as US (California), the most costly cause of damages on buildings are as a result of extreme wind storms included hurricanes and tornados. A hurricane commonly occur during late summer and early fall along coastal regions of the Atlantic and the pacific Oceans wind speeds in excess of 33m/s. They can carry wind speeds in excess of 62m/s over a path width of 75km. Tornados generally have much smaller foot prints than hurricanes, rarely exceeding 1.60km in width with path lengths less than 15km although some have traveled as for as 450km. They can include wind speeds exceeding 90m/s but the low probability of occurrence make them much less of a concern than hurricanes. Due to the much larger area covered by hurricanes, they normally cause twice the damage than tornados in any one year and over 160 times the damage of severe winds(<33m/s) [1].

Steel moment-resisting frames (SMRFs) have been used extensively for many years in regions of high seismicity. At one time, riveted connections were common in such frames. However, since 1950's, the connections have been fabricated using welds or high strength bolts which are easier to install and provides more predictable clamping force. Fully-Restrained (FR) moment frames with welded connections were believed to behave in a ductile manner, bending under earthquake loading. As a result, this became one of the most common types of construction used for major buildings in areas subject to severe earthquakes. However, the January 17, 1994 Northridge (U.S.) and January 17, 1995 Hyogo-Ken Nanbu (Kobe, Japan) earthquakes changed this belief [2].

The poor performance of welded steel beam-column connections led to numerous investigations, including the SAC Project (SAC, 1996). The SAC Joint Venture was formed by Structural Engineers Association of California (SEAOC), the Applied Technology Council (ATC), and the Consortium of Universities for Research in Earthquake Engineering (CUREE). The main purpose of this undertaking was the need for understanding the reasons for the occurrence of brittle fractures in welded connections during 1994 Northridge earthquake. Furthermore, the SAC project provided new guidelines for design to avoid such brittle behavior in future earthquakes.

Although no lives were lost in the Northridge earthquake as a result of poor performance of steel frame buildings, the subsequent inspection and repair of the damaged steel buildings were very costly. The most common methods used for the repair of steel buildings are upgrades of the individual connections and addition of steel braces, or addition of energy dissipation systems [2].

In the wake of this event, earthquake-resistant design guidelines for steel frames in high-seismic regions changed significantly. In this dissertation, practices which were prevalent before 1994 will be referred to as pre-Northridge designs, and those after 1994 will be referred to as post-Northridge design [2].

The current state-of-the-art with regard to behavior of different types of braced frames is also described in the following sections.

2.2 Braced Frames

The lateral load resisting system in braced frames is provided by braces which act as axially loaded members in a vertical truss arrangement. “A structural steel building frame, including interconnected vertical and horizontal columns and beams is furnished with bracing against wind and seismic forces” [3]. In traditional braced frames, the braces are the structural fuses. They yield in tension and absorb energy. However, the braces buckle in compression leads to a sudden loss of stiffness and progressive degrading behavior which limits the amount of energy dissipation.

“Braced frames were originally designed to resist wind loading” [4]. Virtually none of the lateral load is carried by the beam-column connections in a braced frame; rather, the system relies on the axial forces developed in its bracing members. Bracing systems advanced in the 1960s and 1970s in terms of seismic applications and have long been regarded as an economical alternative to moment frames due to the reduced material requirements and ease of fabrication and erection resulting in lower labor costs. These systems also provide an efficient restriction of lateral frame drift which was realized following the 1971 San Fernando earthquake [4].

Connections in Braced frames are generally designed to be simple connections. With respect to geometry, braced frames are divided into two categories: Concentric Braced Frames (CBFs) and Eccentric Braced-Frames (EBFs). According to their behavior, these two falls into the category of buckling- permitted braced frames.

In the following sections, the literature on concentrically braced frames (CBFs) in steel structures is reviewed, describing the Knee, zipper and X or cross wind bracing and their behavior; therefore, EBF practice will not be discussed in this dissertation.

2.3 Concentrically Braced Frames

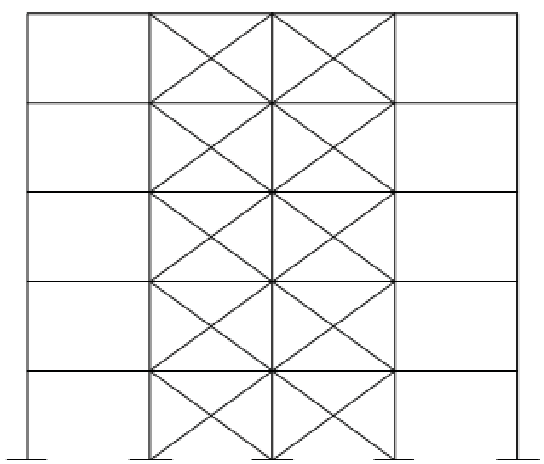
For many years, the Concentrically Braced Frames (CBFs) have been used in steel construction. Steel CBFs are strong, stiff and ductile, and are therefore ideal for lateral load resisting framing systems. In order to have the best performance from a CBF, the brace must fail before any other component of the frame does [5].

CBFs are systems where braces are placed as diagonals or placed to form an X (or cross bracing) or as V or inverted-V (or chevron bracing) so that their points of action coincide. CBFs can undergo complete truss action which gives them high initial stiffness. However, beyond the linear-elastic range they behave as brittle because once buckling of the compression braces occur and is followed by yielding of the tension braces at the same storey level, as a result the structure cannot resist the lateral forces [6].

2.3.1 Cross Bracing

In construction, Cross Bracing is a system in which diagonal supports intersect. The cross bracing is usually seen with two diagonal supports placed in an X shaped manner. X bracing is the simplest and possibly the most common type of bracing which have been used for many years [7].

The diagonal braces can also be placed as such that they cover more than one storey of a building (Fig 2.1)



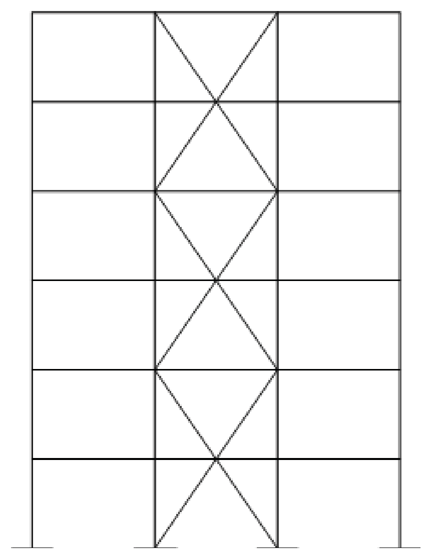
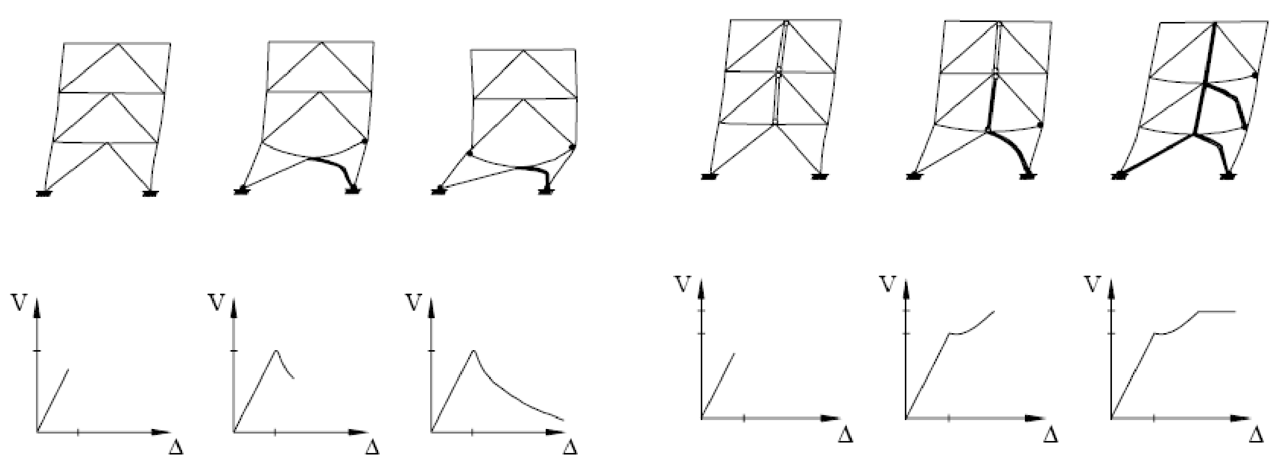


Figure 2.1: Typical configurations of CBFs with X bracing.

2.3.2 Zipper Bracing

"Diagonal and chevron systems can provide large lateral strength and rigidity but do not provide great ductility as buckling of the diagonals leads to rapid loss of strength without much force redistribution” [8]. The loss of strength in chevron system is due to the unbalanced vertical forces that arise at the connections to the floor beams due to the unequal axial capacity of the braces in tension and compression. In order to prevent undesirable deterioration of lateral strength of the frame, very strong beams, much stronger than would have been required for ordinary loads are needed to resist this potentially significant post-buckling force redistribution, in combination with appropriate gravity loads [7].

Thus conventional concentrically braced steel frames cannot re-distribute large unbalanced vertical forces caused by brace buckling through the system. In order to limit the inter-storey drifts using efficient stiffness and strength, new braced steel frame configurations are developed. The zipper frame is designed to distribute the unbalanced vertical forces along its height using the zipper column, a vertical structural element which has been connected to the gusset plates at mid-span of beams starting from the first to the top storey of the frame (Fig 2.2) [9].



(a) Conventional braced frame (b) Zipper frame

Figure 2.2: Comparison of the collapse mechanism and load-displacement relationships for zipper and conventional braced frames [7].

However, the inelastic behavior of the entire frame strongly depends on the brace hysteresis and the interaction of the zipper columns. Due to the nature of the geometry, the braces provide most of the lateral stiffness until they buckle. Once the braces buckle, a large reduction in the brace stiffness will cause drastic force re-distributions in the frame [9].

The zipper frame configuration was first proposed by Khatib in 1988 (cited in [9]), the frame has the same geometry as the conventional Chevron braced frame (Fig 2.3a), except a vertical structural element, the zipper column, is added at the beam mid-span points from the second to the top storey of the frame (Fig 2.3b).

In the event of lateral loading, the compression brace in the ground will buckle. The unbalanced vertical force will then be transmitted through zipper column to the mid-span of the second floor beam. The zipper column will mobilize the stiffness of all the beams and the remaining braces to resist this unbalanced vertical load. Nearly simultaneous brace buckling over the height of a building will result in a more uniform distribution of damage, instability and collapse. The reduced lateral load capacity and softening during force deformation response of the zipper frame, lead to the modification of the conventional zipper frame by increasing the brace size of the top-storey braces. This configuration is named as suspended zipper frame as shown in fallowing page, Figure 2.3c [9].

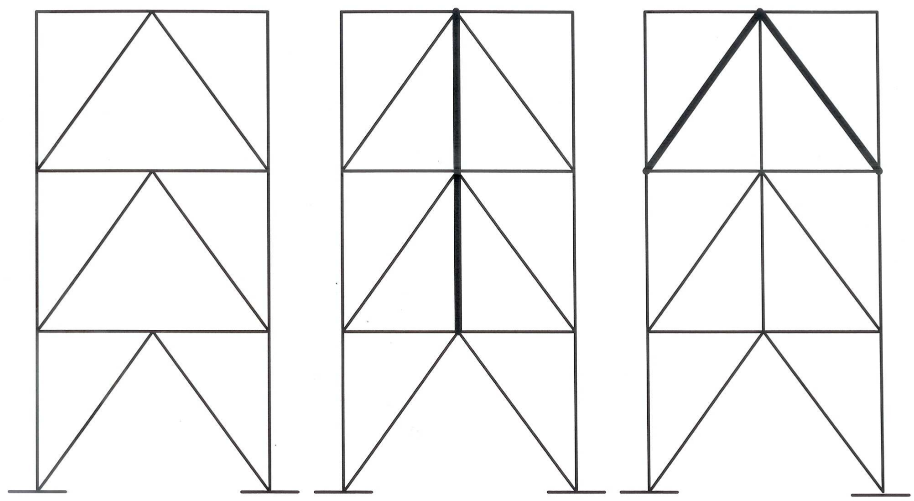


Figure 2.3: Configuration of inverted V braced frame systems [9].

2.3.3 Knee Bracing

A new structural system for lateral load resistant steel structures is called the knee brace frame (KBF), which is a new kind of energy dissipating frame that combines excellent ductility and lateral stiffness. Diagonal braces which provide the lateral stiffness have been connected to the ductile knee members. The knee element will yield first during a severe lateral loading so that no damage occurs to the major structural members and the rehabilitation is easy and economical (Fig 2.4) [10].

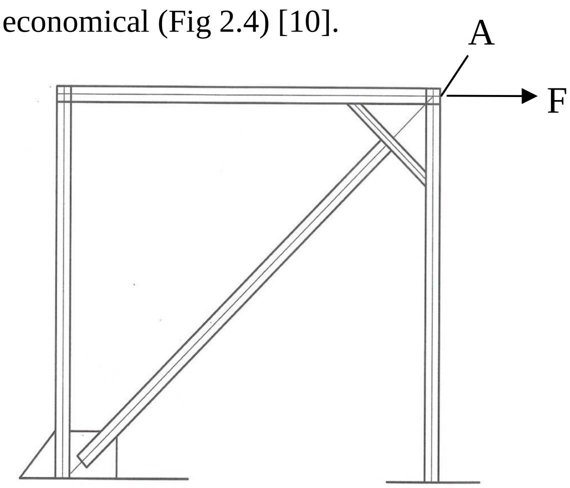


Figure 2.4: Configuration of Knee braced frame systems.

The CBF is much stiffer than the Moment Resisting Frame (MRF), but it cannot meet the ductility requirement due to the buckling of the brace. KBF have enough ductility and also achieves excellent lateral stiffness (Fig 2.5).

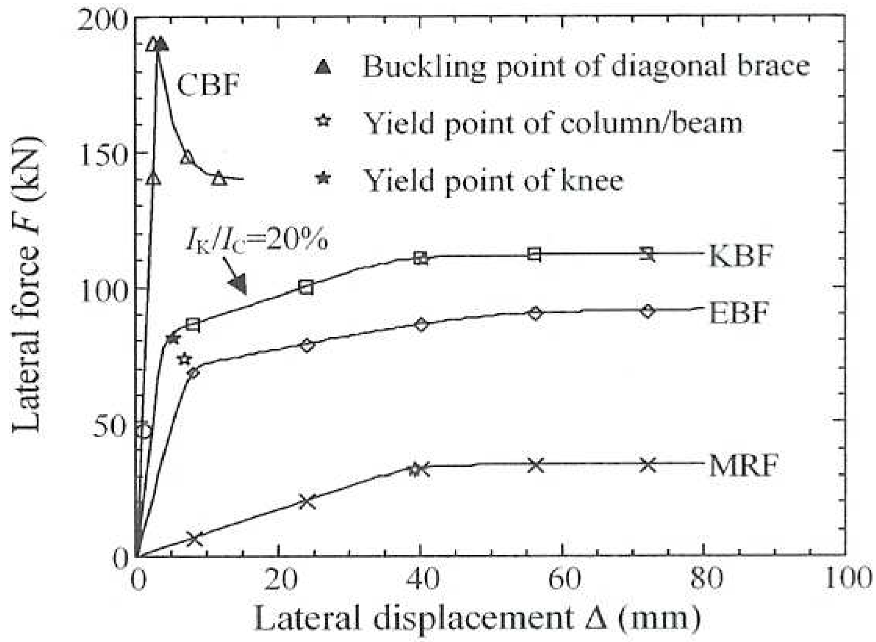


Figure 2.5: Performance comparisons of frames [10].

Under the action of the lateral force at point A (Fig. 2.4), the knee member will yield. Plastic hinges in the connections of knee to column and knee to beam, and the midpoint of the knee will develop simultaneously and the structure turns into the energy dissipating stage of the knee, which means that the brace system has reached its ultimate bearing capacity, and the succeeding load should be carried by the main frame until further plastic hinges occur in the columns or the beam, after which a secondary energy dissipating stage occurs. Obviously, by making full use of the first stage of energy dissipation, the major structural members can survive a severe lateral loading without receiving any permanent damage as shown in fallowing page, Figure 2.6 [10].

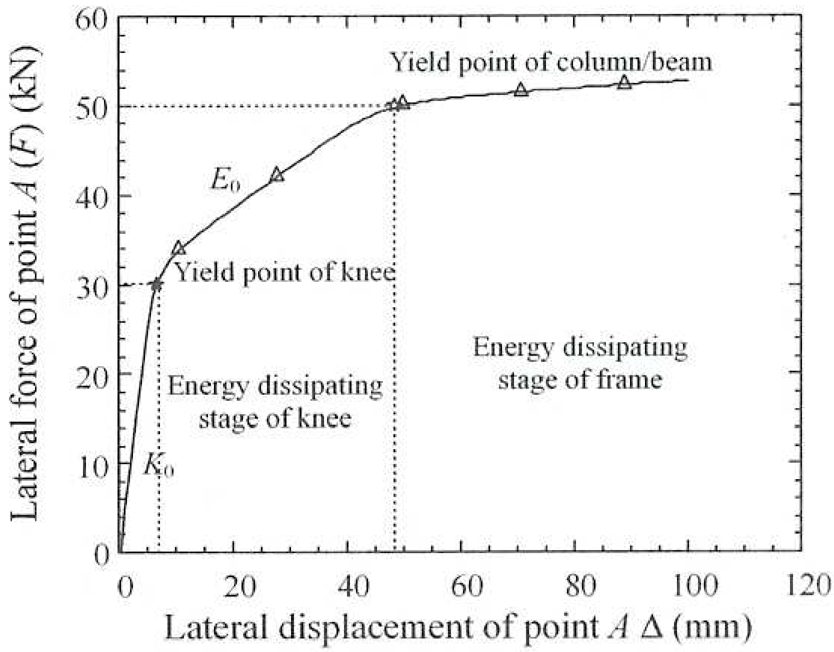


Figure 2.6: Lateral force-displacement curve of KBF [10].

The structure could have maximum lateral load resistance if the knee bracing and inclined brace were parallel to the diagonal of the frame, that means:

$$x = \frac{B_2}{B} = \frac{H_2}{H} \qquad \text{(Eqn 2.1)}$$

Which x is between 0.15 and 0.5 (Fig 2.7) [10].

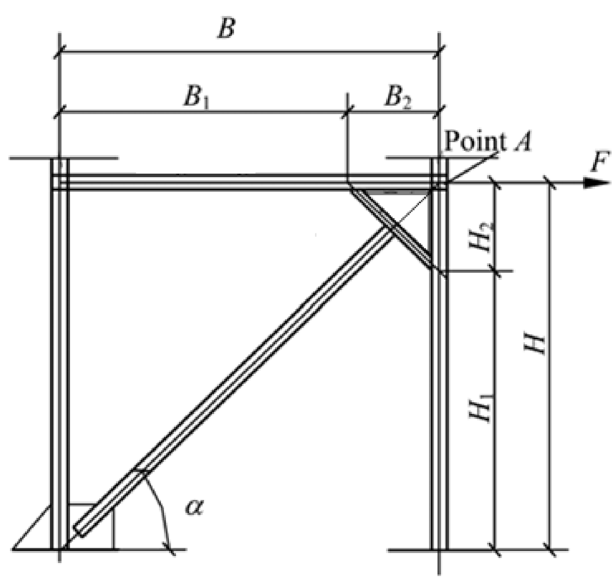


Figure 2.7: Configuration of Knee braced frame systems [10].

Figure 2.8 shows the force displacement curves of frames with different *x* values. By decreasing the *x* value greatly increases the ultimate structural bearing capacity and ductility. The ultimate load reduces as *x* increases, at the same time, the ductility tend to decrease. With further increasing of *x*, the lateral stiffness of the structure in the elastic stage appears somewhat small and the safety of the major structural members is difficult to control. Therefore, it is better to choose *x* of 0.15 to 0.30 [10].

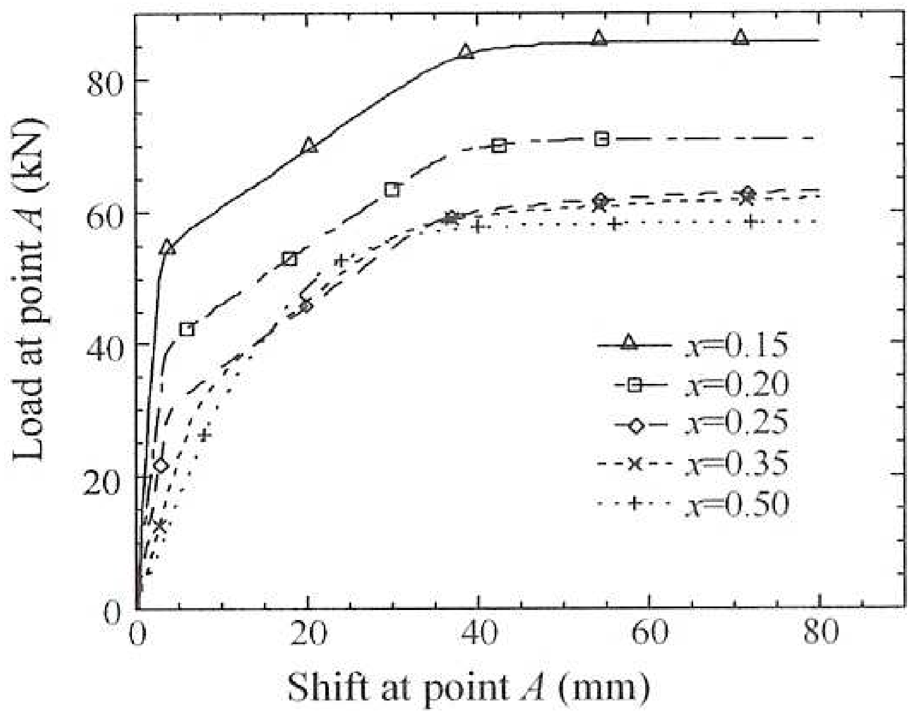


Figure 2.8: Force-displacement curves of frames with different x values [10].

In order to have lateral stiffness, large cross sections are usually chosen for brace members. This is not only costly but also it is difficult to construct and there is waste of material. But, the KBF can be built by using small cross section knee elements. From Figure 2.9 increasing the cross section of the inclined brace members cannot improve the lateral stiffness of the structure. So for economy and convenience of construction, the cross sectional area of brace members of KBF should be small rather than large in order to satisfy the requirement of stability [10].

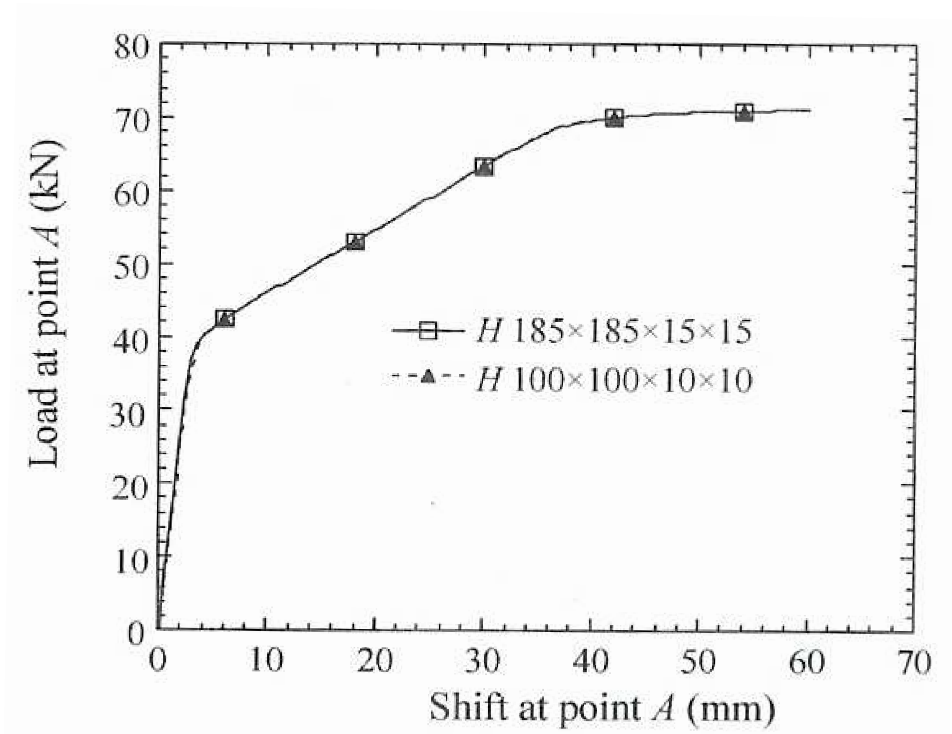
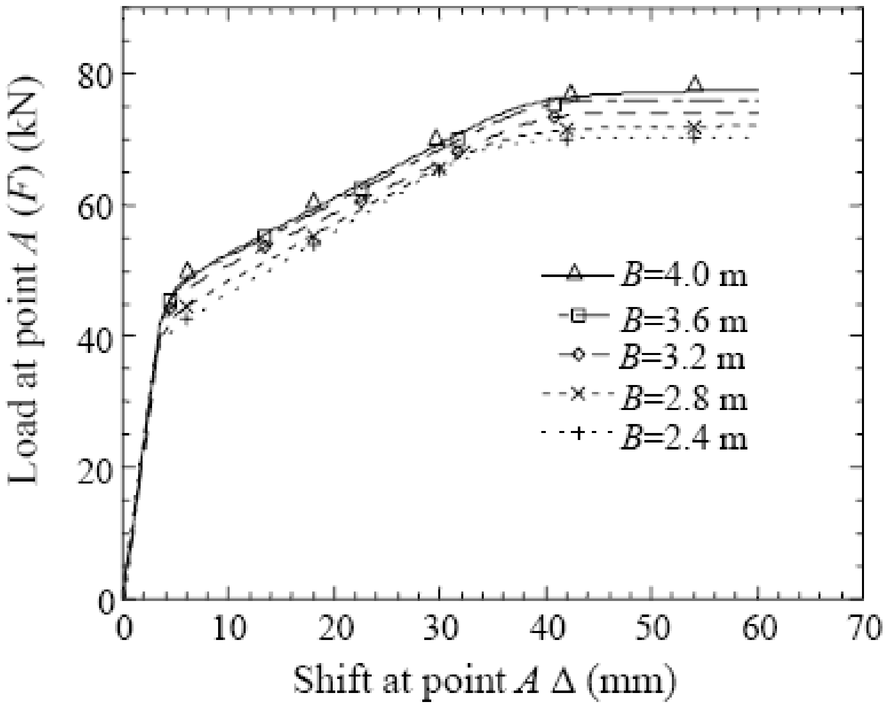
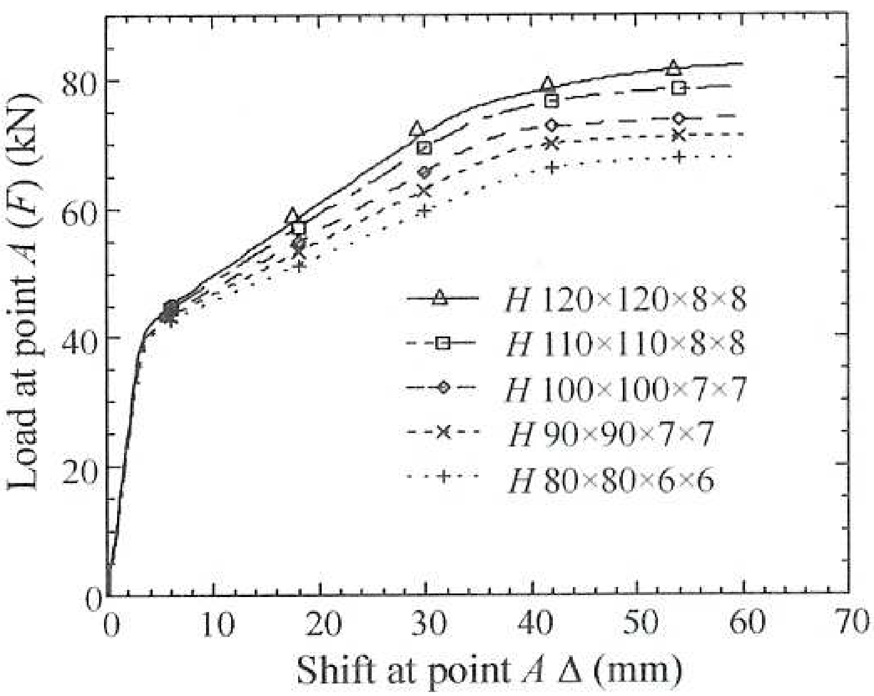


Figure 2.9: Force-displacement curves of frames with different brace sections [10].

In a building, since the length of beams and columns cannot be changed easily, the lateral behavior of the frame can be improved through adjusting the knee elements and the cross sectional dimensions of beam and columns. As the main frame element, changing the cross section area of column is much more effective than changing the beam (Fig 2.10 and Fig 2.11) [10].

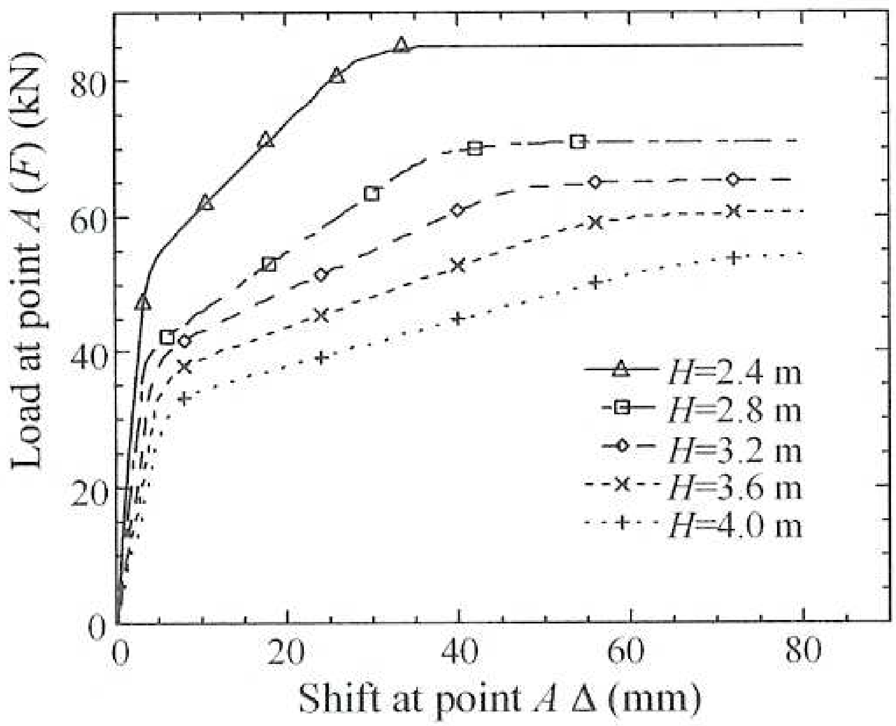


(a)



(b)

Figure 2.10: Lateral performances of frames with different beams. (a) Force-displacement curves of frames with different beam lengths and (b) with different beam sections [10].



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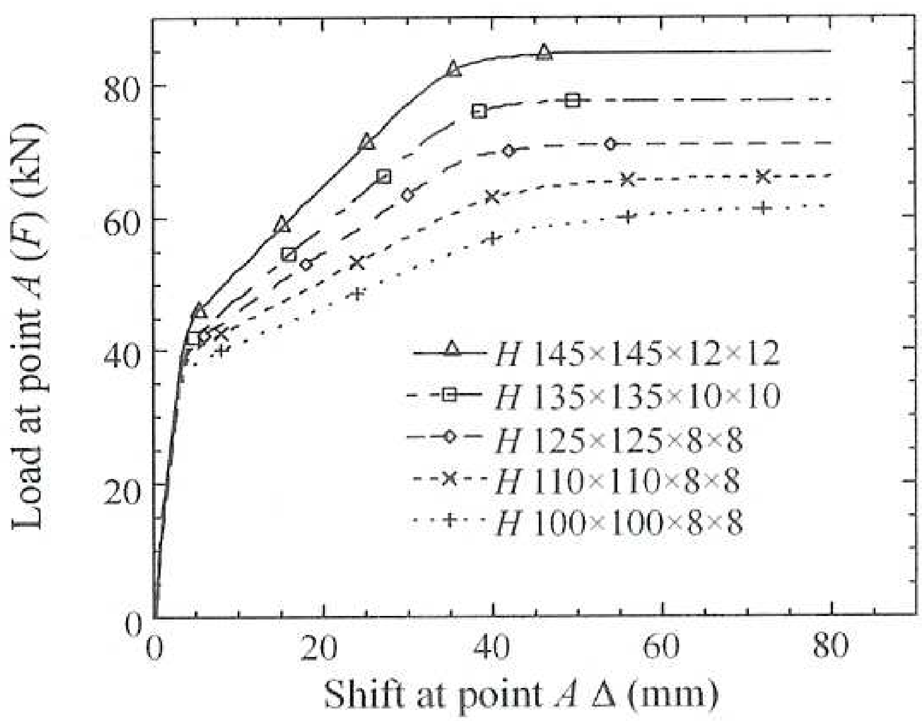


(b)

Figure 2.11: Lateral performances of frames with (a) different column length and (b) different column sections [10].

CHAPTER 3

METHODOLOGY

3.1 Introduction

Forces from gravity, wind and seismic events are imposed on all structures. Forces that act vertically are gravity loads. Forces that act horizontally, such as wind and seismic, require lateral load resisting systems to be built into structures. As lateral loads are applied to a structure, horizontal diaphragms (floors and roofs) transfer the load to the lateral load resisting system (Fig 3.1) [7].

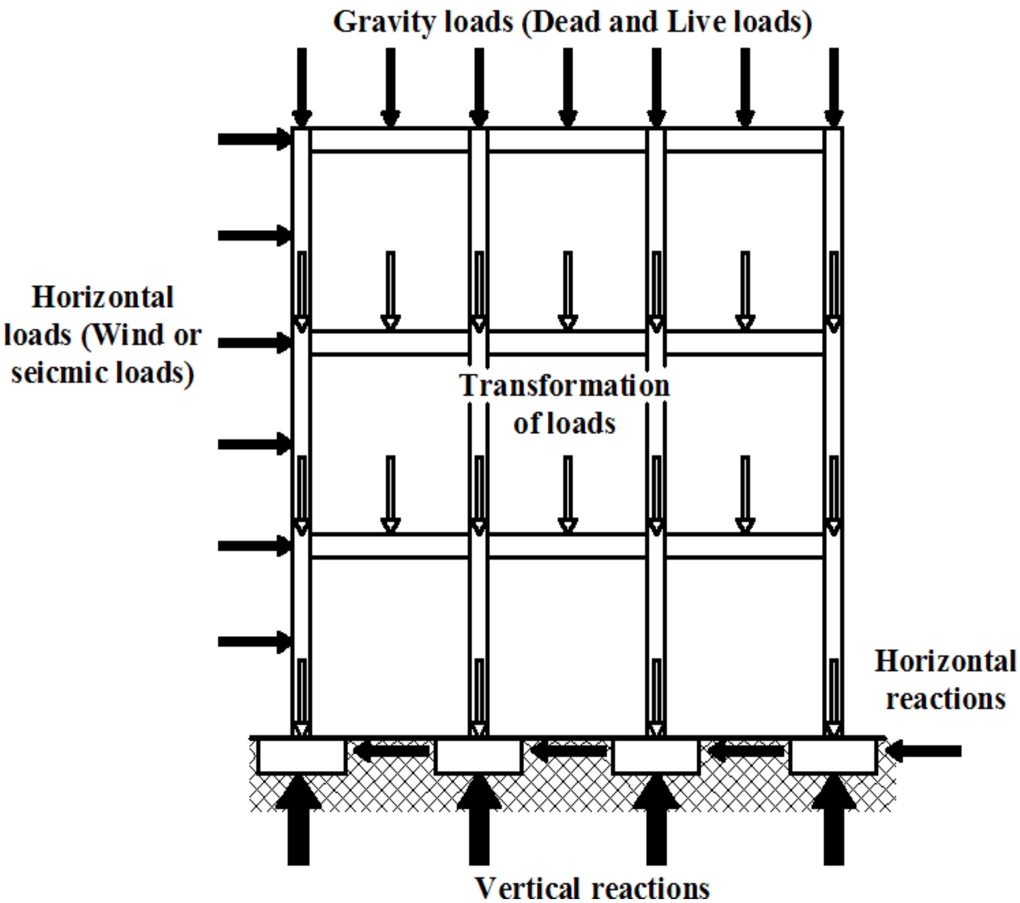


Figure 3.1: Transformation of loads on a structure.

Design of steel structural systems of multi-storey buildings with lateral forces is one of the most complex and time consuming tasks for structural engineering. To fulfill this, the lateral load resisting system in frames, are provided by braces which act as axial load members in a vertical truss arrangement. Steel-braced frames are recognized as a very efficient and economical system for resisting lateral forces. Braced frame systems are efficient because framing members resist primarily axial loads with little or no bending in the members until the compression braces in the system buckle.

One of the most difficult and important parts of the design process is the determination of an appropriate configuration of a structural system for a given building. In the structural analysis conducted by ETABS software version 9.2.0, dead, live, and wind loads (BS5950-2000) [11], as well as their combination, are considered.

Using outputs from the ETABS software produces a complete and detailed structural design. In this research ETABS software provides values of 576 designs, including the total weight, weight of braces, weight of beams, weight of columns and maximum lateral displacement of whole structure for five, ten, fifteen, and twenty stories steel structure.

The values of the total weight of structural systems have been used to compares their designs. First, the total weight of a structural system is one of the measures of its efficiency. Secondly it is a good estimator of the cost of a structural system. Finally, the most appropriate bracing type and its optimal location can be obtained.

3.2 Types of Braces and Steel Brace Profiles

The structural elements are designed using several groups of sections for three different kinds of braces, including cross bracing, zipper bracing and knee bracing (Fig 3.2). Four types of steel brace profiles were used:

1. Universal Angle section [Equal Angle (EA) and Unequal Angle (UA)],
2. Rectangular Hollow section (RHHF),
3. Circular Hollow section (CHHF),
4. I Section [Universal Column (UC)]

Typical bracing members include Angles, Channels, Rectangular and Circular Hollow Sections. Hollow sections are a common selection for lateral bracing members because of their efficiency in carrying compressive loads, greater strength and ductility requirements, their improved aesthetic appearance and because of the wide range of section sizes that are readily available. EA and UA have the unsymmetrical shape and they may cause simultaneous biaxial bending about both principal axes and as result failure. UC is heavier than other steel sections used as bracing members, but commonly used because of its low cost and can reduce lateral displacement caused by lateral loading.

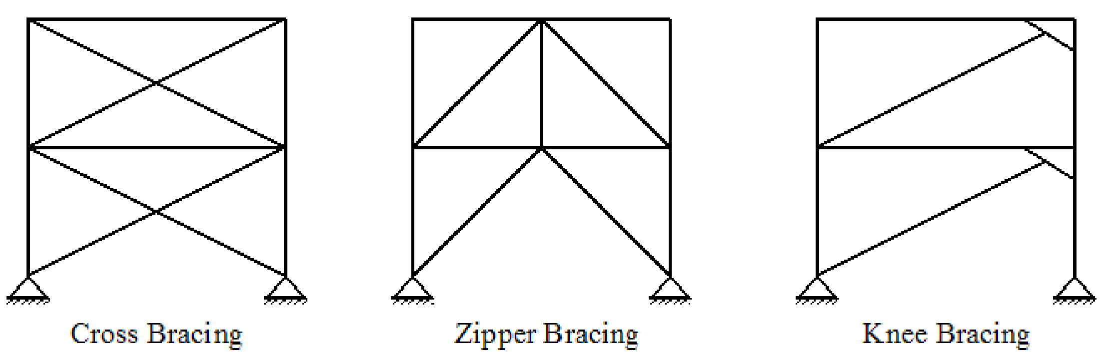


Figure 3.2: Three types of braces.

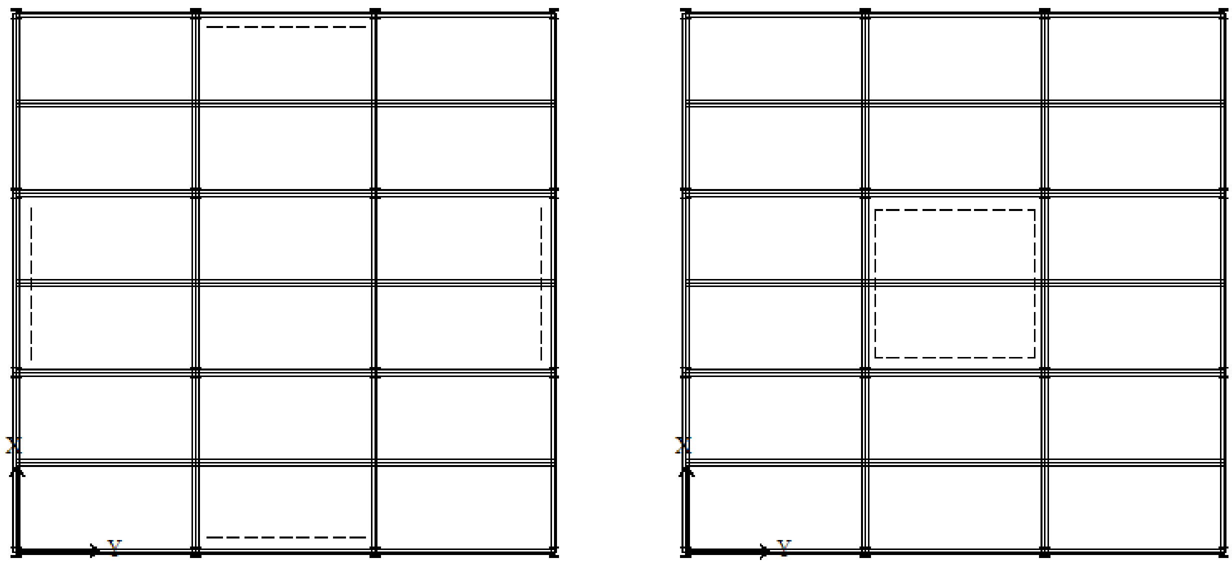
One type of steel section for beam [Universal Beam (UB)] and column [Universal Column (UC)] for all structural system were used from British steel sections (BSS).

Braced Frames (Fig 3.2) are usually designed with simple beam-to-column connections where only shear transfer takes place but may occasionally be combined with moment resisting frames [12]. In braced frames, the beam and column system takes the gravity load such as dead and live loads. Lateral loads such as wind and earthquake loads are taken by a system of braces. Usually bracings are effective only in tension and buckle easily in compression. Therefore in the analysis, only the tension brace is considered to be effective. Braced frames are quite stiff and have been used in very tall buildings.

3.3 Location of the Braces

In this research, to compare different types of braces in different locations of a structure with different number of stories, the braces are placed in central bay and in the core of the structure with secondary beams in Y (or X) direction. There are various ways in which the vertical wind bracings can be located in a building. Location depends partly on the size of building, plan and section arrangements and lateral loads. While locating bracings one needs to make sure that it will also prevent any possible torsion on the building due to asymmetry. So it was decided to locate the bracings at the core and central bay of the perimeter of the building. Both of these locations are fairly common in practice. However, there is no claim that these are the best locations for bracings in general. Due to limited time for this research these locations were considered appropriate.

While all the design in this research consists of three bays, the braces which are located at the two sides of the frame will cover the walls and therefore not leaving space for windows or openings. Thus the possible locations of braces are in core and central bay as shown in the following page in Figure 3.3.

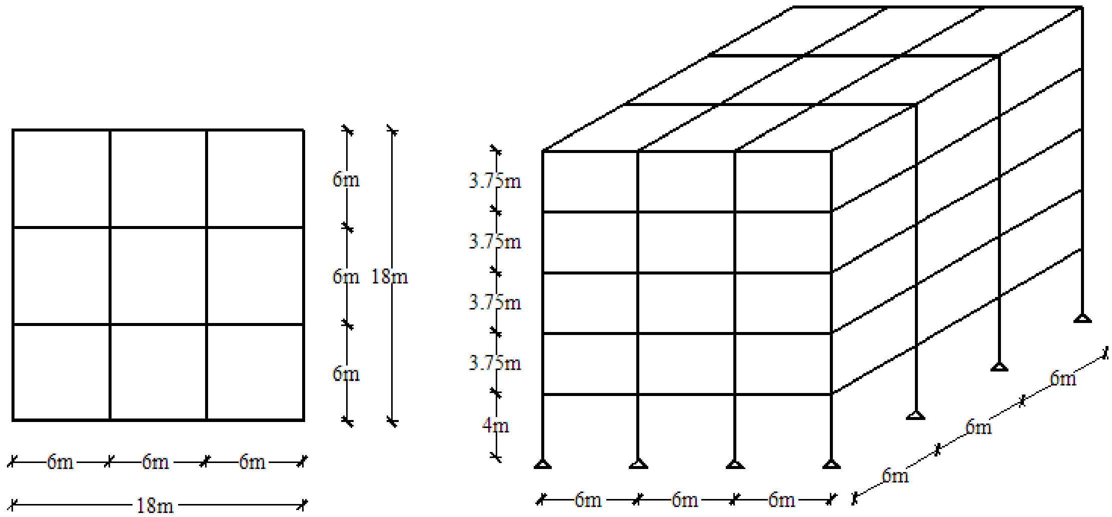


(a) (b)

Figure 3.3: Dotted lines on plans are the location of the braces at (a) central bays, (b) core.

3.4 Modeling

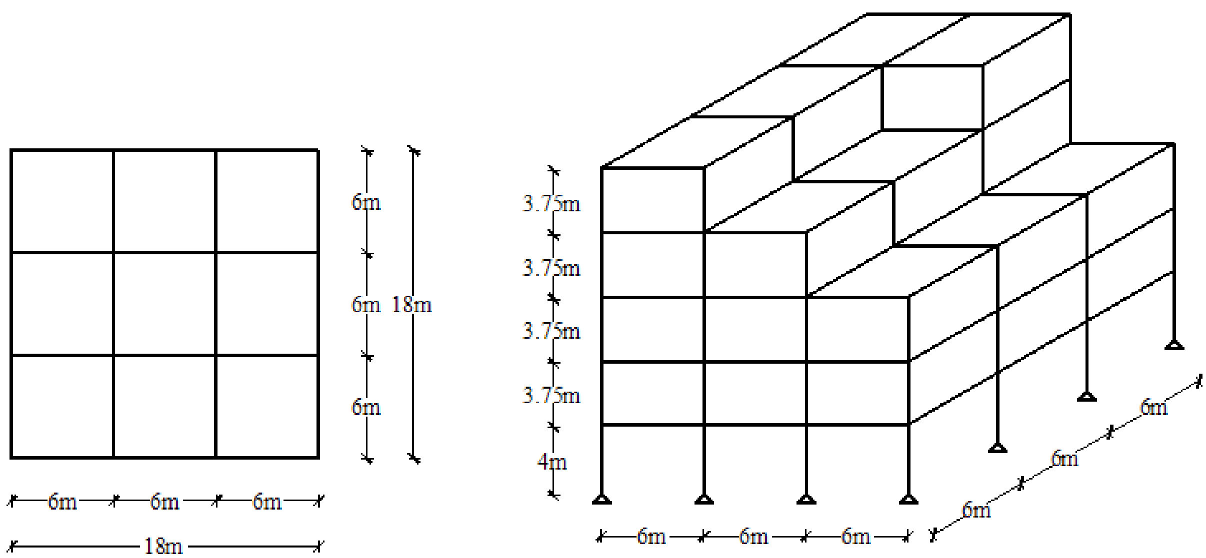
This chapter is considered as a four stage process. The first stage is to identify the configuration of a symmetrical plan and symmetrical section of steel structural system (Fig 3.4).



(a) (b)

Figure 3.4: First type of frame model (a) Symmetrical plan, (b) Symmetrical elevation.

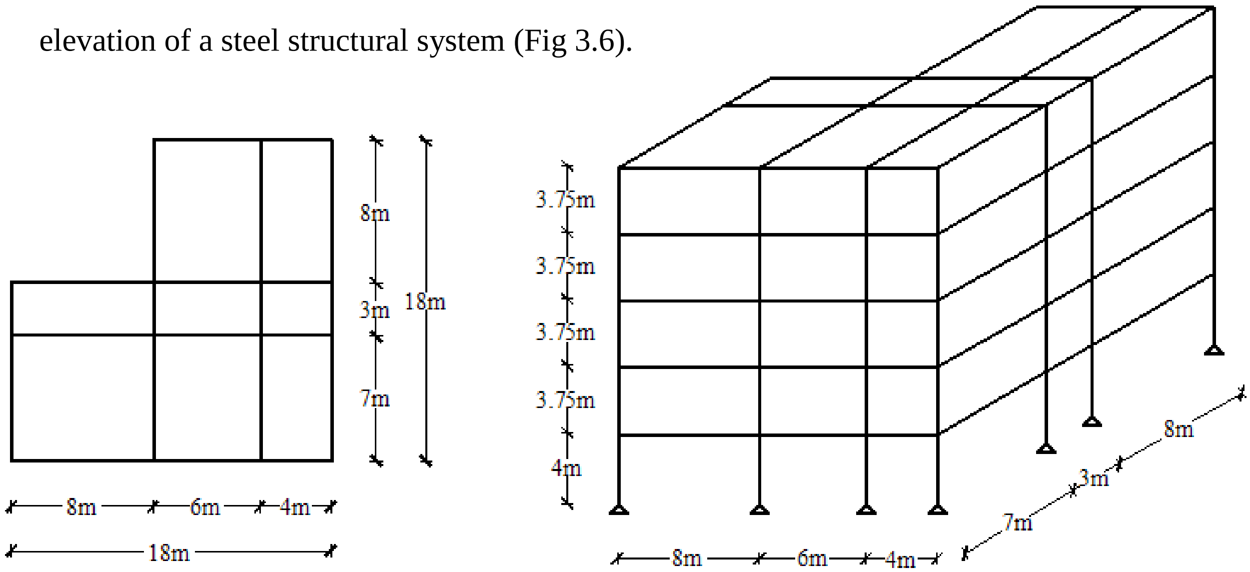
The second stage is to identify the configuration of a symmetrical plan and asymmetrical elevation of a steel structural system (Fig 3.5).



(a) (b)

Figure 3.5: Second type of frame model (a) Symmetrical plan, (b) Asymmetrical elevation.

The third stage is to identify the configuration of an asymmetrical plan and symmetrical elevation of a steel structural system (Fig 3.6).



(a) (b)

Figure 3.6: Third type of frame model (a) Asymmetrical plan, (b) Symmetrical elevation.

The fourth stage is to identify the configuration of an asymmetrical plan and asymmetrical elevation of a steel structural system (Fig 3.7).

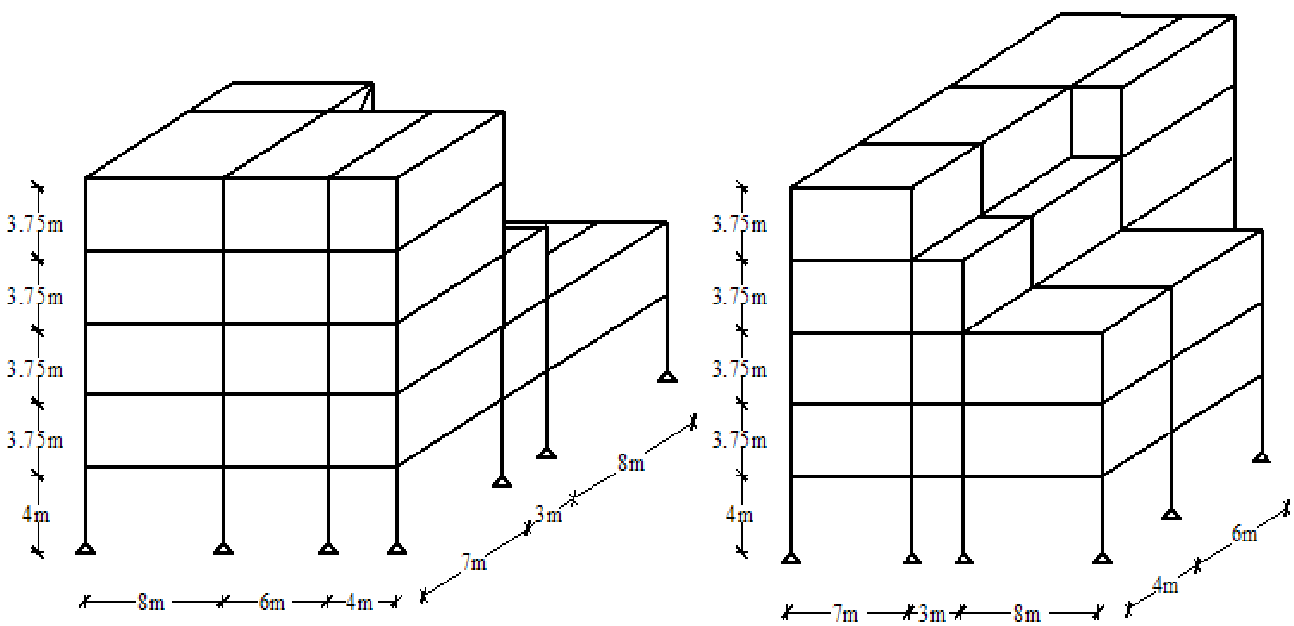


Figure 3.7(a): Fourth type of frame model with two different view of an Asymmetrical elevation

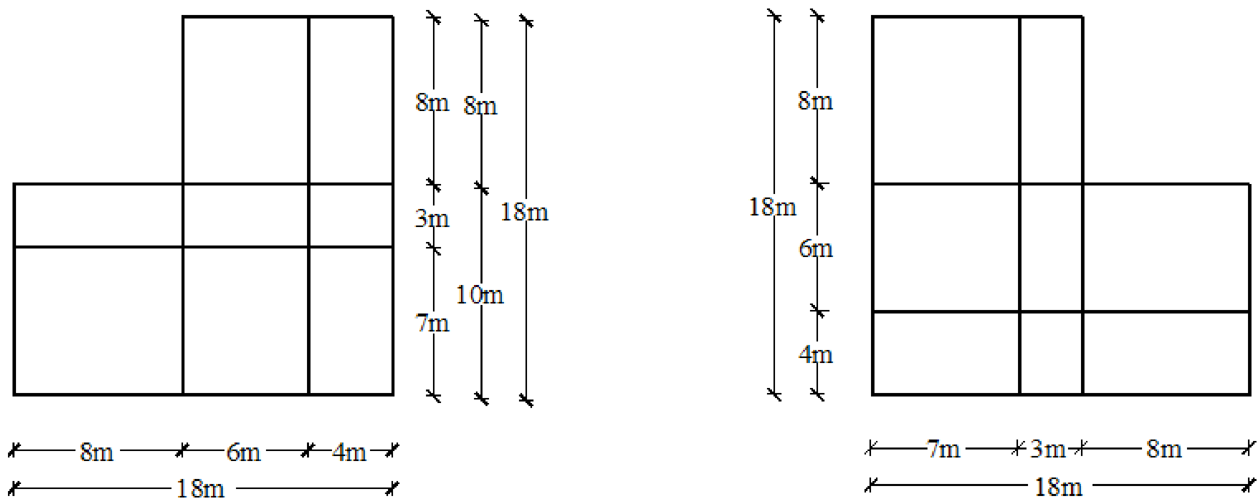


Figure 3.7(b): Fourth type of frame model with two different view of an Asymmetrical plan with two different views.

