JIMMA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING

STRUCTURAL ENGINEERING STREAM

Comparative Study on Structural Efficiency of Diagrids with Beam Column, Shear Wall and Steel Bracing Lateral Load Resisting Systems

A Thesis submitted to the School of Graduate Studies of Jimma University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering (Structural Engineering)

By:

Abdusemed Bedru

May, 2019

Jimma, Ethiopia

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By:

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Co-Advisor: Engr. Solomon Biratu (MSc).

May, 2019

Jimma, Ethiopia

DECLARATION

This research is my original work and has not been presented for a degree in any other university.

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Main Advisor Signature Date

Solomon Biratu (MSc) ______________________ ______________________

Co-Advisor Signature Date

ABSTRACT

Choosing the most efficient and economical lateral load resisting system is a crucial question in designing high rise buildings, especially in high seismic zones. Shear walls and steel bracings are most popular lateral load resisting systems. Recently the use of diagrids for structural efficiency and architectural elegance has generated renewed interest from architectural and structural designers. These structures are emerging as popular structural systems in many developed and developing countries of the world, but in context of our country they are yet to get importance. To transfer the technology of using diagrids as lateral load resisting system to our country, it is very crucial to study the advantages of them over the well-known lateral load resisting systems.

This research is a comparative study, considering a symmetrical G+30 office high rise RC building laterally strengthened by 14 lateral load resisting systems collectively of six different types of shear wall, six different types of steel bracing, rigid frame and four module diagrid. Modal response spectrum analysis for seismic zone IV was carried out based on ESEN 1998-1:2013 using finite element software ETABS v9.6.0. Every independent variable that can affect lateral load resistance of high rise buildings was kept constant except the lateral load resisting systems. The comparison was in terms of four critical parameters; storey displacement, storey drift, time period and base shear.

As per the comparisons made, diagrids have showed a reduction of 7.8% in the X direction and 6.9% in the Y direction in storey displacement, 9.74% in the X direction and 7.31% in the Y direction in storey drift and 8.87% in fundamental time period as compared to the most efficient lateral load resisting system considered in the study. They showed a reduction in base shear of 8228.79KN in the X direction and 9418.25KN in the Y direction as compared to the system with the least base shear considered in the study (bare frame). These results show the best performance of diagrids in terms of reduction in storey displacement, storey drift, time period and base shear for every case and from every lateral load resisting system considered in the study. Therefore, diagrids, in addition to their inherent aesthetic quality and geometrical versatility, are the most efficient lateral load resisting systems in the range of many lateral load resisting systems known.

Keywords: Diagrids, shear walls, steel bracings, rigid frame

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CHAPTER ONE

INTRODUCTION

1.1) Background of the study

Designing tall buildings has become a necessity due to increase in population, scarcity of land, human aspiration to build higher buildings and the likes. Advances in construction technology, materials, structural systems and analysis and design software facilitated the growth of tall buildings. As the height of building increases, the lateral load resisting system becomes more important than the structural system that resists the gravitational loads. Nowadays in modern tall buildings, lateral loads induced by earthquake or wind are often resisted by a various lateral load resisting systems. Shear wall, braced frame, outrigger, braced tube, diagrid can be examples. The main reason for developing these systems is to effectively increase the lateral load resisting capacity of the structure while maintaining the economy as for tall structures the governing factor is lateral loads. In the late 19th century early designs of tall buildings recognized the effectiveness of diagonal bracing members in resisting lateral forces. However, while the structural importance of diagonals was well recognized, their aesthetic potential was not explicitly appreciated. Thus, diagonals were generally embedded within the building cores which were usually located in the interior of the building. A major departure from this design approach occurred when braced tubular structures were introduced in the late 1960s.

Recently the use of perimeter diagonals—hence the term ‘diagrid’—for structural effectiveness and esthetics has generated renewed interest from architectural and structural designers of tall buildings. Due to this, nowadays research topics regarding diagrid lateral load resisting system become very hot. Kim et al. (2010) have investigated the seismic performance evaluation of diagrid system buildings and they concluded that the diagrid structures showed higher over strength with smaller ductility compared with tubular structures. Khushbu et al. (2012) have performed analysis and design of 36 storey diagrid steel building and concluded that most of the lateral load is resisted by diagrid columns on the periphery, while gravity load is resisted by both the internal columns and peripheral diagonal columns. So, internal columns need to be designed for vertical load only. Due to increase in lever arm of peripheral diagonal columns, diagrid structural system is more effective in lateral load resistance. Abhinav et al. (2016) have performed seismic analysis of multi-storey building with shear wall using STAAD Pro and concluded that the building with the shear wall along periphery is much more efficient than all other models. Mohd et al. (2015) have performed comparative study on seismic analysis of G+15 storey building stiffened with bracing and shear wall and concluded that lateral displacement of the building is reduced by 35 % to 45 % by the use of X type steel bracing. Sanjay (2014) investigated effect of different thickness and corresponding reinforcement percentages required for shear walls on multi-storey buildings and concluded that increase of shear wall thickness is not always effective for earthquake resistant design. Sharma et al. (2015) and Viraj et al. (2017) have performed a comparative study between diagrid system, simple frame system and bracing system. From the results it has been concluded that diagrid Structure overall performs better as lateral load resisting system than simple frame and shear wall systems.

The aforementioned researches are the few from the vast researches made regarding lateral load resisting systems. Observing researches regarding diagrids, in spite of the vast studies done about them there is no a comprehensive study which can compare the structural efficiency of these diagrids with the most common lateral load resisting systems (i.e. shear wall and steel bracing). Moreover, in spite of the fact that diagrid structures are emerging as popular structural system in many developed and developing countries of the world, but in context of our country they are yet to get importance. Hence, this research is intended to compare the lateral load resisting efficiency of diagrids with shear wall and steel bracing lateral load resisting systems so as to transfer this diagrid technology to our country.

1.2) Statement of the problem

In modern tall buildings, lateral loads induced by earthquake or wind are often resisted by a various lateral load resisting system. The main reason for developing these systems is to effectively increase the lateral load resisting capacity of the structure while maintaining the economy. Now a day, shear walls and steel bracings are most popular systems to resist lateral load due to earthquake, wind, blast and others.