In these four cases, it has been assumed that buildings have three bays and they have similar total length and width of 18 meters and all have same ground floor height of 4 meters and normal floor height of 3.75 meters.

For each structure categories that have been discussed, some storey level has been assumed. Wind tunnel testing is advisable on buildings higher than 22 stories (10 stories in hurricane areas) or where the building or structure is an unusual shape or construction methodology. Thus highest storey level in this research is 20 stories. To find out the wind effect on structures, these structures has been divided into categories of 5, 10, 15 and 20 stories.

3.5 Wind Loading

The site wind speed V_s on a structure depends on the basic wind speed, V_b, the shape and stiffness of the structure, the roughness and profile of the surrounding ground and the influence of an adjacent structure [13].

$$V_s = V_b \, S_a \, S_d \, S_s \, S_p \qquad \text{(Eqn 3.1)}$$

- The basic wind speed V_b, which has been selected in this research as 30 m/s.
- The altitude factor S_a takes account of general level of the site above sea level. Where in this research the average slopes of the ground is not exceed 0.05 within a kilometer radius of the site, the factor S_a should be taken as 1.0.
- The direction factor S_d may be used to adjust the basic wind speed to produce wind speeds with the same risk of being exceeded in any wind direction. The values are given in Appendix E for all wind directions. If the orientation of the building is unknown or ignored, the value of the direction factor should be taken as 1.0 for all.
- The seasonal factor S_s may be used to reduce the basic wind speed for buildings which are exposed to the wind for specific sub annual periods, in particular for temporary works and building construction. Normally factor S_s should be calculated as 1.0 when wind loads on completed structures and buildings with the following exceptions which has been considered in this research:

1. Temporary structures.
2. Structures where a shorter period of exposure to the wind may be expected.
3. Structures where a longer period of exposure to the wind may be required.

4. Structure where greater than normal safety is required.

- The probability factor S_p has a value of 1.0 or less. Structural designers should only use a probability factor of less than 1.0 if they wish to amend the standard design risk. Using a probability factor of 1.0 represents a once in 50 year risk.

The effective wind speed is calculated from:

$$V_e = V_s \times S_b \quad \text{(Eqn 3.2)}$$

The effective wind speed is converted to dynamic pressure q_s using the relationship:

$$q_s = k\,V_s^2 \quad \text{(Eqn 3.3)}$$

Where k is 0.613 in SI unit (N/m^2 and m/s) and S_b is terrain and building factor [13].

A typical distribution of wind pressure on a multi-storey building is shown in Figure 3.8 in the following page.

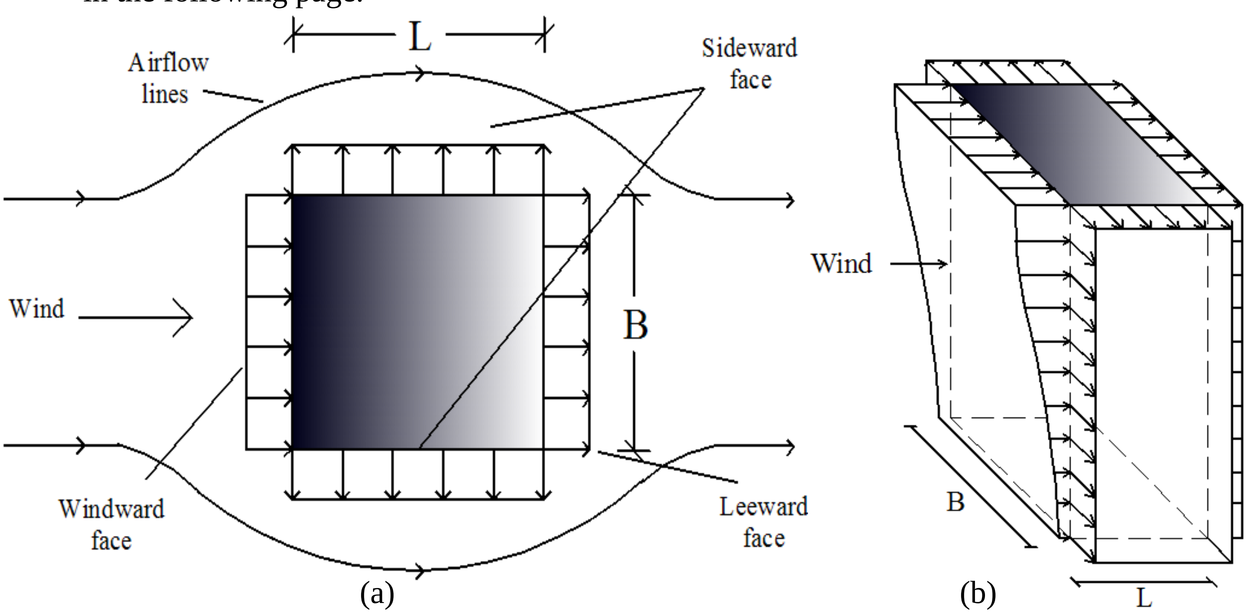


Figure 3.8: Typical wind load distribution on a multi-storey building in (a) plan view and (b) elevation view.

The wind pressure increases with height on the windward side of a building where wind pressure acts inward on the wall. On the other three sides the magnitude of negative wind pressure (acting outward) is constant with height (Figure 3.8).

The pressure coefficients for windward, leeward and sideward faces are given in for a building with B/H≤1, are given in BS6399 [14] where B is the inward depth of the building and H is the height of the building in Figure 3.9 at following page (Appendix E).

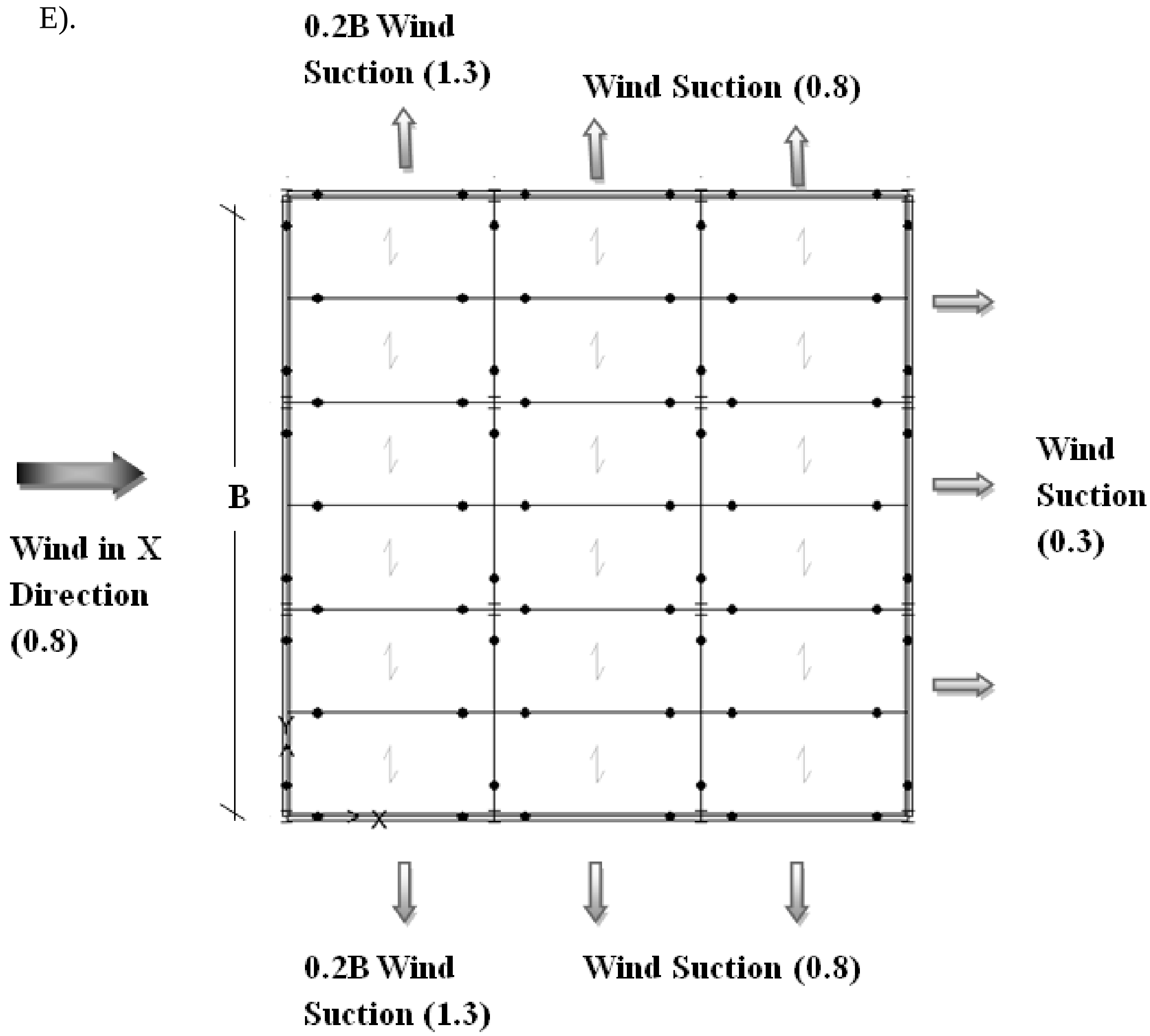


Figure 3.9(a): Pressure coefficients for windward, leeward and sideward of a structure for wind blowing from X direction [14].

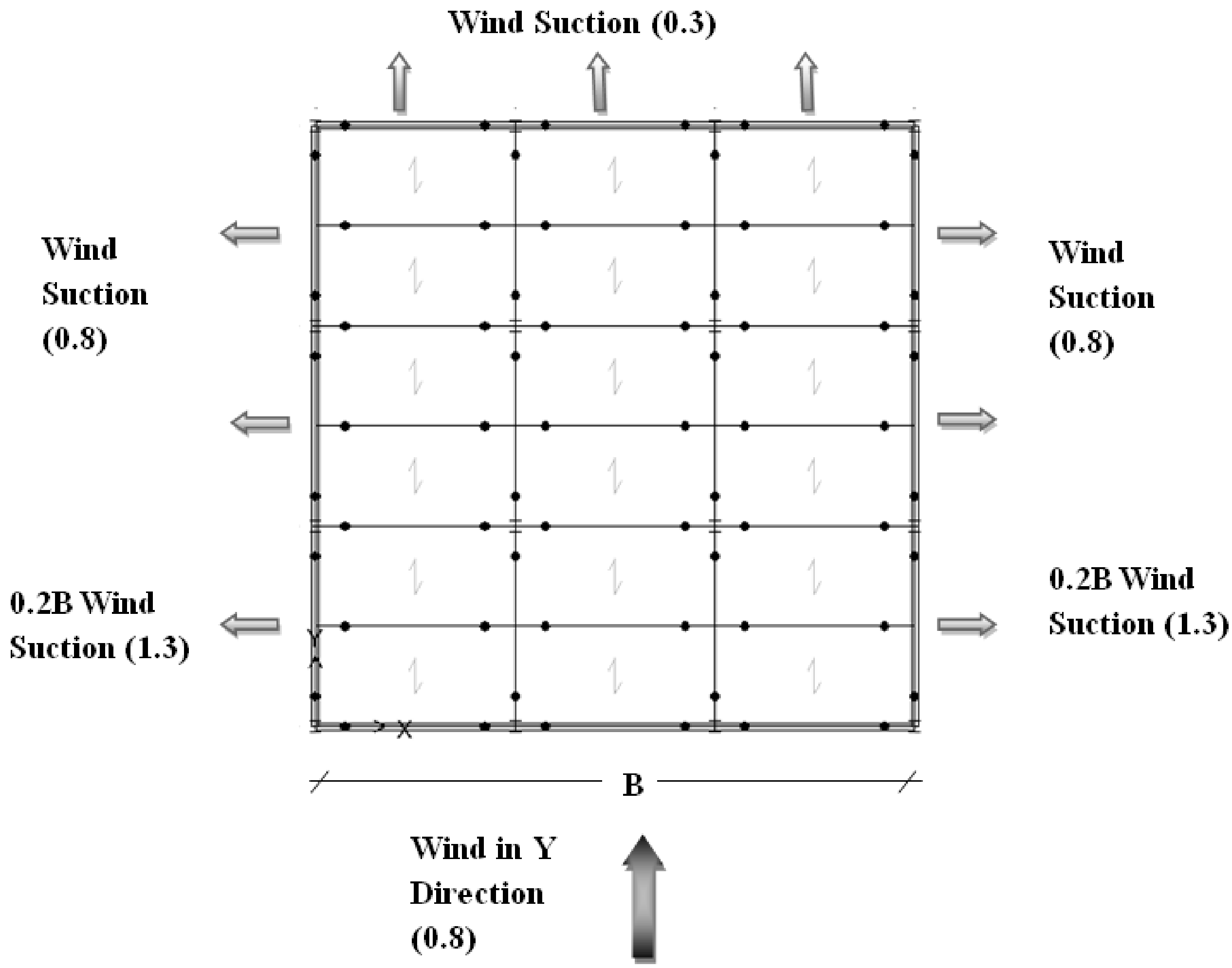


Figure 3.9(b): Pressure coefficients for windward, leeward and sideward of a structure for wind blowing from Y direction [14].

3.6 ETABS

ETABS is a sophisticated, yet easy to use, extremely powerful, special purpose program developed expressly for building systems, analysis and design. ETABS analyses and designs building structures through a model that is created by using the graphical user interface.

Designer should define as many named static load cases as needed. Typically, separate load case definitions would be used for dead load, live load, static earthquake load, wind load, snow load, thermal load, and so on. Loads that are needed to vary independently, for design purposes or because of how they are applied to the building, should be defined as separate load cases.

ETABS allows for the automated generation of static lateral loads for either earthquake or wind load cases based on numerous code specifications. If wind as the load type has been selected, various auto lateral load codes are available. Upon selection of a code which is BS 6399-95 (for this study), the wind loading form is populated with default values and settings, which may be reviewed and edited by the user [15].

3.7 Loading

The un-factored dead, live and wind loads that are used in the structural design of selected building shapes are given in Table 3.1.

Table 3.1: Load magnitudes used in all cases.

Load parameter	Values
Dead load	5.0 kN/m²
Perimeter wall loading	3.5 kN/m²
Live load	3.5 kN/m²
Wind load	
Wind speed	30 m/s

The dead and live loads will not affect the lateral displacements and they are used for all the designs. When self weight of slab composite with a steel deck is 24 kN/m^3 and assuming slab height being average of 100 mm, then the dead load will be 2.4 kN/m^2, assuming another 2.6 kN/m^2 for the floor finishes then the total dead load can be rounded up to 5.0 kN/m^2 and if the building is assumed to be an office building then for live load 3.5 kN/m^2 is used.

3.8 Load Combinations

The design load combinations are the various combinations of the load cases for which the structure needs to be checked. According to the BS 5950-2000 code, if a structure is subjected to dead load (DL), live load (LL) and wind load (WL) and considering that wind forces are reversible, the following load combinations may need to be considered:

1.4 DL

1.4 DL + 1.6 LL

1.0 DL ± 1.4 WL

1.4 DL ± 1.4 WL

1.2 DL + 1.2 LL ± 1.2 WL

3.9 Deflections and Design

In addition to the design considerations already introduced it is necessary to put some limitations for the maximum deflection of the steel structure. The maximum horizontal deflection is given by [16]:

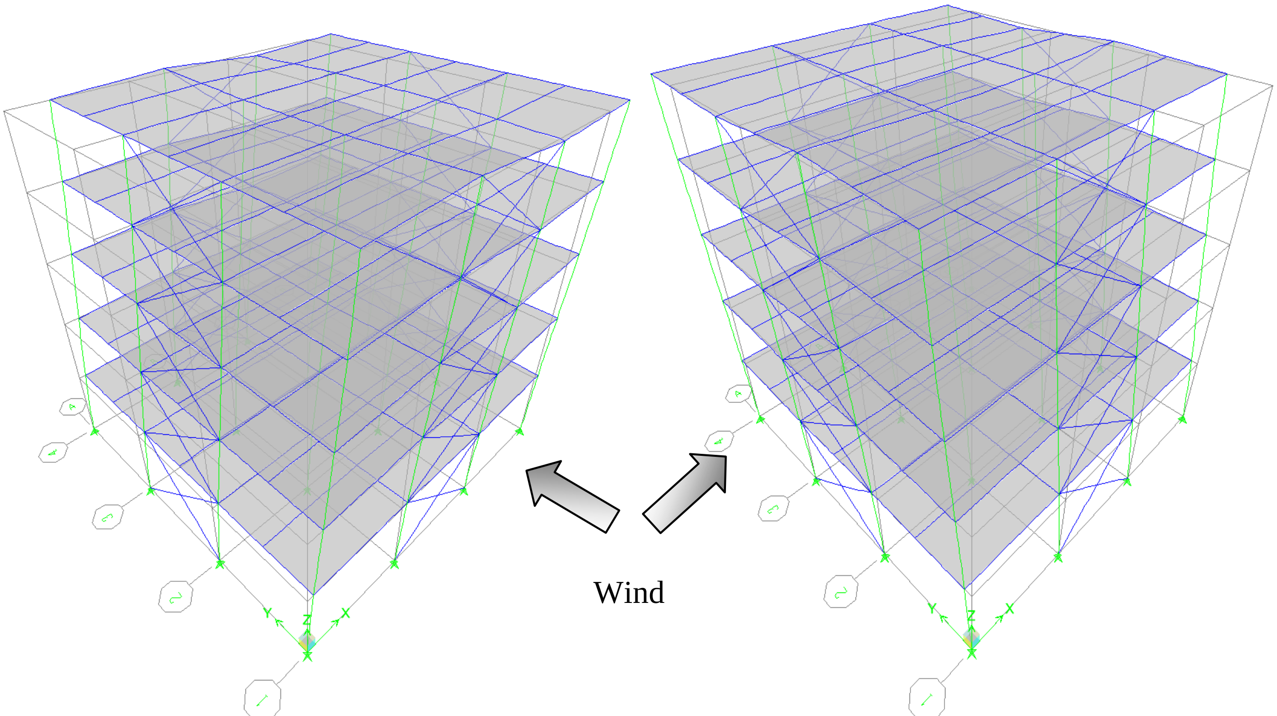
$$MaxD = \frac{H}{300} \qquad \text{(Eqn 3.4)}$$

Where MaxD is maximum horizontal displacement of steel structure and H is the height of the structure in millimeters. Thus the maximum displacements are:

- 63.3 mm for 5^{th} storey
- 125.84 mm for 10^{th} storey
- 188.34 mm for 15^{th} storey
- 250.84 mm for 20^{th} storey

In this study, the structures are designed to have lateral displacement within these limits.

In following page, Figure 3.10 shows ETABS software analysis for the deflection due to wind loads from X and Y directions.



(a) (b)

Figure 3.10: Deflection due to wind loads from (a) X direction and (b) Y direction.

In the following pages Figure 3.11 shows the design results of 3 dimensional five stories, symmetrical plan and section with RHHS cross bracing in the central bay of structure.

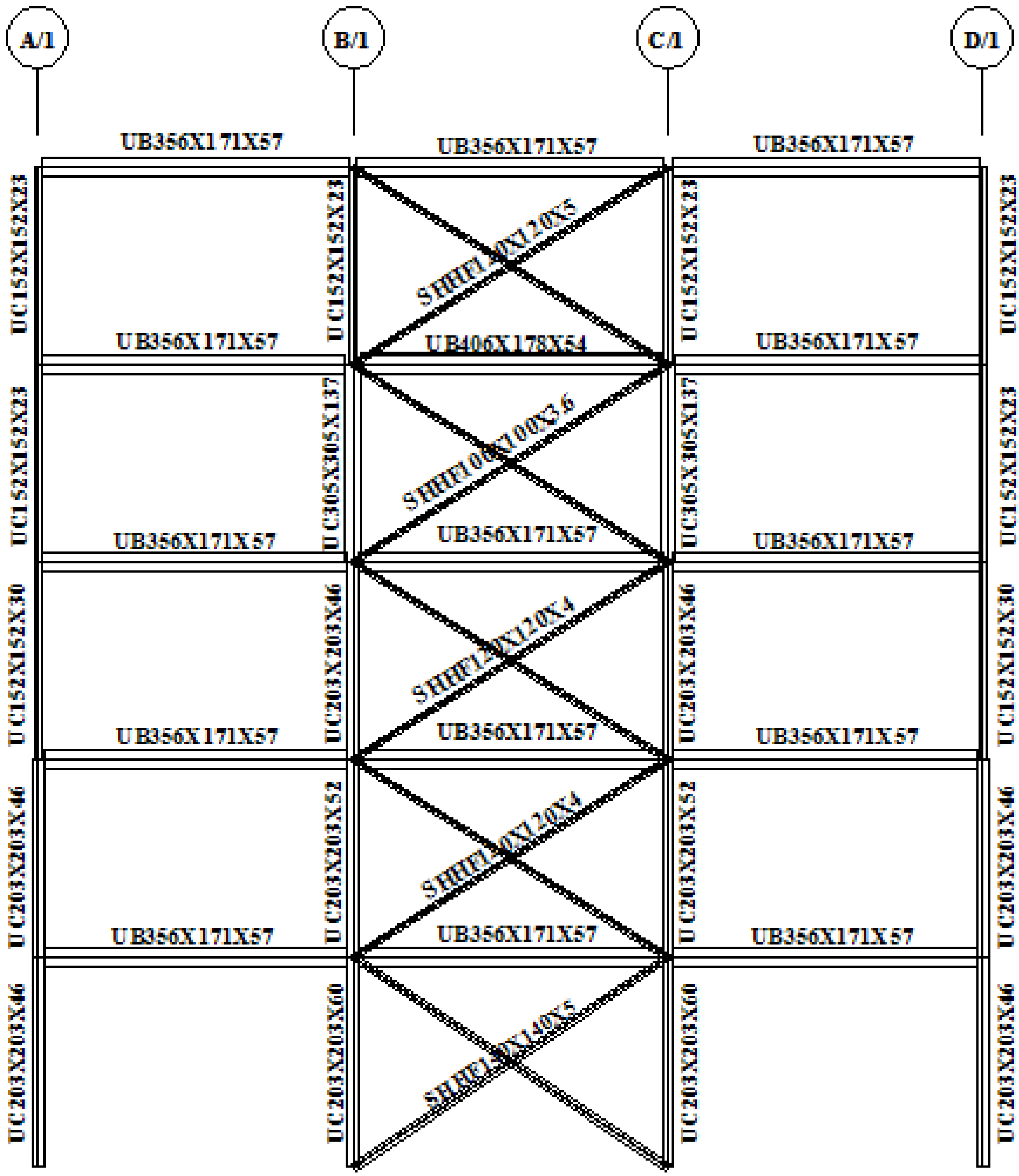


Figure 3.11(a): Design result of symmetrical plan and section with RHS brace steel profile, section 1_1.

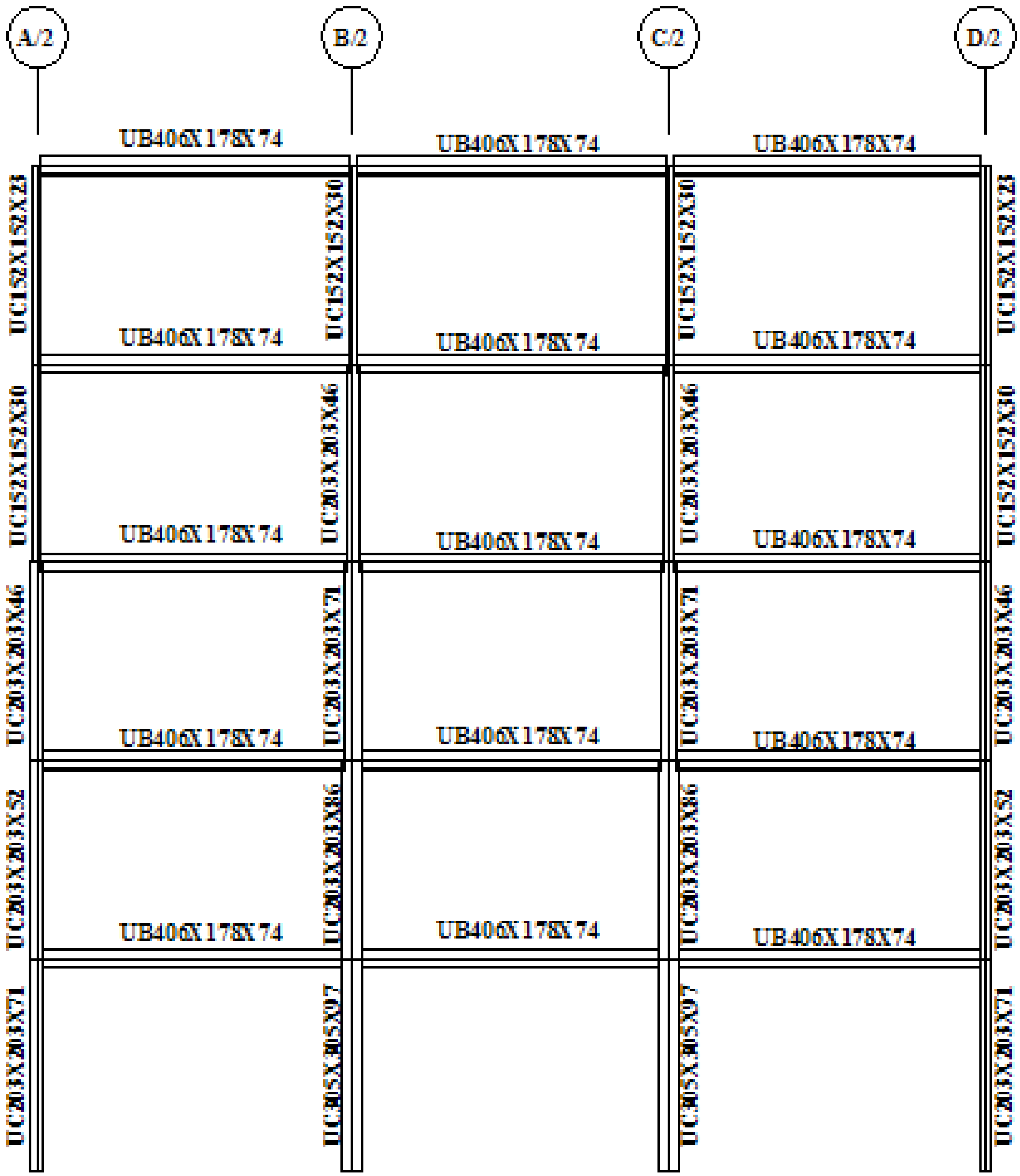


Figure 3.11(b): Design result of symmetrical plan and section with RHS brace steel profile, section 2_2.

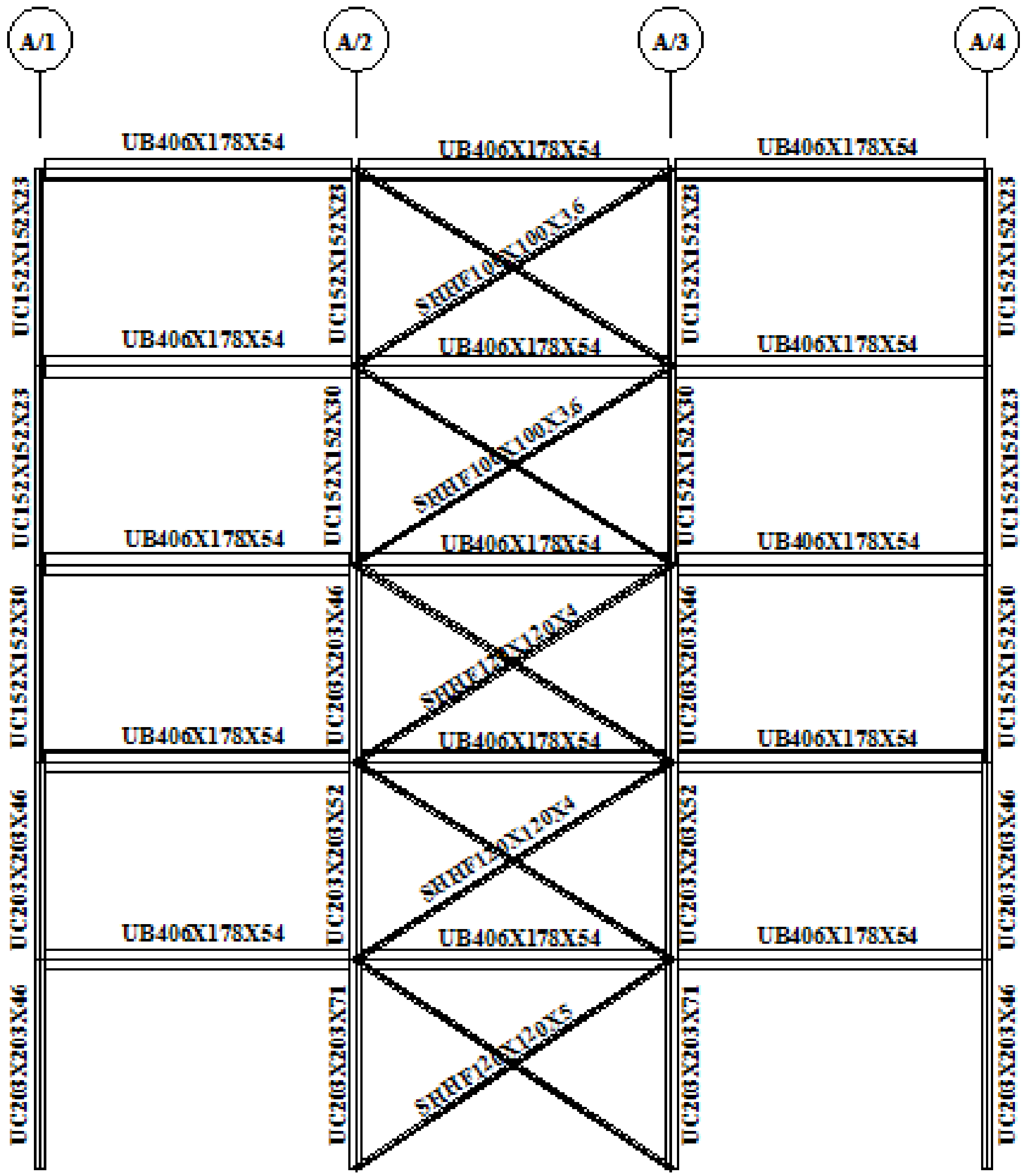


Figure 3.11(c): Design result of symmetrical plan and section with RHS brace steel profile, section A_A.

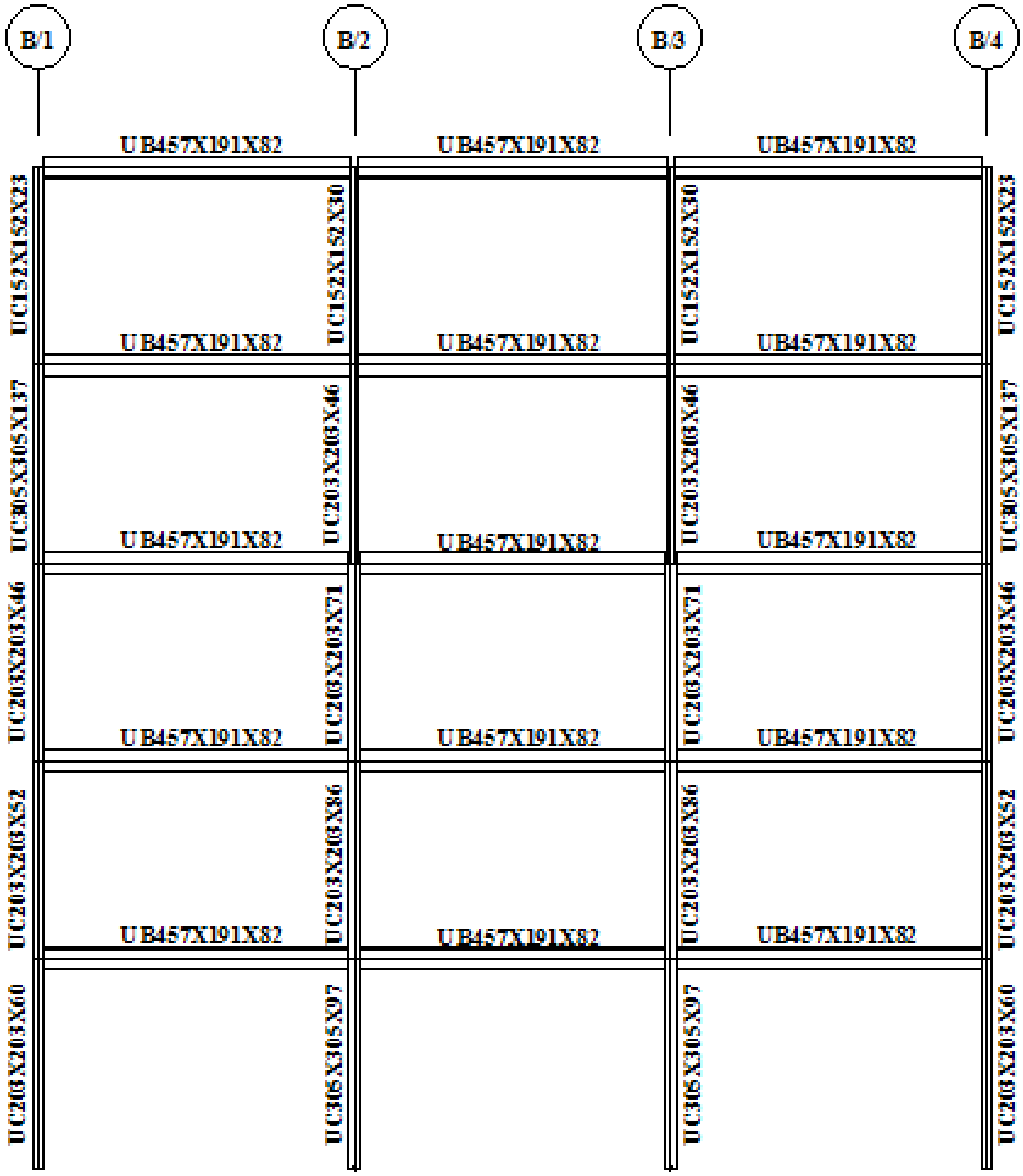


Figure 3.11(d): Design result of symmetrical plan and section with RHS brace steel profile, section B_B.

3.10 Second Order P-Delta Effects

Typically design codes require that second order P-Delta effects be considered when designing steel frames. The P-Delta effects come from two sources. They are the global lateral translation of the frame and the local deformation of elements within the frame. When you consider P-Delta effects in the analysis, the program does a good job of capturing the effect due to the Δ deformation, but it does not typically capture the effect of the δ deformation (unless, in the model, the frame element is broken into multiple pieces over its length) (Fig 3.12) [15].

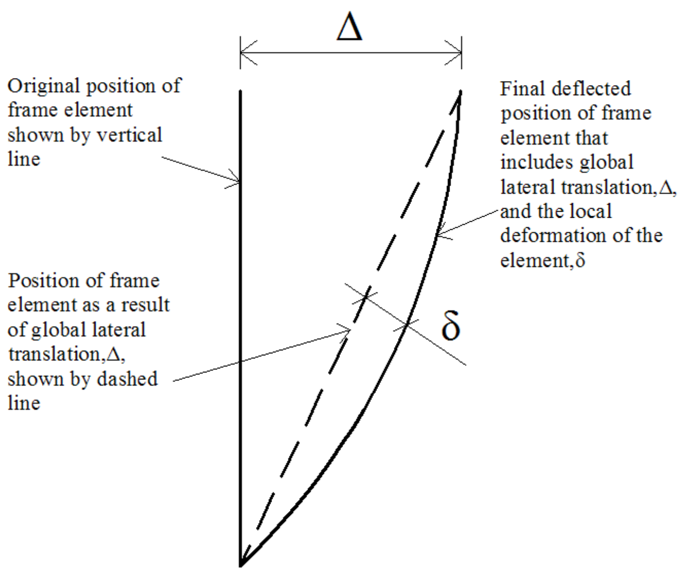


Figure 3.12: The total second order P-Delta Effects on a frame element caused by both Δ and δ.

In ETABS software there are two types of design for secondary P-Delta effect. One of them is iterative based on load combinations which have been time consuming to use for 576 different structures and the other type is non-iterative based on mass which has been used for some of the designs in this study (Table 3.1).

Table 3.2: Lateral displacement in X and Y directions and weight of columns, beams, braces and overall weights of different structures with and without P-Delta effect.

Structural Descriptions	Lateral Displacement (mm)		Weight (ton)			
	X direction	Y direction	Column	Beam	Brace	Total
	Without using P-Delta effect					
5 Stories, central bay AS cross bracing for symmetrical plan and section	3.6	3.5	14.6	68.7	15.1	98.5
5 Stories, central bay RHHS zipper bracing for asymmetrical plan and symmetrical section	6	17.4	19	59.4	1.8	80.3
20 Stories, central bay IS cross bracing for symmetrical plan and section	187.7	200.7	158.6	273.4	93.9	525.9
20 Stories, central bay CHHS zipper bracing for symmetrical plan and asymmetrical section	160.5	188.2	165.4	248.6	21.5	435.5
	Using iterative P-Delta effect					
5 Stories, central bay AS cross bracing for symmetrical plan and section	3.6	3.5	14.6	68.9	15.1	98.6
5 Stories, central bay RHHS zipper bracing for asymmetrical plan and symmetrical section	6	17.5	19	59.6	1.8	80.4
20 Stories, central bay IS cross bracing for symmetrical plan and section	190.3	203.7	158.6	272.5	93.9	525
20 Stories, central bay CHHS zipper bracing for symmetrical plan and asymmetrical section	161.8	189.8	165.7	248.6	21.5	435.8

Table 3.1 shows the 5 and 20 stories cross and zipper bracings at the central bay of structure with different brace steel profile and type of frame models. It can be concluded that the 5 stories with and without P-Delta effect 0.1 to 0.3 percent difference in weight of the structure. But in 20 stories there are 0.4 percent difference in weight and 0.8 percent in lateral displacement. The effect of the consideration of P-Delta non-iterative based on mass is so small that can be ignored. Therefore, P-Delta effect is not considered in the analysis of the frames in this study.

CHAPTER 4

ANALYSIS AND DESIGN

4.1 Introduction

This chapter provides detail on the analysis and design of the four types of structures given in chapter 3, symmetrical plan and section, asymmetrical plan and section, symmetrical plan and asymmetrical section and symmetrical plan and asymmetrical section. The objective is to find out which bracing types, steel profiles and the location of them are more feasible and efficient in order to have minimum weight provided by structural system.

4.2 Symmetrical Plan and Section

The following are the details of the structural system and the design considerations for the multi-storey buildings:

- Number and total length of bays: 3 bays (18 m)
- Structural stories and heights: 5 stories (19 m), 10 stories (37.75 m), 15 stories (56.5 m) and 20 stories (75.25 m)
- Bay width: 6 m
- Types of braces: cross, zipper and knee brace

- Spacing of the secondary beams: 3m
- Location of the braces: center of the bays and at the core of the structure
- Loads: dead, live, wind loads and perimeter wall loadings
- Steel profiles for columns and beams: Universal Column sections (UC), Universal Beam sections (UB) are adopted for columns and beams of the frame respectively
- Wind direction: X and Y directions (Fig 4.1).

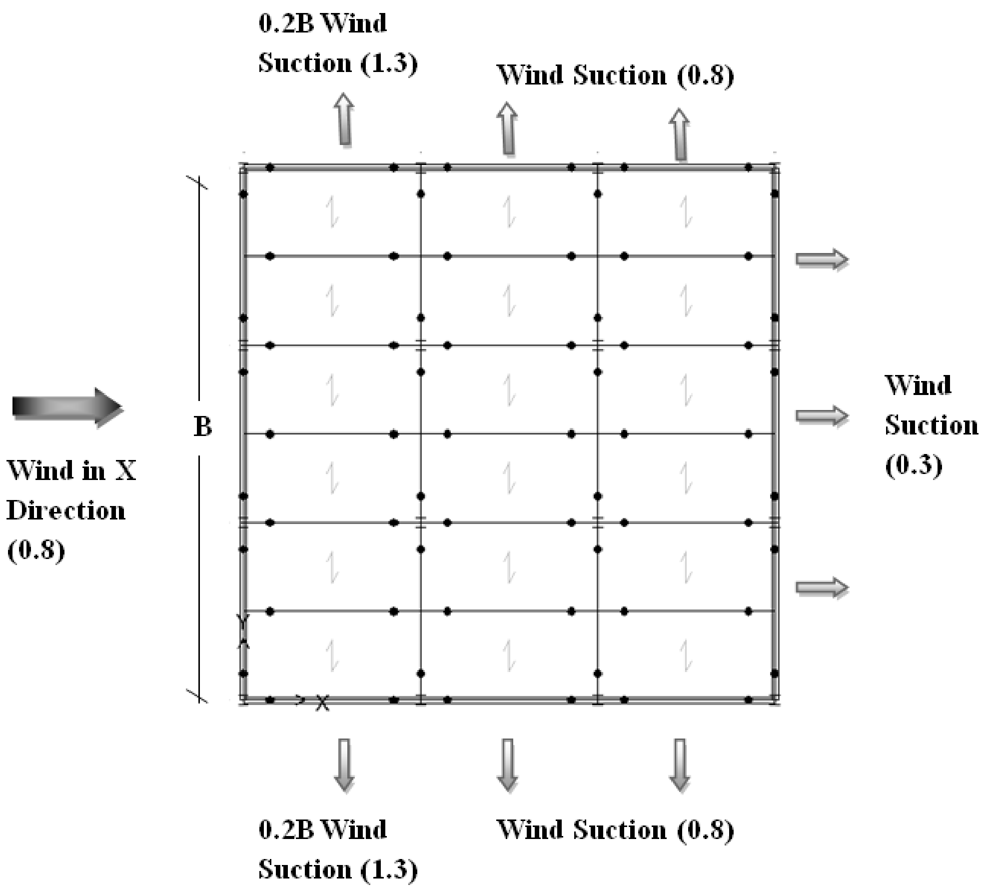


Figure 4.1(a): Building plan layout indicating simple frame with pinned connections with wind in X direction with suctions for symmetrical plan and section [14].

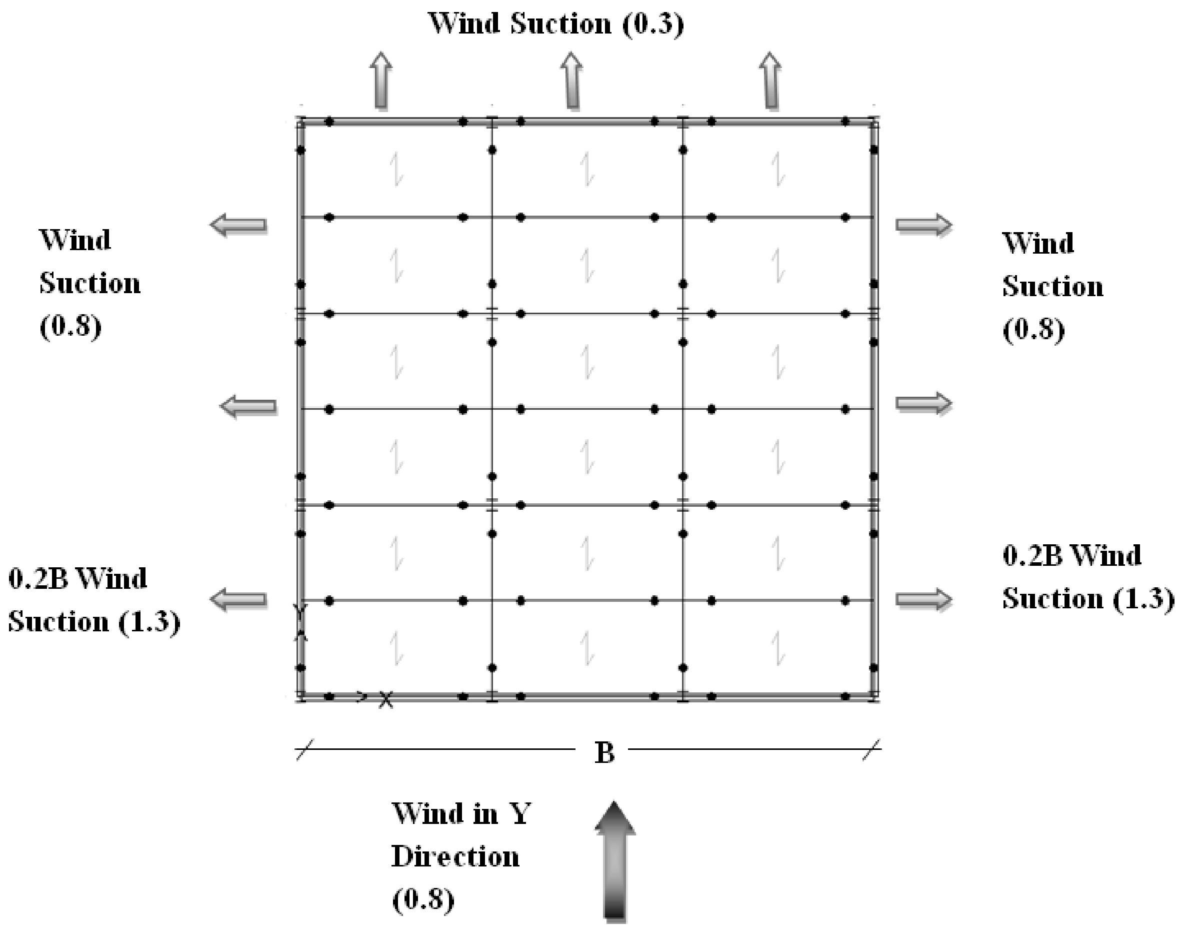


Figure 4.1(b): Building plan layout indicating simple frame with pinned connections with wind in Y direction with suctions for symmetrical plan and section [14].

Only two wind directions are considered, since the building have symmetrical plan and section. According to BS 6399 [14] for each, X and Y direction wind load, there are three other directions of wind suctions (leeward and sideward). The magnitude of dead, live and wind loads used in analysis and design can be found in chapter 3, Table 3.1.

- Four types of steel profiles were used as bracing members: Universal Angle section (UA), Rectangular Hollow Section (RHS), Circular Hollow Section (CHS) and I Section (IS) or Universal Column (UC)

- Connections: simple frame structure where beam to column, beam to beam, brace to beam/column are pinned connections and columns are continuous

Also by referring to chapter 2 (section 2.1.3), the knee braced structure can have a maximum lateral load resistance, if the brace inclination is parallel to the diagonal of the frame, hence:

$$x = \frac{B_2}{B} = \frac{H_2}{H} \qquad \text{(Eqn 2.1)}$$

Where, in this study all values of x are 0.2m for knee braced structures.

Symmetrical structural systems are considered to be in this category. The analysis and design of braces which are located in the central bays and core of the structure are given in the following sections.

- Number of columns, beams and cross or knee braces respectively: 80, 165, 40 (five stories), 160, 330, 80 (ten stories), 240, 495, 120 (fifteen stories) and 320, 660, 160 (twenty stories)
- Number of zipper braces: 56 (five stories), 116 (ten stories), 176 (fifteen stories) and 236 (twenty stories).

All the details of the columns, beams, braces and overall structural weights and lateral displacements in both X and Y directions for each structure are given in Appendix A.

4.2.1 Perimeter Central Bay Bracing

Four different steel profile sections were used for the bracing system to analyze and design the symmetrical plan and section buildings with five, ten, fifteen and twenty stories (Fig 4.2).

4.2.1.1 Central Bay Cross Bracing

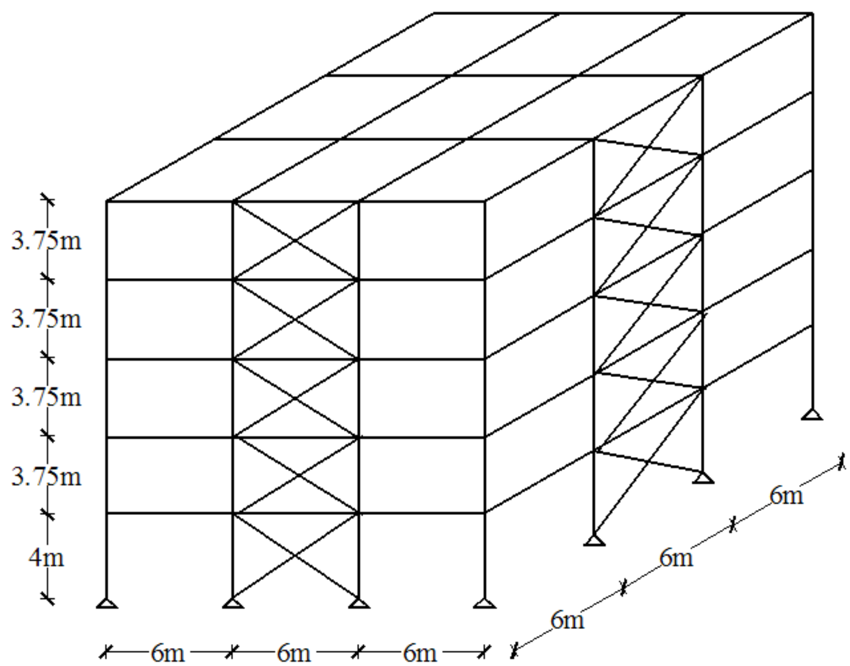


Figure 4.2: Symmetrical Plan and Section with central bays cross bracings.

Table 4.1 shows the weight of columns, beams, braces and whole structure (tone) of such buildings and also the percentage increase between maximum and minimum weight of 5, 10, 15 and 20 storey levels and structural elements for different bracing sections.

Table 4.1: Weights of columns, beams, braces and total by having different steel brace sections for cross bracing in the central bay of structure for symmetrical plan and section.

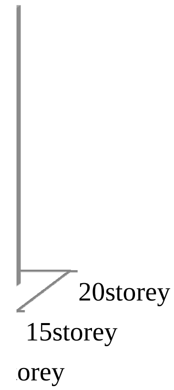
	Brace Sections/No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	14.6	Failed	Failed	Failed
	Rectangular Hollow section	15.8	45.7	93.3	162.3
	Circular Hollow section	13.9	45.0	92.6	160.6
	I section	13.6	44.3	92.7	158.6
Difference between max and min (%)		**16.2**	**3.2**	**0.7**	**2.3**
Beams Weight (ton)	Angle section	68.7	Failed	Failed	Failed
	Rectangular Hollow section	68.4	136.1	203.1	269.2
	Circular Hollow section	69.3	137.6	204.7	271.6
	I section	69.0	137.6	205.4	273.4
Difference between max and min (%)		**1.3**	**1.1**	**1.1**	**1.6**
Braces Weight (ton)	Angle section	15.1	Failed	Failed	Failed
	Rectangular Hollow section	4.2	9.4	15.8	22.7
	Circular Hollow section	4.2	9.2	18.8	33.6
	I section	16.6	48.5	73.2	93.9
Difference between max and min (%)		**295.3**	**427.2**	**363.3**	**313.6**
Total Weight (ton)	Angle section	98.5	Failed	Failed	Failed
	Rectangular Hollow section	88.5	191.3	312.3	454.2
	Circular Hollow section	87.4	191.8	316.1	465.8
	I section	99.1	230.4	371.4	525.9
Difference between max and min (%)		**13.4**	**20.4**	**19.0**	**15.8**

The weights of columns and beams when different bracing sections are used are approximately the same (Table 4.1), while the weight of steel profiles for bracings are changing. The weights of bracings are generally the controlling factor for the overall total weight of structures. The percentage difference in weight between the maximum and minimum overall total weights of five, ten, fifteen and twenty stories are 13.4, 20.4, 19 and 15.8 percent respectively. It is also worth mentioning that there are large differences between maximum and minimum brace weights of all four steel profiles in five to twenty stories. The percentage difference in brace weights are 295.3, 427.2, 363.3 and 313.6 percent. Unfortunately, some of the steel frames with Universal Angle section braces for ten, fifteen and twenty stories have been failed due to lack of capacity and stress. The highest change in weight in both cases is for 10th storey building.

Figure 4.3 represents lateral displacements in X and Y directions for 5th, 10th, 15th and

20storey
5storey
rey

etrical plan and



etrical plan and

According to Table 4.1 and Figure 4.3 the following are the results of the analysis and designs:

- According to Table 4.1, the minimum weight of beams, braces and overall structure for all 16 structural designs is achieved by Rectangular Hollow Sections (RHS) but surprisingly it caused the heaviest column weights in all stories. On the other hand, RHS has the maximum lateral displacement in X direction for fifteen and twenty stories.
- The maximum lateral displacement in Y direction is when Circular Hollow Sections (CHS) is used as bracing member. It also achieved the maximum lateral displacement in X direction for five and ten stories.

- I Sections (IS) provides minimum column weights and maximum beam, brace and total weights but with the minimum lateral displacement in X and Y directions.

4.2.1.2 Central Bay Zipper Bracing

Zipper bracing is used instead of the cross bracing in the central bay of the frame (Fig 4.4).

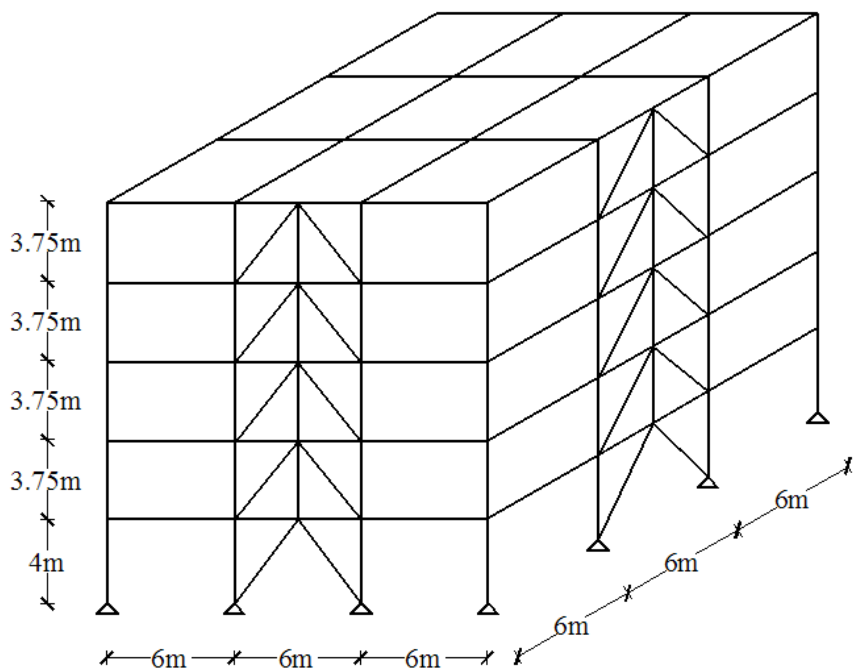


Figure 4.4: Symmetrical Plan and Section in central bay zipper brace.

The structure total weight and the weights of columns, beams and braces are given in table 4.2 and the lateral displacement in X and Y directions are given in Figure 4.5 (a) and 4.5 (b) respectively.

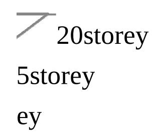
Table 4.2: Weights of columns, beams, braces and total by having different steel brace sections for zipper bracing in the central bay of structure for symmetrical plan and section.

	Brace Sections/No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	15.7	Failed	Failed	Failed
	Rectangular Hollow section	16.5	46.8	96.2	162.0
	Circular Hollow section	14.2	44.8	93.1	158.3
	I section	14.9	47.7	96.3	164.7
Difference between max and min (%)		**10.7**	**6.5**	**3.4**	**4.0**
Beams Weight (ton)	Angle section	65.5	Failed	Failed	Failed
	Rectangular Hollow section	65.7	129.7	193.3	254.5
	Circular Hollow section	64.2	130.0	192.2	253.8
	I section	64.2	130.2	193.6	255
Difference between max and min (%)		**2.3**	**0.4**	**0.7**	**0.4**
Braces Weight (ton)	Angle section	5.3	Failed	Failed	Failed
	Rectangular Hollow section	1.8	4.5	7.9	12.7
	Circular Hollow section	2.3	5.1	10.2	17.5
	I section	5.9	19.4	42.2	56.7
Difference between max and min (%)		**227.8**	**331.2**	**434.2**	**346.5**
Total Weight (ton)	Angle section	86.6	Failed	Failed	Failed
	Rectangular Hollow section	83.9	181.0	297.4	429.1
	Circular Hollow section	80.6	179.9	295.5	429.7
	I section	85.1	197.2	332.1	476.5
Difference between max and min (%)		**7.5**	**9.6**	**12.4**	**11.0**

There are significant differences among the weights of different braces (Table 4.2). The highest percentage variation between the maximum and the minimum overall weights is for 15th storey building. The highest variation of beam and column weight among different types of brace is for 5th storey buildings, which is 2.3 and 10.7 percent respectively.

Table 4.2 indicates failure due to lack of capacity and stress for the 5^{th}, 10^{th}, 15^{th} and

el frames of 10^{th}



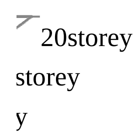


Figure 4.5: Lateral displacement (mm) in (a) X direction (b) Y direction for symmetrical plan and section, central bay zipper brace.

The following are the observations from Table 4.2 and Figure 4.5:

- Rectangular Hollow Sections (RHS) zipper braced system achieves the minimum weight. However, for 20th storey it causes the maximum lateral displacement in X direction.
- On the other hand, I Sections (IS) zipper braced system generally achieves the maximum weight for brace, column and total weight of all steel sections in five to twenty stories and it has the minimum lateral displacement in X and Y directions.
- The CHS zipper braced system has the minimum overall total weight and maximum lateral displacement in X direction for five, ten and fifteen stories.

4.2.1.3 Central Bay Knee Bracing

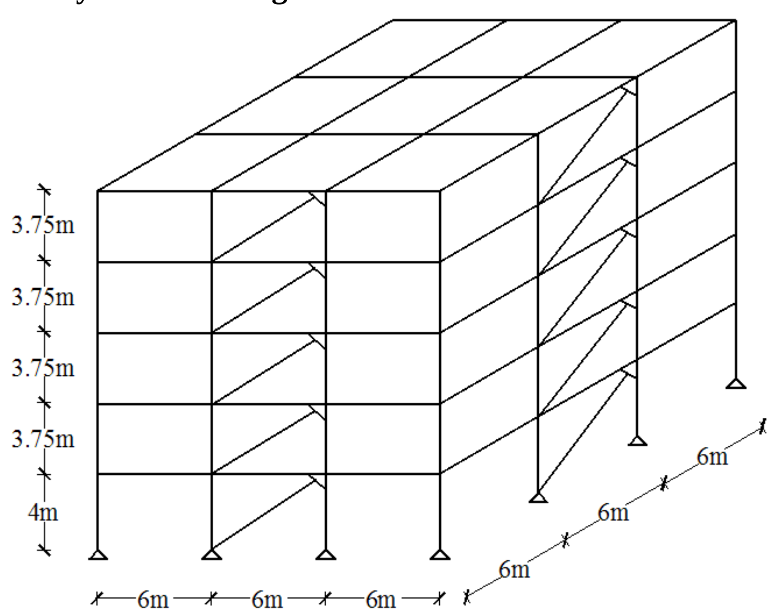


Figure 4.6: Symmetrical Plan and Section central bay knee bracing.

Figure 4.6 shows the central bay knee bracing under consideration. Table 4.3 gives the total weight and weight of columns, beams and braces and Figure 4.7 gives the lateral displacement in X and Y directions for buildings with five to twenty stories with knee bracing in the center of bays.

Table 4.3: Weights of columns, beams, braces and total by having different steel brace sections for knee bracing in the central bay of structure for symmetrical plan and section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	19.8	Failed	Failed	Failed
	Rectangular Hollow section	19.8	51.8	100.0	170.2
	Circular Hollow section	16.5	47.9	98.2	166.3
	I section	17.2	48.9	98.0	163.3
Difference between max and min (%)		**20.0**	**8.1**	**2.0**	**4.1**
Beams Weight (ton)	Angle section	68.9	Failed	Failed	Failed
	Rectangular Hollow section	68.6	136.7	203.9	271.0
	Circular Hollow section	67.8	135.6	202.4	267.9
	I section	68.1	136.2	203.2	269.1
Difference between max and min (%)		**3.2**	**0.8**	**0.7**	**1.2**
Braces Weight (ton)	Angle section	7.3	Failed	Failed	Failed
	Rectangular Hollow section	2.4	5.9	10.5	16.0
	Circular Hollow section	2.5	6.2	11.5	19.3
	I section	5.6	15.5	30.8	50.8
Difference between max and min (%)		**204.2**	**162.7**	**193.4**	**217.5**
Total Weight (ton)	Angle section	96.1	Failed	Failed	Failed
	Rectangular Hollow section	91.0	194.4	314.4	457.2
	Circular Hollow section	86.9	189.8	312.2	453.6
	I section	91.0	200.7	332.0	483.2
Difference between max and min (%)		**10.6**	**5.7**	**6.3**	**6.5**

Table 4.3 shows noticeable differences in total weight and the weights of braces for different steel brace sections. The variation between the maximum and minimum weight is 10.6 to 5.7 percent for total weights and 204.2 to 162.7 percent for bracing weights. As for the weights of beam and column, the highest and lowest variation

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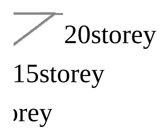

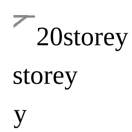

direction for

symmetrical plan and section, central bay knee brace.

For symmetrical plan and section with knee braced frames Table 4.3 and Figure 4.7 indicates the following:

- The lightest weight for the bracing system for all stories is achieved when Rectangular Hollow Sections (RHS) is used for the bracing system. On the other hand it has maximum column and beam weight and for all cases maximum lateral displacement in X direction.

- The maximum brace and total weight of all steel sections for ten to twenty stories is achieved when I sections (IS) are used as bracing members. The IS has minimum lateral displacement in X and Y direction for all stories.
- When Circular Hollow Section (CHS) is used for bracing members, the minimum total weight for all stories and minimum column weight for five, ten and fifteen stories were achieved. On the other hand CHS has maximum lateral displacement in Y direction for ten, fifteen and twenty storey buildings.

4.2.2 Core Bracing

4.2.2.1 Core Cross Bracing

The provision of adequate lateral stiffness, against wind forces is a major concern in the design of multi-storey buildings. Lateral displacement of multi-storey structures increases exponentially with building heights and so does the amount of steel needed to keep displacement within acceptable limits. There are a large number of possibilities in the layout arrangement of the bracing system. Among these, cross type bracings for each floor, zipper or knee type bracings in central bay and core of structure are commonly used in practice. In this stage the three-bay steel frames shown in Figure 4.8 and Table 4.4 is considered to demonstrate the effect of cross bracing in the core of the structural systems in the optimum design of steel frames.

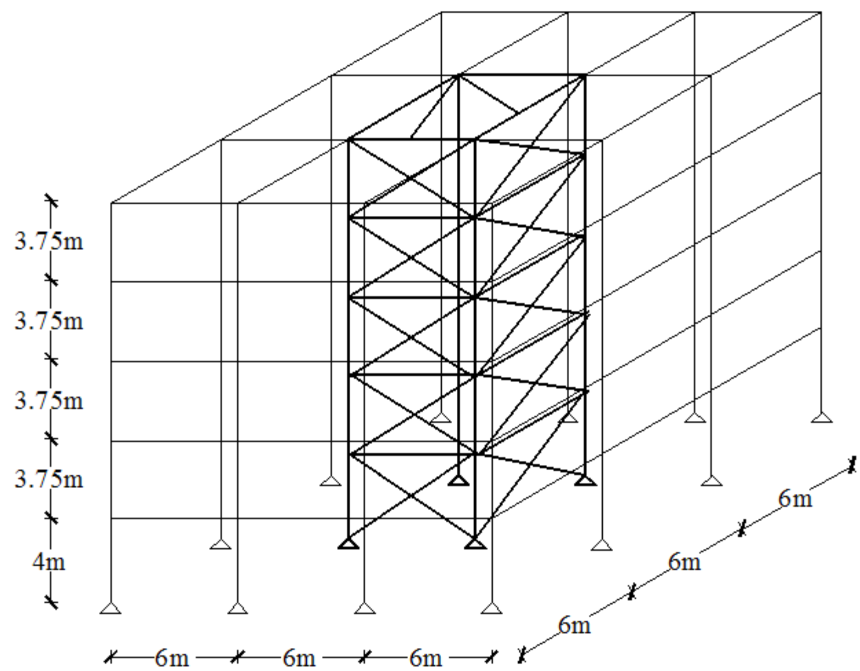

Figure 4.8: Symmetrical Plan and Section core cross bracing.

According to Table 4.4, some of the steel frames with Angle section braces for five, ten, fifteen and twenty stories have been failed due to lack of capacity and stress.

Table 4.4: Weights of columns, beams, braces and the overall total by having different steel profiles for cross bracing in the core of the structure for symmetrical plan and section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	15.4	43.8	87.9	149.5
	Circular Hollow section	14.8	43.3	87.3	148.0
	I section	13.4	41.7	83.3	143.0
Difference between max and min (%)		**15.0**	**5.0**	**5.5**	**4.5**
Beams Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	68.5	136.1	202.8	269.3
	Circular Hollow section	68.2	136.7	203.6	270.0
	I section	68.4	136.4	204.5	271.7
Difference between max and min (%)		**0.4**	**0.4**	**0.8**	**0.9**
Braces Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	4.3	10.0	16.3	23.0
	Circular Hollow section	4.6	12.4	23.3	37.0
	I section	19.1	52.1	93.7	127.8
Difference between max and min (%)		**344.2**	**421.0**	**475.0**	**455.6**
Total Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	88.2	190.0	307.2	441.8
	Circular Hollow section	87.6	192.4	314.2	455.0
	I section	101.0	230.3	381.6	542.5
Difference between max and min (%)		**15.3**	**21.2**	**24.2**	**22.8**

In Table 4.4, there are dramatic differences among the total weight and weights of braces while the steel brace sections are changing. These variations between the maximum and minimum weight is 15.3 to 24.2 percent for total weight and 344.2 to 475 percent for bracing weight. In fact the result of these extremely changes in total weight are because of changes occurring on brace weights. However, the differences between maximum and minimum beam and column weights for all four steel sections are

a

20storey
orey

20storey
orey

Figure 4.9: Lateral displacement (mm) in (a) X direction (b) Y direction for symmetrical plan and section, core cross brace.

According to Table 4.4 and Figure 4.9, the individual designs within the group of the symmetrical plan and section with core cross braced frames can be described as follows:

- The lightest weight of beam, brace and total overall is generally for the Rectangular Hollow Sections (RHS) bracing system. However, column weights are the heaviest with this system and it causes the maximum lateral displacement in X direction.

- The maximum I Sections (IS) bracing system is beam, brace and total weight and the minimum lateral displacement in X direction and maximum in Y direction.

- On the other hand, Circular Hollow Sections (CHS) bracing system caused the maximum lateral displacement in X direction.

4.2.2.2 Core Zipper Bracing

Zipper bracing system is used instead of the cross bracing in the core of the structure (Fig 4.10).

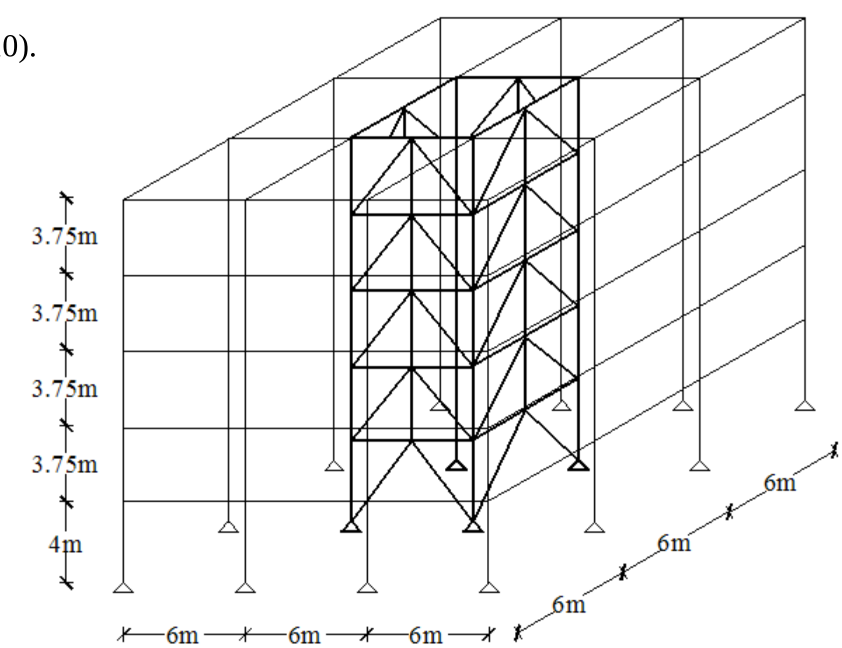

Figure 4.10: Symmetrical Plan and Section core zipper bracing.

Table 4.5: Weights of columns, beams, braces and the overall total by having different steel sections for zipper bracing in the core of the structure for symmetrical plan and section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	15.7	Failed	Failed	Failed
	Rectangular Hollow section	16.0	47.0	89.5	149.5
	Circular Hollow section	15.0	43.5	88.2	149.2
	I section	15.0	47.8	94.4	156.2
Difference between max and min (%)		**6.7**	**9.9**	**7.0**	**4.7**
Beams Weight (ton)	Angle section	62.0	Failed	Failed	Failed
	Rectangular Hollow section	62.2	126.6	190.6	252.9
	Circular Hollow section	63.1	125.8	188.5	251.7
	I section	63.5	127.3	188.6	250.6
Difference between max and min (%)		**2.4**	**1.2**	**1.1**	**0.9**
Braces Weight (ton)	Angle section	6	Failed	Failed	Failed
	Rectangular Hollow section	2.3	5.4	8.5	13.1
	Circular Hollow section	2.5	6.3	10.3	15.3
	I section	7.8	20.6	34.8	56.6
Difference between max and min (%)		**239.0**	**281.5**	**309.4**	**332.0**
Total Weight (ton)	Angle section	84.0	Failed	Failed	Failed
	Rectangular Hollow section	80.5	179.0	288.6	415.5
	Circular Hollow section	80.6	175.7	287.0	416.2
	I section	86.3	195.7	317.8	463.4
Difference between max and min (%)		**7.2**	**11.4**	**10.7**	**11.5**

There are noticeable differences in weights of braces and overall total weights for different steel brace sections. The variation between the maximum and minimum brace and total weight is 332 to 239 percent and 11.5 to 7.2 percent respectively. The steel frames with Angle section braces for ten, fifteen and twenty stories were failed due to lack of capacity and over stress. However, for 5th storey building caused the lowest

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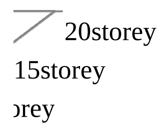


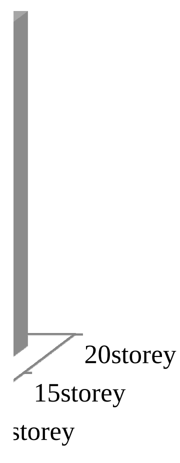


Figure 4.11: Lateral displacement (mm) in (a) X direction (b) Y direction for symmetrical plan and section, core zipper brace.

According to Table 4.5 and Figure 4.11 the following are the summary of results for core zipper braced frames:

- RHS zipper bracing system provides the minimum brace weights for core located zipper brace system. CHS bracing system has the minimum total weight for 10th and 15th stories frames due to achieving minimum column weights. However, CHS bracing systems causes the maximum lateral displacement in X and Y directions.

- On the other hand, the maximum weight for brace and overall total for all frames is achieved by IS bracing system and it caused the minimum lateral displacement in both X and Y directions.

4.2.2.3 Core Knee Bracing

Figure 4.12 shows the building with core knee bracing system under consideration.

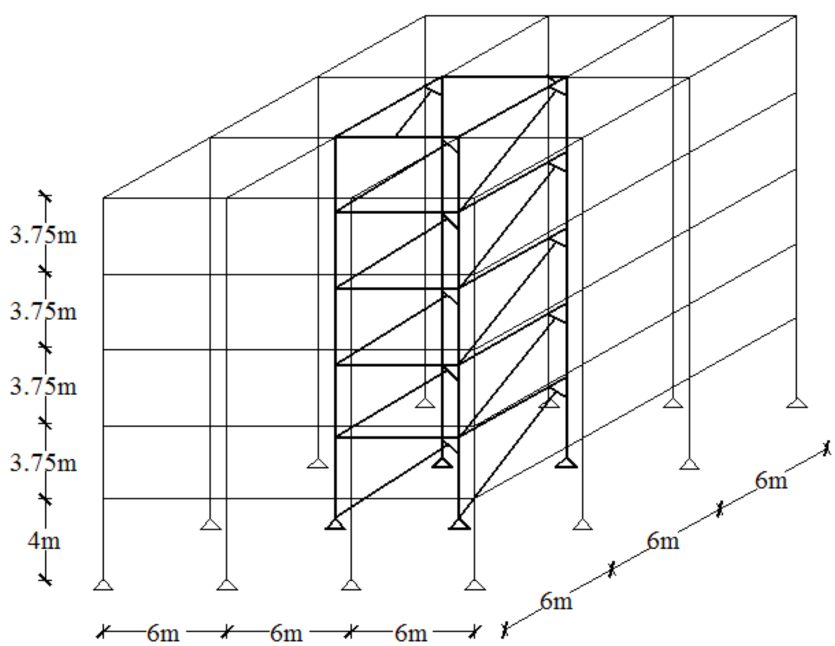


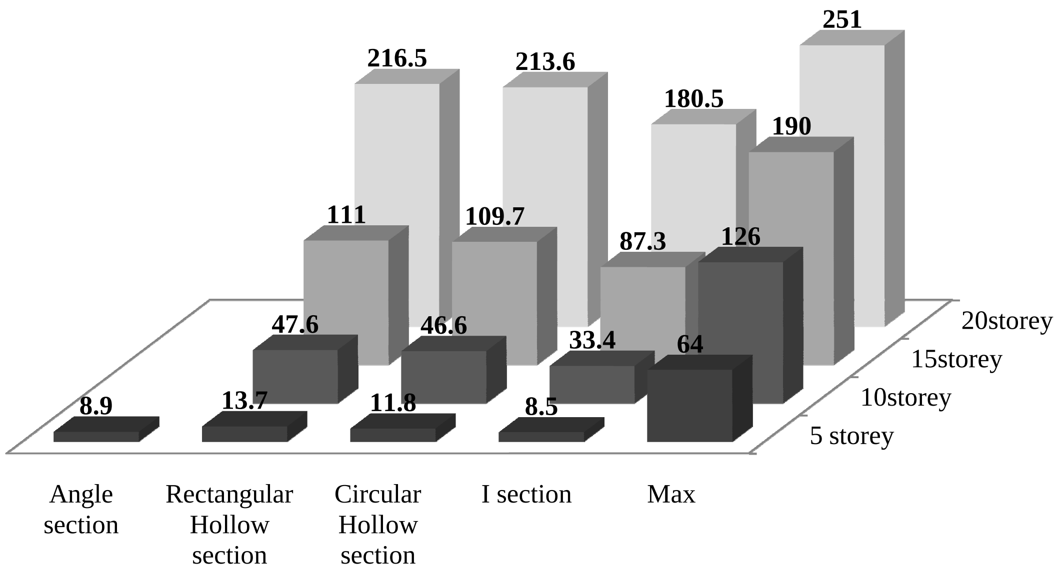
Figure 4.12: Symmetrical Plan and Section core knee bracing.

Table 4.6 and Figure 4.13 gives the steel weights and lateral displacements in X and Y directions for various bracing systems respectively.

Table 4.6: Weights of columns, beams, braces and the overall total by having different steel sections for knee bracing in the core of structure for symmetrical plan and section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	17.9	Failed	Failed	Failed
	Rectangular Hollow section	18.1	48.8	96.4	161.6
	Circular Hollow section	16.7	48.8	96.3	160.6
	I section	16.9	49.0	96.4	160.8
Difference between max and min (%)		**8.4**	**0.4**	**0.1**	**0.6**
Beams Weight (ton)	Angle section	67.1	Failed	Failed	Failed
	Rectangular Hollow section	67.7	134.4	200.2	266.2
	Circular Hollow section	66.6	132.8	197.4	261.5
	I section	66.6	132.2	196.8	261.1
Difference between max and min (%)		**1.6**	**1.7**	**1.7**	**1.9**
Braces Weight (ton)	Angle section	7.5	Failed	Failed	Failed
	Rectangular Hollow section	2.5	6.2	10.7	16.4
	Circular Hollow section	2.7	6.3	11.2	17.2
	I section	5.9	15.3	25.9	38.3
Difference between max and min (%)		**200.0**	**146.8**	**131.2**	**133.5**
Total Weight (ton)	Angle section	92.5	Failed	Failed	Failed
	Rectangular Hollow section	88.3	189.4	307.4	444.1
	Circular Hollow section	86.1	187.8	304.9	439.3
	I section	89.3	196.5	319.1	460.2
Difference between max and min (%)		**7.4**	**4.6**	**4.6**	**4.7**

Table 4.6 indicates the failure of knee braces made of angles in the core of the structure for all steel frames except for 5th storey steel frame.



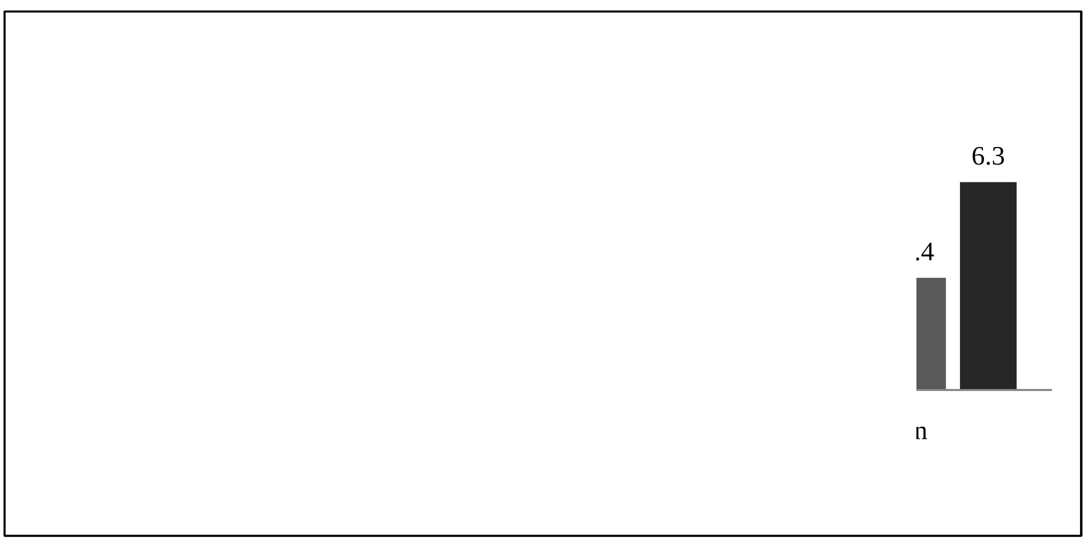
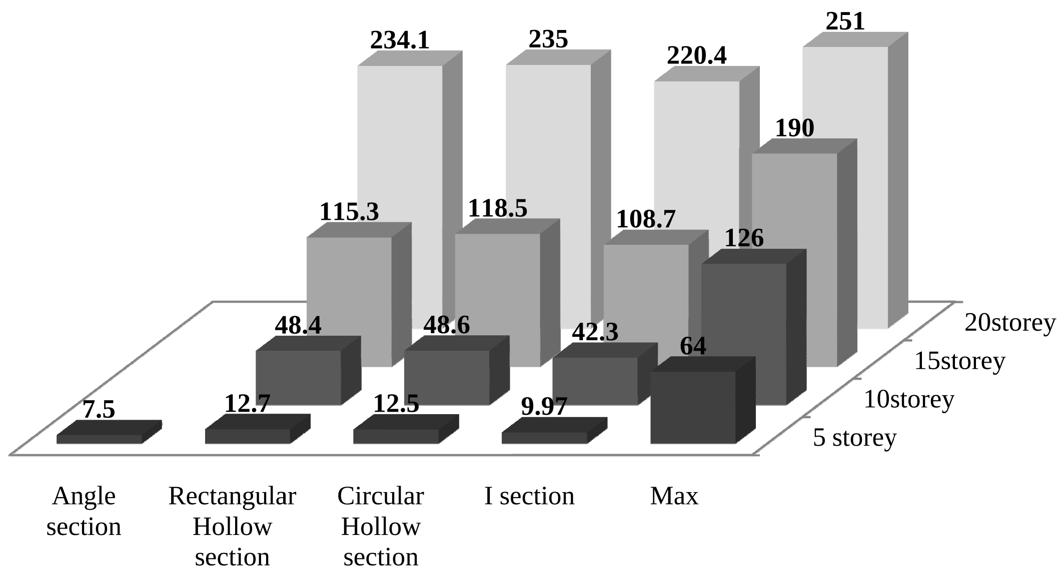


Figure 4.13(a): Lateral displacement (mm) in X direction for symmetrical plan and section, core knee brace.



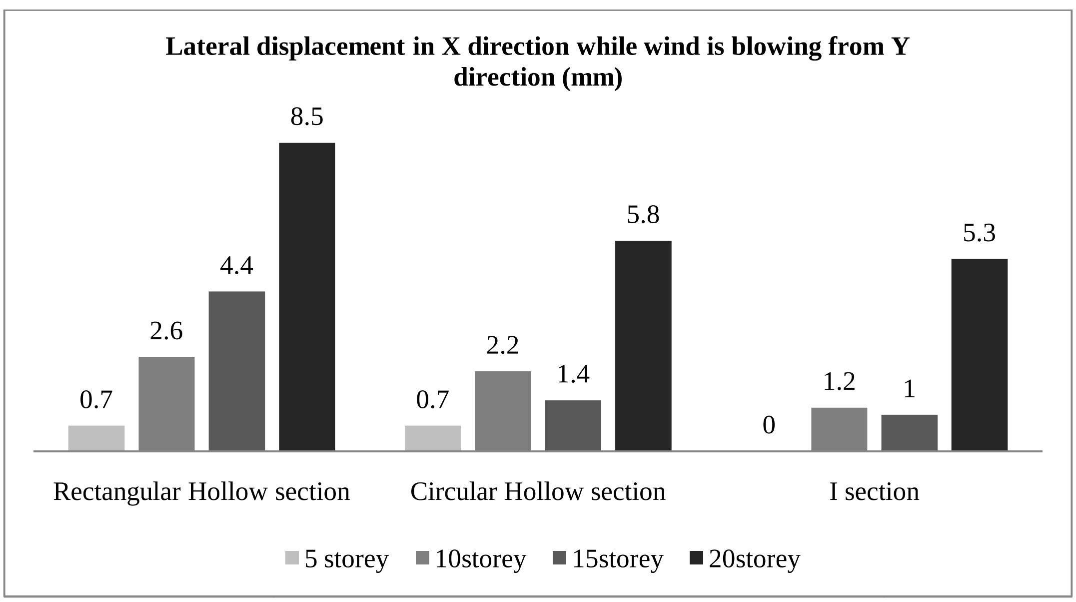


Figure 4.13(b): Lateral displacement (mm) in Y direction for symmetrical plan and section, core knee brace.

According to Figure 4.13, knee brace which is located in the core of structure is the only bracing system in symmetrical plan and section which causes lateral displacement in X direction while wind is blowing from Y direction and lateral displacement in Y direction while wind is blowing from X direction.

Table 4.6 and Figure 4.13 indicate the following outcome for the core knee braced frames:

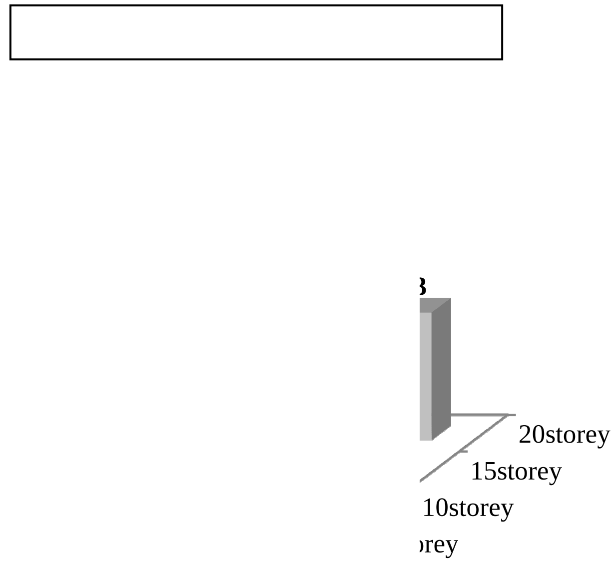
- RHS bracing system achieves the lightest weight for the bracing system for all buildings. On the other hand it causes the maximum beam weight for 15^{th} and 20^{th} stories building and maximum lateral displacement in X direction for all buildings. RHS bracing system also causes the maximum lateral displacement in Y direction while wind is blowing from the X direction.

- The maximum brace and total weights of all buildings is achieved when IS bracing system is used. In terms of lateral displacement, this system causes the minimum lateral displacement in both X and Y directions.
- CHS bracing systems achieved the minimum beam weights. CHS bracing systems has approximately the same brace weight as RHS bracing systems, but it has the minimum beam and brace weight, therefore, it achieved the minimum total weight. On the other hand it has the maximum lateral displacement in Y direction and the maximum displacement in Y direction due to the wind blowing from X direction.

4.2.3 Comparison of Symmetrical Plan and Section

The conducted research has revealed the importance of data visualization in evolutionary design. An evolutionary design support tool allows researchers and engineers to produce thousands of designs. Therefore, evolutionary design opens new ways for different structural design concepts. In this section, the designs of different brace types and steel profiles in five, ten, fifteen and twenty stories tall buildings subjected to the same uniformly distributed wind loading and same blanket of dead and live load will be compared.

Ninety six steel designs were carried out to find out which type of brace is the most efficient and economical as far as the lateral displacements in X and Y directions and the steel weight of buildings are concerned. As a result, the brace weight appears to be the main parameter affecting the total weight of each structure. Figure 4.14 gives the comparison of maximum IS and minimum RHS brace weights of cross, zipper and knee bracing in the central bay and in the core of the steel structures.



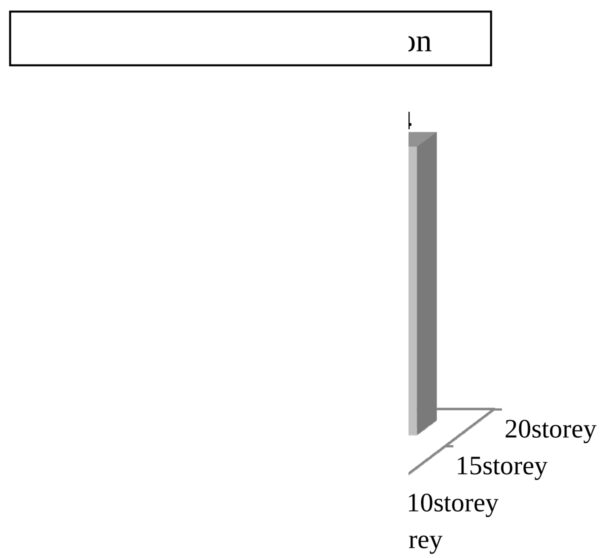
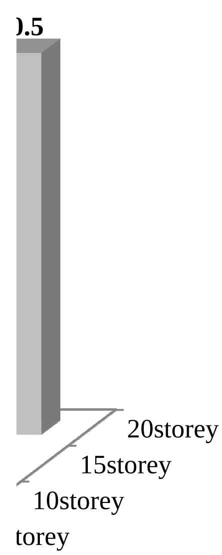


Figure 4.14: Comparison of (a) maximum brace weights (b) minimum brace weights (ton) for symmetrical plan and section

According to these results, generally the maximum and minimum brace weights were achieved when IS and RHS were used as bracing members, respectively.

From Figure 4.14 (a), core cross bracing has the maximum weight. Whilst the central bay cross bracing has the maximum weight when compared to the results of the rest of central bay bracings. On the other hand central bay zipper bracing has the minimum brace weight.

According to the cost of purchasing steel section, the RHS has one of the highest costs due to its manufacturing procedure. Hence, IS has the lowest cost of all. The steel sections of each element have been designed in such a way to have maximum capacity ratio and minimum weights and cost. However, it should be kept in mind that the cost of any structure is not only determined by the weight of members but other parameters, such as fabrication, erection, types of connections would contribute to the final cost.



cement (mm) in X direction for symmetrical plan and section.

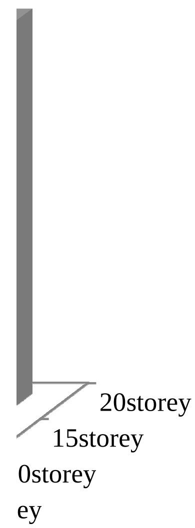


Figure 4.15(b): Comparison of minimum (I Section) lateral displacement (mm) in Y direction for symmetrical plan and section.

Figure 4.15 (a) and (b) shows the minimum lateral displacement in X and Y directions respectively where I Sections were used as bracing members.

From Figure 4.15 (a) and (b), central bay and core knee bracing have the maximum lateral displacement in both X and Y directions for all the stories except for 20 stories building. On the other hand minimum lateral displacement in X and Y directions belong to the core cross bracing system. In fact, central bay cross bracing has the minimum lateral displacement in X and Y directions among all central bay bracing systems.

Overall, there is higher lateral displacement in Y direction due to columns being subject to bending about their minor axis.

4.3 Asymmetrical Plan and Section

The main objective of a structural design is to create a structure that safely accomplishes its function. In civil engineering field steel braced frame is a widely used structure. Its popularity comes from the variety of steel section sizes and the shapes which is used for varying types of braces in a structure. Generally, steel braced frame is not only designed to sustain the gravity loads, but it is also capable of resisting the horizontal loads to ensure the stability of the structure.

The following are the details of the structural systems and the design consideration for multi-storey buildings:

- Number and the total length of bays: 3 bays (18 m)
- Structural stories and heights: 5 stories (19 m), 10 stories (37.75 m), 15 stories (56.5 m) and 20 stories (75.25 m)
- Bay widths: 8m, 6m, 4m (X axis) by 7m, 3m and 8m (Y axis)
- Types of braces: cross, zipper and knee brace
- Four types of steel profiles are used as bracing members: Universal Angle section (UA), Rectangular Hollow Section (RHS), Circular Hollow Section (CHS) and I Section (IS) or Universal Column (UC)
- Location of the braces: center of the bays and at the core of the structure,
- Loads: dead, live, wind load and perimeter wall loadings (Table 3.1)

- Connections: simple frame structure where beam to column, beam to beam, brace to beam/column are pinned connections and columns are continuous

- Steel profiles for columns and beams: Universal Column sections (UC), Universal Beam sections (UB) are adopted for columns and beams of the frame respectively

- Spacing of the secondary beams: 3m (X axis), 3.5m (Y axis)

- The value of x for all knee braced structures: 0.2m

- Number of columns, beams and cross or knee braces respectively: 67, 109, 40 (five stories), 142, 234, 80 (ten stories), 217, 359, 120 (fifteen stories) and 292, 484, 160 (twenty stories)

- Number of zipper braces: 56 (five stories), 116 (ten stories), 176 (fifteen stories) and 236 (twenty stories)

Since the speed and direction of wind are always changing, the exact direction of pressure or suction applied by winds onto the structure is difficult to determine. Thus, some assumptions have been made for each asymmetrical plan and section of the structure. These assumptions are in such a way that each structure is exposed to wind loads in X and Y directions (Fig 4.16).

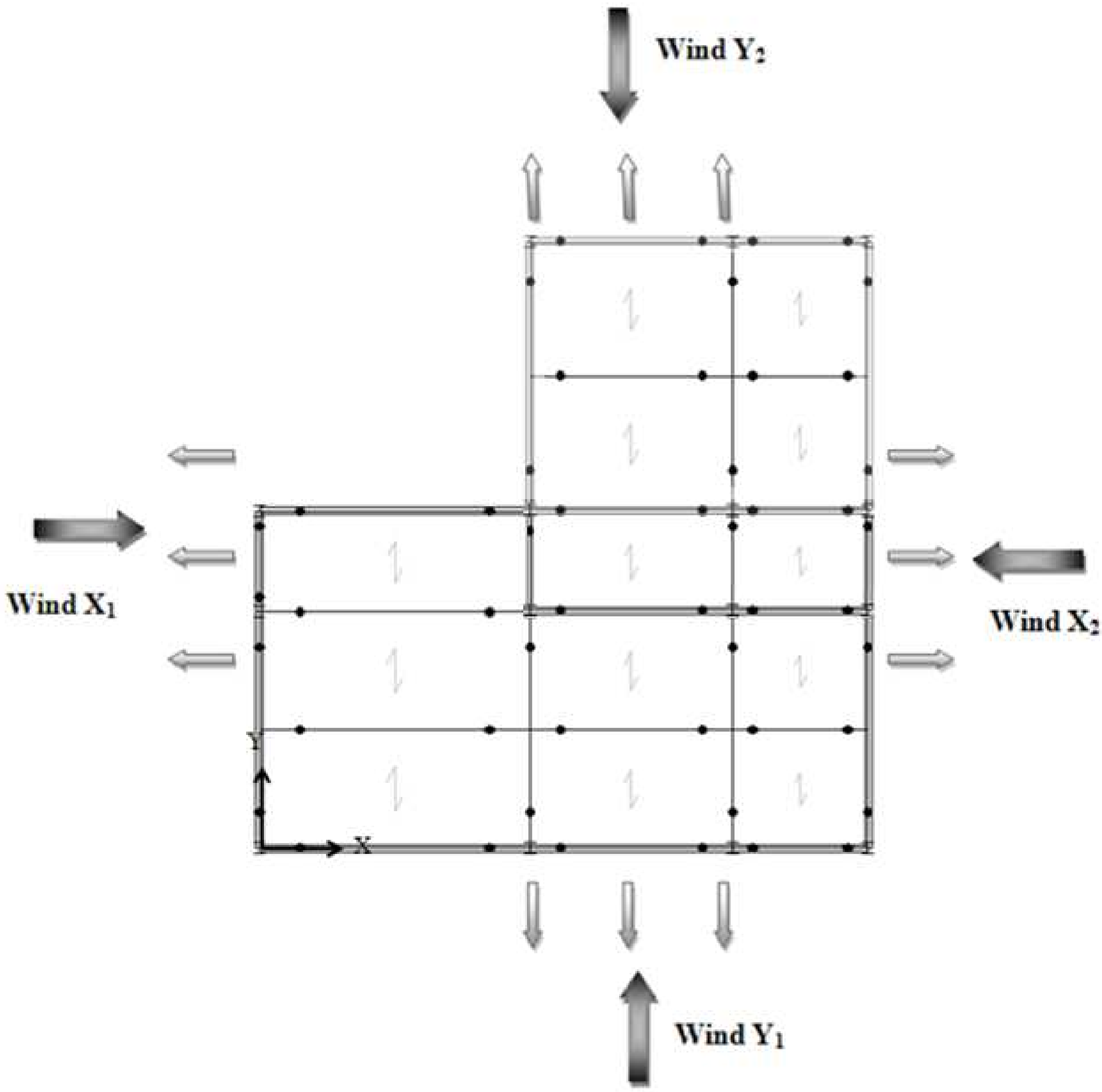


Figure 4.16: Simple frames with pinned connections and direction of winds (top view plan) for asymmetrical plan and section.

- Maximum allowable displacement: 63.3 mm for 5thstorey, 125.84 mm for 10th storey, 188.34 mm for 15th storey, 250.84 mm for 20th storey

Wind in X and Y directions were considered in each design. In spite of the fact that the plans and sections of the structures are not symmetrical, each case has been analyzed and designed in ETABS software according to two wind loads W_1 (W_x and W_y) and W_2 (W_x and W_y) for core and central bay cross bracings (Table 4.7).

Table 4.7: Total weight of core and central bay cross bracings (a) W_1 and (b) W_2 for asymmetrical plan and section.

W_1	Brace Sections/No. of Stories	5	10	15	20
Central bay cross bracing					
Total Weight (ton)	Angle section	82.4	Failed	Failed	Failed
	Rectangular Hollow section	76.7	178.0	301.0	490.2
	Circular Hollow section	75.1	182.0	323.2	506.4
	I section	85.1	216.4	384.4	571.2
Core cross bracing					
Total Weight (ton)	Angle section	81.4	Failed	Failed	Failed
	Rectangular Hollow section	72.0	173.0	341.1	493.6
	Circular Hollow section	77.0	181.3	321.6	489.0
	I section	89.0	215.1	372.3	533.3

(a)

W_2	Brace Sections/ No. of Stories	5	10	15	20
Central bay cross bracing					
Total Weight (ton)	Angle section	82.2	Failed	Failed	Failed
	Rectangular Hollow section	77.0	178.0	292.7	468.3
	Circular Hollow section	76.2	182.3	301.2	499.0
	I section	87.0	218.3	368.2	569.7
Core cross bracing					
Total Weight (ton)	Angle section	81.0	Failed	Failed	Failed
	Rectangular Hollow section	71.4	173.7	300.0	499.5
	Circular Hollow section	77.0	181.1	314.8	448.5
	I section	89.0	216.5	360.6	522.0

(b)

As a result comparing the core and central bay cross bracings, the total weight of structures were generally higher when structures were subjected to wind W_1.

Asymmetrical structural systems are generated in this category, the details of wind load (W_1) for the central bays and core cross bracing are shown in Figure 4.17.

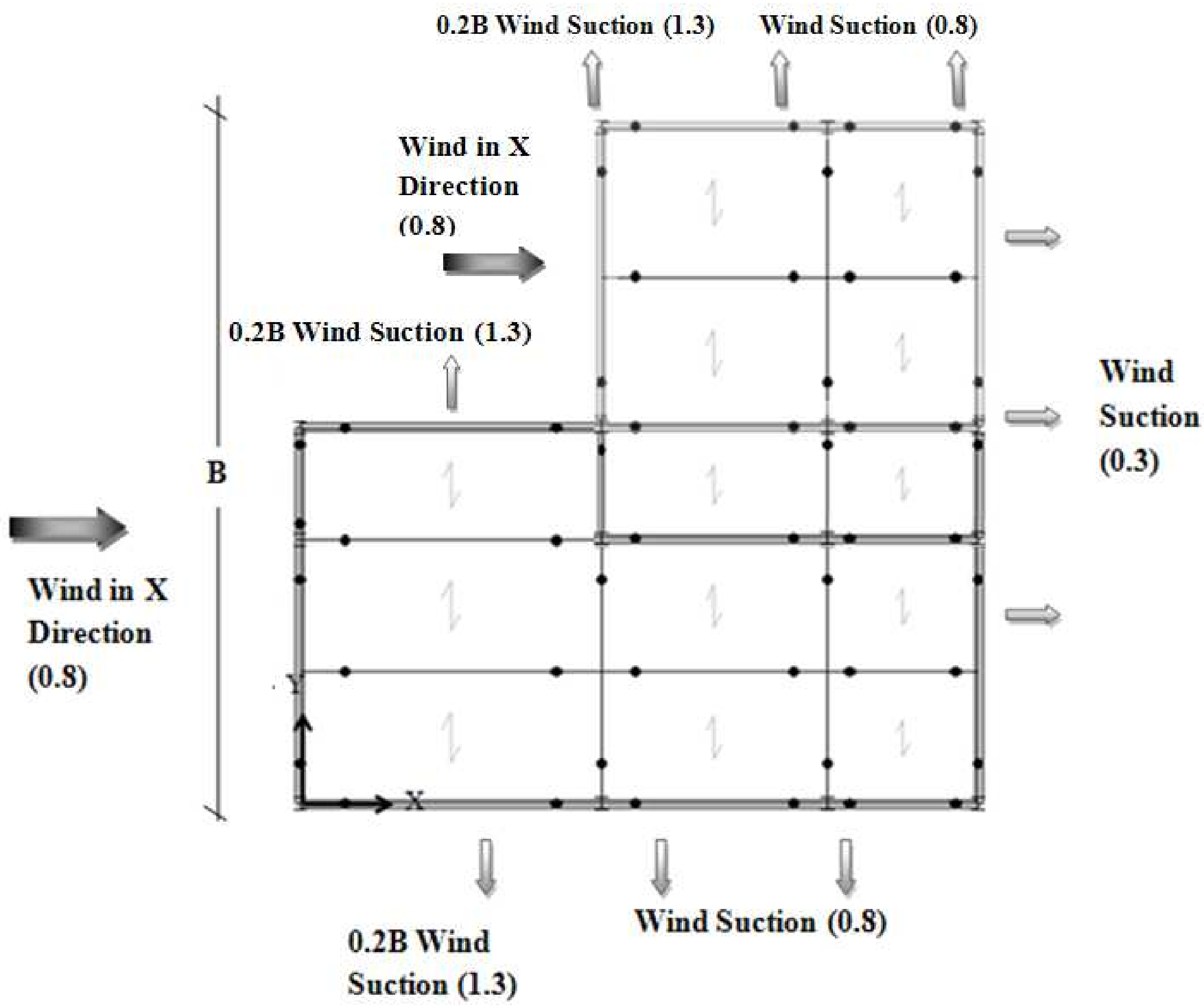


Figure 4.17(a): Building layout indicating wind in X direction with suctions for asymmetrical plan and section.

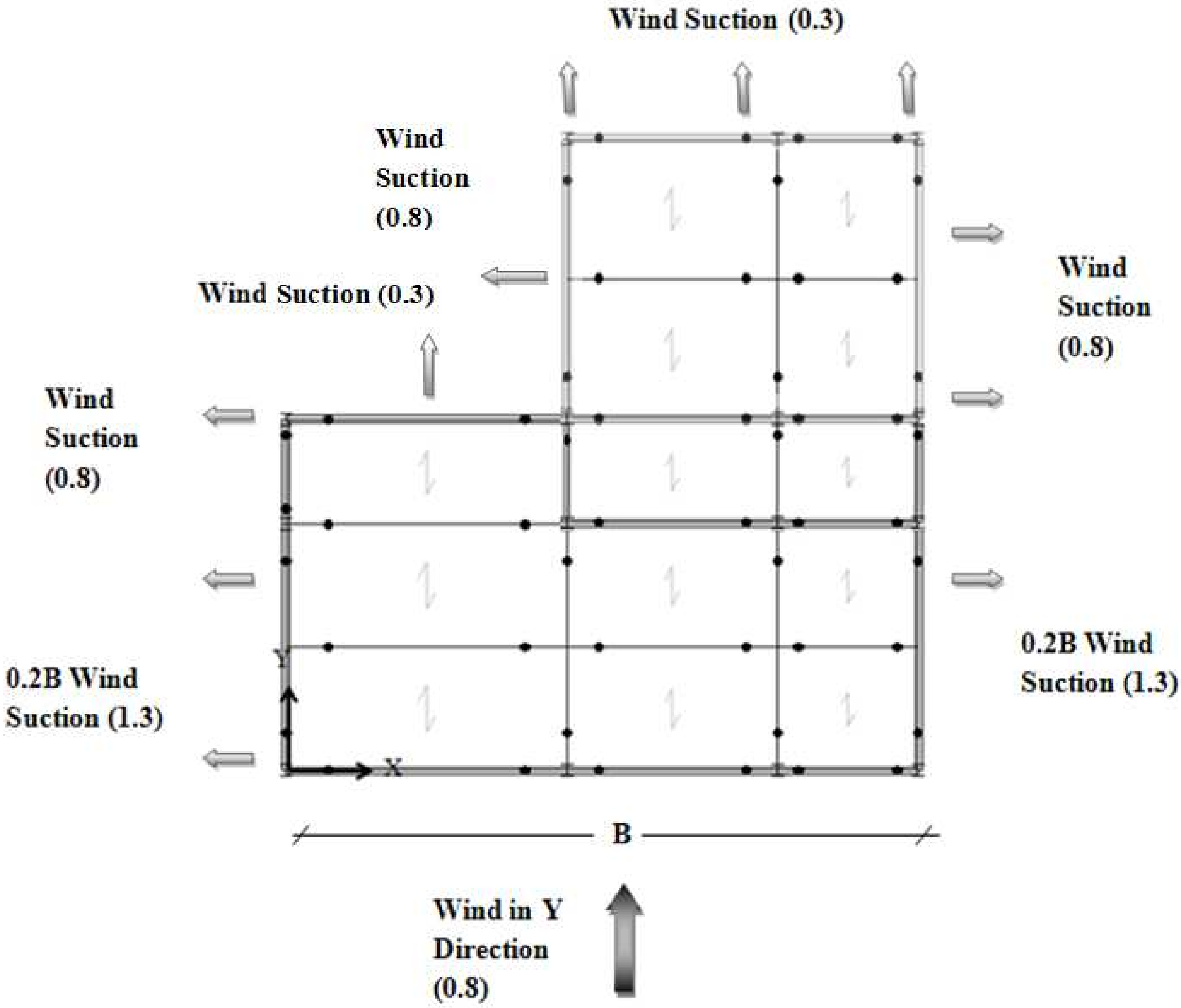
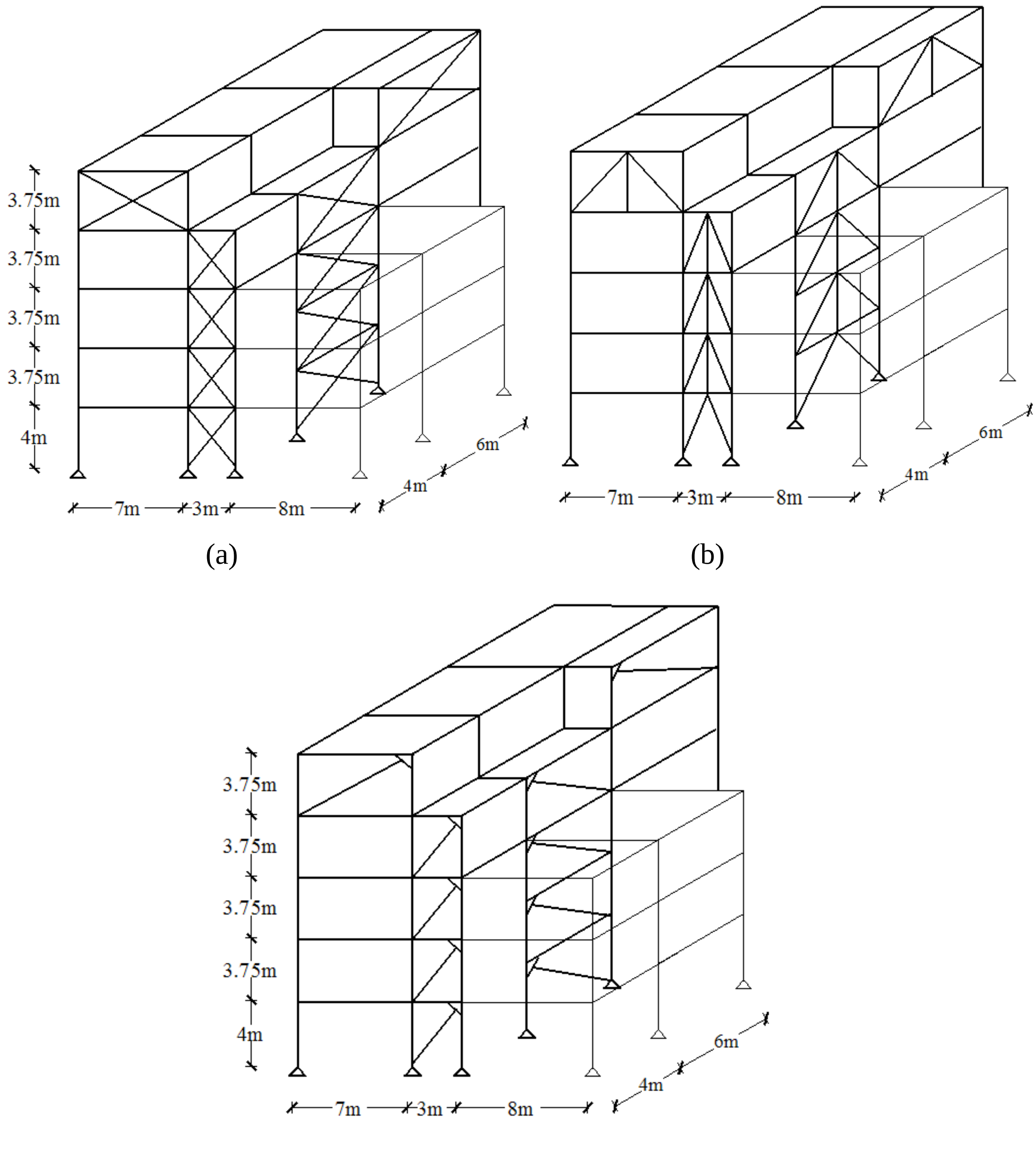


Figure 4.17(b): Building layout indicating wind in Y direction with suctions for asymmetrical plan and section.