Recently the use of perimeter diagonals (diagrids) for structural efficiency and architectural elegance has generated renewed interest from architectural and structural designers. Choosing the most efficient and economical lateral load resisting system is a crucial question in designing high rise buildings, especially in high seismic zones.

Hence, can we laterally strengthen high rise buildings with diagrids more efficiently than shear walls and steel bracings?

1.3 Objectives of the Study

1.3.1) General objective

The general objective of the study was to compare structural efficiency of diagrid lateral load resisting systems with rigid frame, shear wall, and steel bracing lateral load resisting systems in RC high rise buildings.

1.3.2) Specific objectives

- To evaluate the behaviour of rigid frame, shear wall, steel bracing and diagrid lateral load resisting systems subjected to earth quake load based on four parameters; storey displacement, storey drift time period and storey shear using a finite element software ETABS v9.6.0

- To compare the efficiency of diagrids with rigid frame, shear wall and steel bracings based on storey displacement, storey drift, time period and storey shear.

- To establish the best overall performance of diagrids as lateral load resisting system among the known efficient lateral load resisting systems in our country

1.4. Significance of the study

As mentioned above, this research is intended to compare the performance of diagrids with shear wall and steel bracing lateral load resisting systems. Through this, it was understood the structural behavior of different lateral load resisting systems under seismic action. Hence, the research can be used to recognize how diagrids are efficient in lateral load resisting systems over the others and to use them effectively in design of high rise buildings. This can also serve as a guideline how to consider and analyze the possible lateral load resisting systems during seismic design of high rise buildings so as to select the best lateral load resisting systems on the basis of analysis results.

1.5) Scope and limitation of the Study

This research is limited to symmetric six bays by six bays G+30 multi storey RC building which is regular in plan and elevation. The frames are assumed firmly fixed at the bottom and the soil–structure interaction is neglected. Six most critical lateral load resisting systems from each of shear wall and steel bracing and one most critical lateral load resisting system from each of rigid frame and diagrid with a total of 14 models is analysed. The steel bracings are external and concentric. The diagonalization angle of the diagrids is uniform throughout the height of the building. The comparison is based on structural efficiency excluding cost, recommending the cost comparison for future researchers. The analysis is completed using ETABS software.

CHAPTER TWO

RELATED LITERATURE REVIEW

2.1) Lateral loads

There are many types of lateral loads which can act on buildings, from which wind and earthquake are the major ones in the analysis of high rise buildings. The resistance of tall buildings to wind as well as to earthquake is the main determinant in the formulation of new 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. Hence, there is a need for brief introduction of these two major lateral loads.

2.1.1) Wind loads

Wind is the term used for air in motion and is usually applied to the natural horizontal motion of the atmosphere. Motion in a vertical or nearly vertical direction is called a current. Movement of air near the surface of the earth is three-dimensional, with horizontal motion much greater than the vertical motion. Vertical air motion is of importance in meteorology but is of less importance near the ground surface. On the other hand, the horizontal motion of air, particularly the gradual retardation of wind speed and the high turbulence that occurs near the ground surface, are of importance in building engineering (Bungale, 2004).

2.1.2) Earthquake loads

Seismic loading requires an understanding of the structural behavior under large inelastic, cyclic deformations. Behavior under this loading is fundamentally different from wind or gravity loading, requiring much more detailed analysis, and application of a number of stringent detailing requirements to assure acceptable seismic performance beyond the elastic range (Bungale, 2004).

It is generally impractical as well as uneconomical to design a structure to respond in the elastic range to maximum expected earthquake-induced inertia forces. Therefore, in seismic design, yielding is permitted in predetermined structural members or locations, with the provision that the vertical load-carrying capacity of the structure is maintained even after strong earthquakes. However, for certain types of structures such as nuclear facilities, yielding cannot be tolerated and as such, the design needs to be elastic. In general, most earthquake code provisions implicitly require that structures be able to resist

1. Minor earthquakes without any damage.
2. Moderate earthquakes with negligible structural damage and some nonstructural damage.
3. Major earthquakes with some structural and nonstructural damage but without collapse. (Bungale, 2004).

An idea of the behavior of a building during an earthquake may be grasped by considering the simplified response shape shown in Fig. 2.1. As the ground on which the building rests is displaced, the base of the building moves with it. However, the building above the base is reluctant to move with it because the inertia of the building mass resists motion and causes the building to distort. This distortion wave travels along the height of the structure, and with continued shaking of the base, causes the building to undergo a complex series of oscillations. Although both wind and seismic forces are essentially dynamic, there is a fundamental difference in the manner in which they are induced in a structure. Wind loads, applied as external loads, are characteristically proportional to the exposed surface of a structure, while the earthquake forces are principally internal forces resulting from the distortion produced by the inertial resistance of the structure to earthquake motions (Bungale, 2004).

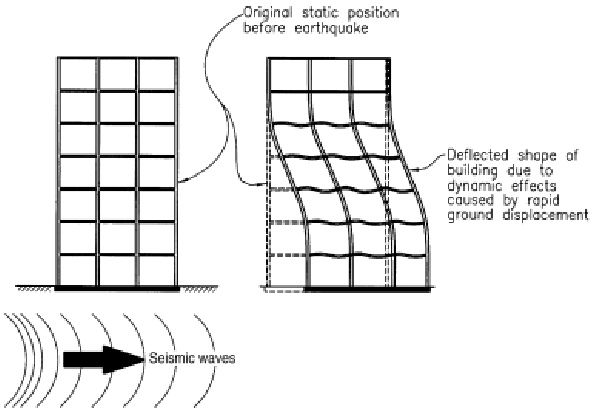


Figure 2. 1: Behavior of a building during earthquakes. (Bungale, 2004)

2.1.2.1) Building behavior

An increase in mass has two undesirable effects on the earthquake design. First, it results in an increase in the force, and second, it can cause buckling or crushing of columns and walls when the mass pushes down on a member bent or moved out of plumb by the lateral forces. This effect is known as the pΔ effect and the greater the vertical forces, the greater the movement due to pΔ (Bungale, 2004).

In general, tall buildings respond to seismic motion differently than low-rise buildings. The magnitude of inertia forces induced in an earthquake depends on the building mass, ground acceleration, the nature of the foundation, and the dynamic characteristics of the structure

a) Influence of soil

The seismic motion that reaches a structure on the surface of the earth is influenced by local soil conditions. Low- to mid-rise buildings typically have periods in the 0.10 to 1.0 sec range, whereas taller, more flexible buildings have periods between 1 and 5 sec or greater. As a building vibrates due to ground motion, its acceleration will be amplified if the fundamental period of the building coincides with the period of vibrations being transmitted through the soil. An obvious design strategy is to ensure that buildings have a natural period different from that of the expected ground vibration to prevent amplification.

b) Damping

Damping is measured as a percentage of critical damping. In a dynamic system, critical damping is defined as the minimum amount of damping necessary to prevent oscillation altogether. The extent of damping depends upon the construction materials, type of connections, and the influence of nonstructural elements on the stiffness characteristics of the building.

c) Building deflections

Lateral deflections that occur during earthquakes should be limited to prevent distress in structural members and architectural components. Non-load bearing in-fills, external wall panels, and window glazing should be designed with sufficient clearance or with flexible supports to accommodate the anticipated movements.

d) Building drift

Drift is generally defined as the lateral displacement of one floor relative to the floor below. Drift control is necessary to limit damage to interior partitions, elevator and stair enclosures, glass, and cladding systems (Bungale, 2004).

2.2) Types of buildings

Basically, there are three main types of buildings: steel buildings, reinforced concrete buildings, and composite buildings (Halis, 2006).

2.2.1) Steel buildings

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.

2.2.2) Reinforced concrete buildings

Although concrete as a structural material has been known since early times, the practical use of reinforced concrete was only introduced in 1867. Particularly, because of its moldability characteristics, and natural fireproof property, architects and engineers utilize the reinforced concrete to shape the building, and its elements in different and elegant forms.

2.2.3) Composite buildings

Concrete and steel systems evolved independently of each other until 1969, the year in which the composite construction, basically described as a steel frame stabilized by reinforced concrete, of a 20-storey building was done by Dr. Fazlur Khan (Halis, 2006).

2.3) Structural systems for tall buildings

Structural systems that can be used for the lateral resistance of tall buildings are classified based on the basic reaction mechanism/structural behavior for resisting the lateral loads. Taking into consideration the studies in the literature the following classification is proposed for the structural systems of tall buildings for all the types (i.e. steel buildings, reinforced concrete buildings, and composite buildings) (Halis, 2006).

2.3.1) Rigid frame systems

Rigid frame systems are utilized in both steel and reinforced concrete construction. Rigid frame systems for resisting lateral and vertical loads have long been accepted for the design of the buildings. Rigid framing, namely moment framing, is based on the fact that beam-to-column connections have enough rigidity to hold the nearly unchanged original angles between intersecting components. Owing to the natural monolithical behavior, hence the inherent stiffness of the joist, rigid framing is ideally suitable for reinforced concrete buildings. On the other hand, for steel buildings, rigid framing is done by modifying the joints by increasing the stiffness in order to maintain enough rigidity in the joints. Especially for the buildings constructed in seismic zones, a special attention should be given to the design and detailing of joints, since rigid frames are more ductile and less vulnerable to severe earthquakes when compared to steel braced or shear-walled structures. In buildings up to 30 stories, frame action usually takes care of lateral resistance except for very slender buildings.

2.3.2) Braced frame and shear-walled frame systems: These systems are stiffer when compared to the rigid frame system, and can be used for buildings over 30 stories, but mostly applicable for buildings about 50 stories in height. However, there are examples for these systems reaching over 100-storey height.

2.3.3) Braced Frame Systems:

This system is a highly efficient and economical system for resisting horizontal loading, and attempts to improve the effectiveness of a rigid frame by almost eliminating the bending of columns and girders, by the help of additional bracings. It behaves structurally like a vertical truss, and comprises of the usual columns and girders, essentially carrying the gravity loads, and diagonal bracing components so that the total set of members forms a vertical cantilever truss to resist the horizontal loading. Depending on architectural and structural characteristics, braces can be classified as four main groups as shown in Fig. 2.5. These are, X, diagonal, K, and Knee bracings. (Halis, 2006).

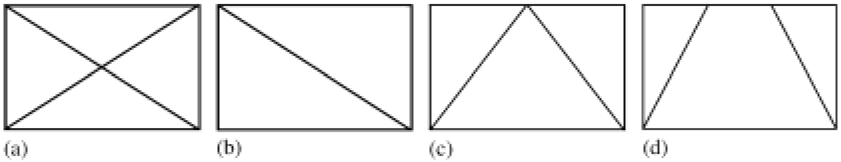


Figure 2. 2: Types of braces: (a) X – the least available space; (b) diagonal – less available space; (c) K – openings possible; (d) Knee – larger openings. (Halis, 2006).

Bracing has been used to stabilize laterally for the majority of the world‘s tallest building structures as well as one of the major retrofit measures. The introduction of steel braces is in steel structures and of RC shear walls in RC structures. However, the use of steel bracing systems for RC buildings may have both practical and economical advantages. There are two types of bracing systems, Concentric Bracing System and Eccentric Bracing System (Kevadkar et al., 2013).

a) The Concentric Bracings

The Bracing is concentric when the center lines of the bracing members intersect. Increase the lateral stiffness of the frame, thus increasing the natural frequency and also usually decreasing the lateral drift. However, increase in the stiffness may attract a larger inertia force due to earthquake. Further, while the bracings decrease the bending moments and shear forces in columns, they increase the axial compression in the columns to which they are connected. Since reinforced concrete columns are strong in compression, it may not pose a problem to retrofit in RC frame using concentric steel bracings.

b) Eccentric Bracings

Reduce the lateral stiffness of the system and improve the energy dissipation capacity. Due to eccentric connection of the braces to beams, the lateral stiffness of the system depends upon the flexural stiffness of the beams and columns, thus reducing the lateral stiffness of the frame. The vertical component of the bracing forces due to earthquake causes lateral concentrated load on the beams at the point of connection of the eccentric bracings (Kevadkar et al., 2013).

2.3.4) Shear-Walled Frame Systems

Shear-walled frame systems are utilized in both reinforced concrete and composite construction. Shear walls may be described as vertical cantilevered beams, which resist lateral wind and seismic loads acting on a building and transmitted to them by the floor diaphragms. These elements can have various shapes such as, circular, curvilinear, oval, box-like, triangular, or rectilinear. (Halis, 2006).