Since the weights of bracings are generally the controlling factors of the overall total weight of the structure and maximum lateral displacement in X and Y directions achieved when I sections are used as bracing members, then from this point onwards the details of the column and beam weights and lateral displacements for each structure are given in Appendix B.

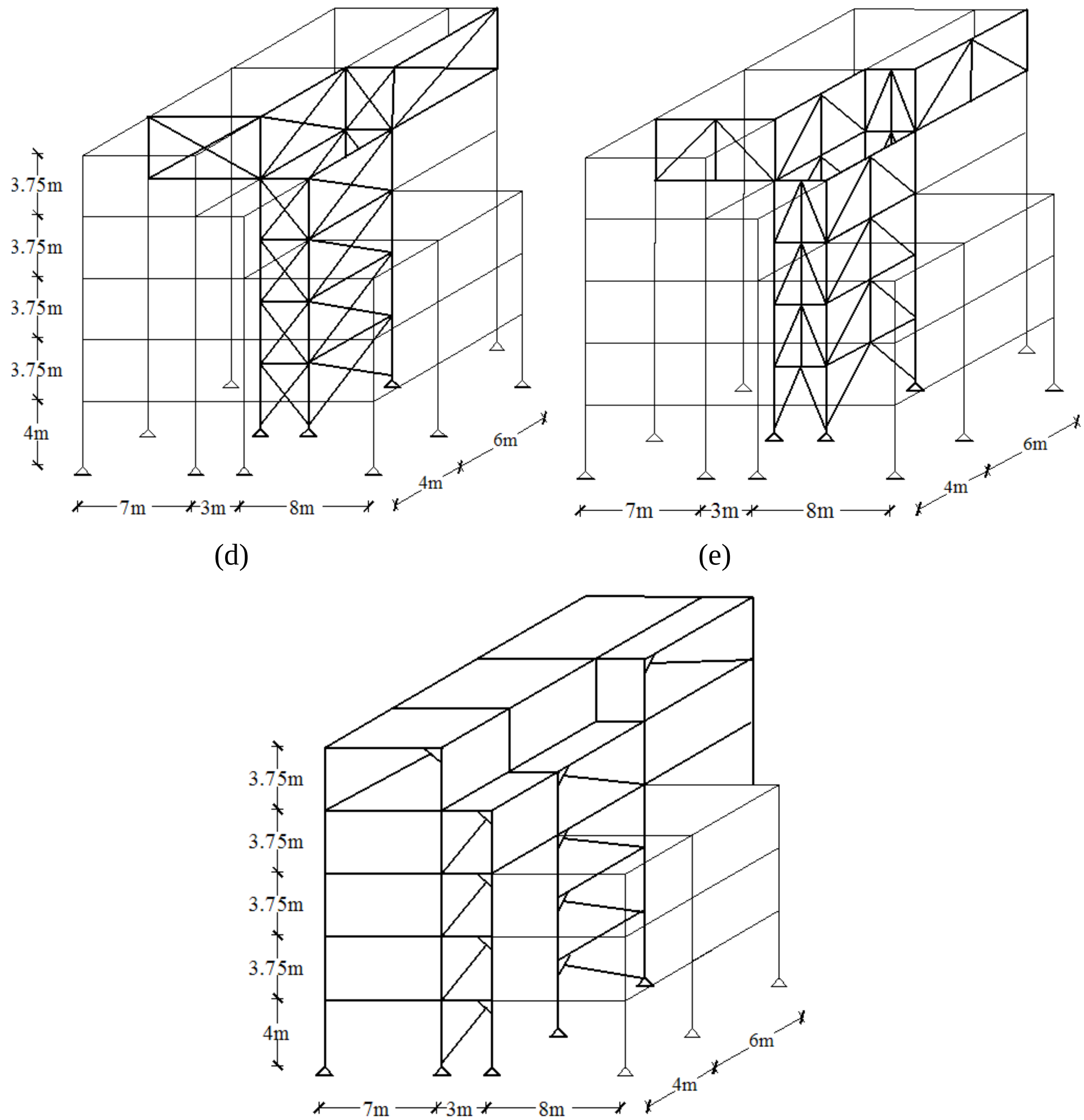
4.3.1 Perimeter Central Bay and Core Bracing

Figure 4.18 shows central bay bracings and core bracings for asymmetrical plan and sections structures.



(c)

Figure 4.18: Asymmetrical Plan and Section central bays (a) cross (b) zipper (c) knee bracings



(d) (e)

(f)

Figure 4.18: Asymmetrical Plan and Section core (d) cross (e) zipper (f) knee bracings.

Table 4.8 shows the weight of braces and the total weight of the whole structure (ton) for varying number of stories and brace types at central bay and core with different steel profiles for braces subjected to wind load 1 (W_1).

Table 4.8: Weights of braces and the overall total weight of different brace types and brace sections in the central bay and core of structure for asymmetrical plan and section.

Asymmetrical Plan and Section		Central Bay Cross Bracing				Central Bay Zipper Bracing				Central Bay Knee Bracing			
Brace Weight (ton)	Brace Sections/No. of Stories	5	10	15	20	5	10	15	20	5	10	15	20
	Angle section	12.4	Failed	Failed	Failed	5.0	11.1	Failed	Failed	5.9	Failed	Failed	Failed
	Rectangular Hollow section	2.9	7.0	16.0	35.6	2.0	4.9	13.5	35.0	2.2	5.1	14.2	33.2
	Circular Hollow section	3.2	11.0	26.9	45.4	2.7	7.7	19.6	38.0	2.4	7.2	16.3	37.2
	I section	14.4	48.0	89.6	121.0	7.1	23.9	56.6	84.4	6.8	23.3	43.3	67.9
Difference between max and min (%)		**396.5**	**585.7**	**460.0**	**239.9**	**255.0**	**388.0**	**319.2**	**141.0**	**209.0**	**357.0**	**205.0**	**104.5**
Total Weight (ton)	Angle section	82.4	Failed	Failed	Failed	77.0	176.7	Failed	Failed	81.0	Failed	Failed	Failed
	Rectangular Hollow section	76.7	177.9	301.0	490.2	77.6	171.0	290.5	470.5	82.8	173.8	304.1	496.3
	Circular Hollow section	75.1	181.7	323.2	506.4	73.5	172.6	294.7	471.8	78.8	178.2	307.4	500.2
	I section	85.1	216.4	384.4	571.2	74.6	191.3	343.9	535.8	82.0	196.7	330.5	524.3
Difference between max and min (%)		**13.3**	**21.6**	**27.7**	**16.5**	**5.6**	**11.9**	**18.4**	**13.8**	**5.1**	**13.2**	**8.7**	**5.6**

Asymmetrical Plan and Section		Core Cross Bracing				Core Zipper Bracing				Core Knee Bracing			
Brace Weight (ton)	Brace Sections/No. of Stories	5	10	15	20	5	10	15	20	5	10	15	20
	Angle section	13.3	Failed	Failed	Failed	5.4	11.5	Failed	Failed	6.0	Failed	Failed	Failed
	Rectangular Hollow section	3.3	8.8	29.2	46.3	2.3	6.5	19.0	43.8	3.0	7.0	16.2	43.1
	Circular Hollow section	5.3	14.7	33.2	54.7	4.4	11.2	31.8	57.7	4.0	10.2	26.5	63.3
	I section	18.0	52.1	89.4	120.0	10.0	29.7	63.1	96.7	10.8	30.5	55.6	89.0
Difference between max and min (%)		**454.5**	**492.0**	**205.0**	**160.0**	**335.0**	**346.0**	**232.0**	**121.0**	**260.0**	**336.0**	**243**	**106.5**
Total Weight (ton)	Angle section	81.4	Failed	Failed	Failed	72.9	167.6	Failed	Failed	78.0	Failed	Failed	Failed
	Rectangular Hollow section	71.9	173.0	341.1	493.6	71.2	168.6	298.6	483.2	76.6	168.6	298.8	488.2
	Circular Hollow section	76.6	181.3	321.6	489.0	71.0	171.3	314.4	503.8	74.3	175.5	311.0	519.2
	I section	88.8	215.1	372.3	533.3	80.0	196.0	354.7	552.1	80.3	200.3	342.7	543.0.
Difference between max and min (%)		**23.5**	**24.4**	**16.0**	**9.0**	**12.7**	**17.0**	**19.0**	**14.2**	**8.0**	**19.0**	**14.7**	**11.2**

4.3.2 Comparison of Asymmetrical Plan and Section

Structural design optimization of steel frames generally requires selection of steel sections for its beams, columns and braces from a discrete set of practically available steel section tables. This selection should be carried out in such a way that the steel frame has the minimum weight or cost while the behavior and performance of the structure is within the limitations described by the code of practice.

In this section, as a result of using different steel brace types and their steel sections designs, the brace and column weights appears to be the main parameter affecting the total weight of each structure. From Table 4.8, Figure 4.19 gives the comparison of the maximum (IS) and the minimum (RHS) brace weights of cross, zipper and

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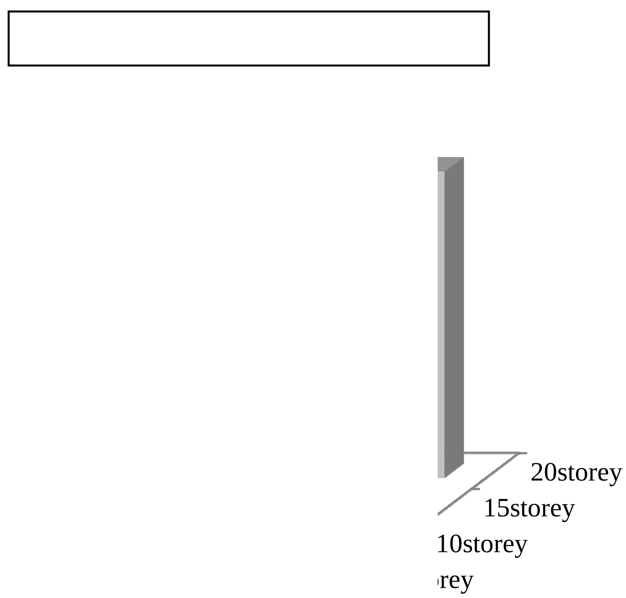


symmetrical

plan and section.

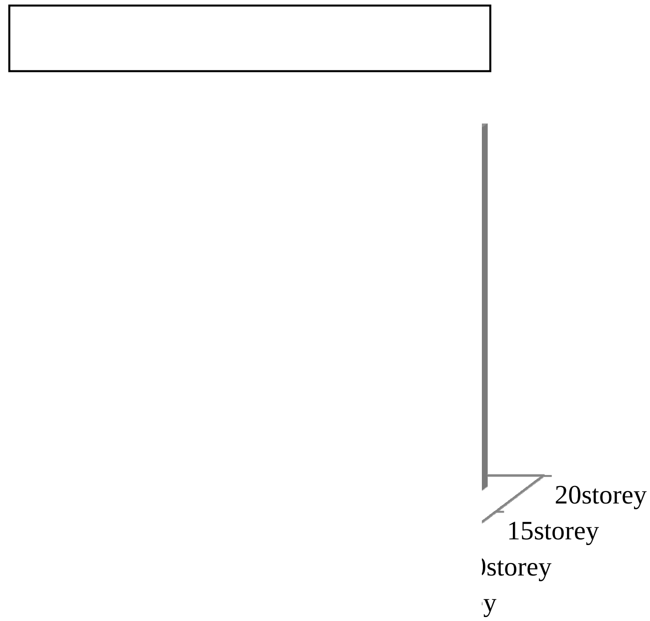


Figure 4.19(b): Comparison of minimum brace weights (ton) for asymmetrical plan and section.

According to these results, generally the maximum and minimum brace weights were achieved when IS and RHS were used as bracing members, respectively.

From Figure 4.19 (a) and (b), core and central bay cross bracing generally has the maximum weight. On the other hand central bay knee bracing and central bay zipper bracing has the minimum brace weight when IS and RHS are used as bracing member respectively. In fact, core knee bracing has the minimum brace weight when compared to rest of core bracings.

There are some differences between lateral displacement in X and Y directions. At this stage, they cannot be divided into many specific ways for maximum and minimum lateral displacements for any of sections. But approximate maximum value of displacement belongs to RHS and minimum for IS.

Figure 4.20 and Figure 4.21 show the minimum lateral displacement in X and Y directions respectively where I Sections were used as bracing members.

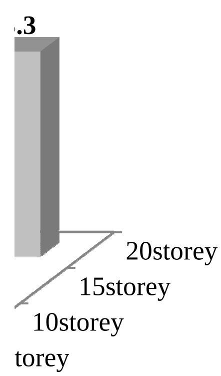


Figure 4.20: Comparison of minimum (I Section) lateral displacement (mm) in X direction for asymmetrical plan and section.

From Figure 4.20, central bay knee bracing has the maximum lateral displacement in X direction and core knee brace has the maximum lateral displacement in X direction. On the other hand minimum lateral displacement in X direction belongs to the core and central bay cross brace.

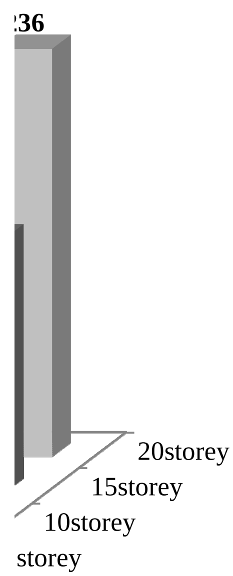


Figure 4.21: Comparison of minimum (I Section) lateral displacement (mm) in Y direction for asymmetrical plan and section.

Figure 4.21, represents the minimum lateral displacement in Y direction which I Sections is used as bracing member. The minimum lateral displacements in Y direction for five, to fifteen stories are central bay and core cross bracing. In addition, core zipper brace has the minimum lateral displacement in Y direction for twenty stories.

Overall, there is higher lateral displacement in Y direction due to columns being subject to bending about their minor axis.

4.4 Asymmetrical Plan and Symmetrical Section

The resistance of tall buildings to wind as well as to earthquake loads is an important part of the design of the structural systems that evolve by the continuous efforts of structural engineers to increase building height while keeping the deflection within acceptable limits and minimizing the amount of materials.

The following are the details of the structural system and the design consideration for the multi-storey buildings considered in this study:

- Number and the total length of bays: 3 bays (18 m)
- Structural stories and heights: 5 stories (19 m), 10 stories (37.75 m), 15 stories (56.5 m) and 20 stories (75.25 m)
- Bay widths: 8m, 6m, 4m (X axis) by 7m, 3m and 8m (Y axis)
- Types of braces: cross, zipper and knee brace
- Spacing of the secondary beams: 3m (X axis), 3.5m (Y axis)

- Four types of steel profiles are used as bracing members: Universal Angle section (UA), Rectangular Hollow Section (RHS), Circular Hollow Section (CHS) and I Section (IS) or Universal Column sections (UC)

- Location of the braces: center of the bays and at the core of the structure

- Connections: simple frame structure where beam to column, beam to beam, brace to beam/column are pinned connections and columns are continuous

- Steel profiles for columns and beams: Universal Column sections (UC), Universal Beam sections (UB) are adopted for columns and beams of the frame respectively

- The value of x for all knee braced structures: 0.2m

- Number of columns, beams and cross or knee braces respectively: 75, 125, 40 (five stories), 150, 250, 80 (ten stories), 225, 375, 120 (fifteen stories) and 300, 500, 160 (twenty stories)

- Number of zipper braces: 56 (five stories), 116 (ten stories), 176 (fifteen stories) and 236 (twenty stories)

- Loads: dead, live, wind load and perimeter wall loadings (Table 3.1)

Since the speed and direction of wind are always changing, the exact direction of pressure or suction applied by the wind to the structure is difficult to determine. Thus, some assumptions for each asymmetrical plan structure have been made.

These assumptions are in such a way that each structure is exposed to wind loads in X and Y directions (Fig 4.22).

- Maximum allowable displacement: 63.3 mm for 5thstorey, 125.84 mm for 10th storey, 188.34 mm for 15th storey, 250.84 mm for 20th storey

Two wind directions (X and Y) were considered in each design. Despite the fact that plans of the structures are not symmetrical, each experiment has been analyzed and designed by ETABS software for two wind loads W_1 (W_x and $W_{y)}$ and W_2 (W_x and W_y) on structures with cross bracings at core and at central bay (Table 4.9).

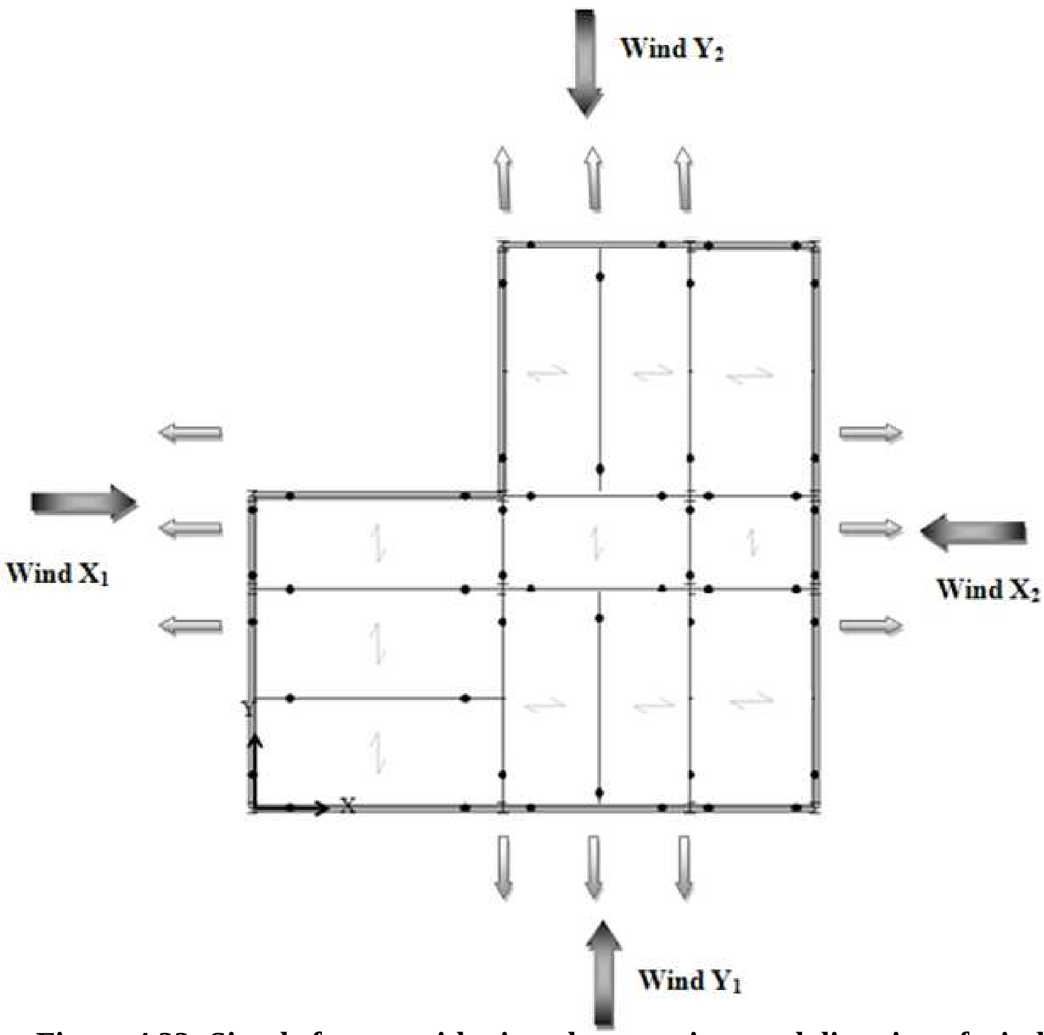


Figure 4.22: Simple frames with pinned connections and direction of winds for asymmetrical plan and symmetrical section.

Table 4.9: Total weight of core and central bay cross bracings (a) W_1 and (b) W_2 for asymmetrical plan and symmetrical section.

W_1	Brace Sections/No. of Stories	5	10	15	20
Central bay cross bracing					
Total Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	80.8	180.1	320.5	518.9
	Circular Hollow section	83.1	186.1	329.0	530.9
	I section	102.8	227.5	382.7	582.2
Core cross bracing					
Total Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	78.3	177.0	301.8	490.5
	Circular Hollow section	81.2	181.2	311.7	495.7
	I section	96.0	221.6	365.7	750.6

(a)

W_2	Brace Sections/ No. of Stories	5	10	15	20
Central bay cross bracing					
Total Weight (ton)	Angle section	86.3	Failed	Failed	Failed
	Rectangular Hollow section	80.6	180.1	301.2	518.8
	Circular Hollow section	83.6	186.0	308.2	531.0
	I section	101.9	227.0	363.4	583.0
Core cross bracing					
Total Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	78.4	177.0	292.3	454.2
	Circular Hollow section	81.3	181.4	302.6	467.8
	I section	96.0	222.2	354.7	527.0

(b)

As a result of cross bracings being placed at the core and central bay of structure, the total weights of the structures were high when subjected to W_1 (Fig. 4.23).

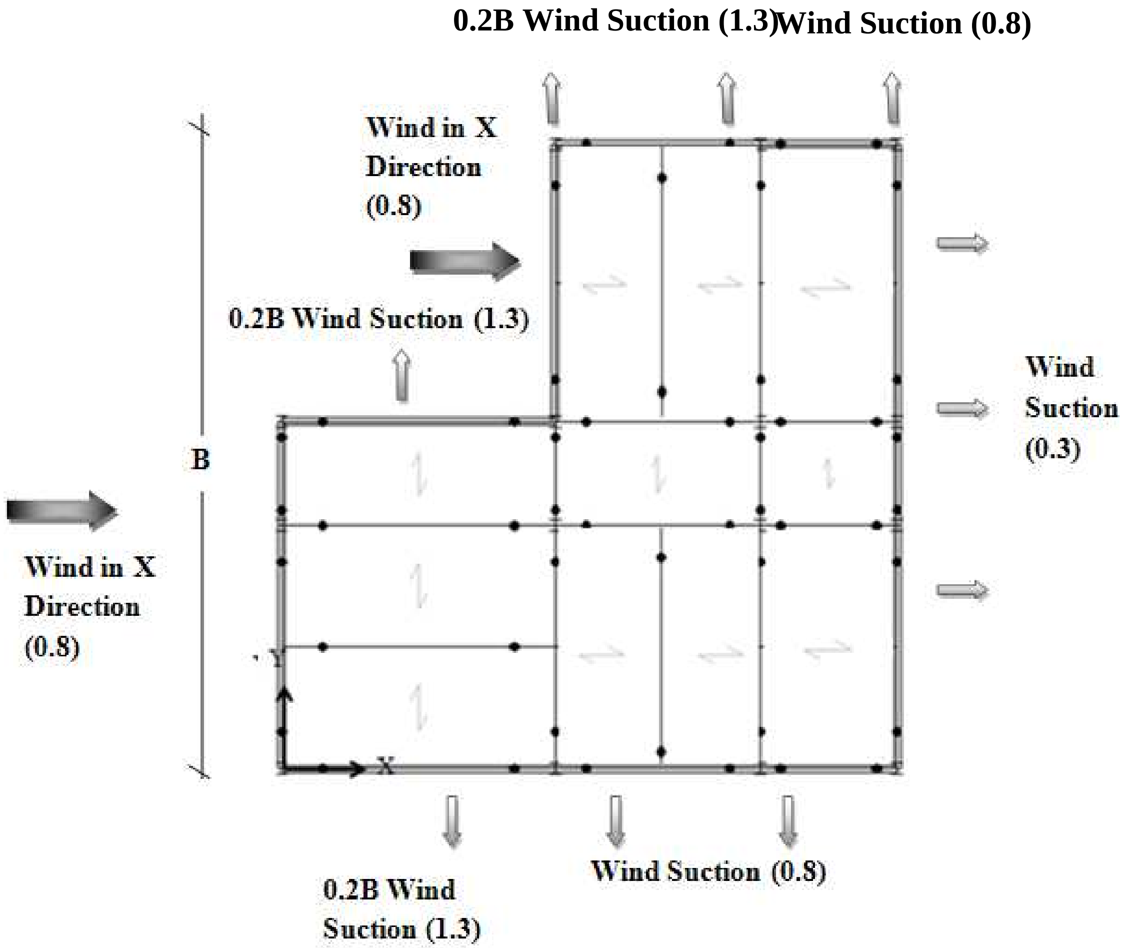


Figure 4.23(a): Building layout indicating wind in X direction with suctions for asymmetrical plan and symmetrical section.

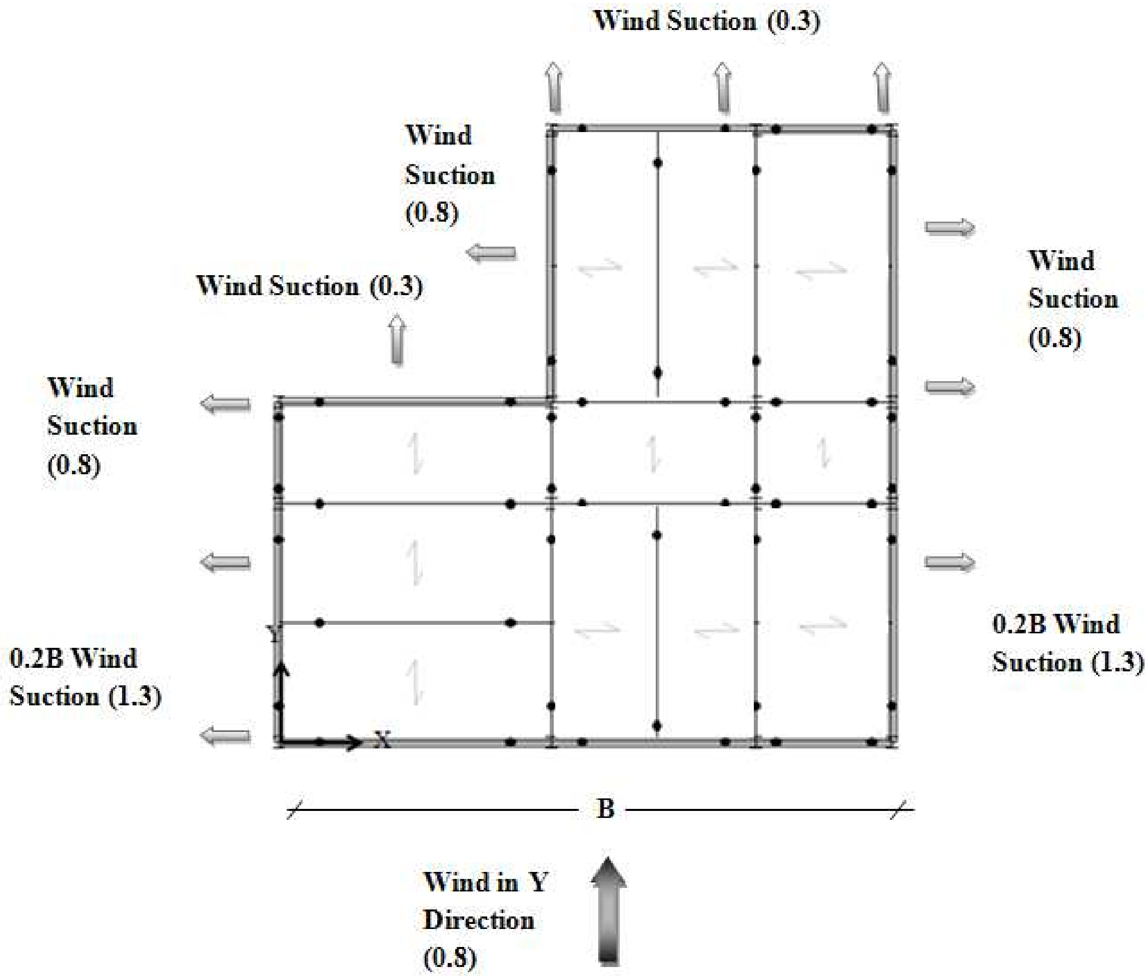


Figure 4.23(b): Building layout indicating wind in Y direction with suctions for asymmetrical plan and symmetrical section.

Since the weight of bracings are generally the controlling factor of the overall total weight of the structure and maximum lateral Displacement in X and Y directions is achieved when I section is used as bracing members, then from this point onwards the details of the column and beam weights and lateral displacements for each structure are given in Appendix C.

4.4.1 Perimeter Central Bay and Core Bracing

Figure 4.24 shows central bay bracings and core bracings for asymmetrical plan and symmetrical sections structures.

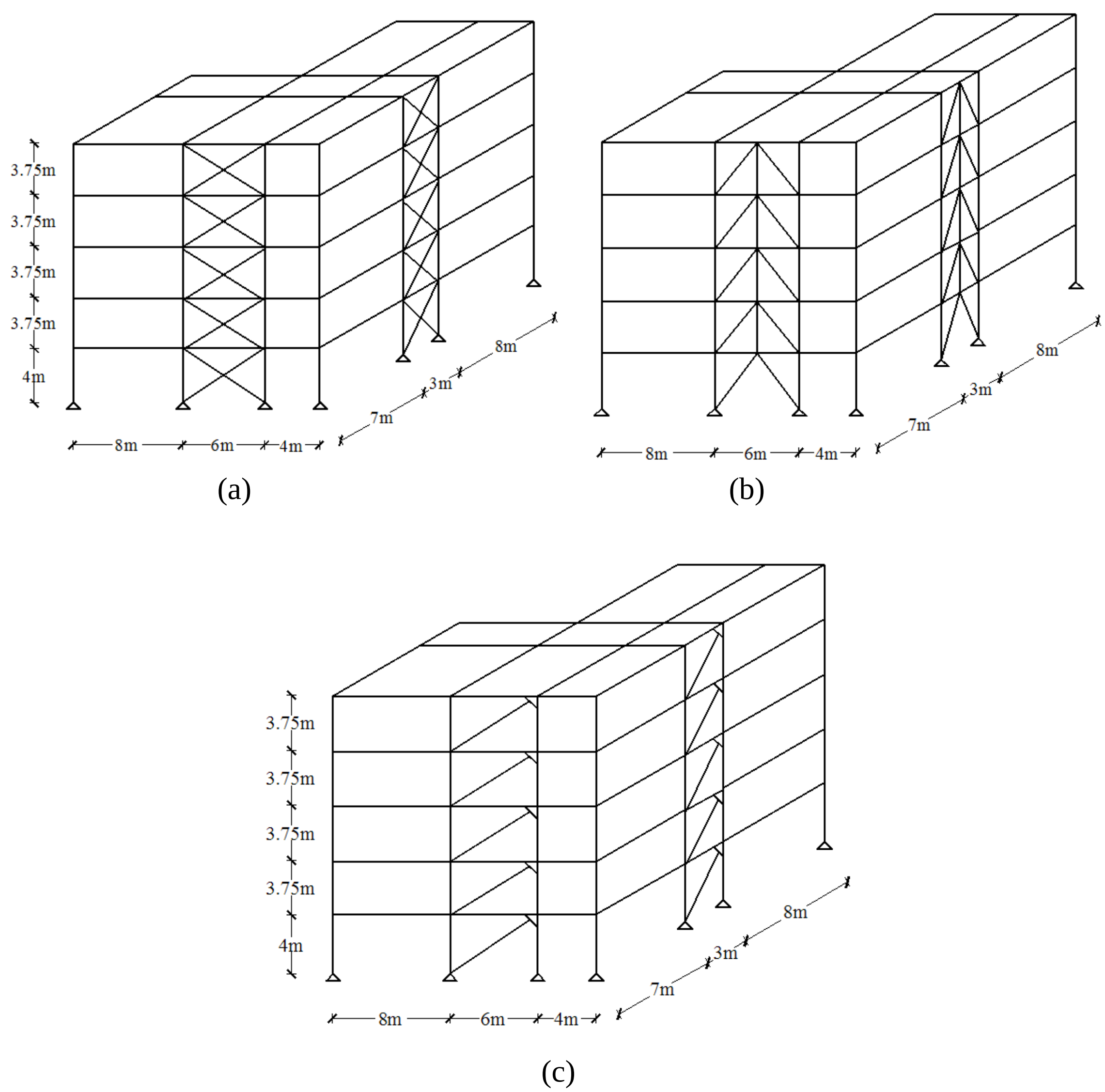
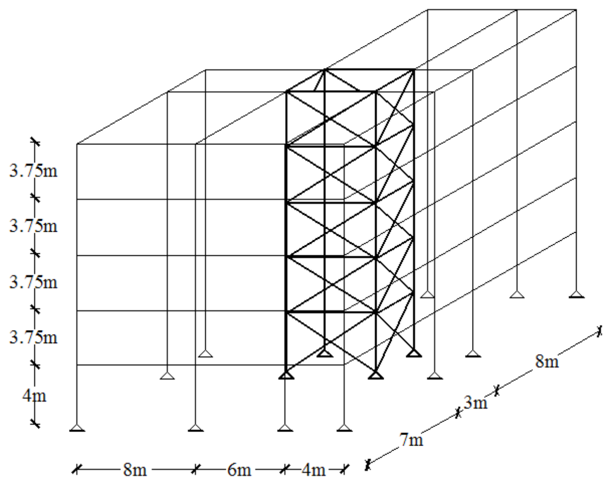
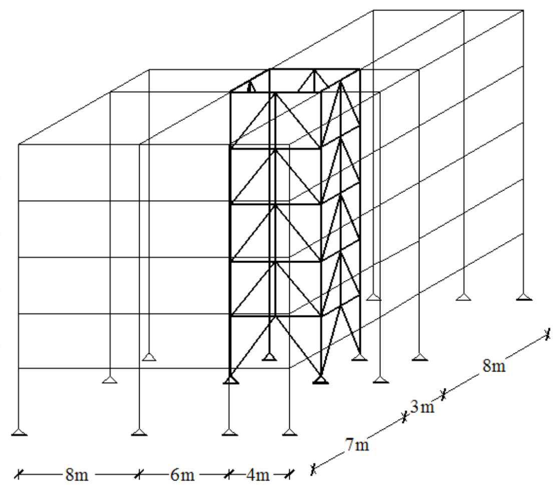


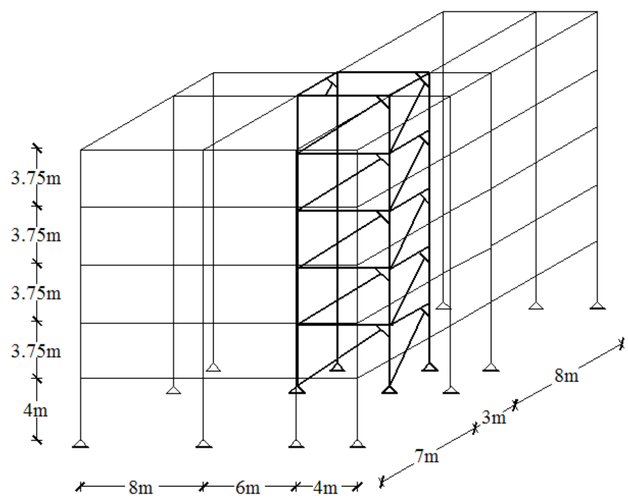
Figure 4.24: Asymmetrical Plan and Symmetrical Section central bays (a) cross (b) zipper (c) knee bracings.



(d)



(e)



(f)

Figure 4.24: Asymmetrical Plan and Symmetrical Section core (d) cross (e) zipper (f) knee bracings.

Table 4.10 shows the weights of braces and the total weights of the whole structure (ton) for varying number of stories and brace types at central bay and core with different steel profiles for braces subjected to wind load 1 (W_1).

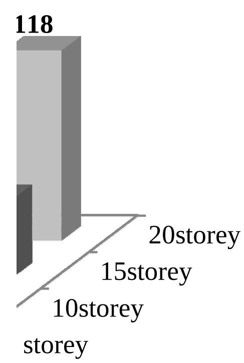
Table 4.10: Weights of braces and the overall total weight of different brace types and brace sections in the central bay and core of structure for asymmetrical plan and symmetrical section.

Asymmetrical Plan and Symmetrical Section		Central Bay Cross Bracing				Central Bay Zipper Bracing				Central Bay Knee Bracing			
Brace Weight (ton)	Brace Sections/No. of Stories	5	10	15	20	5	10	15	20	5	10	15	20
	Angle section	Failed	Failed	Failed	Failed	4.7	10.2	Failed	Failed	5.2	Failed	Failed	Failed
	Rectangular Hollow section	3.0	7.2	16.4	41.3	2.0	4.6	12.5	29.3	2.0	5.0	11.2	29.7
	Circular Hollow section	4.0	12.5	27.7	52.7	2.4	7.0	18.3	35.8	2.3	6.4	14.7	32.0
	I section	21.5	54.3	79.8	106.5	6.5	27.3	57.0	83.0	6.0	22.6	39.0	69.0
Difference between max and min (%)		**617.0**	**654.0**	**386.5**	**158.0**	**225.0**	**493.5**	**356.0**	**183.3**	**200.0**	**352.0**	**248.2**	**132.3**
Total Weight (ton)	Angle section	Failed	Failed	Failed	Failed	78.8	179	Failed	Failed	89.8	Failed	Failed	Failed
	Rectangular Hollow section	80.8	180.1	320.5	518.9	80.3	174.4	294.0	477.4	87.8	183.3	308.5	505.4
	Circular Hollow section	83.1	186.1	329.4	530.9	77.3	173.3	296.6	478.2	85.2	180.5	308.5	502.1
	I section	102.8	227.5	382.7	582.2	78.0	201.3	338.3	527.3	84.8	198.7	329.6	537.2
Difference between max and min (%)		**27.2**	**26.3**	**19.4**	**12.2**	**4.0**	**16.0**	**15.0**	**10.5**	**6.0**	**10.0**	**6.8**	**7.0**
Asymmetrical Plan and Symmetrical Section		**Core Cross Bracing**				**Core Zipper Bracing**				**Core Knee Bracing**			
Brace Weight (ton)	Brace Sections/No. of Stories	5	10	15	20	5	10	15	20	5	10	15	20
	Angle section	Failed	Failed	Failed	Failed	4.8	Failed	Failed	Failed	5.3	Failed	Failed	Failed
	Rectangular Hollow section	3.4	9.0	17.4	46.3	2.3	6.5	20.5	68.3	2.3	7.0	19.0	80.8
	Circular Hollow section	4.0	13.5	27.4	51.0	3.3	11.2	29.8	46.0	3.8	9.9	30.5	102.8
	I section	16.2	53.4	82.2	260.8	7.5	31.4	55.1	78.2	10.4	30.8	48.4	118.0
Difference between max and min (%)		**376.5**	**494.0**	**372.4**	**463.3**	**226.0**	**383.0**	**168.8**	**70.0**	**352.2**	**340.0**	**154.7**	**46.0**
Total Weight (ton)	Angle section	Failed	Failed	Failed	Failed	80.2	Failed	Failed	Failed	84.6	Failed	Failed	Failed
	Rectangular Hollow section	78.3	177.0	301.8	490.5	81.5	169.8	311.5	530.7	84.7	178.4	320.2	562.5
	Circular Hollow section	81.2	181.2	311.7	495.7	77.4	175.7	323.5	488.3	82.3	175.7	332.1	575.0
	I section	96.0	221.6	365.7	750.6	80.7	199.0	339.5	524.1	86.3	203.5	353.2	583.8
Difference between max and min (%)		**22.6**	**25.2**	**21.2**	**53.0**	**5.3**	**17.2**	**9.0**	**8.6**	**4.8**	**15.8**	**10.3**	**3.8**

4.4.2 Comparison of Asymmetrical Plan and Symmetrical Section

For high rise buildings located in the regions where high winds are common, designers must give high priority to the preliminary design phase to select structural system and steel sections for its beams, columns and braces that resist lateral loads efficiently. These selections must be carried out in such a way that the steel frame has the minimum weight or cost while the behavior and performance of the structure is within the limitations described by the code of practice.

Figure 4.25 gives the comparison of maximum and minimum brace weights of cross, zipper and knee bracing types in the central bay and in the core of the steel structures



symmetrical

plan and symmetrical section.

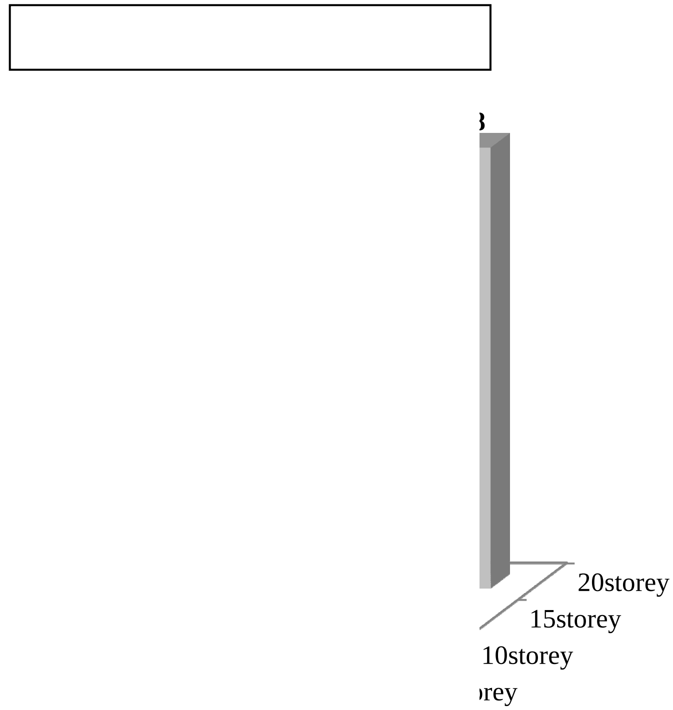


Figure 4.25(b): Comparison of minimum brace weights (ton) for asymmetrical plan and symmetrical section.

According to these results, generally the maximum and minimum brace weights were achieved when IS and RHS were used as bracing members, respectively.

From Figure 4.25 (a), central bay and core cross bracing has the maximum brace weight. On the other hand minimum brace weight is belonging to central bay knee brace. In fact, core zipper bracing has the minimum weight when compared to the results of core located braces.

Figure 4.25 (b) gives the minimum brace weight for brace members which have RHS as bracing members. The heaviest brace a weight for five to ten and fifteen to twenty stories belongs to core cross bracing and core knee bracing respectively, and the lightest brace weight belongs to central bay zipper bracing. Minimum core bracings belongs to core zipper brace for five to ten stories and core cross bracing for fifteen to twenty stories. In addition, maximum central bay brace is cross brace.

There are some differences between lateral displacement in X and Y directions in this stage, they cannot be divided in specific way for maximum and minimum lateral displacement for any of the sections. But approximate maximum value of displacement belongs to RHS and minimum for IS.

Figure 4.26 (a) and (b) shows the minimum lateral displacement in X and Y directions respectively where I Sections were used as bracing members.

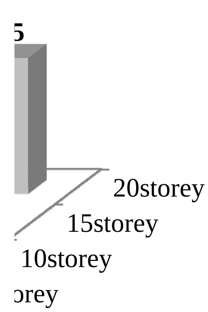


Figure 4.26(a): Comparison of minimum (I Section) lateral displacement (mm) in X direction for asymmetrical plan and symmetrical section.

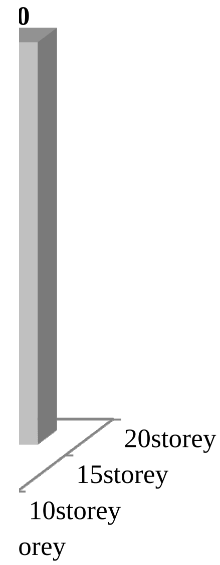


Figure 4.26(b): Comparison of minimum (I Section) lateral displacement (mm) in Y direction for asymmetrical plan and symmetrical section.

From Figure 4.26 (a), central bay knee bracing for five to fifteen stories and central bay cross bracing for 20th storey has the maximum lateral displacement in X direction. On the other hand minimum lateral displacement in X direction belongs to the core cross brace.

Overall, there is higher lateral displacement in Y direction due to columns being subject to bending about their minor axis.

4.5 Symmetrical Plan and Asymmetrical Section

If optimization can be considered as the search for the “perfect design”, different techniques may be used to be able to reach the optimum point. Certainly this point cannot be reached, because it is impossible to get an optimum design under all points of view; however it is the idea or assumption that may give the best position of different types of braces in different locations of steel structures to determine the optimum weight and lateral displacement when the structure is exposed to wind loads.

The following are the details of the structural system and the designs considerations for the multi-storey buildings:

- Number and the total length of bays: 3 bays (18 m)
- Structural stories and heights: 5 stories (19 m), 10 stories (37.75 m), 15 stories (56.5 m) and 20 stories (75.25 m)
- Bay widths: 6m
- Types of braces: cross, zipper and knee brace
- Four types of steel profiles are used as bracing members: Universal Angle section (UA), Rectangular Hollow Section (RHS), Circular Hollow Section (CHS) and I Section (IS) or Universal Column sections (UC)
- Location of the braces: center of the bays and at the core of the structure

- Connections: simple frame structure where beam to column, beam to beam, brace to beam/column are pinned connections and columns are continuous

- Steel profiles for columns and beams: Universal Column sections (UC), Universal Beam sections (UB) are adopted for beams and columns of the frame respectively

- Spacing of the secondary beams: 3m

- The value of x for all knee braced structure: 0.2m

- Number of columns, beams and cross or knee braces respectively: 70, 139, 40 (five stories), 150, 304, 80 (ten stories), 230, 469, 120 (fifteen stories) and 310, 634, 160 (twenty stories)

- Number of zipper braces: 56 (five stories), 116 (ten stories), 176 (fifteen stories) and 236 (twenty stories)

- Loads: dead, live, wind load and perimeter wall loadings (Table 3.1)

Since the speed and direction of wind are always changing, the exact direction of pressure or suction applied by wind onto the structure is difficult to determine. Thus, some assumptions for each symmetrical plan and asymmetrical section structure have been made. These assumptions are in such a way that each structure is exposed to wind loads in X and Y directions (Fig 4.27).

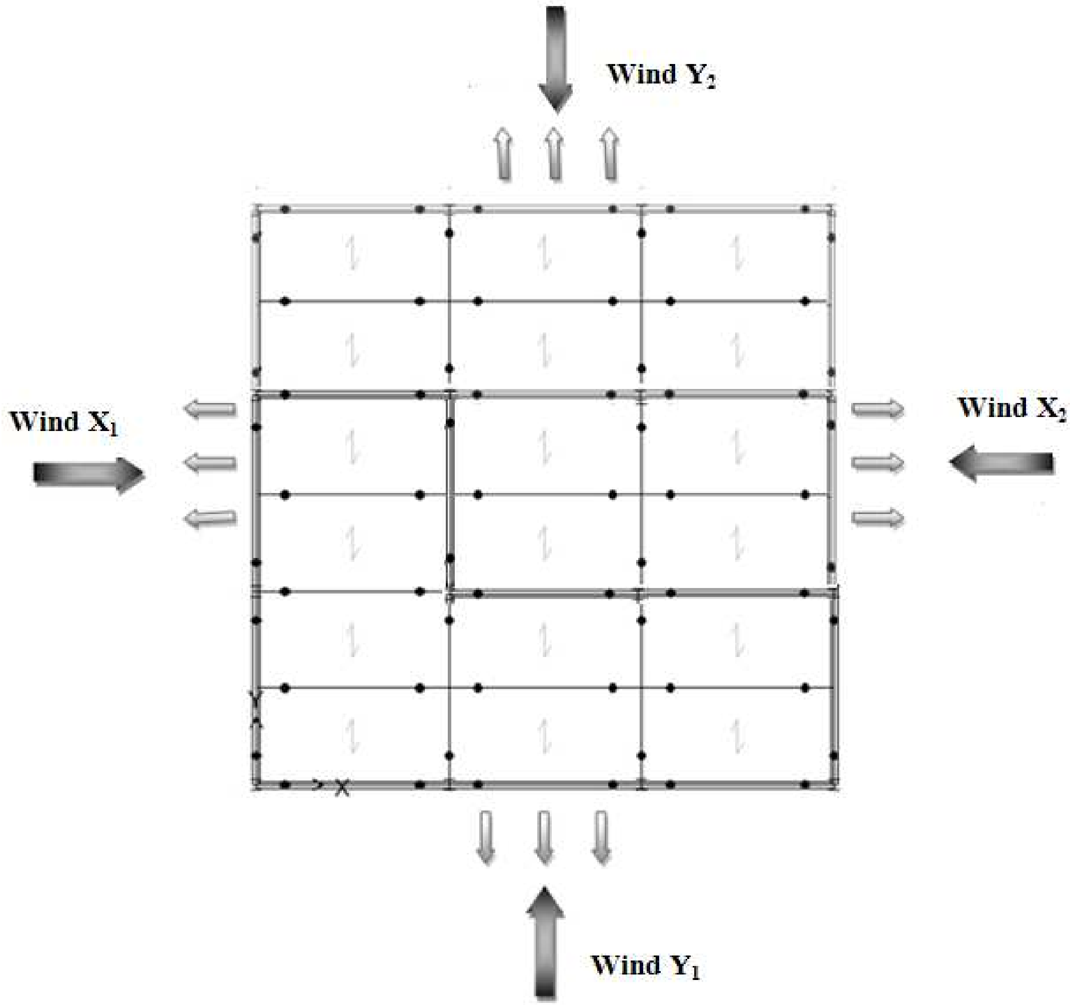


Figure 4.27: Simple frames with pinned connections and direction of winds (top view plan) for symmetrical plan and asymmetrical section.

- Maximum allowable displacement for each storey: 63.3 mm (5^{th}storey), 125.84 mm (10^{th} storey), 188.34 mm (15^{th} storey), 250.84 mm (20^{th} storey)

Two wind directions (X and Y) were considered in each design. In spite of the fact that sections of the structures are not symmetrical, each experiment has been analyzed and designed for two designs exposed wind loads W_1 (W_x and W_y) and W_2 (W_x and W_y) for core and central bay cross bracings (Table 4.11).

Table 4.11: Total weight of core and central bay cross bracings (a) W_1 and (b) W_2 for symmetrical plan and asymmetrical section.

W_1	Brace Sections/No. of Stories	5	10	15	20
Central bay cross bracing					
Total Weight (ton)	Angle section	85.0	Failed	Failed	Failed
	Rectangular Hollow section	79.6	188.8	311.0	449.7
	Circular Hollow section	77.0	189.4	317.4	464.7
	I section	92.0	234.4	403.0	570.0
Core cross bracing					
Total Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	77.3	184.1	301.2	436.0
	Circular Hollow section	75.8	186.0	309.4	453.2
	I section	90.7	227.3	392.0	552.4

(a)

W_2	Brace Sections/No. of Stories	5	10	15	20
Central bay cross bracing					
Total Weight (ton)	Angle section	85.2	Failed	Failed	Failed
	Rectangular Hollow section	80.0	19.0	311.0	450.0
	Circular Hollow section	76.9	189.6	316.6	464.6
	I section	92.7	234.4	400.3	570.0
Core cross bracing					
Total Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	77.3	185.0	301.3	436.0
	Circular Hollow section	77.3	187.0	308.8	455.0
	I section	90.3	226.0	391.7	553.2

(b)

As a result comparing the core and central bay cross bracings, total weight of structures were generally equal when structures subjected to W_1 and W_2.

Symmetrical plan and asymmetrical section structural systems are generated in this category, the details of wind load (W_1) for the central bays and core cross bracing are in Figure 4.28.

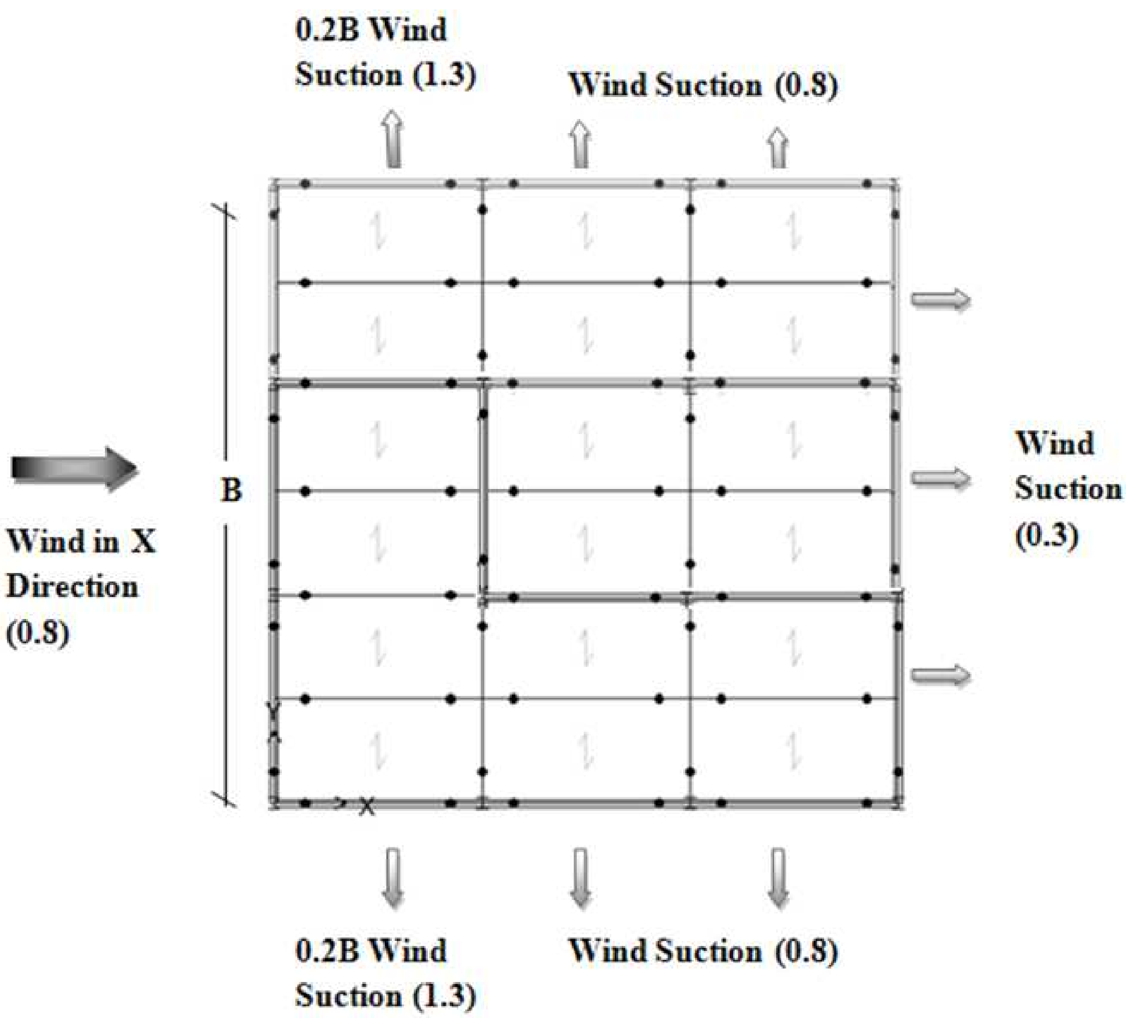


Figure 4.28(a): Building layout indicating wind in X direction with suctions for symmetrical plan and asymmetrical section.