These walls generally start at foundation level and are continuous throughout the building height. Their thickness can be as low as 200mm, or as high as 400mm in high rise buildings. Shear walls are usually provided along both length and width of buildings, Shear walls are like vertically-oriented wide beams that carry earthquake loads downwards to the foundation. Properly designed and detailed buildings with shear walls have shown very good performance in past earthquakes. Shear walls in high seismic regions require special detailing. Since shear walls carry large horizontal earthquake forces, the overturning effects on them are large. Thus, design of their foundations requires special attention. Shear walls should be provided along preferably both length and width. However, if they are provided along only one direction, a proper grid of beams and columns in the vertical plane (called a moment-resistant frame) must be provided along the other direction to resist strong earthquake effects (Kevadkar, et al., 2013).

2.3.5) Outrigger Systems

Outrigger systems are modified form of braced frame and shear-walled frame systems, and utilized in steel and composite constructions. As an innovative and efficient structural system, the outrigger system comprises a central core, including either braced frames or shear walls, with horizontal ‘‘outrigger’’ trusses or girders connecting the core to the external columns. Furthermore, in most cases, the external columns are interconnected by exterior belt girder. Outrigger structures can be used for buildings with over 100 stories. (Halis, 2006).

2.3.6) Framed-Tube Systems

Framed-tube systems, are proper for steel, reinforced concrete and composite construction, and represent a logical evolution of the conventional frame structure. The primary characteristic of a tube is the employment of closely spaced perimeter columns interconnected by deep spandrels, so that the whole building works as a huge vertical cantilever to resist overturning moments. (Halis, 2006).

2.3.7) Braced-Tube Systems

Braced-tube systems can be utilized in steel, reinforced concrete, and composite construction. By adding multistory diagonal bracings to the face of the tube, the rigidity and efficiency of the framed tube can be improved, thus the obtained braced-tube system, also known as trussed tube or exterior diagonal-tube system, could be utilized for greater heights, and allows larger spacing between the columns. This configuration is well suited for tall, slender buildings with small floor areas. This system can be used for buildings with over 100 stories (Halis, 2006).

2.3.8) Bundled-Tube Systems

Bundled-tube systems are proper for steel, reinforced concrete, and composite construction. A single framed tube does not have an adequate structural efficiency, if the building dimensions increase in both height and width. Namely, the wider the structure is in plan, the less effective is the tube. In such cases, the bundled tube, also known as modular tube, with larger spaced columns is preferred. It can be utilized for a 30-storey-high building as well as for ultra-tall structures with over 100 stories.

The above classification is the expansion of the basic structural systems (frame systems, braced or shear walled systems, and tube systems). Nowadays, reinforced concrete and composite structures are in serious competition with the steel structures, and by the advancements in concrete technology, such as manufacturing ultra-high-strength concrete, except ‘outrigger systems’, all the structural systems classified above can be applied in reinforced concrete (Halis, 2016).

2.4) Diagrid System

2.4.1) Concept and definition

The term “diagrid” is somewhat misleading. Diagrid is commonly used to describe a diagonal structural grid. The system is comprised of diagonal members, normally fabricated from structural steel, that are joined at nodal points. The diagonal grid, although often presented as the dominant visual feature in the design of diagrid buildings, is by itself unstable. The diamond-shaped system requires triangulation in order to create sufficiency in the structure. Diagrids or diagonal grids are a structural design strategy for constructing buildings that combine the resistance to gravity and lateral loads into a triangulated system of members that eliminates the need for vertical columns. This system is usually placed on the perimeter of the building. Triangulation is normally achieved where the floor edge beams tie into the grid. The primary idea behind the development of the diagrid system was the recognition of the savings possible in the removal of (most of) the vertical columns. Vertical columns, engineered to carry gravity loads, are incapable of providing lateral stability. The diagonal grid, if properly spaced, is capable of assuming all of the gravity loads as well as providing lateral stability due to its triangular configuration. A pure diagrid structure does not require the traditional reinforced concrete or steel core to provide lateral stability. (Terri, 2014)

The term “diagrid” is a blending of the words “diagonal” and “grid” and refers to a structural system that is single-thickness in nature and gains its structural integrity through the use of triangulation. Diagrid systems can be planar, crystalline or take on multiple curvatures; they often use crystalline forms or curvature to increase their stiffness. Being single-thickness differentiates a diagrid from any three-dimensional triangulated systems such as space frames, space trusses, although it will be shown that some of the developments of diagrid structures have been derived from the details of these three-dimensional systems. Perimeter diagrids normally carry the lateral and gravity loads of the building and are used to support the floor edges. (Terri, 2014)

The followings are common terms used in analysis of diagrids.

- The “module” refers to the number of floors that the diamond shape of the grid spans from tip to tip.
- The “node” is the point of intersection of the diagonal members.
- A “horizontal bracing ring” is created by the connection of the diagrid nodes to the floor edge beam.
- The steepness of the angle of the diagrid is measured as the angle formed between the diagonal and the floor. (Terri, 2014)

2.4.2) Why to choose a diagrid

Diagrids have emerged as an architectural choice in the creation of contemporary buildings. Although there are engineering–based reasons that would suggest the use of a diagrid, discussions with engineers would conclude that architectural design has been the driving motivation. Diagrids are able to adapt to a wide range of non-rectilinear geometric forms, including irregular curves and angles. No other type of framed structure is capable of this task.

There are several functional and economic advantages that underlie the system:

- Increased stability due to triangulation
- Combination of the gravity and lateral load-bearing systems, potentially providing more efficiency
- Provision of alternate load paths (redundancy) in the event of a structural failure
- Reduced use of structural materials translating into environmental savings
- Reduced weight of the superstructure can translate into a reduced load on the foundations
- Ability to provide structural support for a myriad of shapes

Although diagrids are said to be able to save 20% of the weight of steel used – this varies by project and is not to be taken as an absolute –the engineering and fabrication costs can be significantly higher than in traditional framed and/or concealed structural steel buildings. (Terri, 2014)

The difference between conventional exterior-braced frame structures and current diagrid structures is that, for diagrid structures, almost all the conventional vertical columns are eliminated. This is possible because the diagonal members in diagrid structural systems can carry gravity loads as well as lateral forces owing to their triangulated configuration, whereas the diagonals in conventional braced frame structures carry only lateral loads. (Nishith et al., 2014).

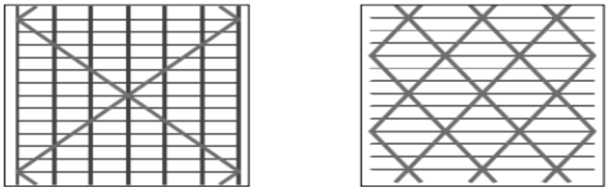


Figure 2. 3: (i) Braced Tube, (ii) Diagrid Structure (Nishith et al., 2014).

2.4.3) Examples of diagrid structures

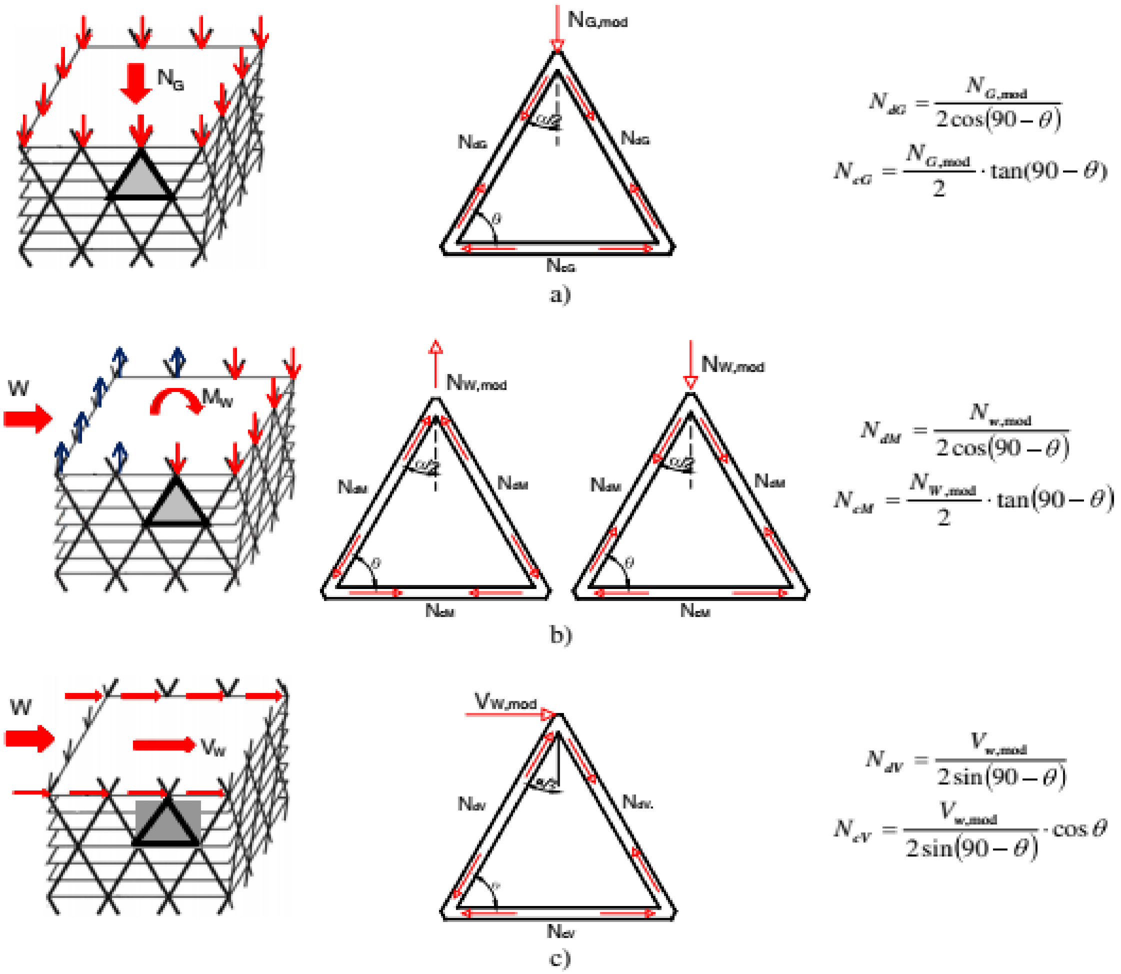
The photographs on figure 2.4 are samples from the plenty of the diagrid structures found in the world taken from the book “diagrid structures; systems, connections and details” written by Terri (2014).

(a) (b) (c) (d)

Figure 2. 4: (a) London city hall, London, England, Building ht.=10 floors; (b) Swiss Re, London, England, Building ht.=40 floors; (c) Hearst Magazine tower, New York City, USA, Building ht.=46 floors; (d) Capital gate, Abu Dhabi, UAE, Building ht.=36 floors(Terri, 2014)

2.4.4) The Triangle Diagrid Module

The analysis of the diagrid structures can be carried out in a preliminary stage by dividing the building elevation into groups of stacking floors, with each group corresponding to a diagrid module. As shown in the studies by Moon et al. (2007) and Moon (2008), the diagrid module under gravity loads G is subjected to a downward vertical force, NG,mod, causing the two diagonals being both in compression and the horizontal chord in tension (Figure 2.5(a)) (Elena et al., 2012).



$$N_{dG} = \frac{N_{G,\text{mod}}}{2\cos(90-\theta)}$$

$$N_{cG} = \frac{N_{G,\text{mod}}}{2} \cdot \tan(90-\theta)$$

$$N_{dM} = \frac{N_{w,\text{mod}}}{2\cos(90-\theta)}$$

$$N_{cM} = \frac{N_{W,\text{mod}}}{2} \cdot \tan(90-\theta)$$

$$N_{dV} = \frac{V_{w,\text{mod}}}{2\sin(90-\theta)}$$

$$N_{cV} = \frac{V_{w,\text{mod}}}{2\sin(90-\theta)} \cdot \cos\theta$$

Figure 2. 5: Diagrid module: (a) effect of gravity load, (b) effect of overturning moment and (c) effect of shear force

Under horizontal load W, the overturning moment MW causes vertical forces in the apex joint of the diagrid modules, NW,mod, with direction and intensity of this force depending on the position of the diagrid module, with upward/ downward direction and maximum intensity for the modules located on the windward/leeward façades, respectively, and gradually decreasing values for the modules located on the web sides (Figure 2.5(b)). The global shear VW causes a horizontal force in the apex joint of the diagrid modules, VW,mod, which intensity depends on the position of the module with respect to the direction of wind load, since the shear force VW is mainly absorbed by the modules located on the web façades, i.e. parallel to the load direction (Figure 2.5(c)). In the formulations provided in Figures 2.5(a, b, c) for deriving internal forces in the diagrid elements, it has been implicitly assumed that the external load is transferred to the diagrid module only at the apex node of the module itself.