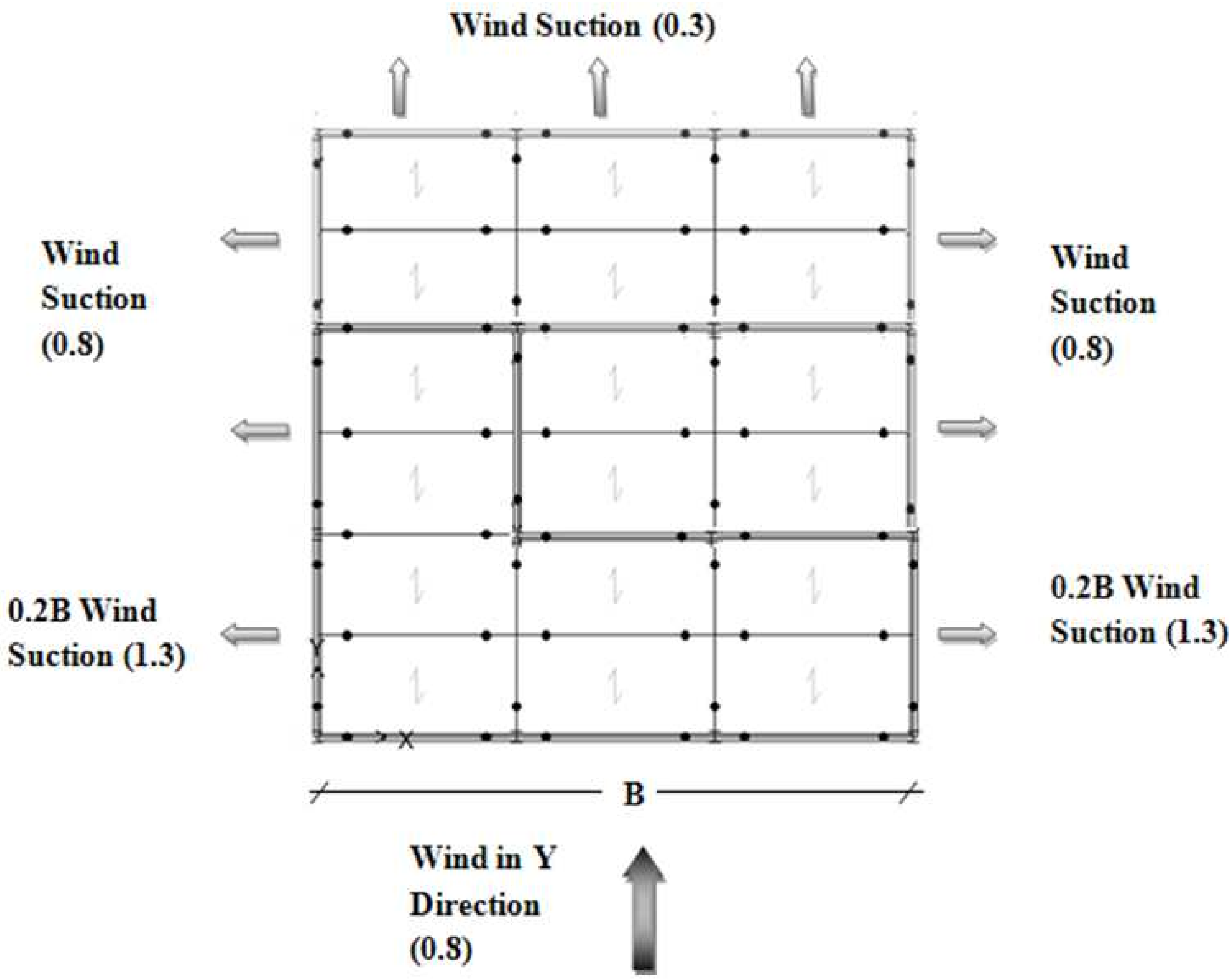


Figure 4.28(b): Building layout indicating wind in Y direction with suctions for symmetrical plan and asymmetrical section.

Since the weights of bracings are generally the controlling factors of the overall total weight of the structure and maximum lateral displacement in X and Y directions achieved when I sections are used as bracing members, then from this point onwards the details of the column and beam weights and lateral displacements for each structure are given in Appendix D.

4.5.1 Perimeter Central Bay and Core Bracing

In this stage the symmetrical plan and asymmetrical section building with cross, zipper and knee bracing in the central bay and core of the structures were used for analyses and design (Fig 4.29).

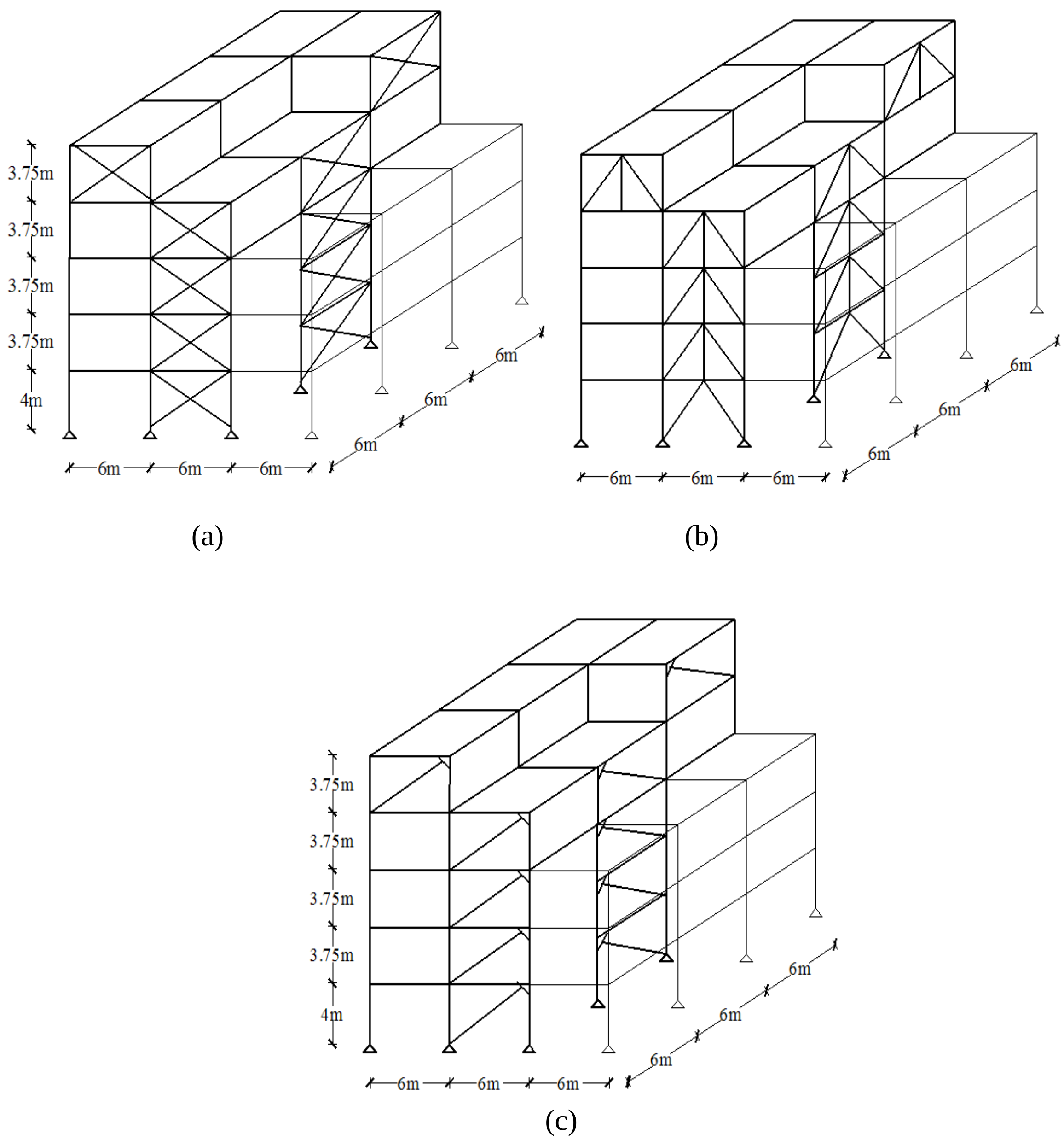
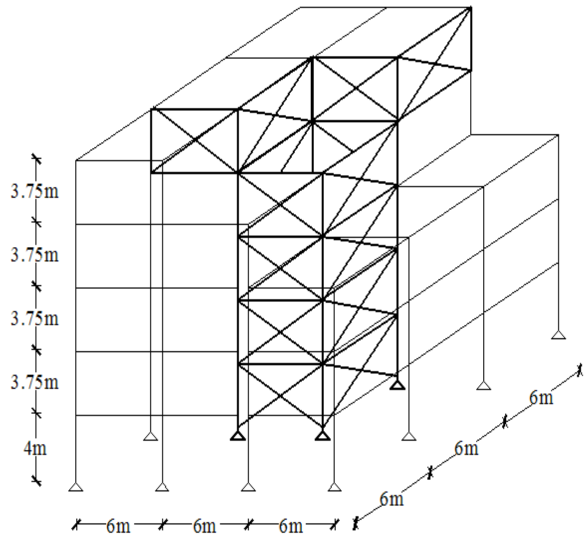
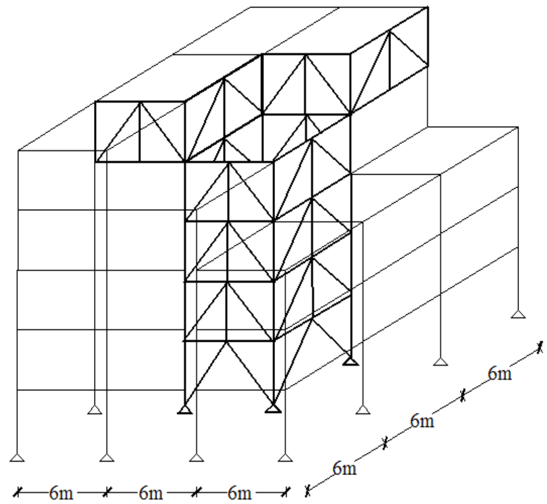


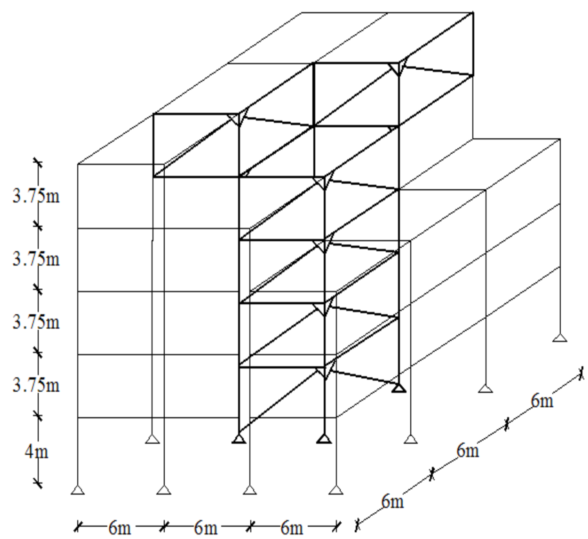
Figure 4.29: Symmetrical Plan and Asymmetrical Section central bays (a) cross (b) zipper (c) knee bracings.



(d)



(e)



(f)

Figure 4.29: Symmetrical Plan and Asymmetrical Section core (d) cross (e) zipper (f) knee bracings.

Table 4.12 shows the weight of brace and whole structure for varying number of stories and brace types with different steel profiles at central bay and core subjected to wind load 1 (W_1).

Table 4.12: Weights of braces and the overall total weight of different brace types and brace sections in the central bay and core of structure for symmetrical plan and asymmetrical section.

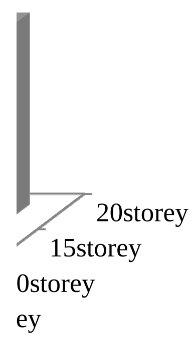
Symmetrical Plan and Asymmetrical Section		Core Cross Bracing				Core Zipper Bracing				Core Knee Bracing			
	Brace Sections/No. of Stories	5	10	15	20	5	10	15	20	5	10	15	20
Brace Weight (ton)	Angle section	Failed	Failed	Failed	Failed	6.0	Failed	Failed	Failed	7.3	Failed	Failed	Failed
	Rectangular Hollow section	4.2	10.5	17.0	25.8	2.6	6.4	9.5	14.0	3.3	6.6	11.0	17.0
	Circular Hollow section	4.2	13.0	25.2	44.0	3.8	8.2	13.8	21.0	3.8	9.3	15.3	22.0
	I section	18.4	56.8	109.3	145.0	8.5	27.5	48.0	83.3	9.8	21.3	39.8	57.2
Difference between max and min (%)		**338.0**	**441.0**	**550.0**	**462.0**	**227.0**	**329.7**	**405.3**	**495.0**	**197.0**	**222.7**	**261.8**	**236.5**
Total Weight (ton)	Angle section	Failed	Failed	Failed	Failed	72.6	Failed	Failed	Failed	83	Failed	Failed	Failed
	Rectangular Hollow section	77.3	184.0	301.2	436.0	71.0	174.4	285.4	413.2	79.5	177.3	295.8	435.0
	Circular Hollow section	75.8	186.0	309.4	453.2	71.0	174.8	289.0	419.0	75.0	180.5	303.2	438.2
	I section	90.7	227.3	392.0	552.4	75.0	196.0	328.6	494.2	82.0	194.8	325.5	470.6
Difference between max and min (%)		**19.6**	**23.5**	**30.0**	**26.7**	**5.6**	**12.4**	**15.0**	**19.6**	**10.7**	**9.8**	**10.0**	**8.2**

Symmetrical Plan and Asymmetrical Section		Core Cross Bracing				Core Zipper Bracing				Core Knee Bracing			
	Brace Sections/No. of Stories	5	10	15	20	5	10	15	20	5	10	15	20
Brace Weight (ton)	Angle section	Failed	Failed	Failed	Failed	6.0	Failed	Failed	Failed	7.3	Failed	Failed	Failed
	Rectangular Hollow section	4.2	10.5	17.0	25.8	2.6	6.4	9.5	14.0	3.3	6.6	11.0	17.0
	Circular Hollow section	4.2	13.0	25.2	44.0	3.8	8.2	13.8	21.0	3.8	9.3	15.3	22.0
	I section	18.4	56.8	109.3	145.0	8.5	27.5	48.0	83.3	9.8	21.3	39.8	57.2
Difference between max and min (%)		**338.0**	**441.0**	**550.0**	**462.0**	**227.0**	**329.7**	**405.3**	**495.0**	**197.0**	**222.7**	**261.8**	**236.5**
Total Weight (ton)	Angle section	Failed	Failed	Failed	Failed	72.6	Failed	Failed	Failed	83	Failed	Failed	Failed
	Rectangular Hollow section	77.3	184.0	301.2	436.0	71.0	174.4	285.4	413.2	79.5	177.3	295.8	435.0
	Circular Hollow section	75.8	186.0	309.4	453.2	71.0	174.8	289.0	419.0	75.0	180.5	303.2	438.2
	I section	90.7	227.3	392.0	552.4	75.0	196.0	328.6	494.2	82.0	194.8	325.5	470.6
Difference between max and min (%)		**19.6**	**23.5**	**30.0**	**26.7**	**5.6**	**12.4**	**15.0**	**19.6**	**10.7**	**9.8**	**10.0**	**8.2**

4.5.2 Comparison of Asymmetrical Plan and Symmetrical Section

Figure 4.30 (a) and (b), gives the comparison of maximum (I Section) and minimum (Rectangular Hollow Sections) brace weights of cross, zipper and knee bracing types for 5, 10, 15 and 20 storey buildings in the central bay and core of the steel structures respectively.

Figure 4.31 (a) and (b) gives the minimum lateral displacement in X and Y directions (I Section) respectively.



ymmetrical plan
and asymmetrical section.

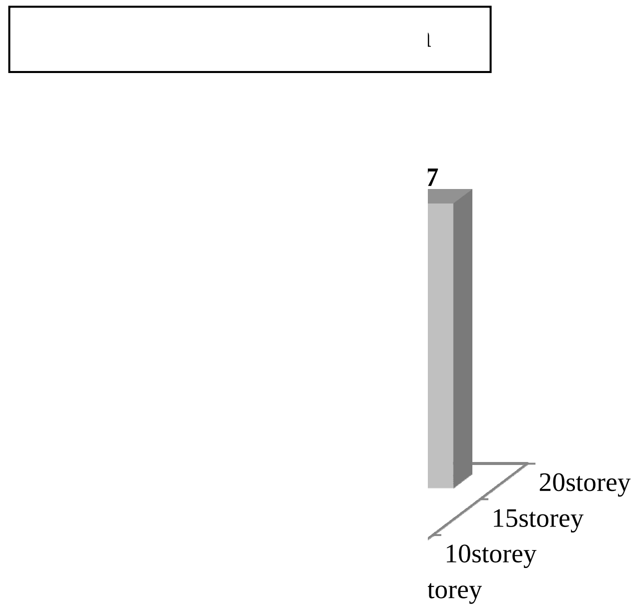
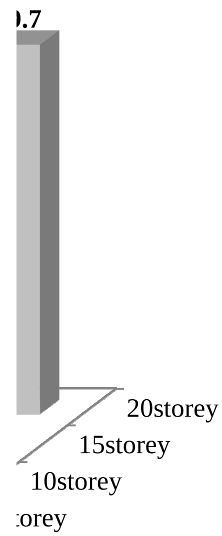


Figure 4.30(b): Comparison of minimum brace weights (ton) for symmetrical plan and asymmetrical section.

From Figure 4.30 (a), central bay cross bracing has the maximum weight whilst the core cross bracing has highest weight when compared to the result of the core bracings. On the other hand central bay zipper brace for 5 and 10 stories has minimum brace weight and core knee brace has the minimum brace weight for 15th and 20th stories.



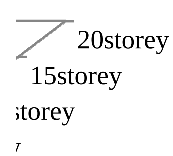


Figure 4.31: Comparison of minimum (I Section) lateral displacement (mm) in (a) X and (b) Y direction for symmetrical plan and asymmetrical section.

From Figure 4.31 (a) and (b) indicate that, central bay and core knee brace has the maximum lateral displacement in both X and Y directions. On the other hand minimum lateral displacement in X and Y directions belong to the central bay and core cross bracing.

Overall, there is higher lateral displacement in Y direction due to columns being subject to bending about their minor axis.

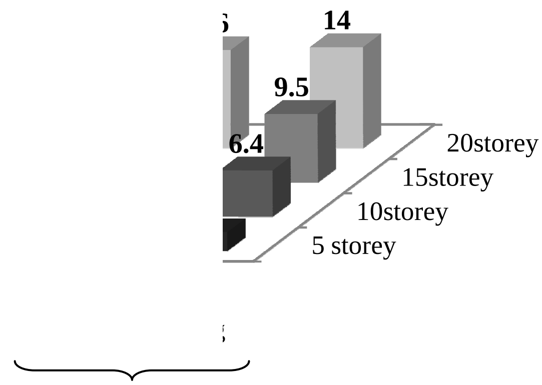
CHAPTER 5

RESULTS AND CONCLUSION

5.1 Results

This study compares the results of the analysis and design of multi-storey steel frames with different bracing systems in terms of their steel weights and lateral deflections. The ETABS software allows the member grouping and selects the required steel sections for beams, columns and bracing members from a set of standard steel sections. This approach is practical due to the fact that it applies serviceability and strength requirements for the frame as specified in BS 5950.

Result indicate that the zipper bracing system at the core and central bay of structure with Rectangular Hollow Sections steel profile produces the lightest frame among those considered in this study (Fig. 5.1) and, the core and central bay cross bracing with I Sections achieved the heaviest frame (Fig 5.2). It is also observed that cross bracing and zipper bracing systems do not provide as much lateral displacement in X and Y directions as the knee bracing system with I Section steel profiles in such frames. However, the minimum lateral displacement achieved when I Sections were used as cross bracing members at core and central bay of structures in X and Y directions (Fig 5.3 and Fig 5.4).



symmetrical

Figure 5.1: The lightest brace weight for core and central bay zipper bracing with Rectangular Hollow Sections steel profile (ton).

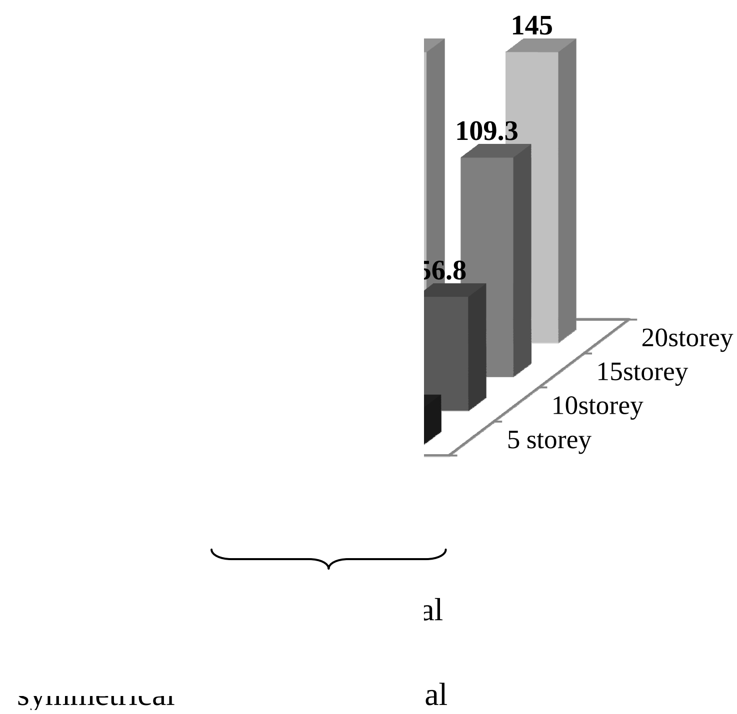


Figure 5.2: The heaviest brace weight for core and central bay cross bracing with I Sections steel profile (ton).

Figure 5.1 shows that core zipper bracing for asymmetrical plan and symmetrical section has the maximum weight whilst the central bay zipper brace for asymmetrical plan and section has the maximum weight when compared to the result of central bay bracings. On the other hand core and central bay zipper brace for symmetrical plan and section has the minimum brace weight.

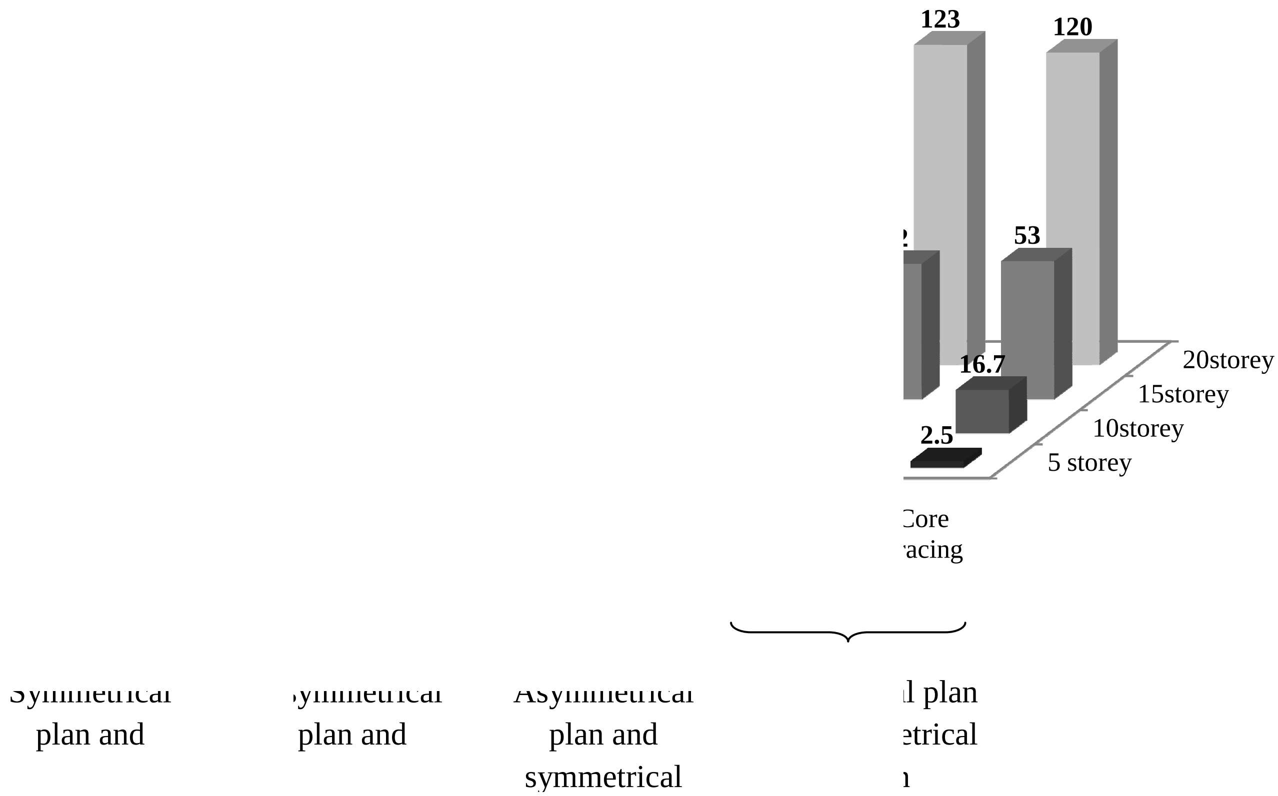


Figure 5.3: The minimum lateral displacement in X direction for core and central bay cross bracing with I Sections steel profile (mm).

Figure 5.3 and 5.4 shows the minimum lateral displacement in X and Y directions respectively. Central bay cross bracing for symmetrical plan and section and asymmetrical plan and symmetrical section have maximum lateral displacement in X direction while core cross bracing for asymmetrical plan and section and asymmetrical plan and symmetrical section have minimum lateral displacement in X direction.

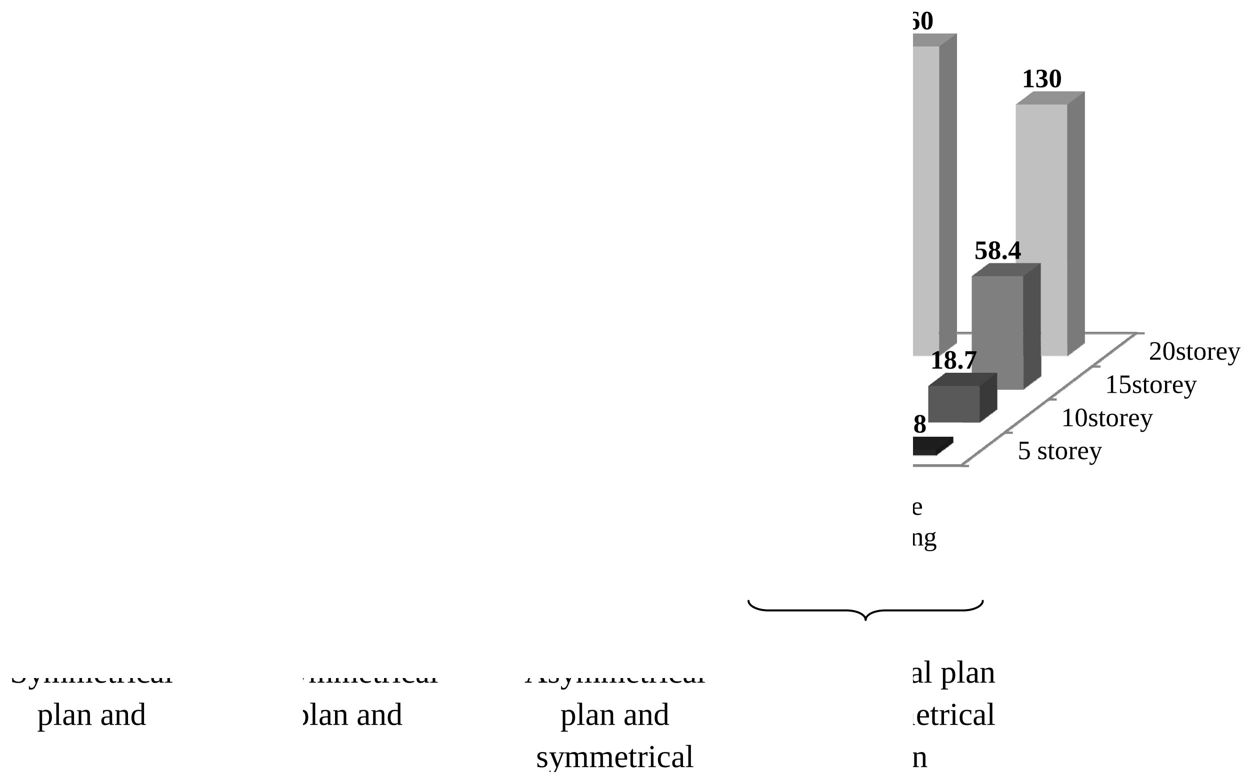


Figure 5.4: The minimum lateral displacement in Y direction for core and central bay cross bracing with I Sections steel profile (mm).

Core cross bracing for symmetrical plan and section and symmetrical plan and asymmetrical section have minimum lateral displacement in Y direction. Comparing Figure 5.3 and 5.4, there is higher lateral displacement in Y direction due to columns being subject to bending about their minor axis.

5.2 Conclusion

The following are the conclusions drawn from the results obtained from this research.

1. Universal Columns are heavy sections. Therefore, they made the bracing system heavy particularly for the low rise buildings with 5 and 10 stories. However, for the 15 and 20 stories buildings since the demand for bracing against lateral loads is more than their steel weight efficiency were higher.

2. Higher than required capacity of universal columns also controlled the lateral deflections in both X and Y directions better than the other steel profiles. However, it should be pointed out that lateral deflections for all other bracing sections were also less than the allowable by the BS 5950. So this can only be an added benefit in case a particular structural design requires bare minimum of lateral deflections.

3. Universal Angles did not perform well in comparison to other profiles. Therefore, it should not be considered for buildings more than 5 stories.

4. Hollow sections are known to be strong profiles both for axial loads and torsion. At the same time comparatively lighter than the other steel sections. This research indicated once again that hollow section profiles, circular and rectangular, generally performed well. Rectangular hollow section being the better one in terms of steel weight.

5. Results also indicated that there is a relationship between the shape of the plan layout and the weight efficiency of the steel system. Symmetrical plan and section provided the lightest section whilst asymmetrical plan and section caused the heaviest central bay bracing and the asymmetrical plan and symmetrical section caused the heaviest core bracing among all the bracing types. So clearly there is a link between the bracing weight efficiency and the layout of projects. Therefore, if engineers want to build an economical structure then the advice is that they should try to keep it symmetrical, if not then be ready to deal with steel profile variations.

5.3 Future Recommendations

The following are the recommendations for future research work:

1. Locating bracings at corner points and any other area in the building with more than three bays.

2. More buildings with different plans and sections can be analyzed and designed to expand on the variety in real life.

3. Use of iterative and non-iterative P-Delta effect.

4. Use of other types of brace sections.

5. Considering high rise structures, skyscrapers (structures with more stories).

6. Use of different direction of wind on structures.

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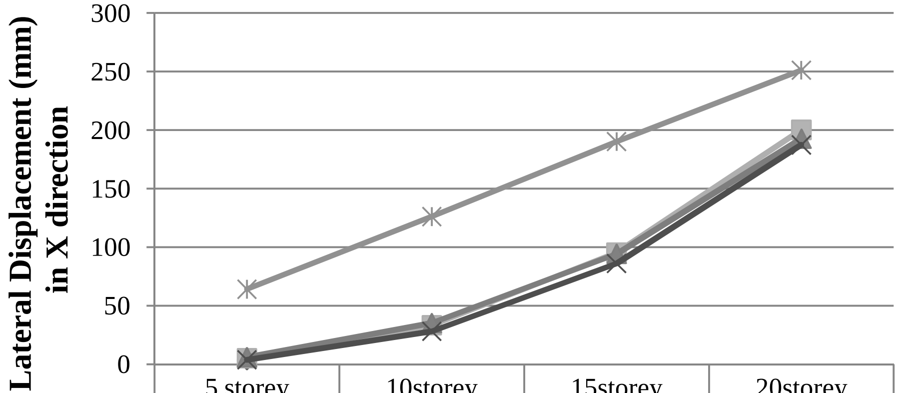
APPENDICES

APPENDIX A

Tables and Figures A give the weights of structural elements and lateral displacement in X and Y directions for symmetrical plan and section of the central bay and core bracing respectively.

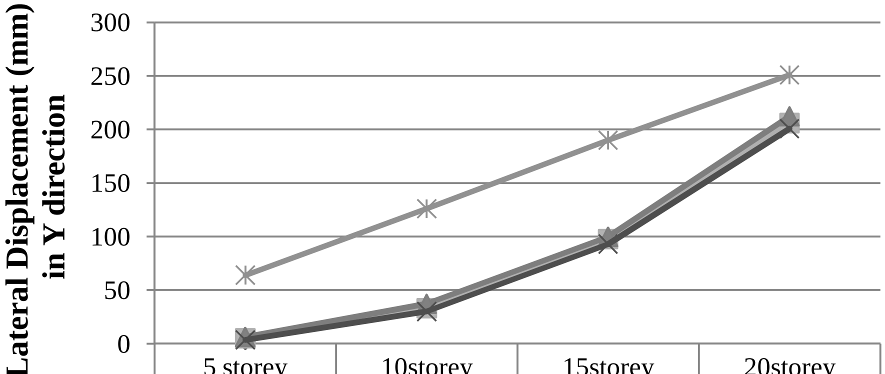
Table A.1: Weights of columns, beams, braces and total by having different steel brace sections for cross bracing in the central bay of structure for symmetrical plan and section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	14.6	Failed	Failed	Failed
	Rectangular Hollow section	15.8	45.7	93.3	162.3
	Circular Hollow section	13.9	45.0	92.6	160.6
	I section	13.6	44.3	92.7	158.6
Difference between max and min (%)		**16.2**	**3.2**	**0.7**	**2.3**
Beams Weight (ton)	Angle section	68.7	Failed	Failed	Failed
	Rectangular Hollow section	68.4	136.1	203.1	269.2
	Circular Hollow section	69.3	137.6	204.7	271.6
	I section	69.0	137.6	205.4	273.4
Difference between max and min (%)		**1.3**	**1.1**	**1.1**	**1.6**
Braces Weight (ton)	Angle section	15.1	Failed	Failed	Failed
	Rectangular Hollow section	4.2	9.4	15.8	22.7
	Circular Hollow section	4.2	9.2	18.8	33.6
	I section	16.6	48.5	73.2	93.9
Difference between max and min (%)		**295.3**	**427.2**	**363.3**	**313.6**
Total Weight (ton)	Angle section	98.5	Failed	Failed	Failed
	Rectangular Hollow section	88.5	191.3	312.3	454.2
	Circular Hollow section	87.4	191.8	316.1	465.8
	I section	99.1	230.4	371.4	525.9
Difference between max and min (%)		**13.4**	**20.4**	**19.0**	**15.8**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	3.6			
Rectangular Hollow section	5	33.2	95.2	200
Circular Hollow section	6	35.1	94.2	192.5
I section	3.8	28.1	86	187.2
Max	64	126	190	251

(a)



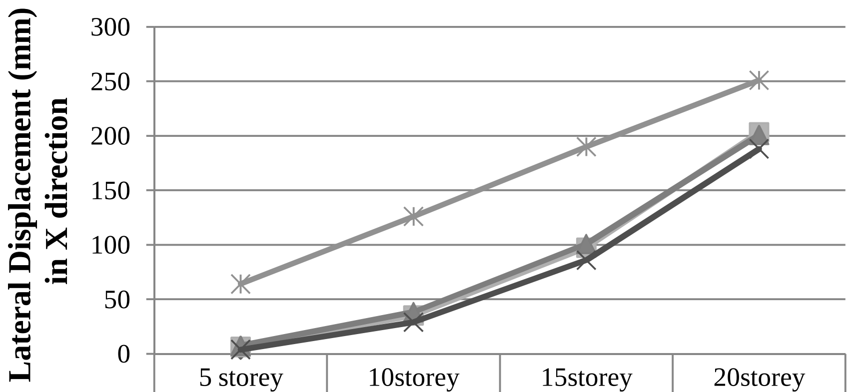
Brace sections	5 storey	10storey	15storey	20storey
Angle section	3.5			
Rectangular Hollow section	5.1	33.2	97.6	205.9
Circular Hollow section	6.2	37.2	99.7	212.2
I section	3.6	30	93	200.7
Max	64	126	190	251

(b)

Figure A.1: Lateral displacement (mm) in (a) X direction (b) Y direction for symmetrical plan and section, central bay cross brace.

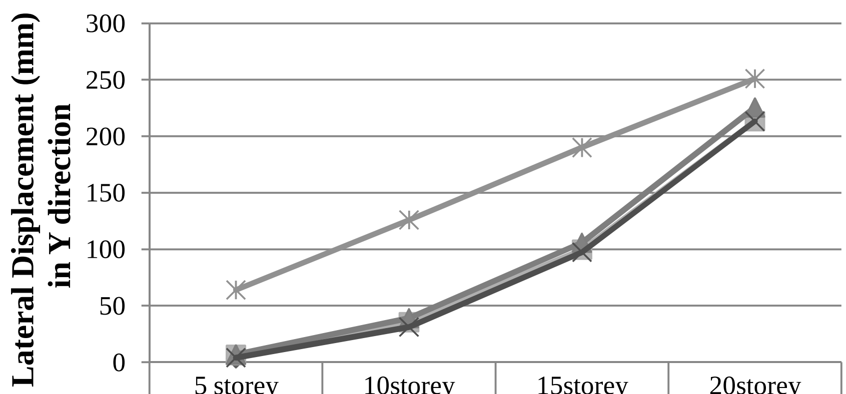
Table A.2: Weights of columns, beams, braces and total by having different steel brace sections for zipper bracing in the central bay of structure for symmetrical plan and section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	15.7	Failed	Failed	Failed
	Rectangular Hollow section	16.5	46.8	96.2	162.0
	Circular Hollow section	14.2	44.8	93.1	158.3
	I section	14.9	47.7	96.3	164.7
Difference between max and min (%)		**10.7**	**6.5**	**3.4**	**4.0**
Beams Weight (ton)	Angle section	65.5	Failed	Failed	Failed
	Rectangular Hollow section	65.7	129.7	193.3	254.5
	Circular Hollow section	64.2	130.0	192.2	253.8
	I section	64.2	130.2	193.6	255.0
Difference between max and min (%)		**2.3**	**0.4**	**0.7**	**0.4**
Braces Weight (ton)	Angle section	5.3	Failed	Failed	Failed
	Rectangular Hollow section	1.8	4.5	7.9	12.7
	Circular Hollow section	2.3	5.1	10.2	17.5
	I section	5.9	19.4	42.2	56.7
Difference between max and min (%)		**227.8**	**331.2**	**434.2**	**346.5**
Total Weight (ton)	Angle section	86.6	Failed	Failed	Failed
	Rectangular Hollow section	83.9	181.0	297.4	429.1
	Circular Hollow section	80.6	179.9	295.5	429.7
	I section	85.1	197.2	332.1	476.5
Difference between max and min (%)		**7.5**	**9.6**	**12.4**	**11.0**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	3.7			
Rectangular Hollow section	6.2	35	97.3	203.2
Circular Hollow section	7.4	38.3	100.8	200.7
I section	3.8	29	85.8	188
Max	64	126	190	251

(a)



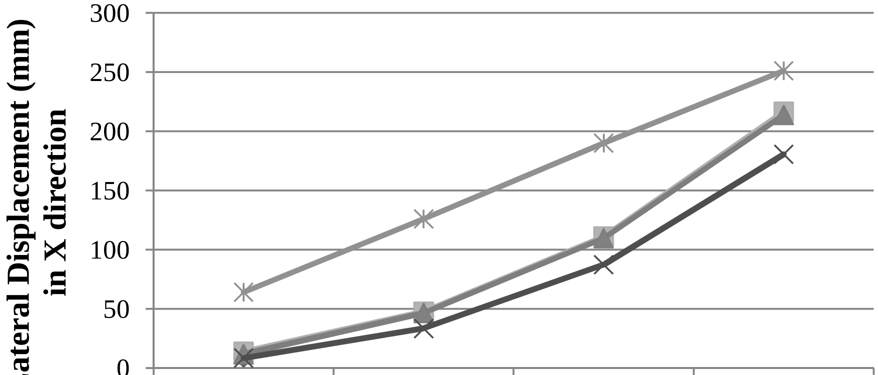
Brace sections	5 storey	10storey	15storey	20storey
Angle section	3.5			
Rectangular Hollow section	6.4	35.4	99.7	213.4
Circular Hollow section	6.8	39	105.7	225.4
I section	3.9	31.1	97.3	213.2
Max	64	126	190	251

(b)

Figure A.2: Lateral displacement (mm) in (a) X direction (b) Y direction for symmetrical plan and section, central bay zipper brace.

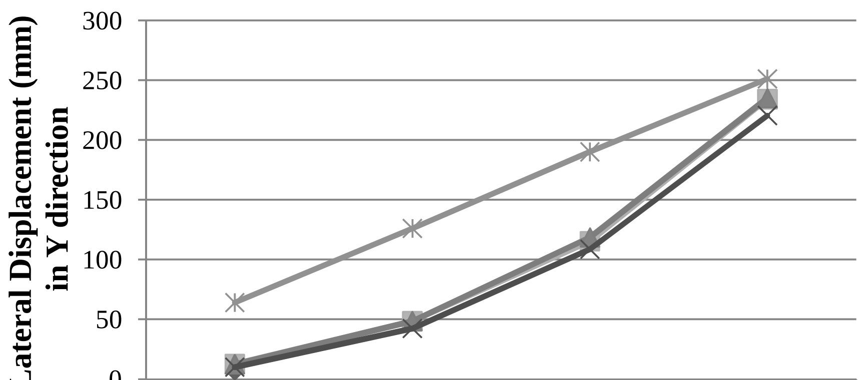
Table A.3: Weights of columns, beams, braces and total by having different steel brace sections for knee bracing in the central bay of structure for symmetrical plan and section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	19.8	Failed	Failed	Failed
	Rectangular Hollow section	19.8	51.8	100.0	170.2
	Circular Hollow section	16.5	47.9	98.2	166.3
	I section	17.2	48.9	98.0	163.3
Difference between max and min (%)		**20.0**	**8.1**	**2.0**	**4.1**
Beams Weight (ton)	Angle section	68.9	Failed	Failed	Failed
	Rectangular Hollow section	68.6	136.7	203.9	271.0
	Circular Hollow section	67.8	135.6	202.4	267.9
	I section	68.1	136.2	203.2	269.1
Difference between max and min (%)		**3.2**	**0.8**	**0.7**	**1.2**
Braces Weight (ton)	Angle section	7.3	Failed	Failed	Failed
	Rectangular Hollow section	2.4	5.9	10.5	16.0
	Circular Hollow section	2.5	6.2	11.5	19.3
	I section	5.6	15.5	30.8	50.8
Difference between max and min (%)		**204.2**	**162.7**	**193.4**	**217.5**
Total Weight (ton)	Angle section	96.1	Failed	Failed	Failed
	Rectangular Hollow section	91.0	194.4	314.4	457.2
	Circular Hollow section	86.9	189.8	312.2	453.6
	I section	91.0	200.7	332.0	483.2
Difference between max and min (%)		**10.6**	**5.7**	**6.3**	**6.5**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	8.9			
Rectangular Hollow section	13.7	47.6	111	216.5
Circular Hollow section	11.8	46.6	109.7	213.6
I section	8.5	33.4	87.3	180.5
Max	64	126	190	251

(a)



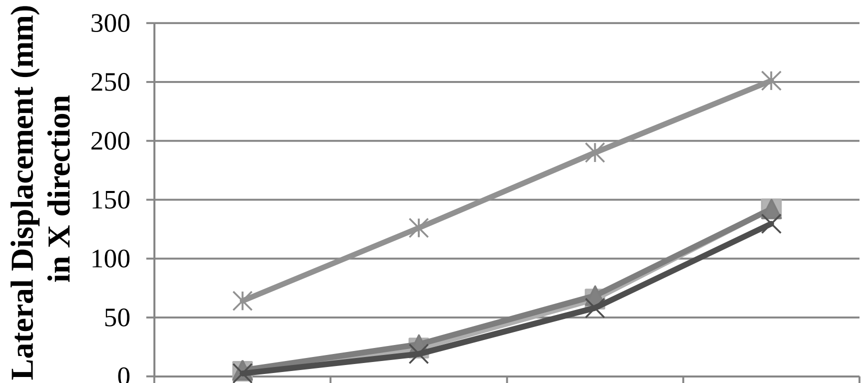
Brace sections	5 storey	10storey	15storey	20storey
Angle section	7.5			
Rectangular Hollow section	12.7	48.4	115.3	234.1
Circular Hollow section	12.5	48.6	118.5	235
I section	9.97	42.3	108.7	220.4
Max	64	126	190	251

(b)

Figure A.3: Lateral displacement (mm) in (a) X direction (b) Y direction for symmetrical plan and section, central bay knee brace.

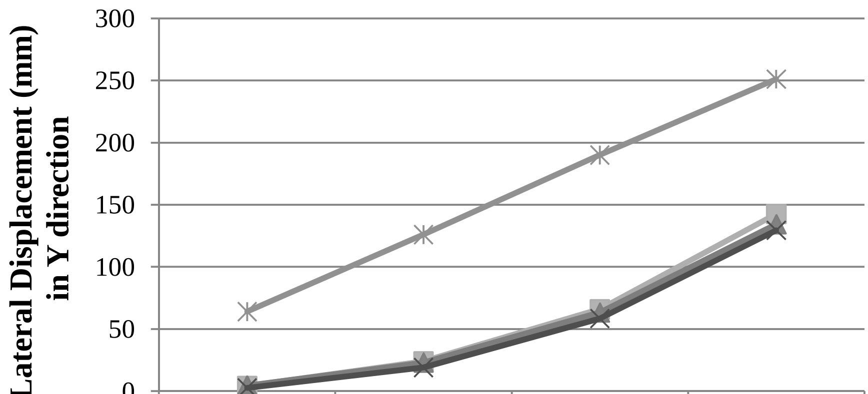
Table A.4: Weights of columns, beams, braces and total by having different steel brace profiles for cross bracing in the core of the structure for symmetrical plan and section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	15.4	43.8	87.9	149.5
	Circular Hollow section	14.8	43.3	87.3	148.0
	I section	13.4	41.7	83.3	143.0
Difference between max and min (%)		**15.0**	**5.0**	**5.5**	**4.5**
Beams Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	68.5	136.1	202.8	269.3
	Circular Hollow section	68.2	136.7	203.6	270.0
	I section	68.4	136.4	204.5	271.7
Difference between max and min (%)		**0.4**	**0.4**	**0.8**	**0.9**
Braces Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	4.3	10.0	16.3	23.0
	Circular Hollow section	4.6	12.4	23.3	37.0
	I section	19.1	52.1	93.7	127.8
Difference between max and min (%)		**344.2**	**421.0**	**475.0**	**455.6**
Total Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	88.2	190.0	307.2	441.8
	Circular Hollow section	87.6	192.4	314.2	455.0
	I section	101.0	230.3	381.6	542.5
Difference between max and min (%)		**15.3**	**21.2**	**24.2**	**22.8**



Brace sections	5 storey	10storey	15storey	20storey
Angle section				
Rectangular Hollow section	4.3	24	65.6	142.3
Circular Hollow section	5.1	27	68.5	142
I section	2.5	19.1	58	129.6
Max	64	126	190	251

(a)



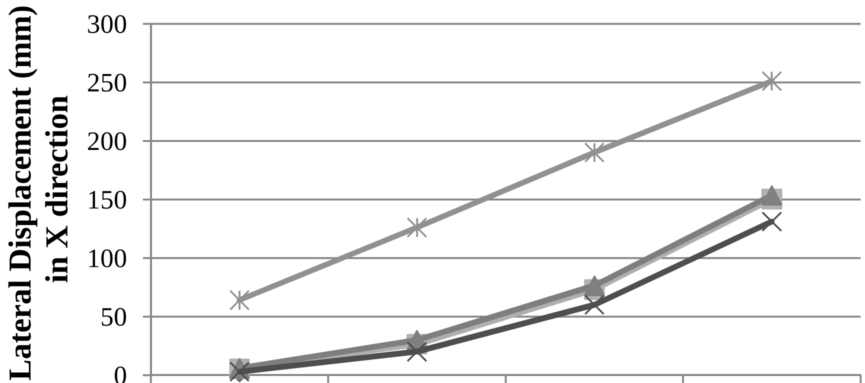
Brace sections	5 storey	10storey	15storey	20storey
Angle section				
Rectangular Hollow section	4.1	24	65.8	142.5
Circular Hollow section	4.4	23	63.3	134.3
I section	2.6	19	58.4	129.5
Max	64	126	190	251

(b)

Figure A.4: Lateral displacement (mm) in (a) X direction (b) Y direction for symmetrical plan and section, core cross brace.

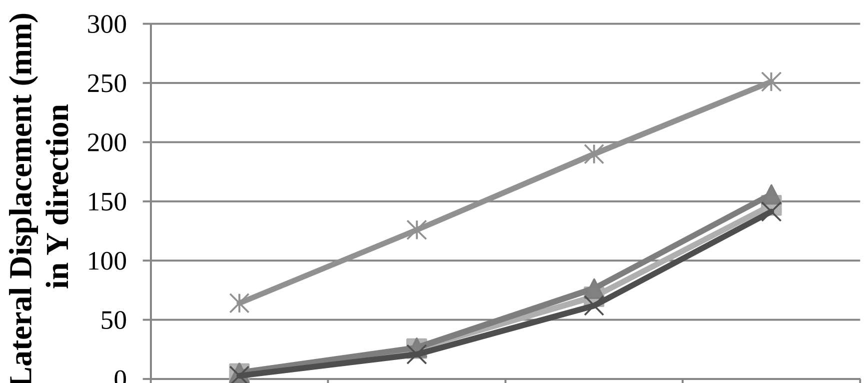
Table A.5: Weights of columns, beams, braces and total by having different steel brace sections for zipper bracing in the core of the structure for symmetrical plan and section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	15.7	Failed	Failed	Failed
	Rectangular Hollow section	16.0	47.0	89.5	149.5
	Circular Hollow section	15.0	43.5	88.2	149.2
	I section	15.0	47.8	94.4	156.2
Difference between max and min (%)		**6.7**	**9.9**	**7.0**	**4.7**
Beams Weight (ton)	Angle section	62.0	Failed	Failed	Failed
	Rectangular Hollow section	62.2	126.6	190.6	252.9
	Circular Hollow section	63.1	125.8	188.5	251.7
	I section	63.5	127.3	188.6	250.6
Difference between max and min (%)		**2.4**	**1.2**	**1.1**	**0.9**
Braces Weight (ton)	Angle section	6.0	Failed	Failed	Failed
	Rectangular Hollow section	2.3	5.4	8.5	13.1
	Circular Hollow section	2.5	6.3	10.3	15.3
	I section	7.8	20.6	34.8	56.6
Difference between max and min (%)		**239.0**	**281.5**	**309.4**	**332.0**
Total Weight (ton)	Angle section	84.0	Failed	Failed	Failed
	Rectangular Hollow section	80.5	179.0	288.6	415.5
	Circular Hollow section	80.6	175.7	287.0	416.2
	I section	86.3	195.7	317.8	463.4
Difference between max and min (%)		**7.2**	**11.4**	**10.7**	**11.5**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	2.8			
Rectangular Hollow section	5.4	26.4	73	150.3
Circular Hollow section	5.8	30	76.3	153.4
I section	2.9	20	60	131
Max	64	126	190	251

(a)



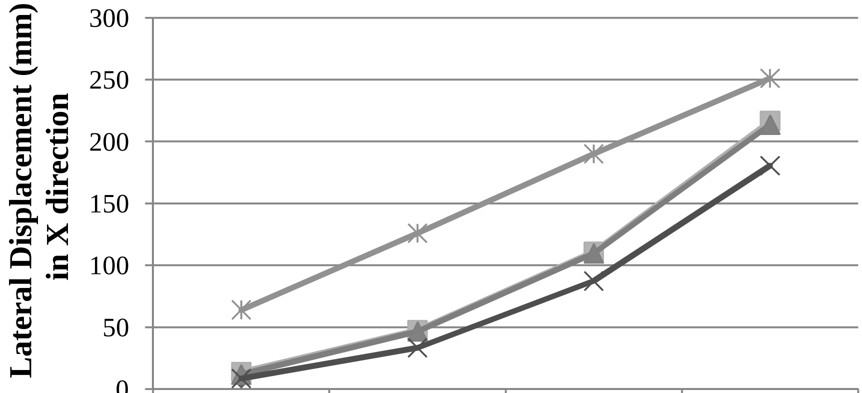
Brace sections	5 storey	10storey	15storey	20storey
Angle section	2.7			
Rectangular Hollow section	4.5	25.6	69.4	146.6
Circular Hollow section	5.3	26.6	76.5	156
I section	2.7	20.9	62	141.3
Max	64	126	190	251

(b)

Figure A.5: Lateral displacement (mm) in (a) X direction (b) Y direction for symmetrical plan and section, core zipper brace.