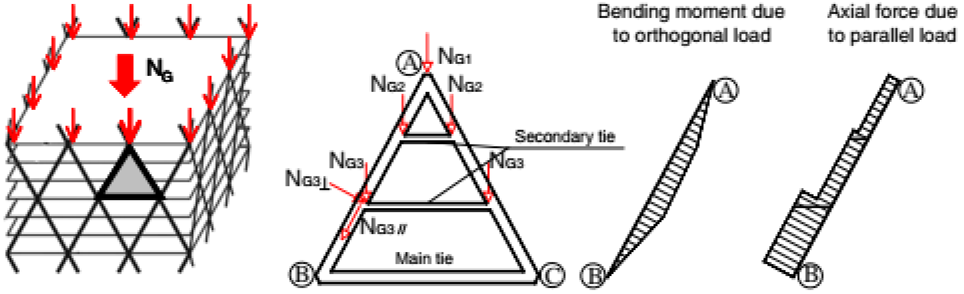


Figure 2. 6: Diagrid module: effect of gravity load along the diagonal length

However, since the triangle module usually expands over a certain number of stories, transfer of loads to the module occurs at every floor level, and thus also concentrated loads along the diagonal length are present (Figure 2.6); as a consequence, bending moment and shear force are expected due to this load condition. However, the introduction of a horizontal member at each floor girder to diagonal intersection, an intermediate chord, allows for the absorption of the force component orthogonal to the diagonal direction, thus preserving the prevailing axial force condition (Elena et al., 2012).

2.4.5) Geometry and Design Criteria

Diagrid structures, like all the tubular configurations, utilize the overall building plan dimension for counteracting overturning moment and providing flexural rigidity. However, this potential bending efficiency of tubular configurations is never fully achievable due to shear deformations that arise in the building 'webs'; with this regard, diagrid systems, which provide shear resistance and rigidity by means of axial action in the diagonal members, rather than bending moment in beams and columns, allows for a nearly full exploitation of the theoretical bending resistance. This is the main reason underlying the extraordinary efficiency of diagrid systems (Elena et al., 2012)

Being the diagrid a triangulated configuration of structural members, the geometry of the single module plays a major role in the internal axial force distribution, as well as in conferring global shear and bending rigidity to the building structure. As shown in the study by Moon et al. (2007), while a module angle equal to 35 ensures the maximum shear rigidity to the diagrid system, the maximum engagement of diagonal members for bending stiffness would correspond to an angle value of 90, i.e. vertical columns. Thus, in diagrid systems, where vertical columns are completely eliminated and both shear and bending stiffness must be provided by diagonals, a balance between these two conflicting requirements should be searched for defining the optimal angle of the diagrid module. However, it is worth noticing that, by varying the aspect ratio of the building, the demand for shear and bending stiffness also varies, being slender buildings more governed by a bending behavior than stocky buildings; therefore, it is expected that by increasing the building slenderness, also the optimal angle of the diagrid module should increase. Some useful indications on optimal angle values for buildings characterized by different aspect ratio are provided in the studies by Moon et al. (2007) and Moon (2008) and reported in the diagram of Figure 2.7, where the top displacement of buildings from 20 to 60 stories is depicted as a function of the diagrid angle; on the basis of these results, in Figure 2.8, the optimal angle values are represented as a function of the number of stories (aspect ratio), showing the expected increase with the building height (Elena et al., 2012).

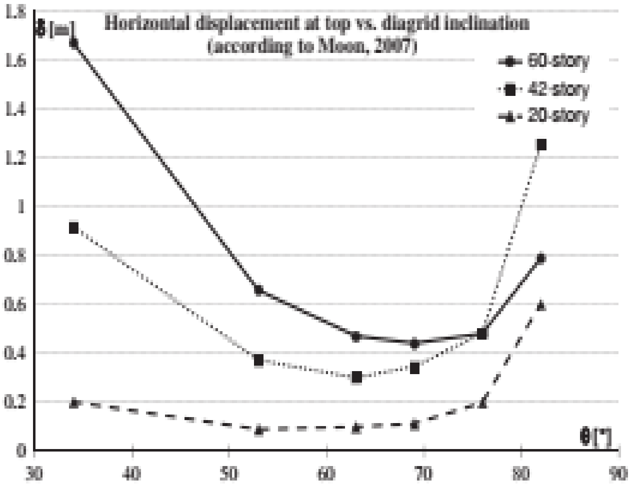


Figure 2. 7: Building top displacement versus diagrid angle (redrawn from Moon et al., 2007)

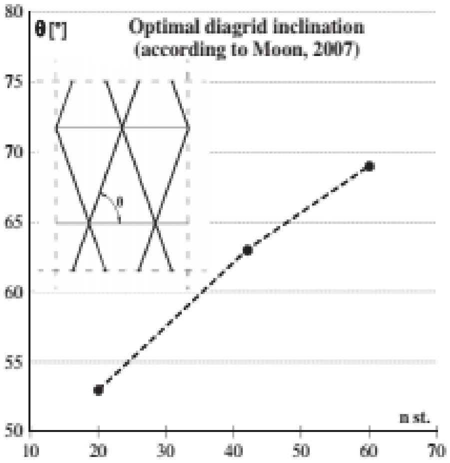


Figure 2. 8: Optimal diagrid inclination for different building heights.

Furthermore, for very tall buildings, i.e. buildings with aspect ratio of the order of 7 or more, the relative demand for shear and bending stiffness is not uniformly distributed along elevation, and a varying-angle diagrid configuration, with steeper angles towards the base, generates more efficient design solutions (i.e. less material consumption) than uniform angle configurations (Moon 2008; Zhang et al., 2010). In Figure 2.9, the results of the study by Zhang et al. (Zhang et al., 2010) are reported in a chart format, which provides the optimal values of angle couples (θ1 at the top and θ2 at the base) versus the number of stories: it is interesting to notice that the θ1 and θ2 angles are coincident for 30-story buildings while significantly diverge in the case of larger number of stories (Elena et al., 2012).

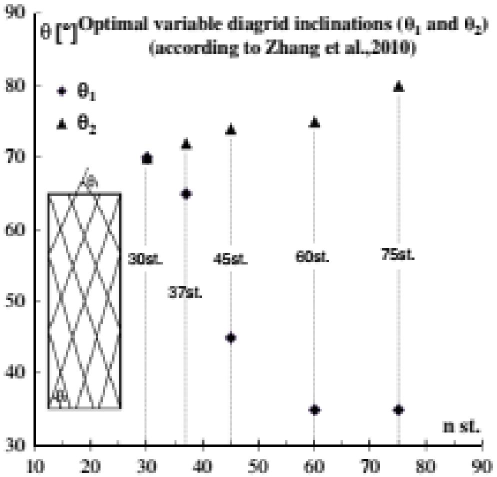


Figure 2. 9: Optimal couples of angles for variable—inclination diagrid.

CHAPTER THREE

RESEARCH METHODOLOGY

This chapter presents and describes the approaches and techniques the researcher used to collect data and investigate the research problem.

3.1) Study Design

There are various methods that can be used to conduct research and these can be either quantitative, qualitative or combination of both. Based on this, the paper has a quantitative nature (comparative) aiming to gather data from fourteen (14) modeling and analysis using ETABS software. The lateral load analysis of the study is based on the new code ESEN 1998-1:2013 which is the direct copy of Euro code 8 designs manual. The model is a G+30 building with plan dimension 42mx36m and storey height 3m. The plan is 6bayx6bay with each bay 7m in the X direction and 6m in the Y direction. Finite element software ETABS v9.6.0 is used to develop 3D model and to carry out a linear dynamic analysis such as modal response spectrum analysis.

3.2) Study Variables

3.2.1) Dependent Variables

The dependent variables of this study are:

- Storey displacement
- Storey drift
- Time period
- Storey shear.

3.2.2) Independent Variables

Since major parameters are kept constant except the type of lateral load resisting systems, the independent variables are:

- Thickness and location of shear walls
- Type and location of steel bracings
- Type of rigid frame
- Type of diagrid

3.3) Data Collection Procedure

A comparative study is made by considering a G+30 office high rise RC building laterally strengthened by 14 most efficient lateral load resisting systems, aiming to compare the structural efficiency of diagrids with other lateral load resisting systems. The fourteen (14) lateral load resisting systems are as follows:

1. Rigid frame system (beam-column system)
2. Shear wall system (one bay L-shaped at all corners with thickness=200mm)
3. Shear wall system (one bay L-shaped at all corners with thickness=300mm)
4. Shear wall system (one bay L-shaped at all corners with thickness=400mm)
5. Shear wall system (two bays at the middle of the outer perimeter of the plan thickness=200mm)
6. Shear wall system (two bays at the middle of the outer perimeter of the plan thickness=300mm)
7. Shear wall system (two bays at the middle of the outer perimeter of the plan thickness=400mm)
8. X-steel bracing system (one bay L-shaped at all corners)
9. V-steel bracing system (one bay L-shaped at all corners)
10. Inverted V-steel bracing system (one bay L-shaped at all corners)
11. X-steel bracing system (two bays at the middle of the outer perimeter of the plan)
12. V-steel bracing system (two bays at the middle of the outer perimeter of the plan)
13. Inverted V-steel bracing system (two bays at the middle of the outer perimeter of the plan)
14. Four storeys module diagrid

The G+ 30 building, which is laterally strengthened by the above fourteen lateral load resisting systems, is modeled and analysed using ETABS v9.6.0 software (the analysis is a linear and dynamic analysis). Every independent variable that can affect lateral load resistance of high rise buildings is kept constant except the type of lateral load resisting systems. Then, four critical parameters, that can help to compare the lateral load resisting systems, are extracted from ETABS (i.e. storey displacement, storey drift, time period and storey shear). Finally, tabulating and graphing the ETABS results in Excel, the above four parameters systematically are compared.

Justification for the selection of the samples

The samples of the shear walls and steel bracings are selected based on previous comparative research results on lateral load resisting systems. Different researchers suggest different type of shear wall and steel bracing lateral load resisting systems as the most efficient based on different criteria. So, for structural designers it was recommended to analyse different types of lateral resisting systems before deciding the efficient one for a particular structure.

- ✓ For the steel bracings the most efficient and popular arrangements are taken (X, V and Chevron)
- ✓ The thickness of shear walls can be as low as 200mm, or as high as 400mm in high rise buildings (Kevadkar, et al., 2013). So, the sample is taken in this range

The number of storey is selected based on the maximum number of stories rigid frames can be used as a lateral load resisting system. In buildings up to 30 stories, frame action usually takes care of lateral resistance except for very slender buildings (Halis, 2006). So, as the study area is in high rise buildings, the maximum number of stories for which rigid frames can be designed is considered for a better comparison.

3.4) Data Quality Assurance

In order to assure data quality the following measures are taken:

- ➢ The ETABS software is checked for the known simple structural systems to check whether it is working well or not.
- ➢ The structural modeling, the loading and the different connections of the frame system and the lateral load resisting system are double checked to remove errors.
- ➢ In case of any unreliable (illogical) results due to some unobserved errors, the structure is re-modeled and reanalyzed.
- ➢ A due attention and care is taken when extracting results from ETABS and plotting them in Excel.

CHAPTER FOUR

STRUCTURAL MODELING AND ANALYSIS

4.1) Methods of analysis

The lateral load analysis of this study is based on the new code ESEN 1998-1:2013 which is the direct copy of Euro code 8 Design Manual. Relevant articles, figures and tables referred in this chapter are summarized in appendix D. The analysis has been done using finite element software ETABS v9.6.0 to assess the seismic behaviour of a G+30 story high rise building. The following sections describe the finite element ETABS model and the material properties used in the analysis to achieve accurate and reliable results.

4.1.1) Method of analysis

For this specific study Modal response spectrum analysis is used due to the fact that the structure can't satisfy the fundamental period criteria given in the code for applying the lateral force method of analysis due to its height (90m)

In using this method it is checked that the maximum number of modes specified meet the 90% mass participation requirement by the code.