Table A.6: Weights of columns, beams, braces and total by having different steel brace sections for knee bracing in the core of structure for symmetrical plan and section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	17.9	Failed	Failed	Failed
	Rectangular Hollow section	18.1	48.8	96.4	161.6
	Circular Hollow section	16.7	48.8	96.3	160.6
	I section	16.9	49.0	96.4	160.8
Difference between max and min (%)		**8.4**	**0.4**	**0.1**	**0.6**
Beams Weight (ton)	Angle section	67.1	Failed	Failed	Failed
	Rectangular Hollow section	67.7	134.4	200.2	266.2
	Circular Hollow section	66.6	132.8	197.4	261.5
	I section	66.6	132.2	196.8	261.1
Difference between max and min (%)		**1.6**	**1.7**	**1.7**	**1.9**
Braces Weight (ton)	Angle section	7.5	Failed	Failed	Failed
	Rectangular Hollow section	2.5	6.2	10.7	16.4
	Circular Hollow section	2.7	6.3	11.2	17.2
	I section	5.9	15.3	25.9	38.3
Difference between max and min (%)		**200.0**	**146.8**	**131.2**	**133.5**
Total Weight (ton)	Angle section	92.5	Failed	Failed	Failed
	Rectangular Hollow section	88.3	189.4	307.4	444.1
	Circular Hollow section	86.1	187.8	304.9	439.3
	I section	89.3	196.5	319.1	460.2
Difference between max and min (%)		**7.4**	**4.6**	**4.6**	**4.7**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	8.9			
Rectangular Hollow section	13.7	47.6	111	216.5
Circular Hollow section	11.8	46.6	109.7	213.6
I section	8.5	33.4	87.3	180.5
Max	64	126	190	251

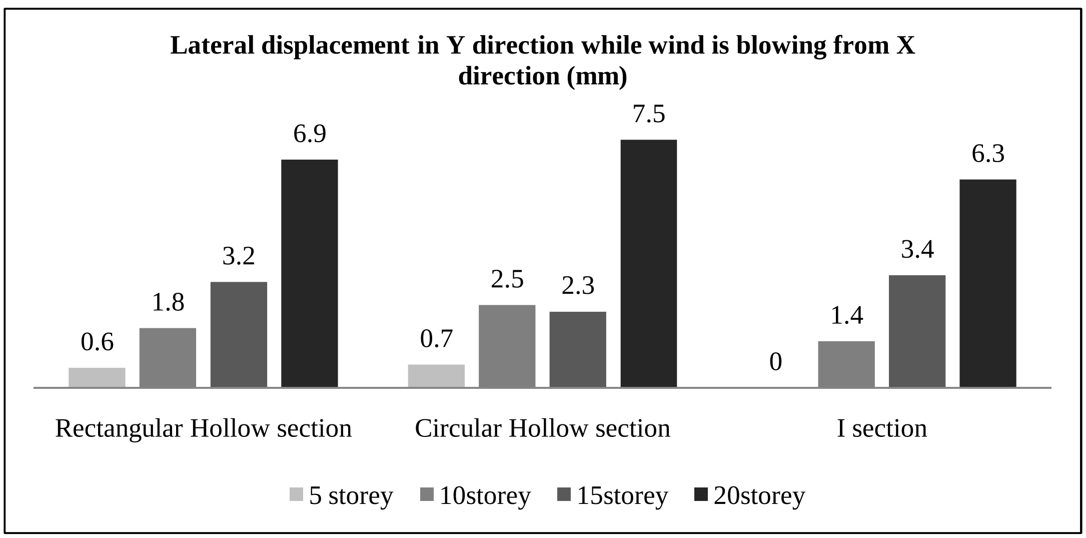
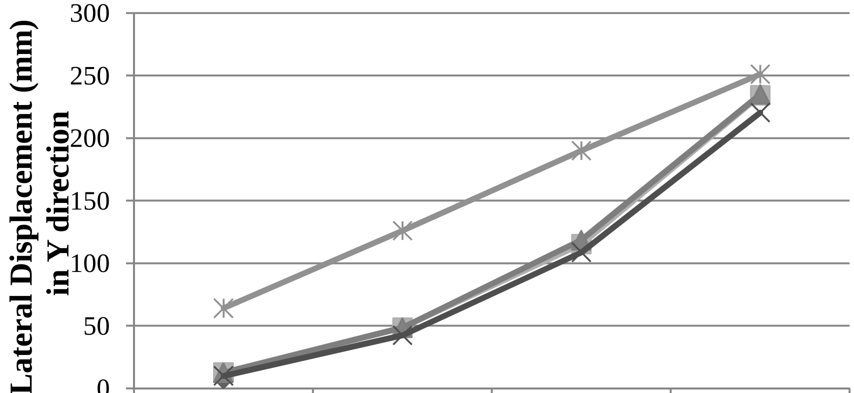


Figure A.6 (a): Lateral displacement (mm) in X direction for symmetrical plan and section, core knee brace.



Brace sections	5 storey	10storey	15storey	20storey
Angle section	7.5			
Rectangular Hollow section	12.7	48.4	115.3	234.1
Circular Hollow section	12.5	48.6	118.5	235
I section	9.97	42.3	108.7	220.4
Max	64	126	190	251

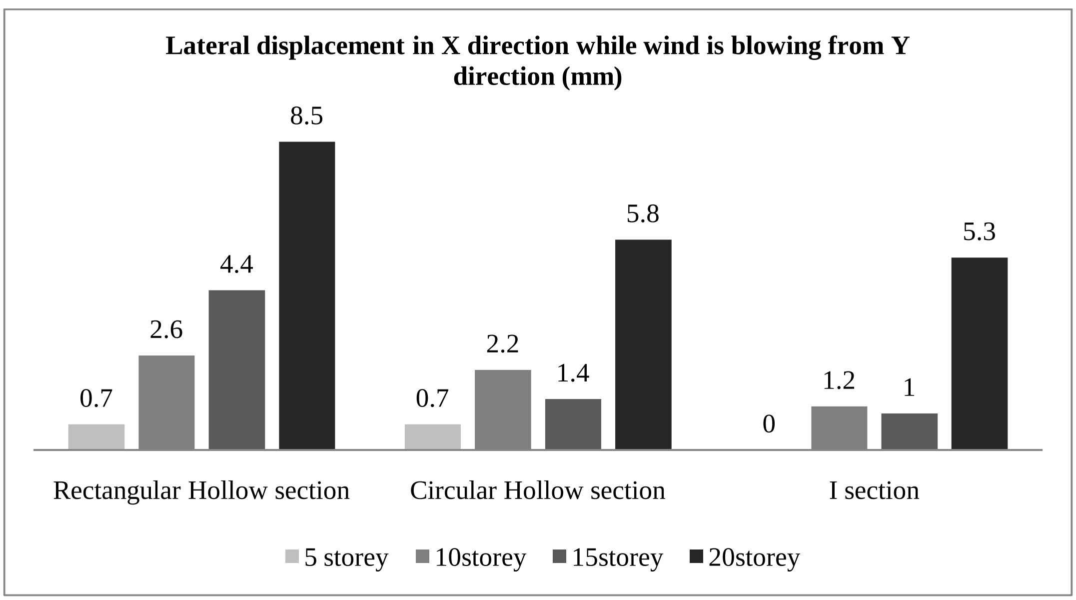


Figure A.6 (b): Lateral displacement (mm) in Y direction for symmetrical plan and section, core knee brace.

APPENDIX B

Table B.1 represents the weight of structural elements when subjected to wind W_2 for central bay and core cross bracing. Table B.2 and Figure B.1 give the weights of structural elements and the lateral displacements in X and Y directions for asymmetrical plan and section of the central bay and core bracing respectively.

Table B.1: Beam, column, brace and total weight subjected to W_2 for (a) central bay and (b) core cross bracing for asymmetrical plan and section.

W_2	Brace Sections/No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	17.7	Failed	Failed	Failed
	Rectangular Hollow section	22.2	58.6	105.5	204.7
	Circular Hollow section	20.6	58.0	103.7	221.0
	I section	21.2	57.2	102.8	218.0
Beams Weight (ton)	Angle section	52.0	Failed	Failed	Failed
	Rectangular Hollow section	52.0	112.2	172.2	231.5
	Circular Hollow section	52.0	112.4	172.2	231.7
	I section	52.0	112.7	173.4	232.7
Braces Weight (ton)	Angle section	12.4	Failed	Failed	Failed
	Rectangular Hollow section	2.8	7.2	15.0	32.0
	Circular Hollow section	3.5	12.0	25.3	46.3
	I section	14.0	48.5	92.0	119.3
Total Weight (ton)	Angle section	82.2	Failed	Failed	Failed
	Rectangular Hollow section	77.0	178.0	292.7	468.3
	Circular Hollow section	76.2	182.3	301.2	499.0
	I section	87.0	218.3	368.2	569.7

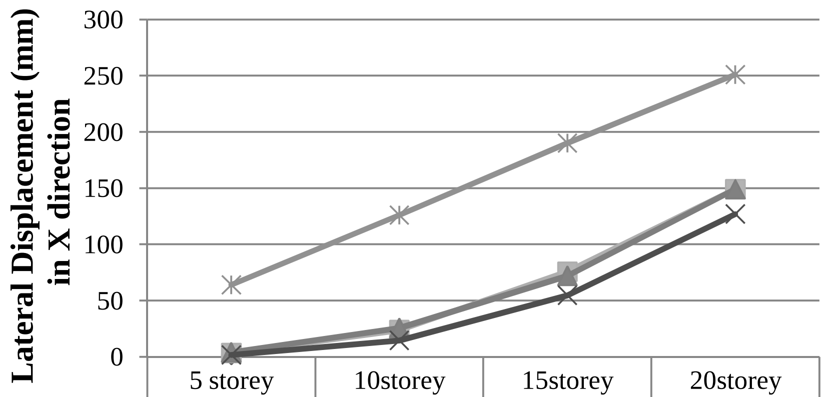
(a)

W_2	Brace Sections/No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	15.5	Failed	Failed	Failed
	Rectangular Hollow section	15.7	53.0	107.8	216.6
	Circular Hollow section	19.3	53.7	107.0	170.0
	I section	18.4	50.0	95.6	168.0
Beams Weight (ton)	Angle section	52.0	Failed	Failed	Failed
	Rectangular Hollow section	52.2	112.2	172.2	231.7
	Circular Hollow section	52.0	112.3	172.7	232.8
	I section	52.2	113.0	174.0	233.2
Braces Weight (ton)	Angle section	13.2	Failed	Failed	Failed
	Rectangular Hollow section	3.5	8.6	20.0	51.2
	Circular Hollow section	5.8	15.0	35.2	45.6
	I section	18.2	53.5	91.0	120.8
Total Weight (ton)	Angle section	80.8	Failed	Failed	Failed
	Rectangular Hollow section	71.4	173.7	300.0	499.5
	Circular Hollow section	77.0	181.0	314.8	448.5
	I section	88.8	216.5	360.6	522.0

(b)

Table B.2: Weights of columns, beams, braces and total by having different steel brace sections for cross bracing in the central bay of structure for asymmetrical plan and section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	18.0	Failed	Failed	Failed
	Rectangular Hollow section	21.7	58.7	112.7	223.1
	Circular Hollow section	19.8	58.5	124.4	229.6
	I section	18.6	55.7	121.8	217.3
Difference between max and min (%)		**20.5**	**5.4**	**10.4**	**5.7**
Beams Weight (ton)	Angle section	52.0	Failed	Failed	Failed
	Rectangular Hollow section	52.1	112.2	172.0	231.5
	Circular Hollow section	52.0	112.2	171.9	231.3
	I section	52.0	112.7	172.9	232.8
Difference between max and min (%)		**0.2**	**0.4**	**0.5**	**0.6**
Braces Weight (ton)	Angle section	12.4	Failed	Failed	Failed
	Rectangular Hollow section	2.9	7.0	16.0	35.6
	Circular Hollow section	3.2	11.0	26.9	45.4
	I section	14.4	48.0	89.6	121.0
Difference between max and min (%)		**396.5**	**585.7**	**460.0**	**239.9**
Total Weight (ton)	Angle section	82.4	Failed	Failed	Failed
	Rectangular Hollow section	76.7	177.9	301.0	490.2
	Circular Hollow section	75.1	181.7	323.2	506.4
	I section	85.1	216.4	384.4	571.2
Difference between max and min (%)		**13.3**	**21.6**	**27.7**	**16.5**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	1.6			
Rectangular Hollow section	3.4	23.7	75.6	149
Circular Hollow section	4	25.6	72	149
I section	1.6	14.6	54.7	127
Max	64	126	190	251

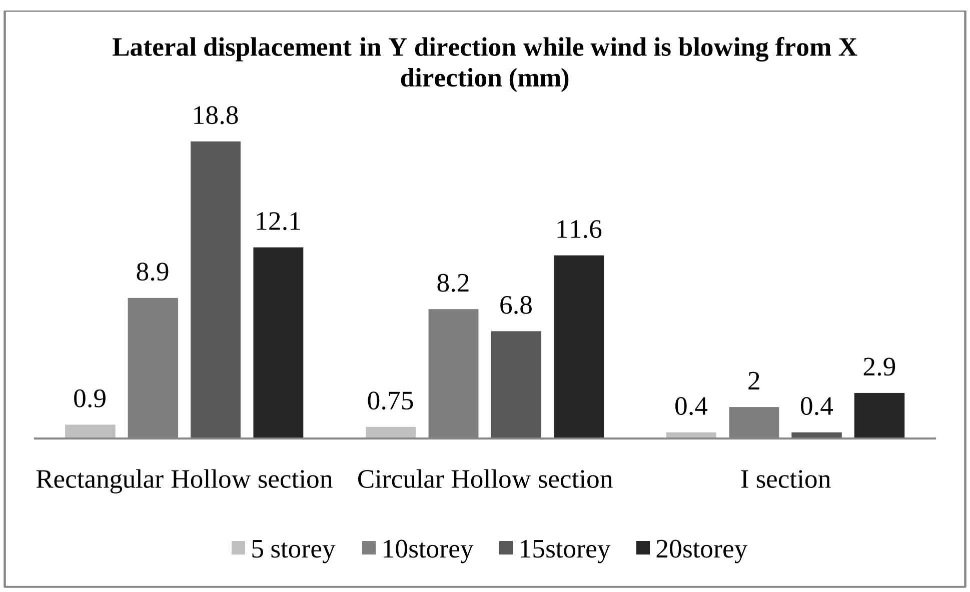
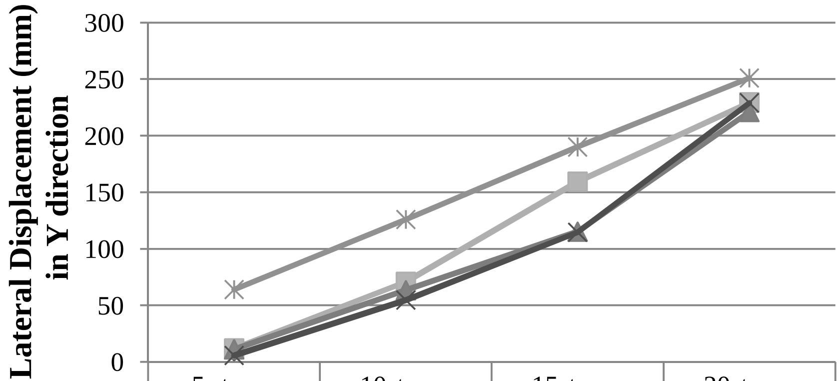


Figure B.1 (a): Lateral displacement (mm) in X direction for asymmetrical plan and section, central bay cross brace.



Brace sections	5 storey	10storey	15storey	20storey
Angle section	9.3			
Rectangular Hollow section	12	70.8	159.3	229.3
Circular Hollow section	11	63.3	115.1	221
I section	5.7	54.6	114.6	229
Max	64	126	190	251

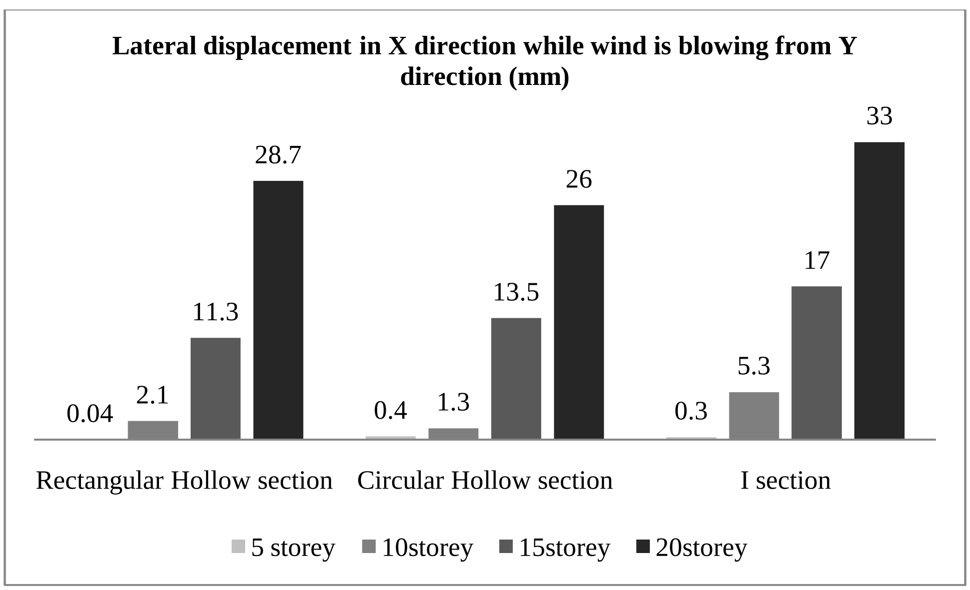
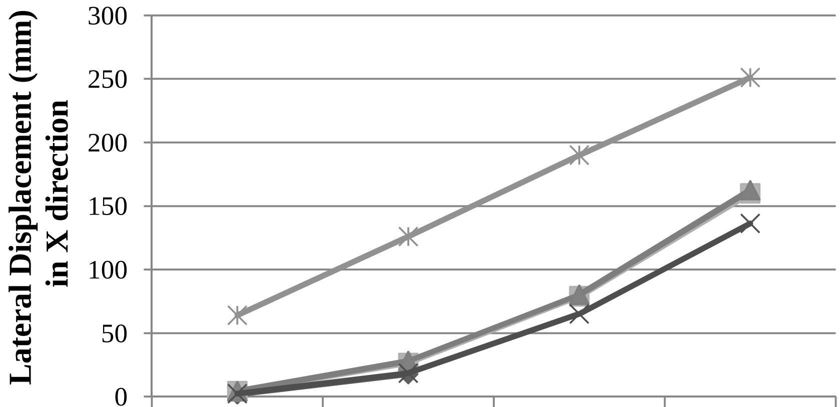


Figure B.1 (b): Lateral displacement (mm) in (a) Y direction for asymmetrical plan and section, central bay cross brace.

Table B.3: Weights of columns, beams, braces and total by having different steel brace sections for zipper bracing in the central bay of structure for asymmetrical plan and section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	23.7	60.0	Failed	Failed
	Rectangular Hollow section	26.2	58.9	112.4	215.6
	Circular Hollow section	22.0	58.4	110.7	213.6
	I section	18.9	58.9	121.7	230.8
Difference between max and min (%)		**38.6**	**2.7**	**9.9**	**8.0**
Beams Weight (ton)	Angle section	48.2	105.8	Failed	Failed
	Rectangular Hollow section	49.4	107.1	164.5	219.8
	Circular Hollow section	48.7	106.5	164.3	220.3
	I section	48.6	108.4	165.6	220.6
Difference between max and min (%)		**1.6**	**2.4**	**0.8**	**0.4**
Braces Weight (ton)	Angle section	5.0	11.1	Failed	Failed
	Rectangular Hollow section	2.0	4.9	13.5	35.0
	Circular Hollow section	2.7	7.7	19.6	38.0
	I section	7.1	23.9	56.6	84.4
Difference between max and min (%)		**255.0**	**388.0**	**319.2**	**141.0**
Total Weight (ton)	Angle section	77.0	176.7	Failed	Failed
	Rectangular Hollow section	77.6	171.0	290.5	470.5
	Circular Hollow section	73.5	172.6	294.7	471.8
	I section	74.6	191.3	343.9	535.8
Difference between max and min (%)		**5.6**	**11.9**	**18.4**	**13.8**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	1.9	17.7		
Rectangular Hollow section	4.2	26.5	79	160
Circular Hollow section	4.4	28.1	80.2	162.4
I section	2.3	18.5	65	136.2
Max	64	126	190	251

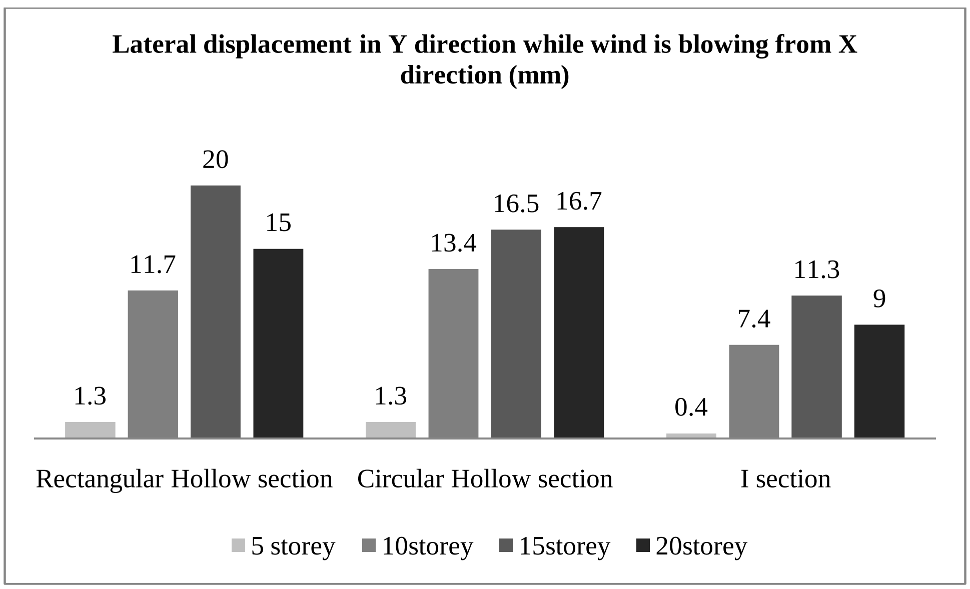
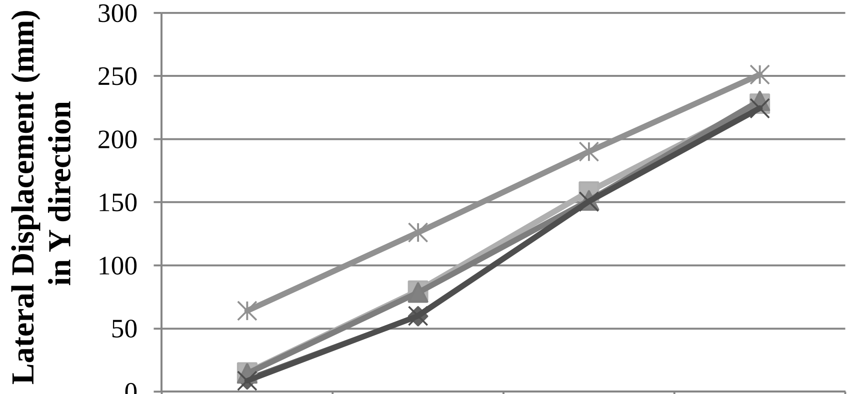
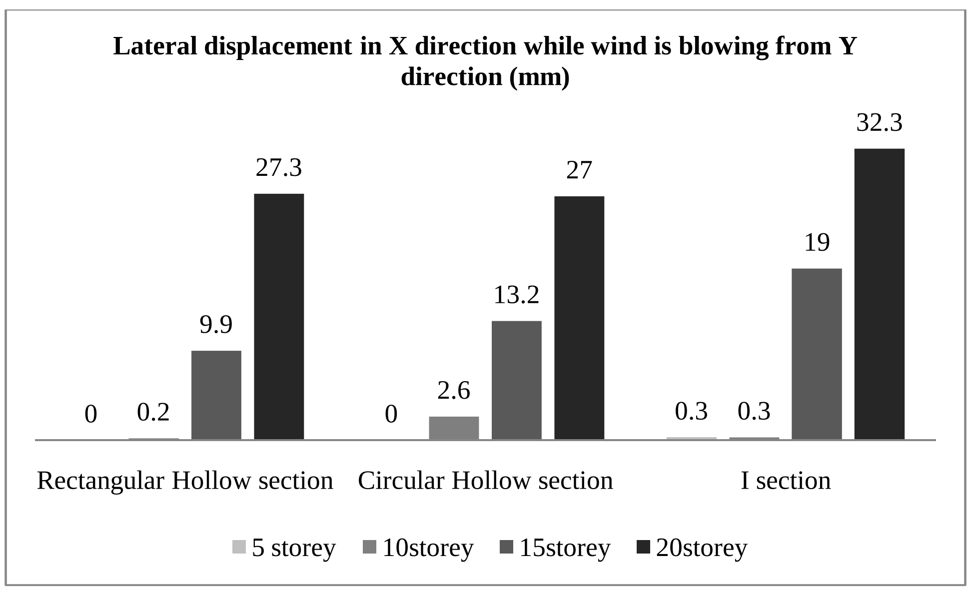


Figure B.2 (a): Lateral displacement (mm) in X direction for asymmetrical plan and section, central bay zipper brace.



Brace sections	5 storey	10storey	15storey	20storey
Angle section	9.7	59.8		
Rectangular Hollow section	15.2	80	158.4	228.1
Circular Hollow section	14.4	78.5	151.4	230.2
I section	8.7	60	150.5	224.4
Max	64	126	190	251

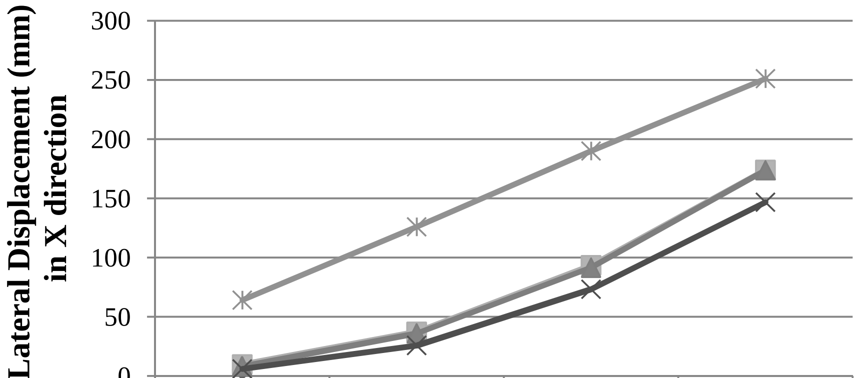


(b)

Figure B.2 (b): Lateral displacement (mm) in Y direction for asymmetrical plan and section, central bay zipper brace.

Table B.4: Weights of columns, beams, braces and total by having different steel brace sections for knee bracing in the central bay of structure for asymmetrical plan and section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	21.0	Failed	Failed	Failed
	Rectangular Hollow section	26.9	53.0	112.8	226.4
	Circular Hollow section	23.7	57.5	117.6	230.0
	I section	23.0	60.0	114.2	225.1
Difference between max and min (%)		**28.0**	**13.2**	**4.2**	**2.2**
Beams Weight (ton)	Angle section	54.0	Failed	Failed	Failed
	Rectangular Hollow section	53.7	115.6	177.1	236.7
	Circular Hollow section	52.7	113.5	173.5	233.0
	I section	52.1	113.3	173.0	231.3
Difference between max and min (%)		**3.6**	**2.0**	**2.4**	**2.3**
Braces Weight (ton)	Angle section	5.9	Failed	Failed	Failed
	Rectangular Hollow section	2.2	5.1	14.2	33.2
	Circular Hollow section	2.4	7.2	16.3	37.2
	I section	6.8	23.3	43.3	67.9
Difference between max and min (%)		**209.0**	**357.0**	**205.0**	**104.5**
Total Weight (ton)	Angle section	81.0	Failed	Failed	Failed
	Rectangular Hollow section	82.8	173.8	304.1	496.3
	Circular Hollow section	78.8	178.2	307.4	500.2
	I section	82.0	196.7	330.5	524.3
Difference between max and min (%)		**5.1**	**13.2**	**8.7**	**5.6**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	5.5			
Rectangular Hollow section	9.7	37.2	93.5	174
Circular Hollow section	8.2	36	91.5	173.7
I section	6	25.8	73.2	146.8
Max	64	126	190	251

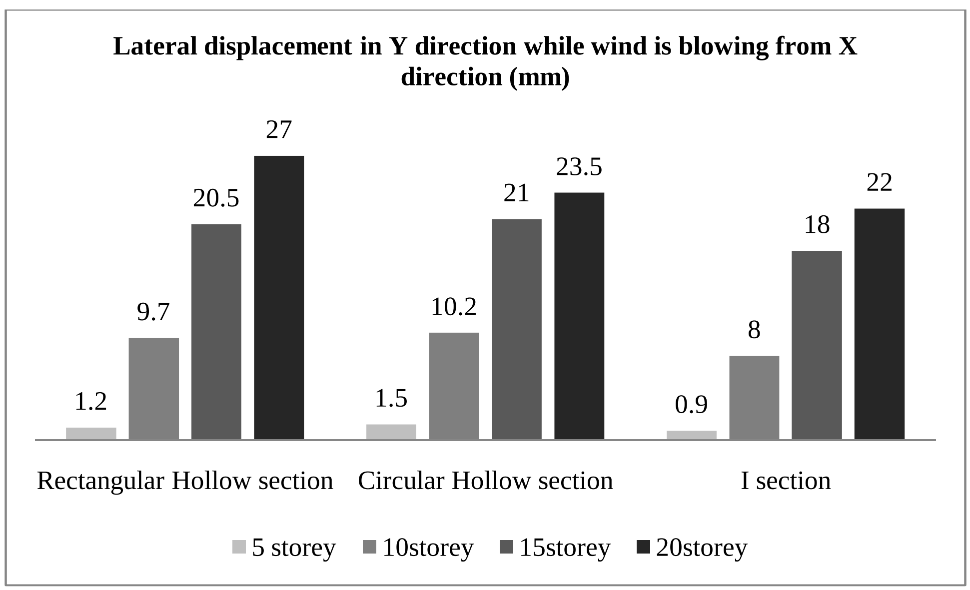
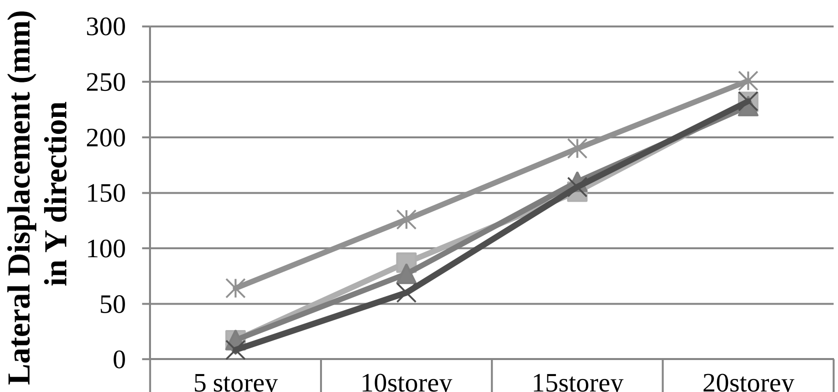


Figure B.3 (a): Lateral displacement (mm) in X direction for asymmetrical plan and section, central bay knee brace.



Brace sections	5 storey	10storey	15storey	20storey
Angle section	13.3			
Rectangular Hollow section	17.1	87	151	232
Circular Hollow section	17.4	77	160	228.2
I section	8.5	60	155.2	232.5
Max	64	126	190	251

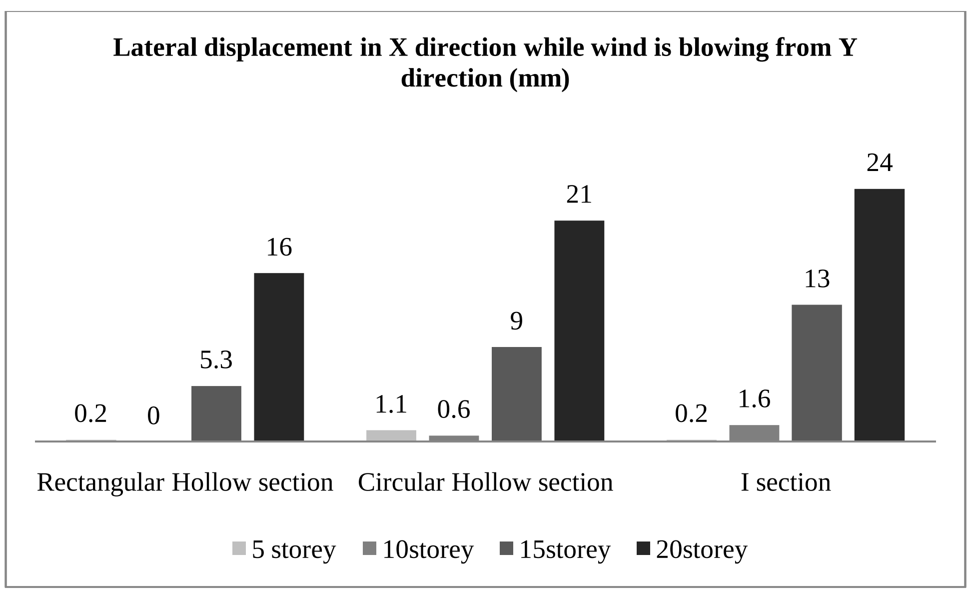
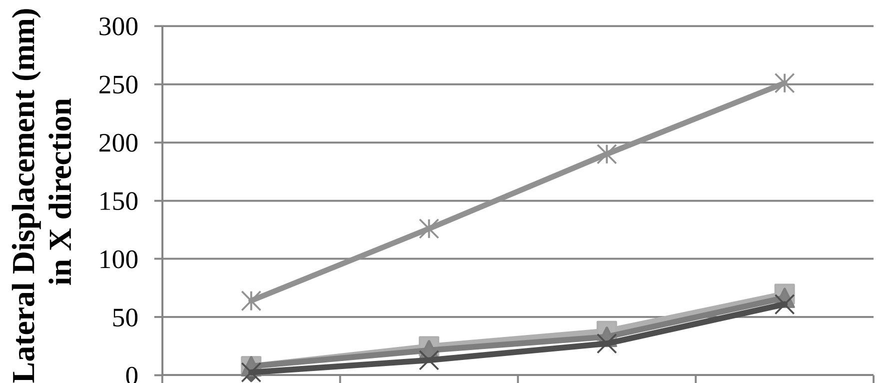


Figure B.3 (b): Lateral displacement (mm) in Y direction for asymmetrical plan and section, central bay knee brace.

Table B.5: Weights of columns, beams, braces and total by having different steel brace sections for cross bracing in the core of structure for asymmetrical plan and section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	15.9	Failed	Failed	Failed
	Rectangular Hollow section	16.4	52.2	140.1	215.5
	Circular Hollow section	19.3	54.1	116.0	202.0
	I section	18.8	50.2	109.8	180.5
Difference between max and min (%)		**21.4**	**7.8**	**28.5**	**19.4**
Beams Weight (ton)	Angle section	52.1	Failed	Failed	Failed
	Rectangular Hollow section	52.1	112.0	171.8	231.8
	Circular Hollow section	52.0	112.4	172.4	232.2
	I section	52.0	112.8	173.1	232.9
Difference between max and min (%)		**0.2**	**0.7**	**0.8**	**0.5**
Braces Weight (ton)	Angle section	13.3	Failed	Failed	Failed
	Rectangular Hollow section	3.3	8.8	29.2	46.3
	Circular Hollow section	5.3	14.7	33.2	54.7
	I section	18.0	52.1	89.4	120.0
Difference between max and min (%)		**454.5**	**492.0**	**205.0**	**160.0**
Total Weight (ton)	Angle section	81.4	Failed	Failed	Failed
	Rectangular Hollow section	71.9	173.0	341.1	493.6
	Circular Hollow section	76.6	181.3	321.6	489.0
	I section	88.8	215.1	372.3	533.3
Difference between max and min (%)		**23.5**	**24.4**	**16.0**	**9.0**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	3			
Rectangular Hollow section	7.7	24.8	38	69.8
Circular Hollow section	7.8	21.6	33.1	66.6
I section	2.5	13	27.3	61
Max	64	126	190	251

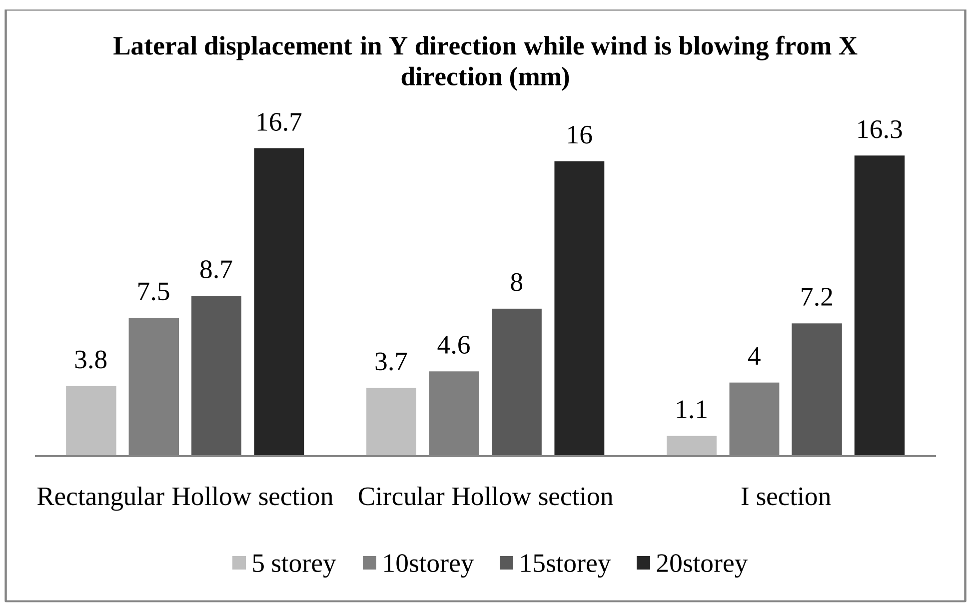
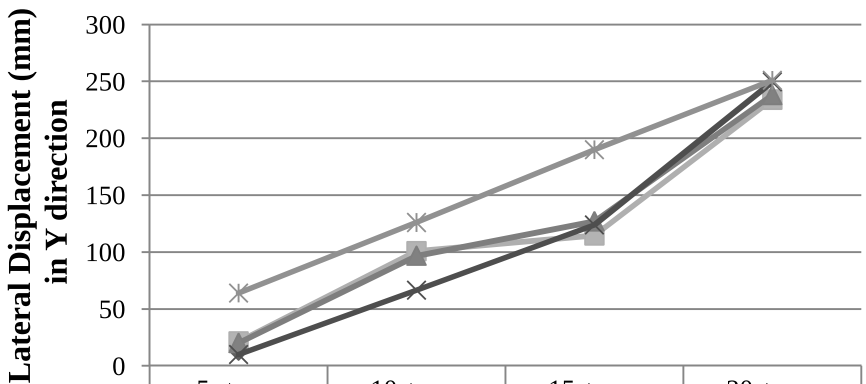


Figure B.4 (a): Lateral displacement (mm) in X direction for asymmetrical plan and section, core cross brace.



Brace sections	5 storey	10storey	15storey	20storey
Angle section	13.3			
Rectangular Hollow section	21.3	100.7	114.5	234
Circular Hollow section	20	96.7	126.9	238
I section	10	66.4	123.8	249.5
Max	64	126	190	251

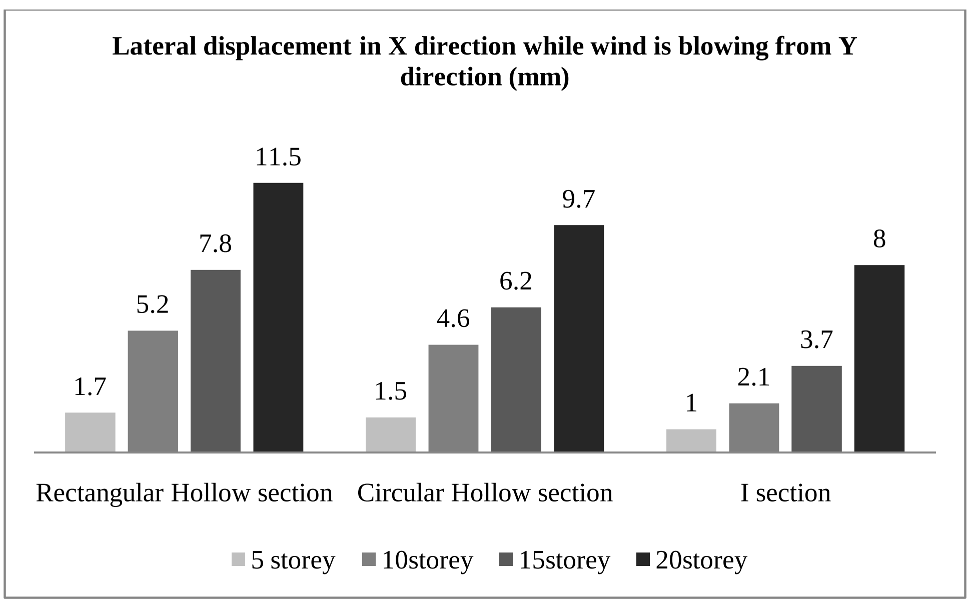
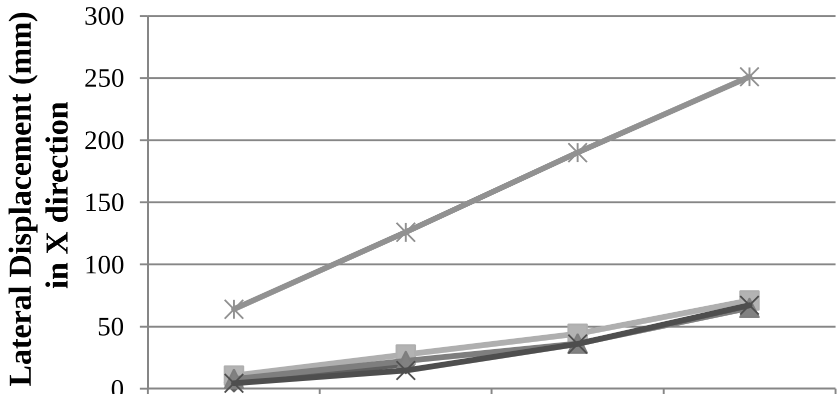


Figure B.4 (b): Lateral displacement (mm) in Y direction for asymmetrical plan and section, core cross brace.

Table B.6: Weights of columns, beams, braces and total by having different steel brace sections for zipper bracing in the core of structure for asymmetrical plan and section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	18.8	48.5	Failed	Failed
	Rectangular Hollow section	20.2	51.6	109.0	211.5
	Circular Hollow section	16.6	50.4	112.5	218.7
	I section	19.7	56.1	121.7	227.7
Difference between max and min (%)		**21.7**	**15.7**	**11.6**	**7.6**
Beams Weight (ton)	Angle section	48.7	107.5	Failed	Failed
	Rectangular Hollow section	48.7	110.4	170.5	227.8
	Circular Hollow section	50.0	109.7	170.1	227.4
	I section	50.3	110.2	169.8	227.7
Difference between max and min (%)		**3.3**	**2.7**	**0.4**	**0.2**
Braces Weight (ton)	Angle section	5.4	11.5	Failed	Failed
	Rectangular Hollow section	2.3	6.5	19.0	43.8
	Circular Hollow section	4.4	11.2	31.8	57.7
	I section	10.0	29.7	63.1	96.7
Difference between max and min (%)		**335.0**	**346.0**	**232.0**	**121.0**
Total Weight (ton)	Angle section	72.9	167.6	Failed	Failed
	Rectangular Hollow section	71.2	168.6	298.6	483.2
	Circular Hollow section	71.0	171.3	314.4	503.8
	I section	80.0	196.0	354.7	552.1
Difference between max and min (%)		**12.7**	**17.0**	**19.0**	**14.2**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	5.3	20		
Rectangular Hollow section	10.7	27.6	44.4	71
Circular Hollow section	7.9	22.4	36.4	65.1
I section	4.5	14.7	36	67.2
Max	64	126	190	251

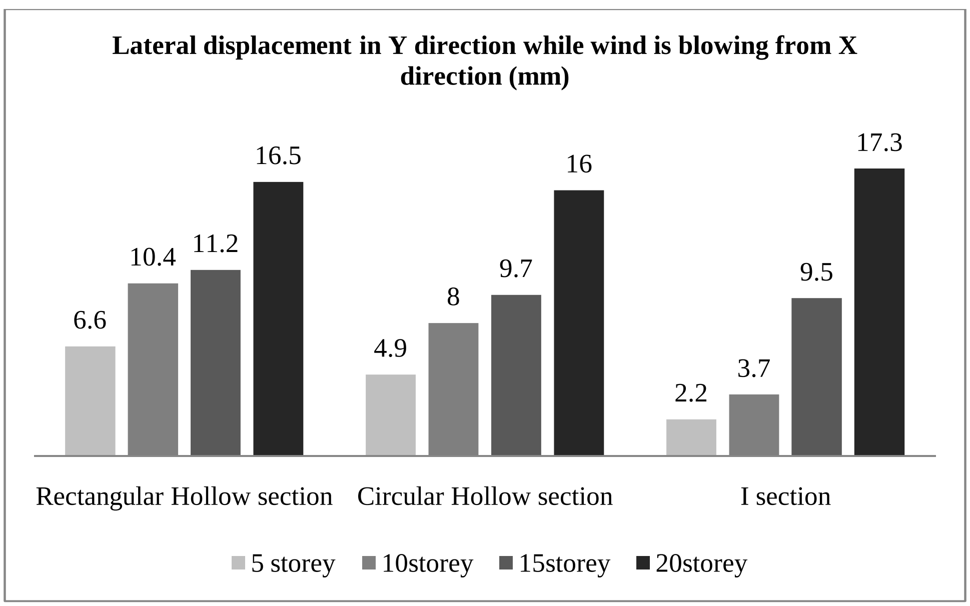
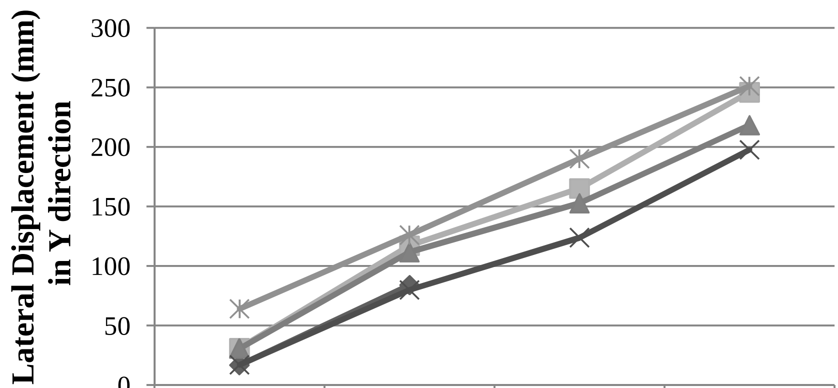


Figure B.5 (a): Lateral displacement (mm) in X direction for asymmetrical plan and section, core zipper brace.



Brace sections	5 storey	10storey	15storey	20storey
Angle section	16.7	84		
Rectangular Hollow section	31	117	165	245.8
Circular Hollow section	30.7	111.5	152.7	218.3
I section	17	79.9	123.8	197.5
Max	64	126	190	251

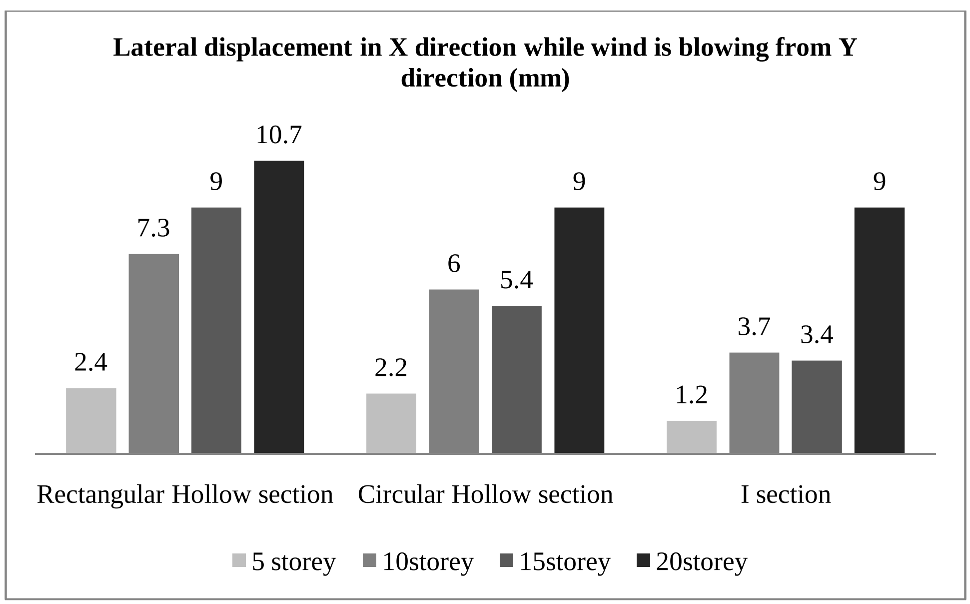
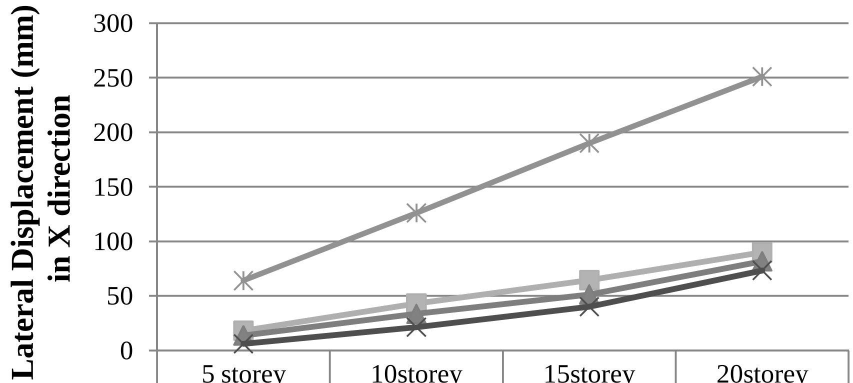


Figure B.5 (b): Lateral displacement (mm) in Y direction for asymmetrical plan and section, core zipper brace.

Table B.7: Weights of columns, beams, braces and total by having different steel brace sections for knee bracing in the core of structure for asymmetrical plan and section.

	Brace Sections/Storey	5	10	15	20
Columns Weight (ton)	Angle section	18.0	Failed	Failed	Failed
	Rectangular Hollow section	19.6	45.8	106.6	211.0
	Circular Hollow section	17.7	52.0	110.4	223.9
	I section	17.2	56.8	113.3	222.0
Difference between max and min (%)		**13.9**	**9.2**	**6.3**	**6.1**
Beams Weight (ton)	Angle section	54.0	Failed	Failed	Failed
	Rectangular Hollow section	54.1	115.8	175.9	234.2
	Circular Hollow section	52.7	113.3	174.0	232.0
	I section	52.2	113.0	173.8	232.0
Difference between max and min (%)		**3.6**	**2.5**	**1.2**	**0.9**
Braces Weight (ton)	Angle section	6.0	Failed	Failed	Failed
	Rectangular Hollow section	3.0	7.0	16.2	43.1
	Circular Hollow section	4.0	10.2	26.5	63.3
	I section	10.8	30.5	55.6	89.0
Difference between max and min (%)		**260.0**	**336.0**	**243.0**	**106.5**
Total Weight (ton)	Angle section	78.0	Failed	Failed	Failed
	Rectangular Hollow section	76.6	168.6	298.8	488.2
	Circular Hollow section	74.3	175.5	311.0	519.2
	I section	80.3	200.3	342.7	543.0
Difference between max and min (%)		**8.0**	**19.0**	**14.7**	**11.2**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	13.5			
Rectangular Hollow section	18	43	64.4	89.8
Circular Hollow section	13.6	33.5	51.3	81.6
I section	6	21.2	40	73.3
Max	64	126	190	251

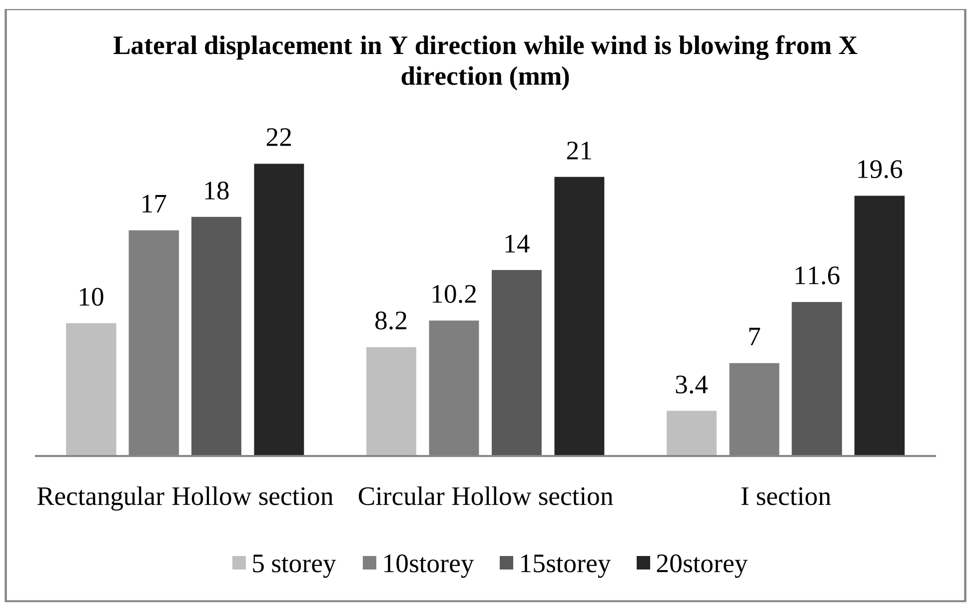
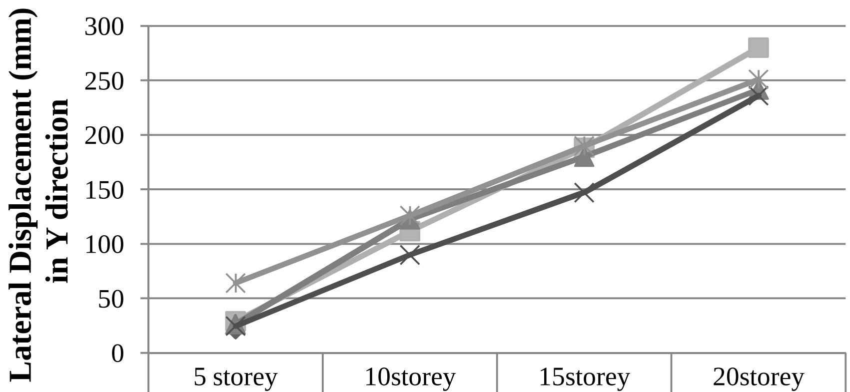


Figure B.6 (a): Lateral displacement (mm) in X direction for asymmetrical plan and section, core knee brace.



Brace sections	5 storey	10storey	15storey	20storey
Angle section	21.5			
Rectangular Hollow section	29	111.7	188.2	280
Circular Hollow section	26.4	122.5	180	241.6
I section	24.6	89.8	147	236
Max	64	126	190	251

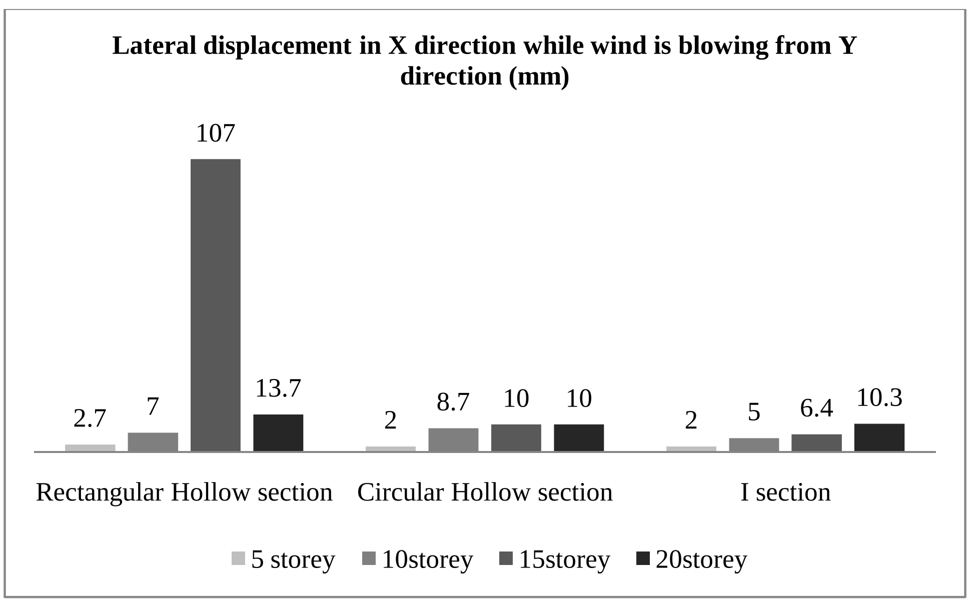


Figure B.6 (b): Lateral displacement (mm) Y direction for asymmetrical plan and section, core knee brace.

APPENDIX C

Table C.1 represents the weight of structural elements when subjected to wind W_2 for central bay and core cross bracing. Table C.2 and Figure C.1 give the weights of structural elements and the lateral displacements in X and Y directions for asymmetrical plan and symmetrical section of the central bay and core bracing respectively.

Table C.1: Beam, column, brace and total weight subjected to W_2 for (a) central bay and (b) core cross bracing for asymmetrical plan and symmetrical.

W_2	Brace Sections/No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	13.8	Failed	Failed	Failed
	Rectangular Hollow section	16.7	52.2	106.2	237.5
	Circular Hollow section	19.0	52.8	104.0	238.4
	I section	20.7	52.4	102.2	235.4
Beams Weight (ton)	Angle section	61.2	Failed	Failed	Failed
	Rectangular Hollow section	61.0	120.7	180.6	240.0
	Circular Hollow section	60.6	120.7	180.6	240.0
	I section	60.6	120.7	181.4	240.3
Braces Weight (ton)	Angle section	11.3	Failed	Failed	Failed
	Rectangular Hollow section	3.0	7.2	14.5	41.3
	Circular Hollow section	4.0	12.5	23.6	52.7
	I section	20.6	53.8	79.8	107.2
Total Weight (ton)	Angle section	86.3	Failed	Failed	Failed
	Rectangular Hollow section	80.6	180.0	301.2	518.8
	Circular Hollow section	83.6	186.0	308.2	531.0
	I section	102.0	227.0	363.4	583.0

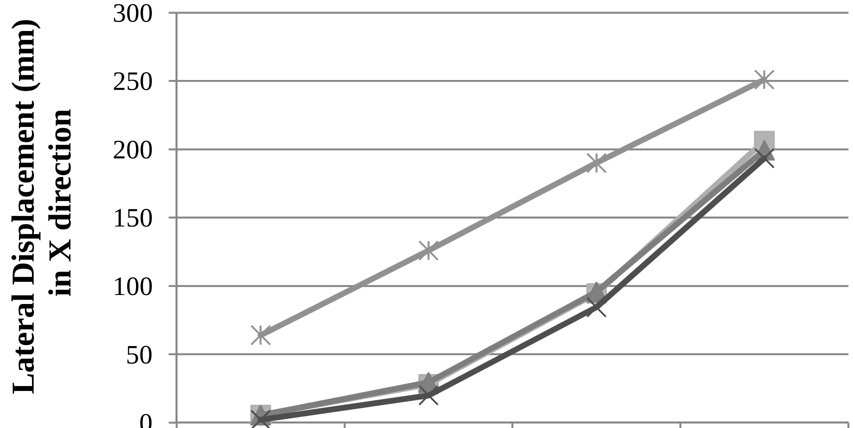
(a)

W_2	Brace Sections/No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	14.0	47.0	95.0	184.5
	Circular Hollow section	16.3	46.8	95.6	180.7
	I section	19.3	46.8	88.8	181.6
Beams Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	61.0	121.0	181.0	240.5
	Circular Hollow section	61.0	121.0	181.0	240.6
	I section	60.6	121.2	182.5	241.0
Braces Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	3.5	9.0	16.4	29.2
	Circular Hollow section	4.0	13.5	26.2	39.5
	I section	16.0	54.0	83.4	104.4
Total Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	78.4	177.0	292.3	454.2
	Circular Hollow section	81.3	181.4	302.6	467.8
	I section	96.0	222.2	354.7	527.0

(b)

Table C.2: Weights of columns, beams, braces and total by having different steel brace sections for cross bracing in the central bay of structure for asymmetrical plan and symmetrical.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	16.8	52.2	123.7	237.5
	Circular Hollow section	18.3	52.8	121.2	238.4
	I section	20.7	52.5	122.0	235.4
Difference between max and min (%)		**23.2**	**1.1**	**2.0**	**1.3**
Beams Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	61.0	120.7	180.4	240.0
	Circular Hollow section	60.7	120.7	180.5	240.0
	I section	60.6	120.7	181.0	240.3
Difference between max and min (%)		**0.5**	**0.0**	**0.3**	**0.1**
Braces Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	3.0	7.2	16.4	41.3
	Circular Hollow section	4.0	12.5	27.7	52.7
	I section	21.5	54.3	79.8	106.5
Difference between max and min (%)		**617.0**	**654.0**	**386.5**	**158.0**
Total Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	80.8	180.1	320.5	518.9
	Circular Hollow section	83.1	186.1	329.4	530.9
	I section	102.8	227.5	382.7	582.2
Difference between max and min (%)		**27.2**	**26.3**	**19.4**	**12.2**



Brace sections	5 storey	10storey	15storey	20storey
Rectangular Hollow section	5.6	28.1	94.5	206
Circular Hollow section	5.4	29.4	95.7	199.3
I section	2.1	20	84.4	193.5
Max	64	126	190	251

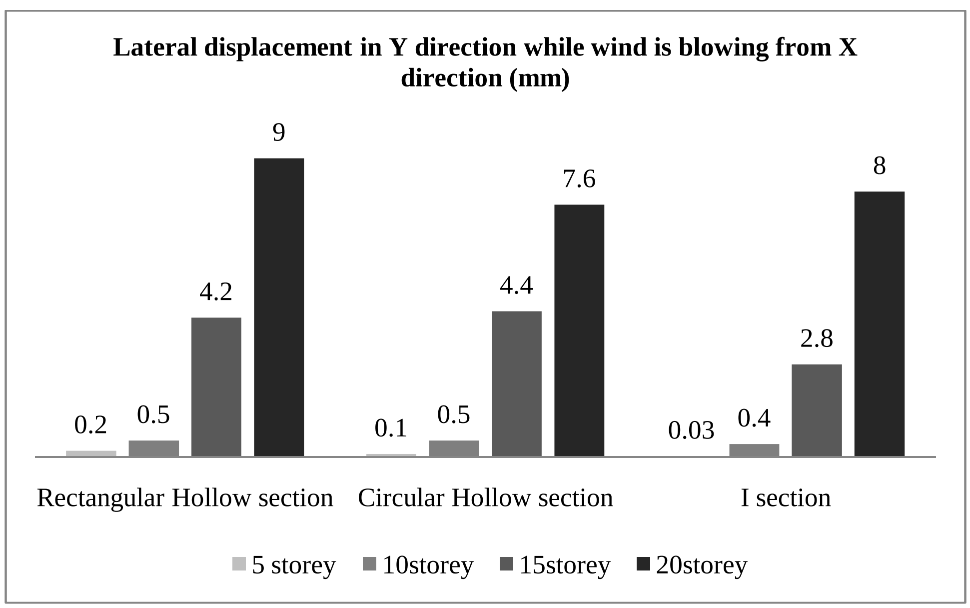
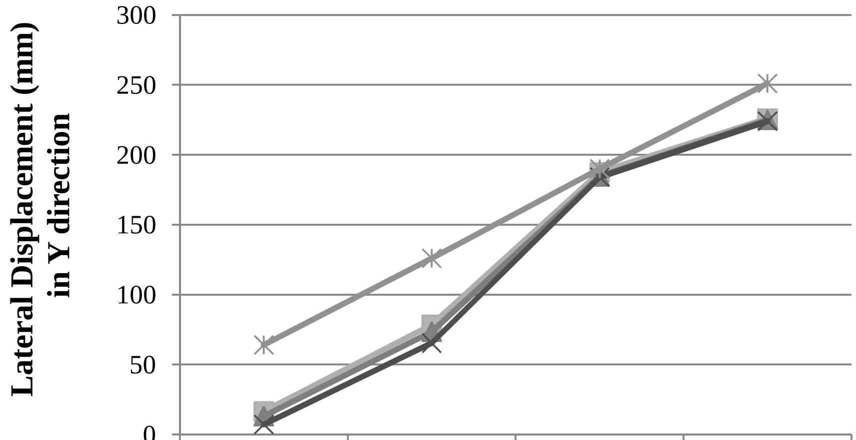


Figure C.1 (a): Lateral displacement (mm) in X direction for asymmetrical plan and symmetrical, central bay cross brace.



Brace sections	5 storey	10storey	15storey	20storey
Rectangular Hollow section	16.4	78.5	187.5	225.8
Circular Hollow section	13	73.5	184.6	225
I section	7.1	65.3	184.1	224
Max	64	126	190	251

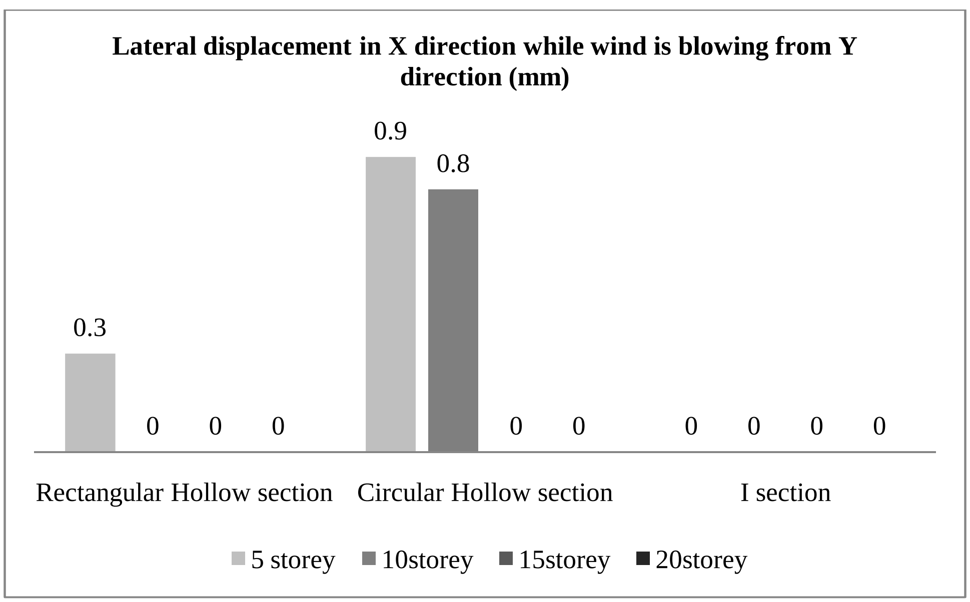
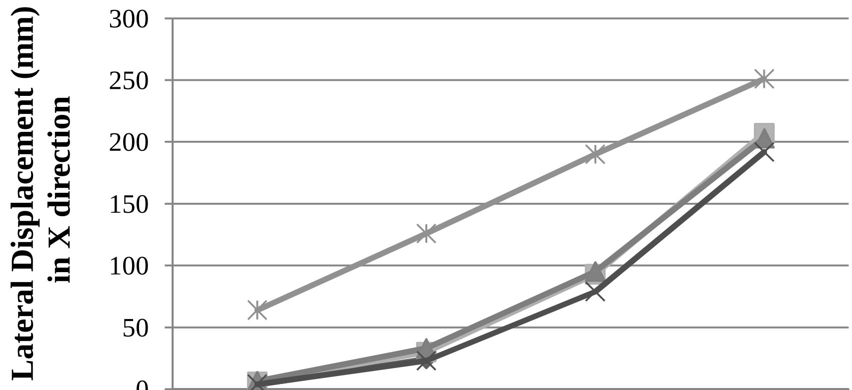


Figure C.1 (b): Lateral displacement (mm) in Y direction for asymmetrical plan and symmetrical, central bay cross brace.

Table C.3: Weights of columns, beams, braces and total by having different steel brace sections for zipper bracing in the central bay of structure for asymmetrical plan and symmetrical.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	15.5	51.0	Failed	Failed
	Rectangular Hollow section	19.0	51.7	105.6	216.7
	Circular Hollow section	16.0	48.3	103.4	211.3
	I section	13.6	55.7	105.0	212.5
Difference between max and min (%)		**39.7**	**15.3**	**2.1**	**2.5**
Beams Weight (ton)	Angle section	58.7	117.7	Failed	Failed
	Rectangular Hollow section	59.4	118.0	176.0	231.4
	Circular Hollow section	59.0	118.0	174.8	231.0
	I section	58.0	118.3	176.3	231.7
Difference between max and min (%)		**2.4**	**0.5**	**0.8**	**0.1**
Braces Weight (ton)	Angle section	4.7	10.2	Failed	Failed
	Rectangular Hollow section	2.0	4.6	12.5	29.3
	Circular Hollow section	2.4	7.0	18.3	35.8
	I section	6.5	27.3	57.0	83.0
Difference between max and min (%)		**225.0**	**493.5**	**356.0**	**183.3**
Total Weight (ton)	Angle section	78.8	179.0	Failed	Failed
	Rectangular Hollow section	80.3	174.4	294.0	477.4
	Circular Hollow section	77.3	173.3	296.6	478.2
	I section	78.0	201.3	338.3	527.3
Difference between max and min (%)		**4.0**	**16.0**	**15.0**	**10.5**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	3.6	24.2		
Rectangular Hollow section	6	30	93	207
Circular Hollow section	6.5	33	95.2	203
I section	4	23	79	191.8
Max	64	126	190	251

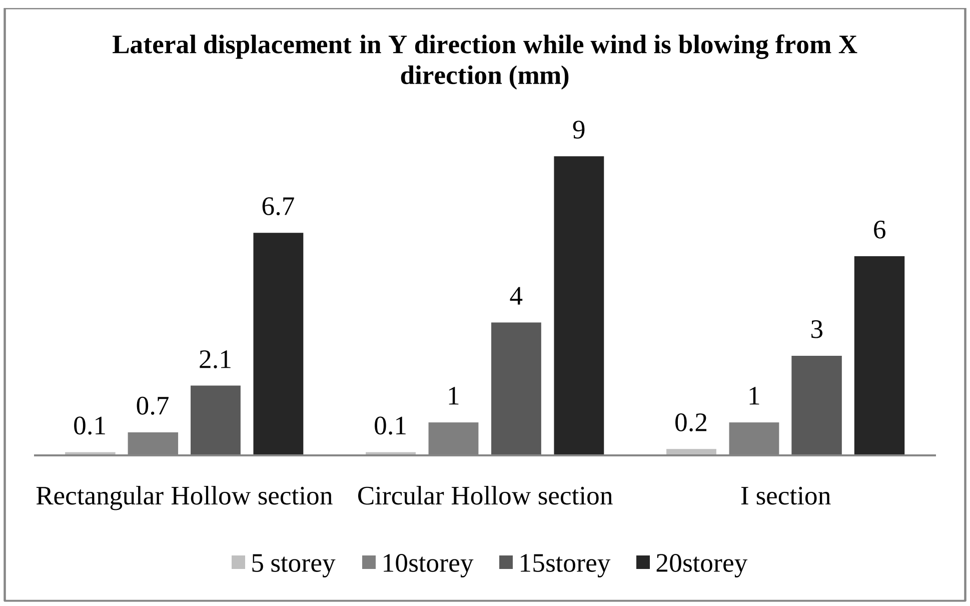
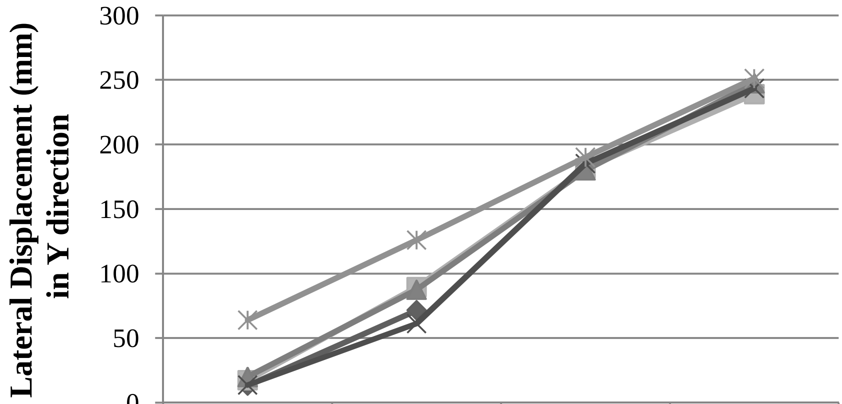


Figure C.2 (a): Lateral displacement (mm) in X direction for asymmetrical plan and symmetrical, central bay zipper brace.



Brace sections	5 storey	10storey	15storey	20storey
Angle section	13.2	71.5		
Rectangular Hollow section	17.4	89.5	181.4	239
Circular Hollow section	20	87.6	180	247.4
I section	13.7	61.3	185.2	243.4
Max	64	126	190	251

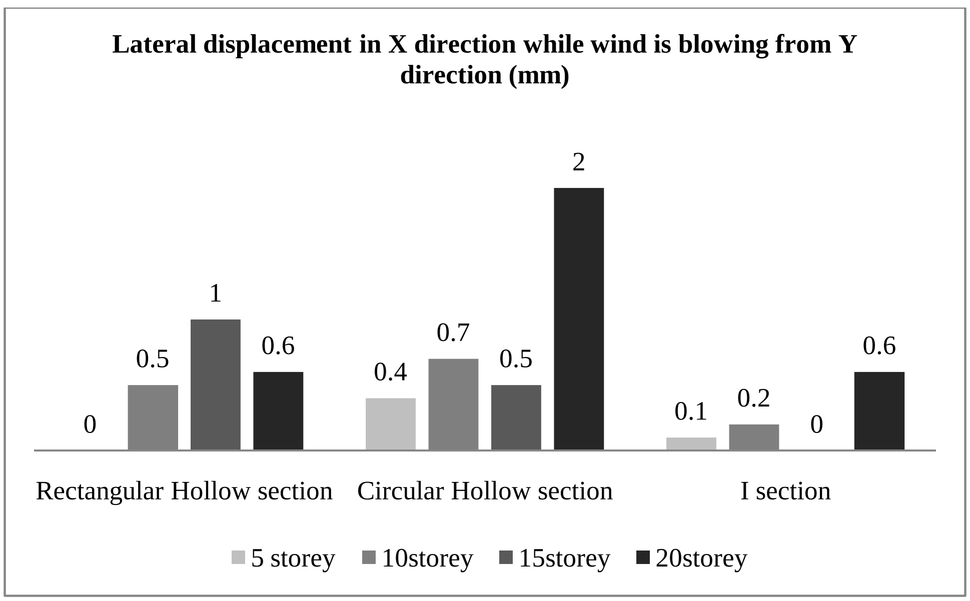
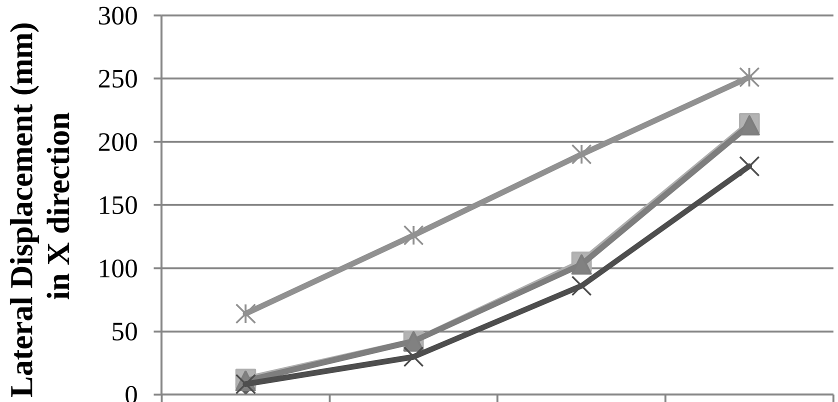


Figure C.2 (b): Lateral displacement (mm) in Y direction for asymmetrical plan and symmetrical, central bay zipper brace.

Table C.4: Weights of columns, beams, braces and total by having different steel brace sections for knee bracing in the central bay of structure for asymmetrical plan and symmetrical.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	21.7	Failed	Failed	Failed
	Rectangular Hollow section	23.0	53.4	111.0	229.5
	Circular Hollow section	20.6	51.2	110.6	227.7
	I section	17.4	54.0	107.5	226.0
Difference between max and min (%)		**32.2**	**5.5**	**3.2**	**1.5**
Beams Weight (ton)	Angle section	62.9	Failed	Failed	Failed
	Rectangular Hollow section	92.8	125.0	186.3	246.3
	Circular Hollow section	62.2	123.0	183.2	242.3
	I section	61.5	122.0	183.0	242.0
Difference between max and min (%)		**2.3**	**2.4**	**1.8**	**1.8**
Braces Weight (ton)	Angle section	5.2	Failed	Failed	Failed
	Rectangular Hollow section	2.0	5.0	11.2	29.7
	Circular Hollow section	2.3	6.4	14.7	32.0
	I section	6.0	22.6	39.0	69.0
Difference between max and min (%)		**200.0**	**352.0**	**248.2**	**132.3**
Total Weight (ton)	Angle section	89.8	Failed	Failed	Failed
	Rectangular Hollow section	87.8	183.3	308.5	505.4
	Circular Hollow section	85.2	180.5	308.5	502.1
	I section	84.8	198.7	329.6	537.2
Difference between max and min (%)		**6.0**	**10.0**	**6.8**	**7.0**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	8.5			
Rectangular Hollow section	12.4	42.3	105	214.6
Circular Hollow section	11	42.2	103	213
I section	8.4	30	86.1	180.6
Max	64	126	190	251

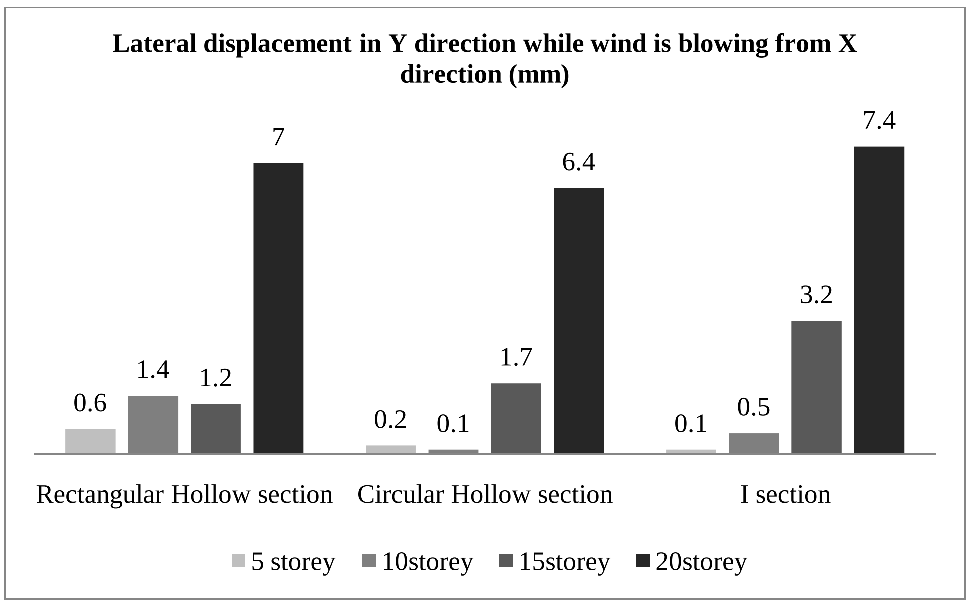
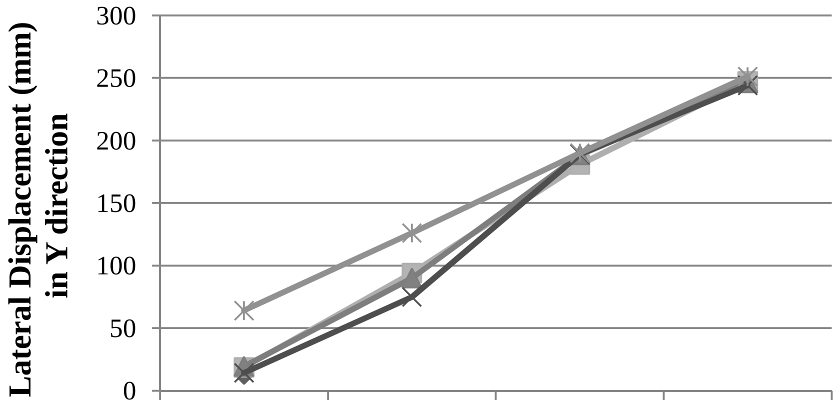


Figure C.3 (a): Lateral displacement (mm) in X direction for asymmetrical plan and symmetrical, central bay knee brace.



Brace sections	5 storey	10storey	15storey	20storey
Angle section	13			
Rectangular Hollow section	18.6	94	180.7	247.2
Circular Hollow section	19.4	90	188.4	246
I section	14.2	74.8	189	244
Max	64	126	190	251

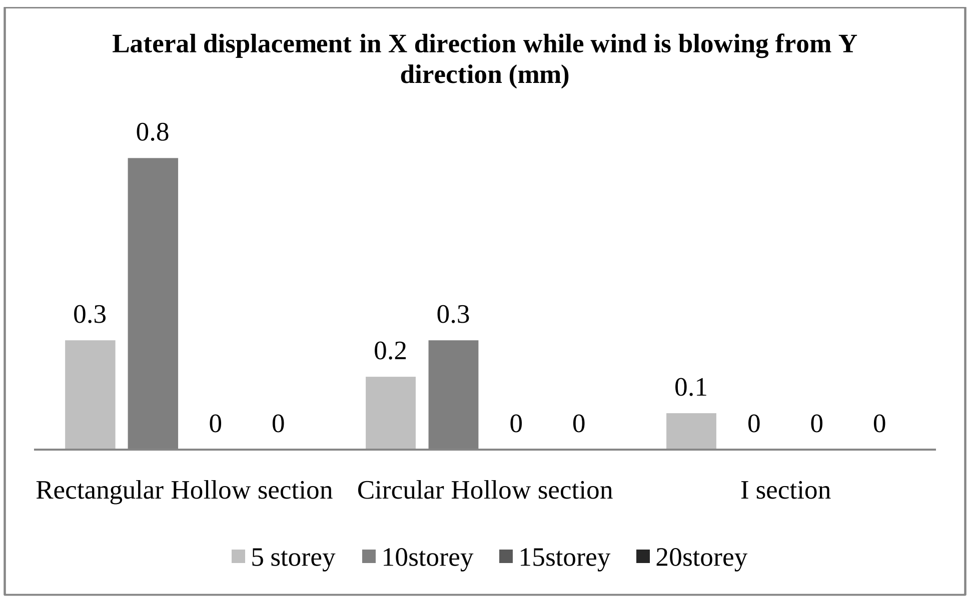
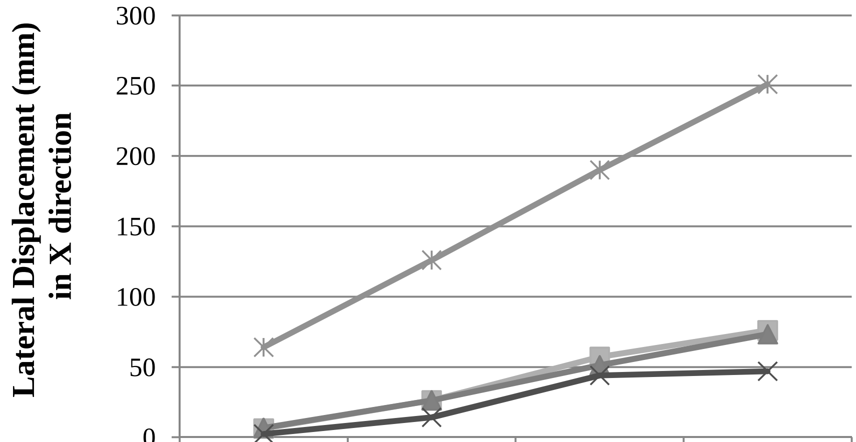


Figure C.3 (b): Lateral displacement (mm) in Y direction for asymmetrical plan and symmetrical, central bay knee brace.

Table C.5: Weights of columns, beams, braces and total by having different steel brace sections for cross bracing in the core of structure for asymmetrical plan and symmetrical.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	13.9	47.0	103.4	203.7
	Circular Hollow section	16.2	46.8	103.4	204.3
	I section	19.2	46.8	101.6	231.2
Difference between max and min (%)		**38.0**	**0.4**	**1.8**	**13.5**
Beams Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	61.0	120.8	181.0	240.5
	Circular Hollow section	61.0	121.0	181.0	240.5
	I section	60.6	121.3	182.0	258.6
Difference between max and min (%)		**0.7**	**0.2**	**0.5**	**7.5**
Braces Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	3.4	9.0	17.4	46.3
	Circular Hollow section	4.0	13.5	27.4	51.0
	I section	16.2	53.4	82.2	260.8
Difference between max and min (%)		**376.5**	**494.0**	**372.4**	**463.3**
Total Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	78.3	177.0	301.8	490.5
	Circular Hollow section	81.2	181.2	311.7	495.7
	I section	96.0	221.6	365.7	750.6
Difference between max and min (%)		**22.6**	**25.2**	**21.2**	**53.0**



Brace sections	5 storey	10storey	15storey	20storey
Rectangular Hollow section	6.2	26.2	57.1	76
Circular Hollow section	6.7	26.3	51.2	73.3
I section	2.3	14.2	44	47
Max	64	126	190	251

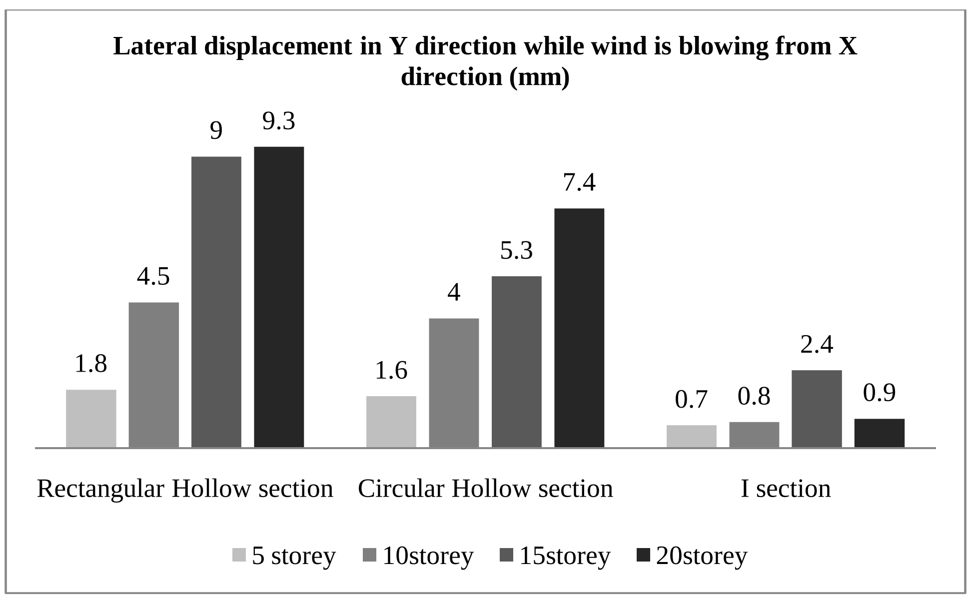
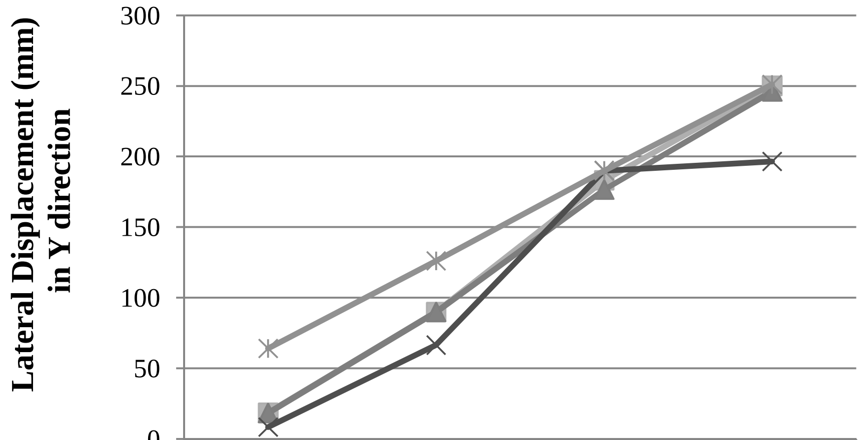


Figure C.4 (a): Lateral displacement (mm) in X direction for asymmetrical plan and symmetrical, core cross brace.



Brace sections	5 storey	10storey	15storey	20storey
Rectangular Hollow section	18.4	89.8	183.1	250
Circular Hollow section	18.2	89.8	176.5	246
I section	8.3	66.4	190	196.4
Max	64	126	190	251

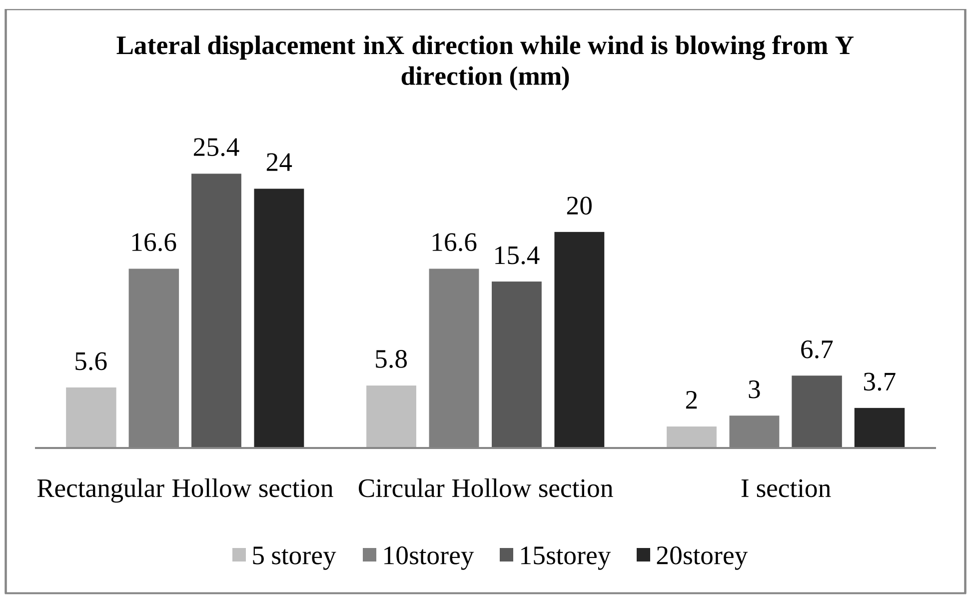
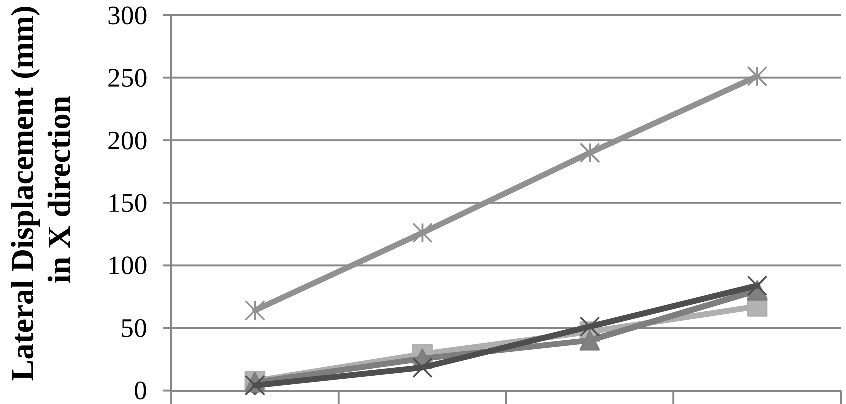


Figure C.4 (b): Lateral displacement (mm) in Y direction for asymmetrical plan and symmetrical, core cross brace.

Table C.6: Weights of columns, beams, braces and total by having different steel brace sections for zipper bracing in the core of structure for asymmetrical plan and symmetrical.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	17.7	Failed	Failed	Failed
	Rectangular Hollow section	20.6	42.6	110.6	227.7
	Circular Hollow section	14.5	44.8	114.8	204.6
	I section	13.5	48.6	106.0	209.3
Difference between max and min (%)		**52.6**	**14.0**	**8.3**	**11.3**
Beams Weight (ton)	Angle section	57.7	Failed	Failed	Failed
	Rectangular Hollow section	58.7	120.7	180.2	234.7
	Circular Hollow section	59.6	119.6	179.0	237.6
	I section	59.6	119.0	178.4	236.5
Difference between max and min (%)		**3.3**	**1.4**	**1.0**	**1.2**
Braces Weight (ton)	Angle section	4.8	Failed	Failed	Failed
	Rectangular Hollow section	2.3	6.5	20.5	68.3
	Circular Hollow section	3.3	11.2	29.8	46.0
	I section	7.5	31.4	55.1	78.2
Difference between max and min (%)		**226.0**	**383.0**	**168.8**	**70.0**
Total Weight (ton)	Angle section	80.2	Failed	Failed	Failed
	Rectangular Hollow section	81.5	169.8	311.5	530.7
	Circular Hollow section	77.4	175.7	323.5	488.3
	I section	80.7	199.0	339.5	524.1
Difference between max and min (%)		**5.3**	**17.2**	**9.0**	**8.6**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	4.3			
Rectangular Hollow section	7.6	29	47	67.1
Circular Hollow section	6.5	25.4	40	80
I section	4.1	18.2	51	83.7
Max	64	126	190	251

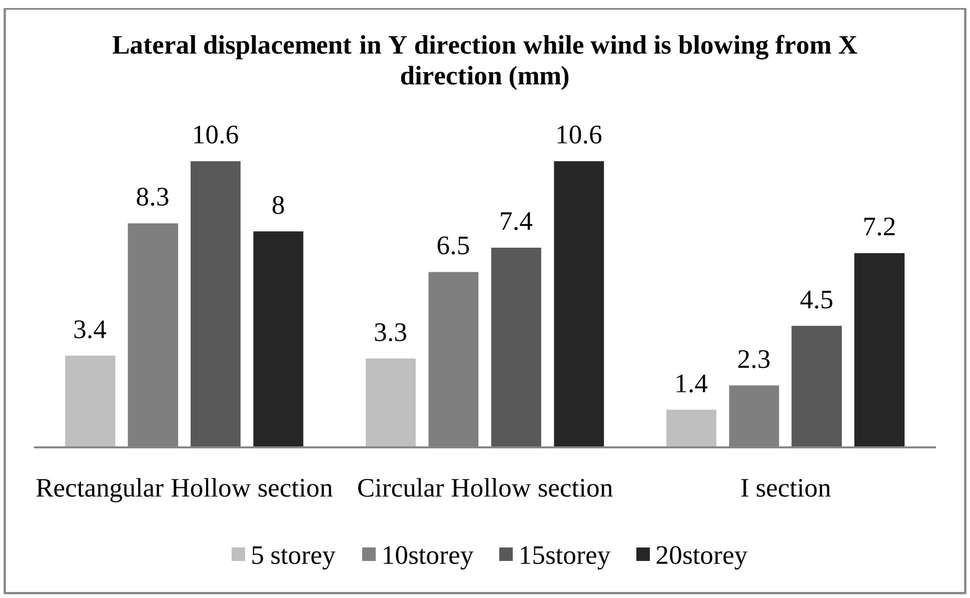
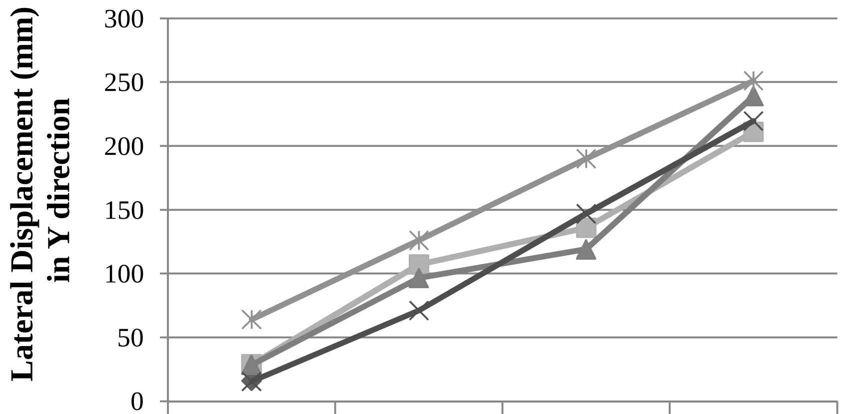


Figure C.5 (a): Lateral displacement (mm) in X direction for asymmetrical plan and symmetrical, core zipper brace.



Brace sections	5 storey	10storey	15storey	20storey
Angle section	15.9			
Rectangular Hollow section	28.8	107	135.9	211
Circular Hollow section	28.5	96.5	119	239
I section	15.5	71.1	146.8	219.5
Max	64	126	190	251

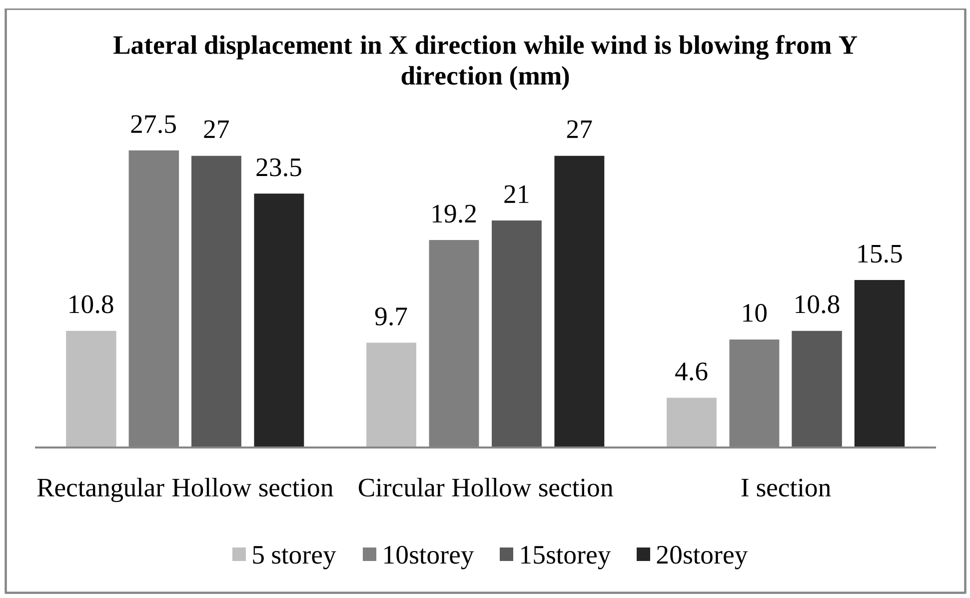
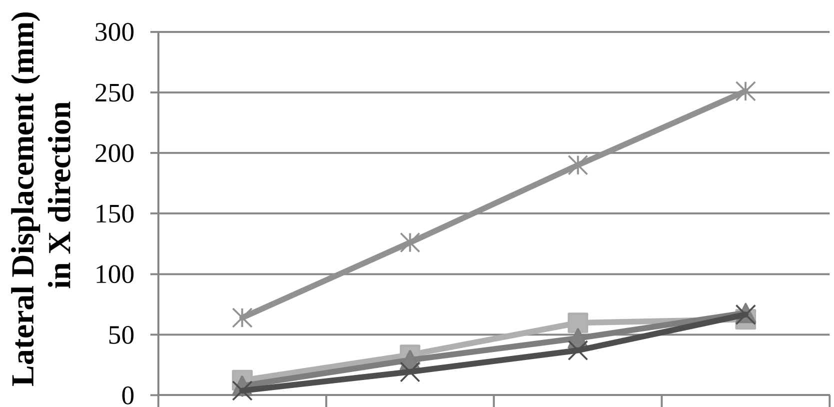


Figure C.5 (b): Lateral displacement (mm) in Y direction for asymmetrical plan and symmetrical, core zipper brace.

Table C.7: Weights of columns, beams, braces and total by having different steel brace sections for knee bracing in the core of structure for asymmetrical plan and symmetrical.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	16.9	Failed	Failed	Failed
	Rectangular Hollow section	20.0	46.8	117.0	230.5
	Circular Hollow section	17.0	43.5	119.6	231.0
	I section	15.6	50.9	124.0	225.1
Difference between max and min (%)		**28.2**	**17.2**	**6.0**	**2.7**
Beams Weight (ton)	Angle section	62.3	Failed	Failed	Failed
	Rectangular Hollow section	62.4	124.5	184.3	251.2
	Circular Hollow section	61.5	122.2	182.0	241.3
	I section	60.3	121.8	181.0	240.8
Difference between max and min (%)		**3.5**	**2.2**	**1.8**	**4.3**
Braces Weight (ton)	Angle section	5.3	Failed	Failed	Failed
	Rectangular Hollow section	2.3	7.0	19.0	80.8
	Circular Hollow section	3.8	9.9	30.5	102.8
	I section	10.4	30.8	48.4	118.0
Difference between max and min (%)		**352.2**	**340.0**	**154.7**	**46.0**
Total Weight (ton)	Angle section	84.6	Failed	Failed	Failed
	Rectangular Hollow section	84.7	178.4	320.2	562.5
	Circular Hollow section	82.3	175.7	332.1	575.0
	I section	86.3	203.5	353.2	583.8
Difference between max and min (%)		**4.8**	**15.8**	**10.3**	**3.8**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	7.2			
Rectangular Hollow section	12.3	33.4	59.8	62.6
Circular Hollow section	7.8	29	47	68
I section	3.8	19.2	37	66.5
Max	64	126	190	251

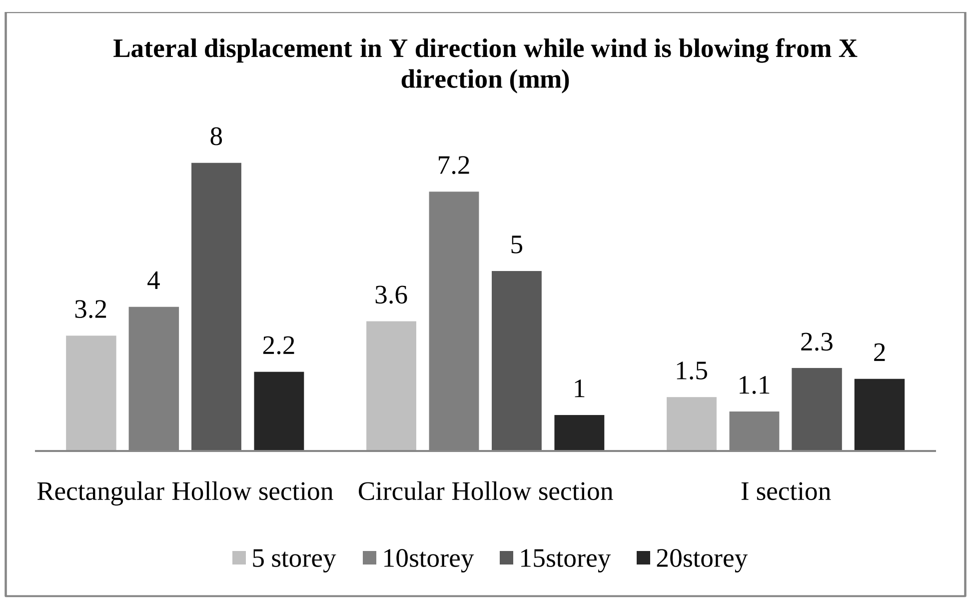
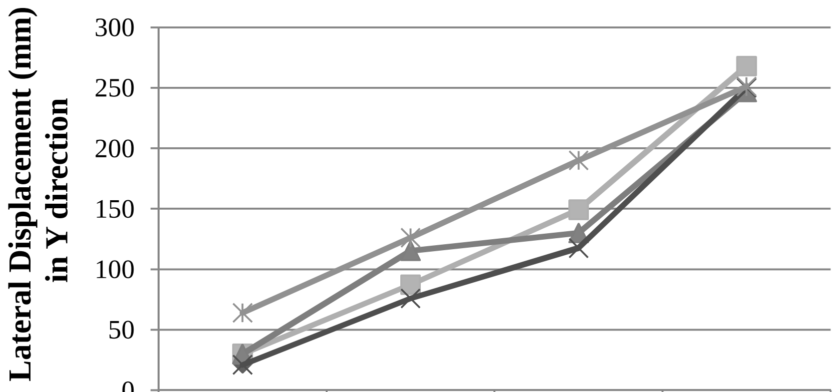


Figure C.6 (a): Lateral displacement (mm) in X direction for asymmetrical plan and symmetrical, core knee brace.



Brace sections	5 storey	10storey	15storey	20storey
Angle section	22.3			
Rectangular Hollow section	30	87.3	149.2	268
Circular Hollow section	30	115.3	130	246.5
I section	21	75.8	117.5	250
Max	64	126	190	251

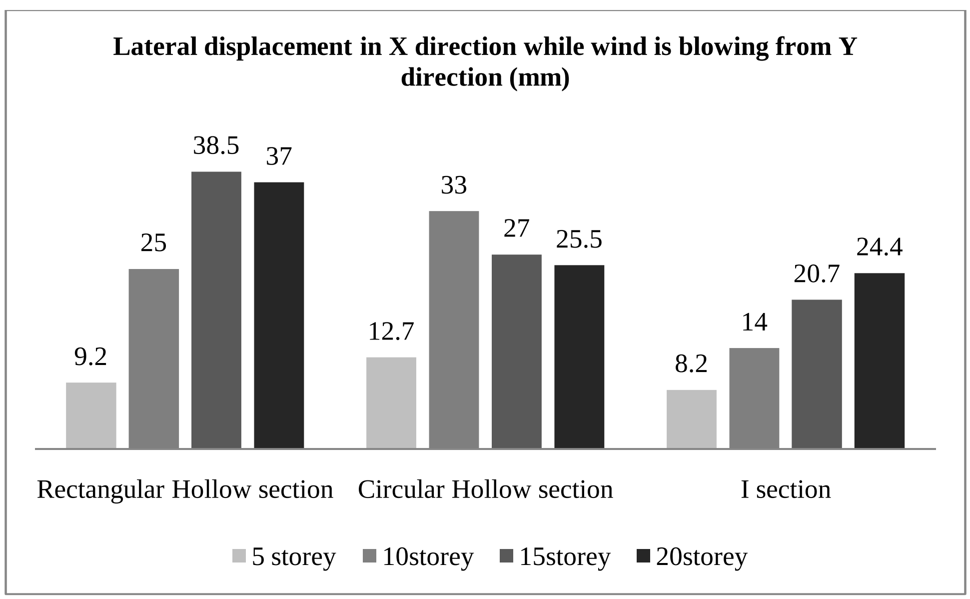


Figure C.6 (b): Lateral displacement (mm) in Y direction for asymmetrical plan and symmetrical, core knee brace.

APPENDIX D

Table D.1 represents the weight of structural elements when subjected to wind W_2 for central bay and core cross bracing. Table D.2 and Figure D.1 give the weights of structural elements and the lateral displacements in X and Y directions for symmetrical plan and asymmetrical section of the central bay and core bracing respectively.

Table D.1: Beam, column and total weight subjected to W_2 for (a) central bay and (b) core cross bracing for symmetrical plan and asymmetrical section.

W_2	Brace Sections/No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	14.0	Failed	Failed	Failed
	Rectangular Hollow section	19.7	56.0	103.0	166.2
	Circular Hollow section	17.0	54.0	101.5	164.2
	I section	15.4	49.8	100.5	162.5
Beams Weight (ton)	Angle section	57.0	Failed	Failed	Failed
	Rectangular Hollow section	56.8	124.4	192.0	259.5
	Circular Hollow section	56.7	124.6	192.4	260.2
	I section	57.0	126.3	194.5	262.5
Braces Weight (ton)	Angle section	14.0	Failed	Failed	Failed
	Rectangular Hollow section	3.5	9.3	16.0	24.3
	Circular Hollow section	3.0	11.0	22.7	40.2
	I section	20.0	58.3	105.3	145.0
Total Weight (ton)	Angle section	85.2	Failed	Failed	Failed
	Rectangular Hollow section	80.0	190.0	311.0	450.0
	Circular Hollow section	77.0	189.6	316.6	464.6
	I section	92.7	234.4	400.3	570.0

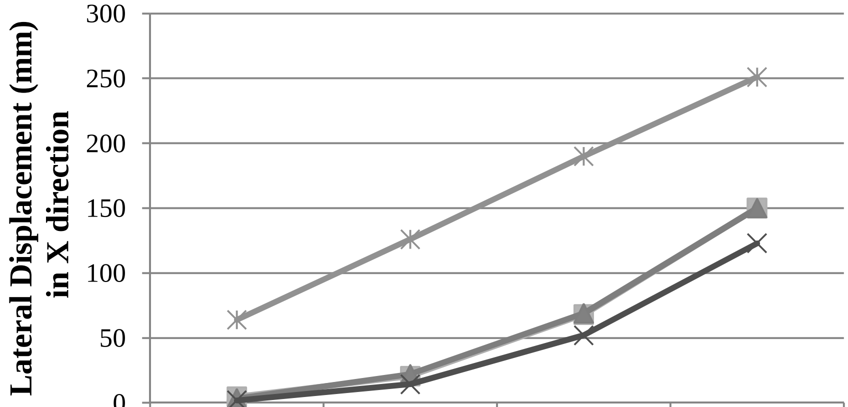
(a)

W_2	Brace Sections/No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	16.5	50.7	92.7	151.7
	Circular Hollow section	15.7	48.6	92.5	150.8
	I section	15.6	46.4	89.2	146.4
Beams Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	56.6	123.8	191.4	258.3
	Circular Hollow section	56.7	124.5	191.6	258.6
	I section	56.7	125.4	193.7	261.2
Braces Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	4.2	10.6	17.2	26.0
	Circular Hollow section	4.8	14.0	24.7	45.5
	I section	18.0	54.3	108.7	145.6
Total Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	77.3	185.0	301.3	436.0
	Circular Hollow section	77.3	187.0	308.8	455.0
	I section	90.3	226.0	391.7	553.2

(b)

Table D.2: Weights of columns, beams, braces and total by having different steel brace sections for cross bracing in the central bay of structure for symmetrical plan and asymmetrical section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	13.8	Failed	Failed	Failed
	Rectangular Hollow section	19.0	55.5	103.0	166.2
	Circular Hollow section	16.3	53.5	101.5	164.3
	I section	14.3	49.5	99.8	162.4
Difference between max and min (%)		**37.7**	**8.0**	**3.2**	**2.3**
Beams Weight (ton)	Angle section	57.0	Failed	Failed	Failed
	Rectangular Hollow section	56.7	124.3	192.0	259.2
	Circular Hollow section	56.8	124.6	192.5	260.2
	I section	57.2	126.0	194.5	262.7
Difference between max and min (%)		**0.9**	**1.4**	**1.3**	**1.3**
Braces Weight (ton)	Angle section	14.0	Failed	Failed	Failed
	Rectangular Hollow section	4.0	9.0	16.0	24.3
	Circular Hollow section	4.0	11.2	23.4	40.2
	I section	20.5	58.8	108.7	145.0
Difference between max and min (%)		**412.5**	**553.4**	**579.4**	**496.7**
Total Weight (ton)	Angle section	85.0	Failed	Failed	Failed
	Rectangular Hollow section	79.6	188.8	311.0	449.7
	Circular Hollow section	77.0	189.4	317.4	464.7
	I section	92.0	234.4	403.0	570.0
Difference between max and min (%)		**19.5**	**24.0**	**29.6**	**26.7**



Brace sections

	5 storey	10storey	15storey	20storey
Angle section	1.9			
Rectangular Hollow section	4.8	20.5	68	150.3
Circular Hollow section	3.4	22	69	150
I section	1.9	14.3	52	123
Max	64	126	190	251

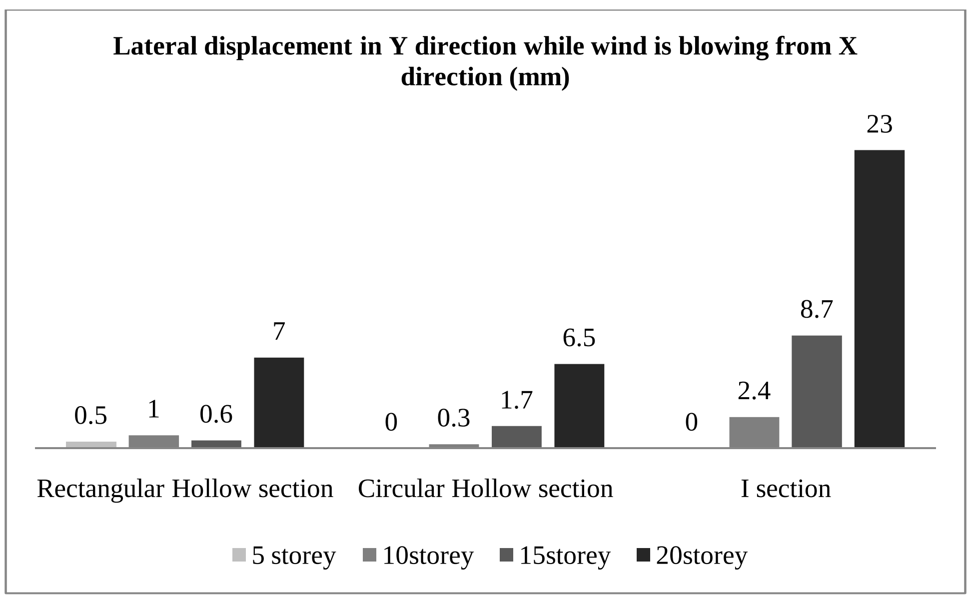
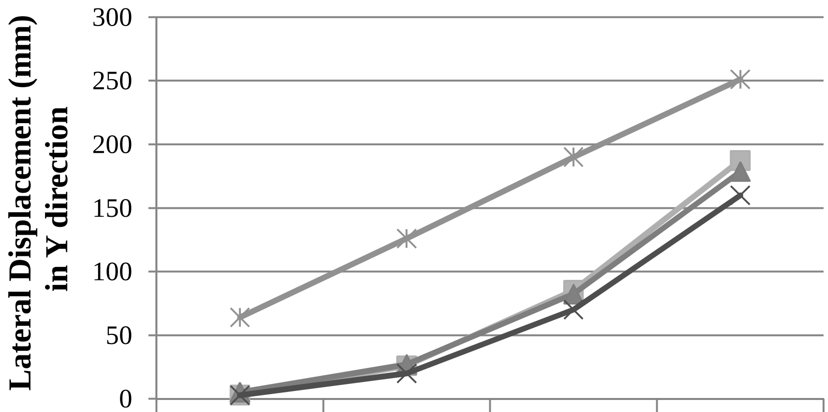


Figure D.1 (a): Lateral displacement (mm) in X direction for symmetrical plan and asymmetrical section, central bay cross brace.



Brace sections	5 storey	10storey	15storey	20storey
Angle section	3			
Rectangular Hollow section	3	26	85.3	187.3
Circular Hollow section	5.1	27	82.3	178.6
I section	2.8	20	70	160
Max	64	126	190	251

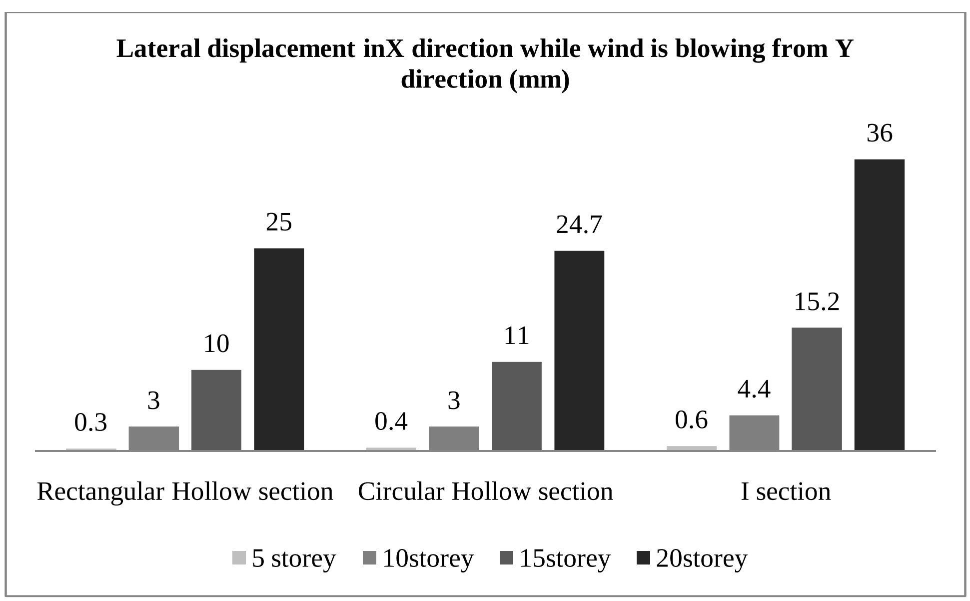
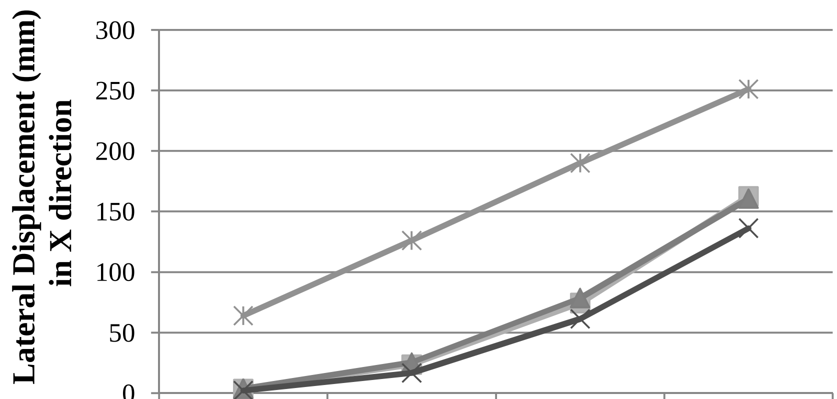


Figure D.1 (b): Lateral displacement (mm) in Y direction for symmetrical plan and asymmetrical section, central bay cross brace.

Table D.3: Weights of columns, beams, braces and total by having different steel brace sections for zipper bracing in the central bay of structure for symmetrical plan and asymmetrical section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	19.4	Failed	Failed	Failed
	Rectangular Hollow section	18.2	57.0	103.8	167.6
	Circular Hollow section	17.6	55.5	102.3	165.4
	I section	14.4	58.8	115.2	186.5
Difference between max and min (%)		**34.7**	**6.0**	**12.6**	**12.7**
Beams Weight (ton)	Angle section	52.0	Failed	Failed	Failed
	Rectangular Hollow section	55.2	121.0	184.8	249.0
	Circular Hollow section	53.2	120.2	184.5	248.6
	I section	52.2	122.0	186.5	250.0
Difference between max and min (%)		**2.3**	**1.5**	**1.1**	**0.6**
Braces Weight (ton)	Angle section	5.7	Failed	Failed	Failed
	Rectangular Hollow section	2.3	5.5	9.0	13.6
	Circular Hollow section	2.5	8.4	15.8	21.5
	I section	8.0	20.4	48.0	87.6
Difference between max and min (%)		**247.8**	**270.0**	**433.3**	**544.0**
Total Weight (ton)	Angle section	77.2	Failed	Failed	Failed
	Rectangular Hollow section	75.7	183.5	297.7	430.2
	Circular Hollow section	73.3	184.0	302.6	435.5
	I section	74.7	201.4	350.0	524.2
Difference between max and min (%)		**5.3**	**9.7**	**17.6**	**21.8**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	1.7			
Rectangular Hollow section	3.3	23.5	74.4	162.6
Circular Hollow section	3.7	25.3	78.5	160.5
I section	2.1	16.6	61.3	136.2
Max	64	126	190	251

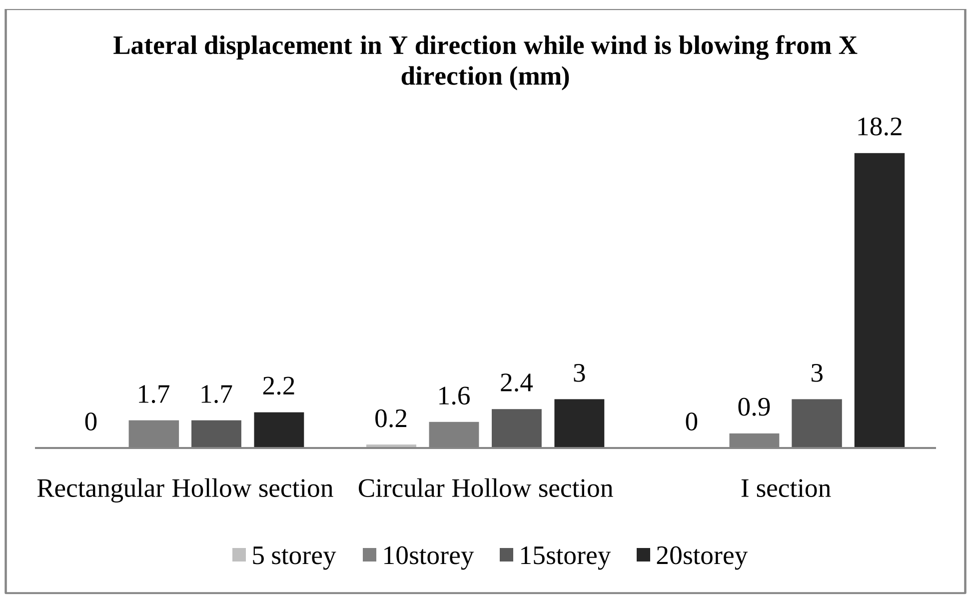
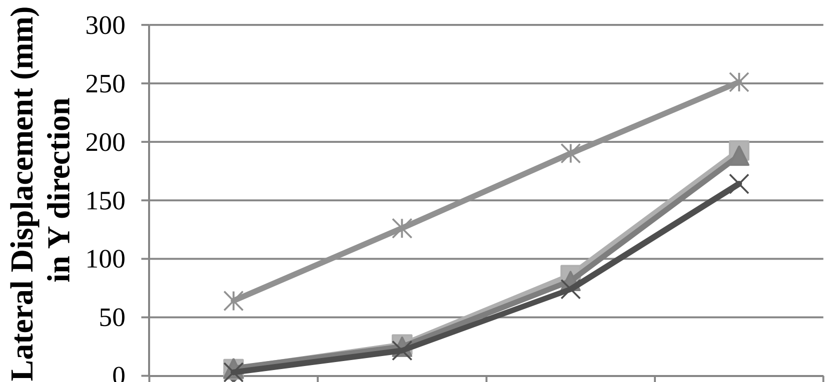


Figure D.2 (a): Lateral displacement (mm) in X direction for symmetrical plan and asymmetrical section, central bay zipper brace.



Brace sections	5 storey	10storey	15storey	20storey
Angle section	2.8			
Rectangular Hollow section	5.5	26.5	86	192.6
Circular Hollow section	6.1	24.7	81	188.2
I section	2.9	21.4	74	164
Max	64	126	190	251

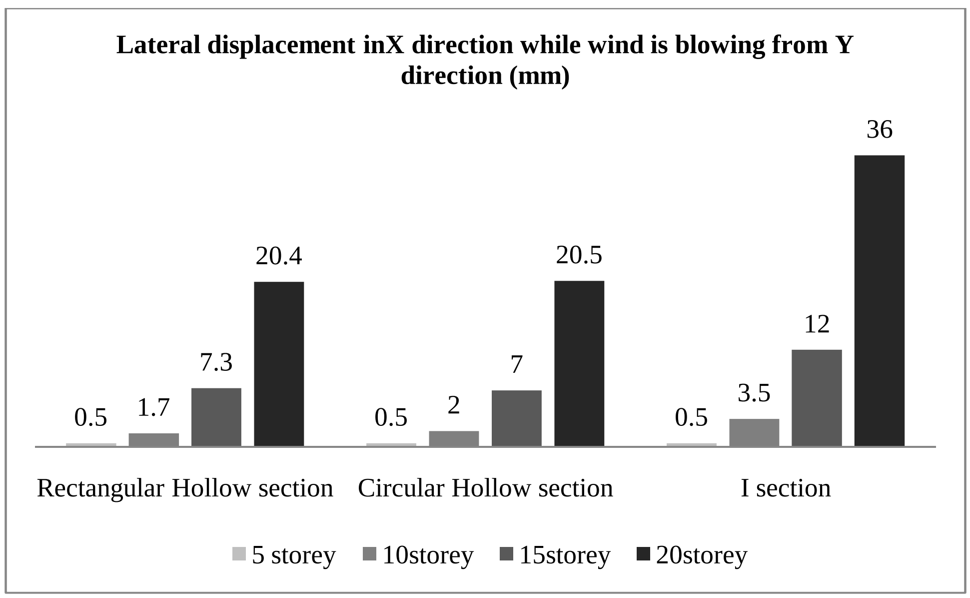
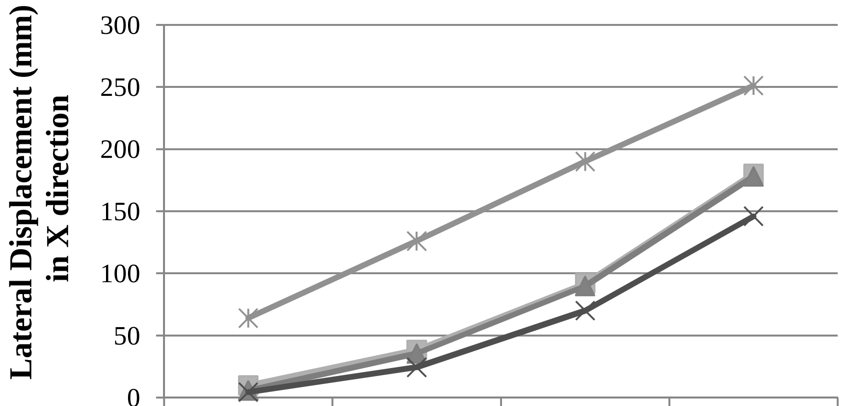


Figure D.2 (b): Lateral displacement (mm) in Y direction for symmetrical plan and asymmetrical section, central bay zipper brace.

Table D.4: Weights of columns, beams, braces and total by having different steel brace sections for knee bracing in the central bay of structure for symmetrical plan and asymmetrical section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	22.5	Failed	Failed	Failed
	Rectangular Hollow section	28.4	53.0	100.2	168.0
	Circular Hollow section	22.3	58.0	105.0	170.4
	I section	21.0	57.0	104.2	169.4
Difference between max and min (%)		**35.2**	**9.4**	**4.8**	**1.4**
Beams Weight (ton)	Angle section	59.0	Failed	Failed	Failed
	Rectangular Hollow section	58.3	127.4	196.0	266.0
	Circular Hollow section	57.0	126.0	194.0	261.2
	I section	56.5	127.3	195.0	261.3
Difference between max and min (%)		**4.4**	**1.1**	**1.0**	**1.8**
Braces Weight (ton)	Angle section	7.2	Failed	Failed	Failed
	Rectangular Hollow section	2.7	6.2	11.0	16.8
	Circular Hollow section	4.0	10.0	15.0	23.2
	I section	8.2	24.6	46.0	69.0
Difference between max and min (%)		**203.7**	**296.8**	**318.2**	**310.7**
Total Weight (ton)	Angle section	88.7	Failed	Failed	Failed
	Rectangular Hollow section	89.3	186.7	307.0	451.0
	Circular Hollow section	83.4	194.0	314.0	454.8
	I section	85.6	209.0	345.3	499.7
Difference between max and min (%)		**7.0**	**12.0**	**12.5**	**10.8**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	7.4			
Rectangular Hollow section	9.8	38.4	92	180
Circular Hollow section	5.7	35.5	89.8	178
I section	4.4	24.4	70	146
Max	64	126	190	251

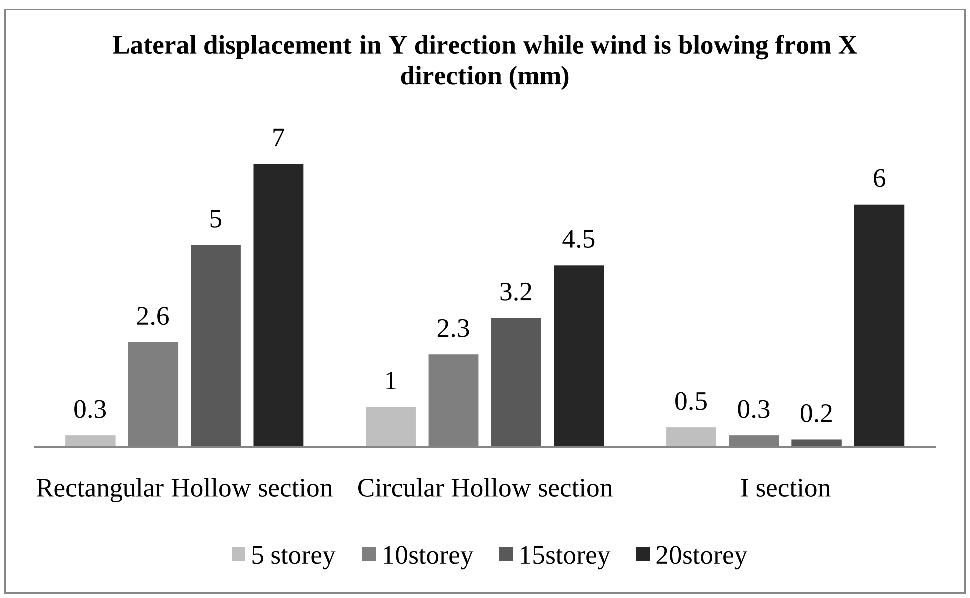
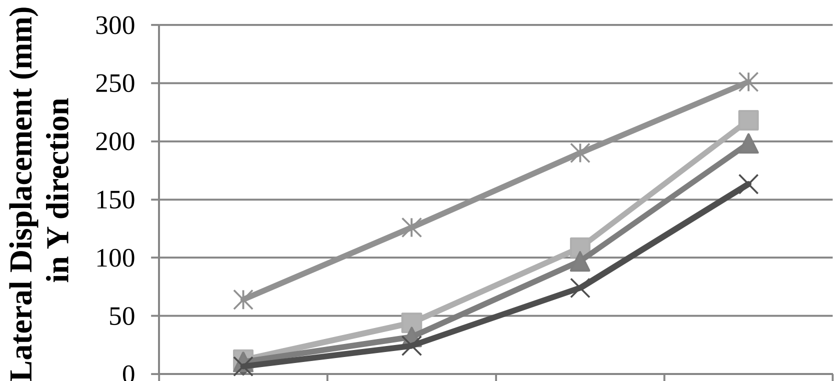


Figure D.3 (a): Lateral displacement (mm) in X direction for symmetrical plan and asymmetrical section, central bay knee brace.



Brace sections	5 storey	10storey	15storey	20storey
Angle section	7.5			
Rectangular Hollow section	12.3	44	108.7	218
Circular Hollow section	10.5	32	97	198.3
I section	6.7	24.4	74	163.2
Max	64	126	190	251

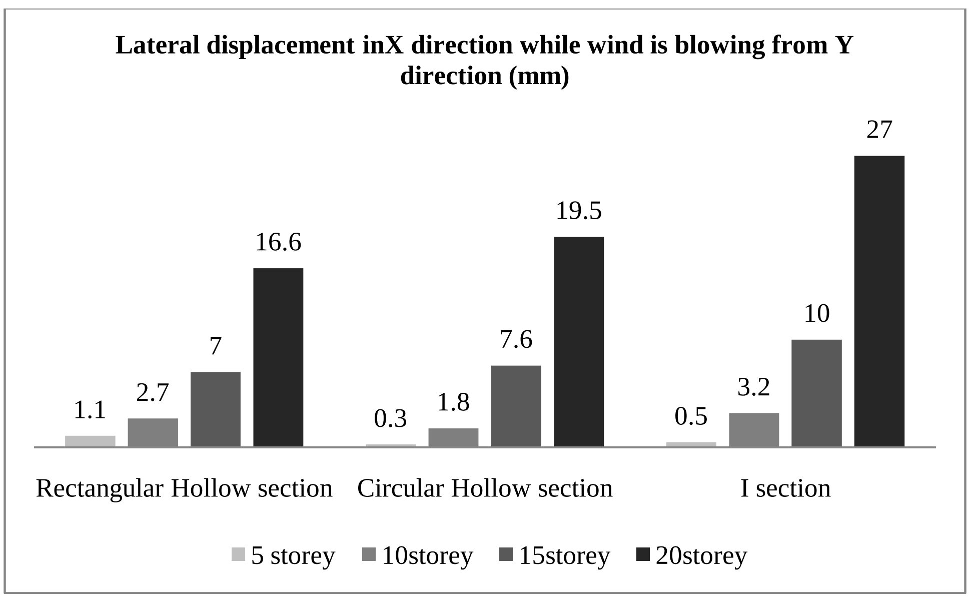
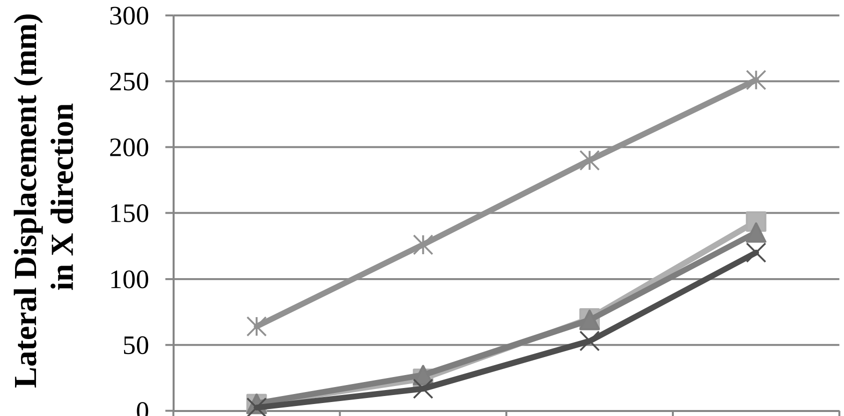


Figure D.3 (b): Lateral displacement (mm) in Y direction for symmetrical plan and asymmetrical section, central bay knee brace.

Table D.5: Weights of columns, beams, braces and total by having different steel brace sections for cross bracing in the core of structure for symmetrical plan and asymmetrical section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	16.5	49.7	92.7	151.7
	Circular Hollow section	15.0	48.0	92.7	150.8
	I section	15.5	45.3	89.0	146.0
Difference between max and min (%)		**10.0**	**9.7**	**4.0**	**3.9**
Beams Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	56.6	124.0	191.4	258.3
	Circular Hollow section	56.7	124.6	191.5	258.5
	I section	56.8	125.2	193.8	261.4
Difference between max and min (%)		**0.3**	**0.9**	**1.2**	**1.2**
Braces Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	4.2	10.5	17.0	25.8
	Circular Hollow section	4.2	13.0	25.2	44.0
	I section	18.4	56.8	109.3	145.0
Difference between max and min (%)		**338.0**	**441.0**	**550.0**	**462.0**
Total Weight (ton)	Angle section	Failed	Failed	Failed	Failed
	Rectangular Hollow section	77.3	184.0	301.2	436.0
	Circular Hollow section	75.8	186.0	309.4	453.2
	I section	90.7	227.3	392.0	552.4
Difference between max and min (%)		**19.6**	**23.5**	**30.0**	**26.7**



Brace sections	5 storey	10storey	15storey	20storey
Rectangular Hollow section	5.1	24.3	70	143.6
Circular Hollow section	5.5	27.2	69	135.2
I section	2.5	16.7	53	120
Max	64	126	190	251

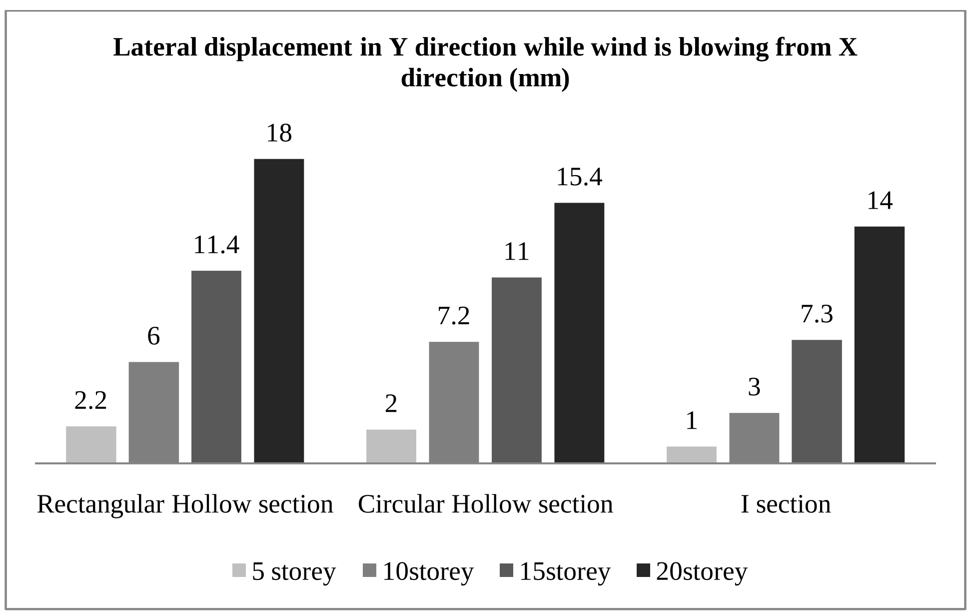
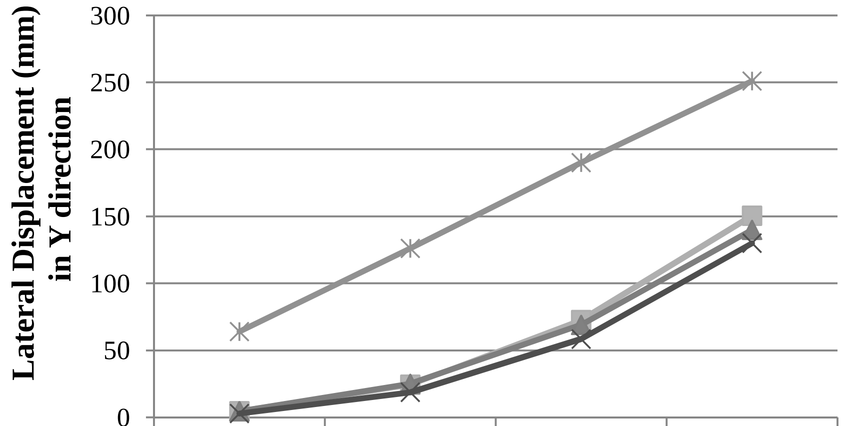


Figure D.4 (a): Lateral displacement (mm) in X direction for symmetrical plan and asymmetrical section, core cross brace.



Brace sections	5 storey	10storey	15storey	20storey
Rectangular Hollow section	4.5	24.3	72.5	150.5
Circular Hollow section	4.5	25	69	140
I section	2.8	18.7	58.4	130
Max	64	126	190	251

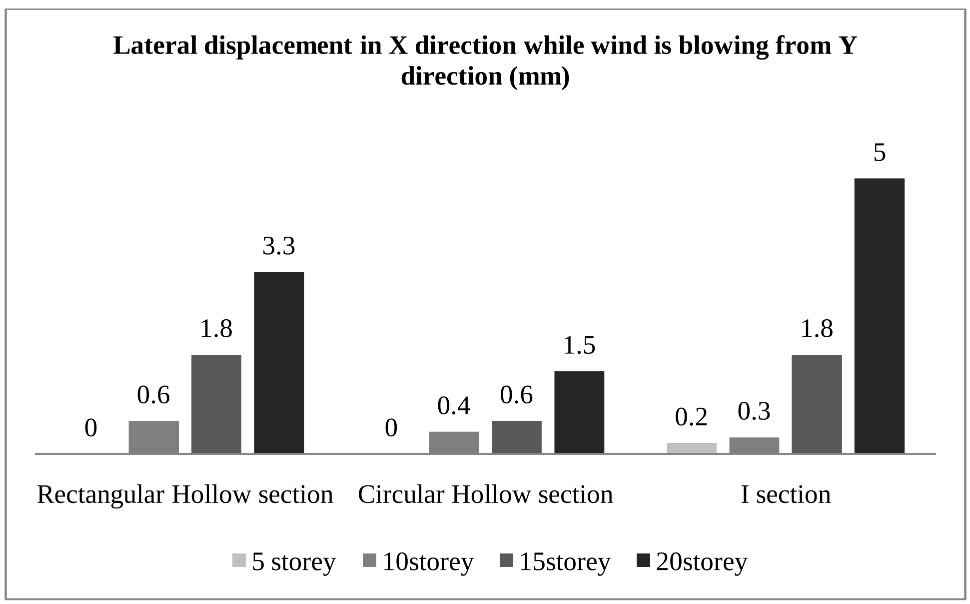
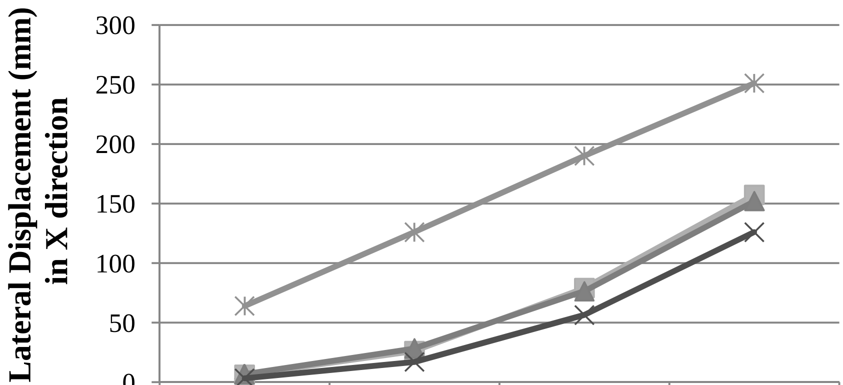


Figure D.4 (b): Lateral displacement (mm) in Y direction for symmetrical plan and asymmetrical section, core cross brace.

Table D.6: Weights of columns, beams, braces and total by having different steel brace sections for zipper bracing in the core of structure for symmetrical plan and asymmetrical section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	16.2	Failed	Failed	Failed
	Rectangular Hollow section	17.5	51.0	94.6	153.6
	Circular Hollow section	15.5	50.0	95.0	154.0
	I section	14.7	51.0	99.3	166.3
Difference between max and min (%)		**19.0**	**2.0**	**5.0**	**8.3**
Beams Weight (ton)	Angle section	50.3	Failed	Failed	Failed
	Rectangular Hollow section	51.0	117.0	181.3	245.6
	Circular Hollow section	51.8	116.6	180.2	244.0
	I section	52.0	117.6	181.2	244.6
Difference between max and min (%)		**3.4**	**0.8**	**0.6**	**0.6**
Braces Weight (ton)	Angle section	6.0	Failed	Failed	Failed
	Rectangular Hollow section	2.6	6.4	9.5	14.0
	Circular Hollow section	3.8	8.2	13.8	21.0
	I section	8.5	27.5	48.0	83.3
Difference between max and min (%)		**227.0**	**329.7**	**405.3**	**495.0**
Total Weight (ton)	Angle section	72.6	Failed	Failed	Failed
	Rectangular Hollow section	71.0	174.4	285.4	413.2
	Circular Hollow section	71.0	174.8	289.0	419.0
	I section	75.0	196.0	328.6	494.2
Difference between max and min (%)		**5.6**	**12.4**	**15.0**	**19.6**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	3			
Rectangular Hollow section	6.2	26.2	79	157.2
Circular Hollow section	6.8	28.4	76.3	152
I section	3.3	17	56.4	126
Max	64	126	190	251

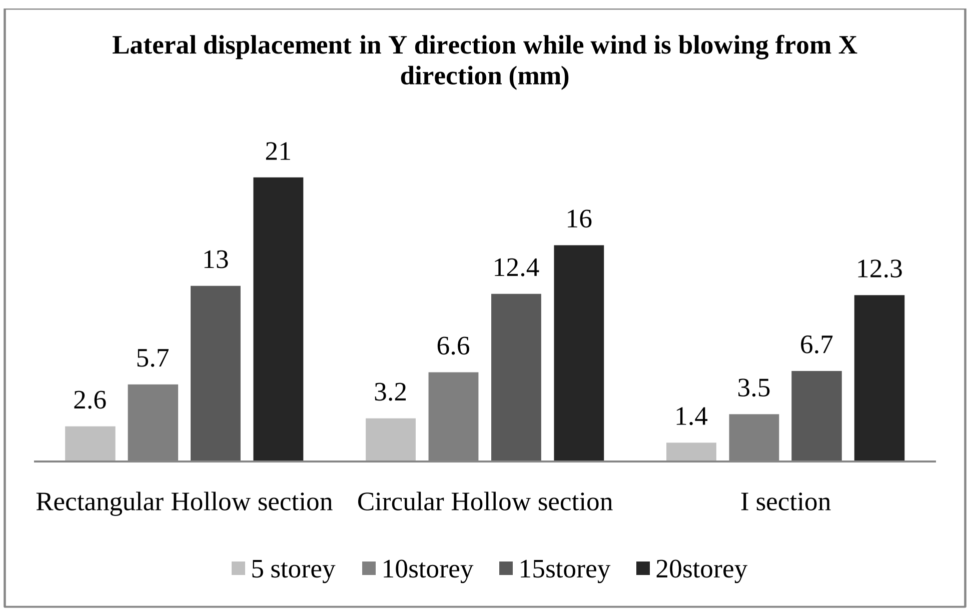
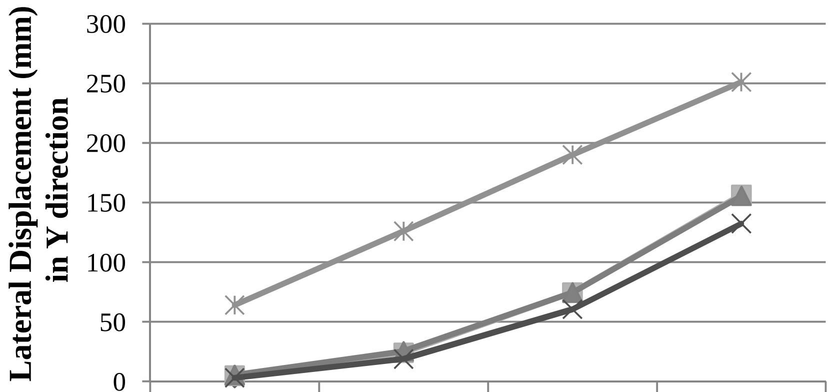


Figure D.5 (a): Lateral displacement (mm) in X direction for symmetrical plan and asymmetrical section, core zipper brace.



Brace sections	5 storey	10storey	15storey	20storey
Angle section	2.8			
Rectangular Hollow section	4.8	24	74.4	156.5
Circular Hollow section	5.5	25.3	74.6	155.5
I section	3	18.8	60.5	132.4
Max	64	126	190	251

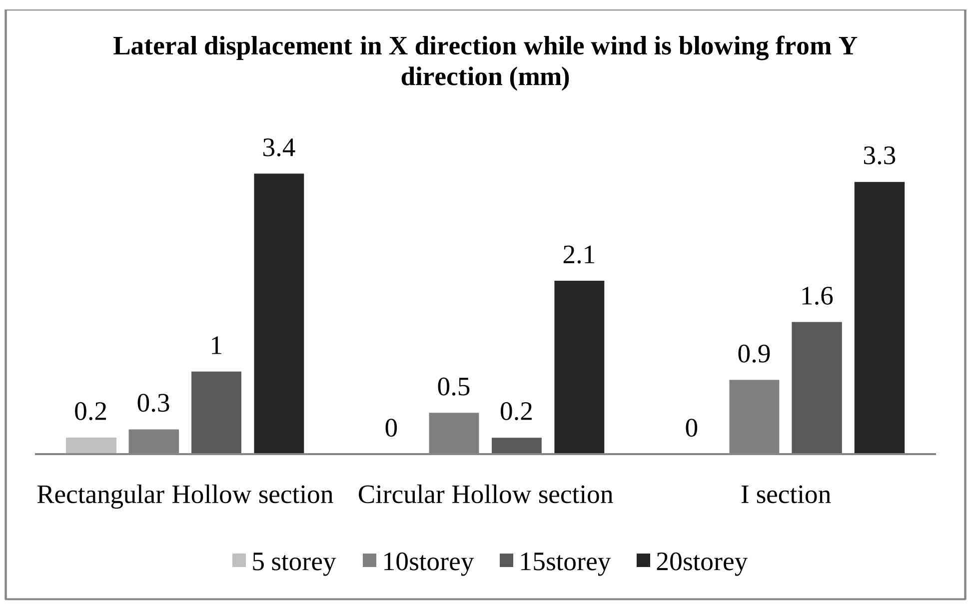
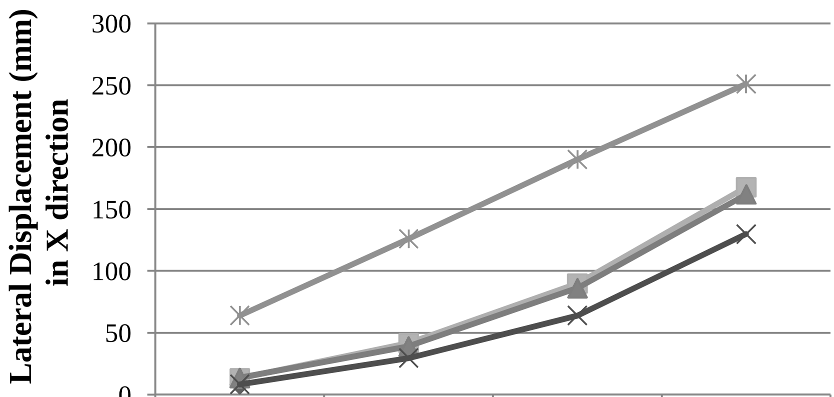


Figure D.5 (b): Lateral displacement (mm) in Y direction for symmetrical plan and asymmetrical section, core zipper brace.

Table D.7: Weights of columns, beams, braces and total by having different steel brace sections for knee bracing in the core of structure for symmetrical plan and asymmetrical section.

	Brace Sections/ No. of Stories	5	10	15	20
Columns Weight (ton)	Angle section	19.0	Failed	Failed	Failed
	Rectangular Hollow section	19.7	46.8	93.8	160.0
	Circular Hollow section	15.3	49.0	99.0	161.8
	I section	16.6	51.5	97.7	161.5
Difference between max and min (%)		**28.7**	**10.0**	**5.5**	**1.1**
Beams Weight (ton)	Angle section	56.7	Failed	Failed	Failed
	Rectangular Hollow section	56.5	124.0	191.0	258.0
	Circular Hollow section	55.8	122.2	188.8	254.4
	I section	55.6	122.0	188.0	252.0
Difference between max and min (%)		**1.9**	**1.6**	**1.6**	**2.4**
Braces Weight (ton)	Angle section	7.3	Failed	Failed	Failed
	Rectangular Hollow section	3.3	6.6	11.0	17.0
	Circular Hollow section	3.8	9.3	15.3	22.0
	I section	9.8	21.3	39.8	57.2
Difference between max and min (%)		**197.0**	**222.7**	**261.8**	**236.5**
Total Weight (ton)	Angle section	83.0	Failed	Failed	Failed
	Rectangular Hollow section	79.5	177.3	295.8	435.0
	Circular Hollow section	75.0	180.5	303.2	438.2
	I section	82.0	194.8	325.5	470.6
Difference between max and min (%)		**10.7**	**9.8**	**10.0**	**8.2**



Brace sections	5 storey	10storey	15storey	20storey
Angle section	8.3			
Rectangular Hollow section	13.2	41.6	89.8	167.5
Circular Hollow section	13.6	39	86	161.7
I section	8.4	29.6	64	129.7
Max	64	126	190	251

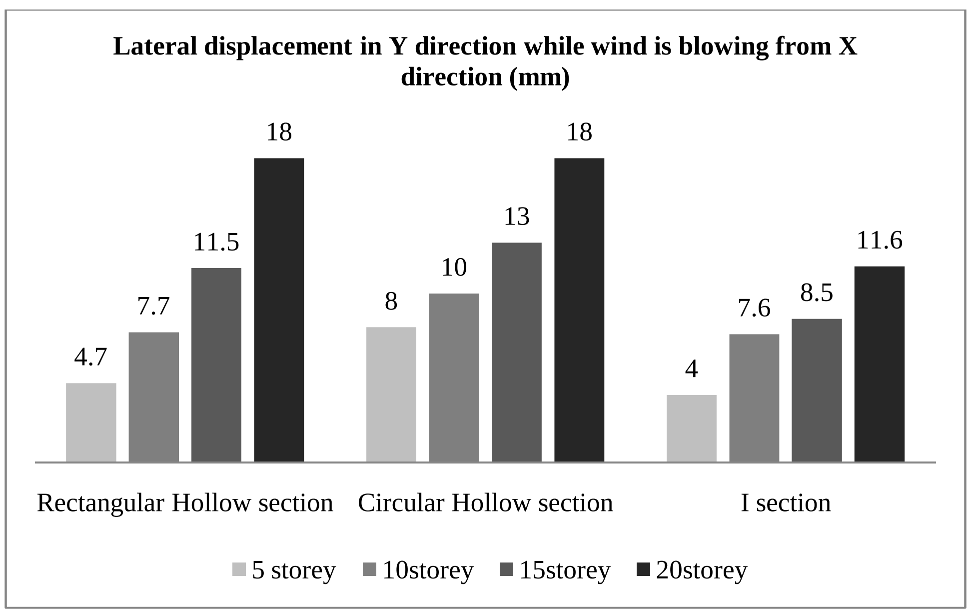
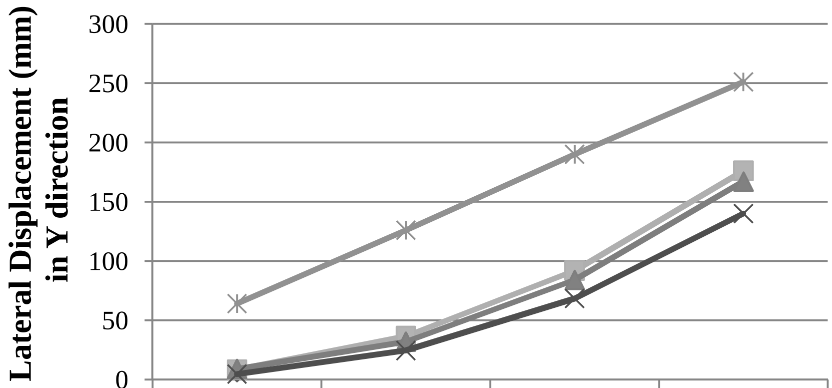


Figure D.6 (a): Lateral displacement (mm) in X direction for symmetrical plan and asymmetrical section, core knee brace.



Brace sections	5 storey	10storey	15storey	20storey
Angle section	6.4			
Rectangular Hollow section	8.4	36.6	92	176
Circular Hollow section	9	32	84	167
I section	4.6	24.5	68.3	140
Max	64	126	190	251

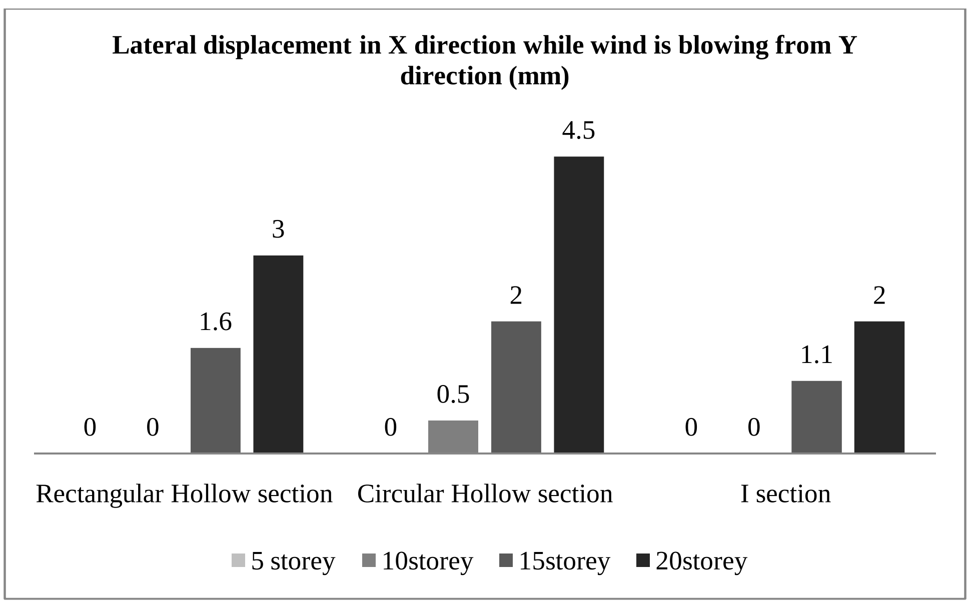


Figure D.6 (b): Lateral displacement (mm) in Y direction for symmetrical plan and asymmetrical section, core knee brace.

APPENDIX E

Table E.1 direction factor S_d. Table E.2 and Figure E.1 give External presssure coeficients C_{pe} for vertical walls and key to wall pressure respectively and Table E.3 terrain and building factor [13].

Table E.1: Direction factor S_d

Direction (Degree)	Direction Factor S_d
0^o North	0.78
30^o	0.73
60^o	0.73
90^o East	0.74
120^o	0.73
150^o	0.80
180^o South	0.85
210^o	0.93
240^o	1.00
270^o West	0.99
300^o	0.91
330^o	0.82
360^o North	0.78
NOTE. Interpolation may be used within this Table	

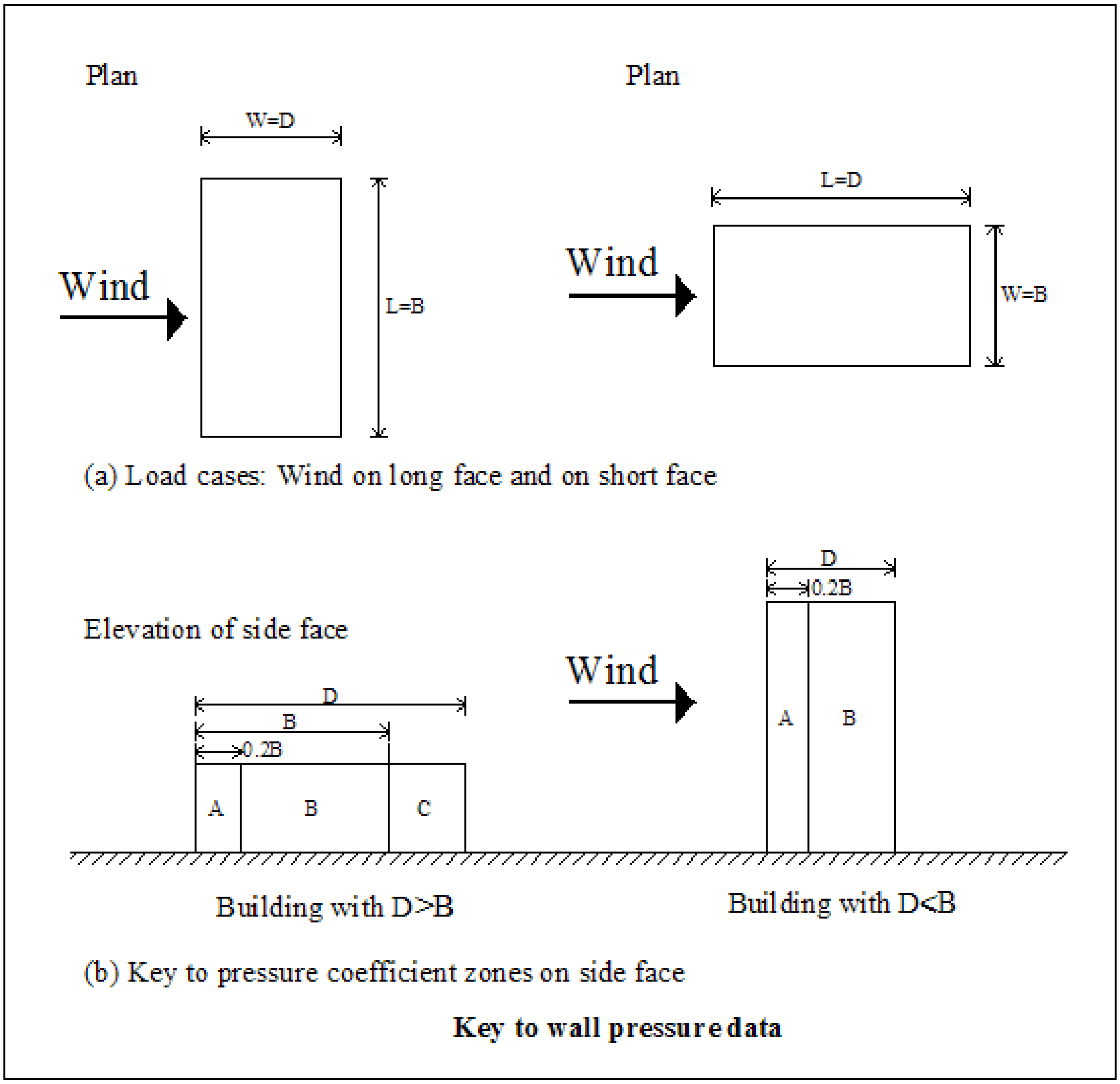


Figure E.1: Key to wall pressure data.

Table E.2: External presssure coeficients C_{pe} for vertical walls

Vertical wall face	**Span ratio building**		**Vertical wall face**		**Expoare case**	
	$B/H \leq 1$	$B/H \geq 4$			Isolated	Funnelling
Windward face	+0.8	+0.6	Side face	Zone A	-1.3	-1.6
Leeward (rear) face	-0.3	-0.1		Zone B	-0.8	-0.9
				Zone C	-0.4	-0.9

Table E.3: Factor S_b for standard method

Site in country					Site in town, extending ≥ 2km upwind from the site			
Effective H_e (m)	Closest distance to sea (km)				Effective H_e (m)	Closest distance to sea (km)		
	0	2	10	≥100		2	10	≥100
≤ 2	1.48	1.40	1.35	1.26	≤ 2	1.18	1.15	1.07
5	1.65	1.62	1.57	1.45	5	1.60	1.45	1.36
10	1.78	1.78	1.73	1.62	10	1.73	1.69	1.58
15	1.85	1.85	1.82	1.71	15	1.85	1.82	1.71
20	1.90	1.90	1.89	1.77	20	1.90	1.89	1.77
30	1.96	1.96	1.96	1.85	30	1.96	1.96	1.85
50	2.04	2.04	2.04	1.95	50	2.04	2.04	1.95
100	2.12	2.12	2.12	2.07	100	2.12	2.12	2.07

NOTE 1. Interpolation may be used within each table.
NOTE 2. Value assumed a diagonal dimension α=5m.
NOTE 3. If H_e > 100m use the directional method.