4.1.2) Earth quake parameters

The following table shows earthquake parameters used in the study.

Table 4. 1: Earthquake parameters

Parameters	Value	Remark
Seismic Zone	IV	To consider the maximum effect of the earth quake
Bed Rock acceleration ratio ($\alpha o = ag/g$)	0.15	ESEN value for zone IV (appendex-D.2)
Importance factor, I	1	Assuming office building (appendix-D.4)
Behavior factor, q	depends on lateral load resisting system	Sec 4.1.3
Ground type	B	Assumption
Spectrum type	Type-1	Suitable type of spectra for zone IV
Lower bound factor(β)	0.2	ESEN recommendation (appendex-D.3)

4.1.3) Behaviour factor

The behaviour factor *q* is an approximation of the ratio of the seismic forces that the structure would experience if its response was completely elastic with 5% viscous damping, to the seismic forces that may be used in the design, with a conventional elastic analysis model, still ensuring a satisfactory response of the structure.

i) Structural types

Based on the provisions of the code as indicated in appendix-D.3 it is assumed for all shear wall systems wall-equivalent dual system and for all steel bracing systems frame equivalent dual system. The ductility class assumed is DCM.

The above assumptions are checked as per the code definition at the end of the analysis and found correct.

ii) Behavior factor for the study

a) Column beam system

$q= q_o k_w \geq 1.5$

$q_o = 3.0\alpha u/\alpha 1$ …………………………………………………… frame system

$\alpha u/\alpha 1=1.3$ …………………………………………….….. multistorey, multi-bay frames

kw = 1 ……………………………………………………….. frame system

Therefore, q=3x1.3x1= 3.9

b) Shear wall system

$q_o = 3.0\alpha u/\alpha 1$ …………………………………………………… dual system

$\alpha u/\alpha 1=1.2$ …………………………………………………….. wall-equivalent dual

$0.5 \leq (1+\alpha o)/3 \leq 1$ ……………………………………………. wall-equivalent system

$\alpha_o = \Sigma\ h_{wi} / \Sigma l_{wi}$

When the shear wall is at the corner (one bay)

αo= 8x90/(8x(6+7)/2)= 13.8

kw = (1+13.8)/3= 4.9 > 1

q=3x1.2x1= 3.6

When the shear wall is at the middle (two bays)

αo= 4x90/4x13= 6.9

kw = (1+7.5)/3= 2.6 > 1

q=3x1.2x1= 3.6

c) Bracing systems

Since no code-specified q factor for steel-braced RC frames are known, earth quake analysis is done using q=5.5 for all RC frames braced with X, V, inverted V (chevron) and diagrid bracings based on previous studies. This choice is a very conservative choice as compared to the results of two related works showing a q factor ranging from 6.5 to 8 for X-braced (Maheri et al., 2008) and from 7 to 9 for Chevron-braced intermediate RC frame dual systems (Akbari et al., 2013)

4.1.4) Seismic Mass Source according to ESEN 1998-1

The inertial effects of the design seismic action shall be evaluated by taking into account the presence of the masses associated with all gravity loads appearing in the following combination of actions:

$$\sum G_{k,j} + \sum \psi_{E,i} \, x Q_{k,i}$$

Where $\psi E,i$ is the combination coefficient for variable action i

The combination coefficients $\psi E,i$ take into account the likelihood of the loads Qk,i not being present over the entire structure during the earthquake.

$\psi Ei= \phi.\psi 2i$

For this specific study our mass source coefficients can be calculated as follows (appendix-D.4)

Φ=0.8 --------------- storeys with correlated occupancies

ψ2=0.3 -------------- office building

$\psi Ei= \phi.\psi 2i=0.8x0.3=0.24$

4.1.5) Considering Effect of Cracking according to ESEN 1998-1

In concrete, composite steel-concrete and masonry buildings the stiffness of the load bearing elements should, in general, be evaluated taking into account the effect of cracking. Unless a more accurate analysis of the cracked elements is performed, the elastic flexural and shear stiffness properties of concrete and masonry elements may be taken to be equal to one-half of the corresponding stiffness of the uncracked elements. Torsional stiffness of the cracked section should be set equal to 10% of the torsional stiffness of the un-cracked section.

- In this paper to satisfy the above requirements, stiffness properties of slabs with shell properties, beams, columns and walls has been reduced to 50%.

4.1.6) Accidental torsional effects

In order to account for uncertainties in the location of masses and in the spatial variation of the seismic motion, the calculated center of mass at each floor i shall be considered as being displaced from its nominal location in each direction by an accidental eccentricity:

eai= ±0.05.Li

Where eai is the accidental eccentricity of storey mass i from its nominal location, applied in the same direction at all floors;

Li is the floor-dimension perpendicular to the direction of the seismic action.

- In ETABS software 5% is specified in the eccentricity ratio to satisfy the above requirements regarding minimum accidental torsion effect.

4.1.7) Response spectrum scale factor

Scale factor= I g / q, where I = occupancy factor, g=acceleration due to gravity and q=behavior factor of the system. For this study response spectrum scale factor is calculated based on the code recommendation and finally checked the 85% requirement of the code (i.e. dynamic base shear should be more than 85% of the static base shear) and found correct.

4.1.8) Selection of optimum diagrid module

Being the diagrid a triangulated configuration of structural members, the geometry of the single module plays a major role in the internal axial force distribution, as well as in conferring global shear and bending rigidity to the building structure. For this reason two types of diagrid module is selected and compared based on previous research works to get the optimum one.

a) Two storey module diagrid

X-direction Diagonal angle = tan-1 (module height / base width) = tan-1 (3m / 7m) = 23.2^{o}

Y-direction Diagonal angle = tan-1 (module height / base width) = tan-1 (3m / 6m) =26.6^{o}

b) Four storey module diagrid

X-direction Diagonal angle = tan-1 (module height / base width) = tan-1 (6m / 7m) = 40.6^{o}

Y-direction Diagonal angle = tan-1 (module height / base width) = tan-1 (6m / 6m) = 45^{o}

From the above two diagrid modules the optimum one for a G+ 30 storeys building as per the graph of optimal angle of diagrids drawn by Moon (2007) is the four storey module diagrid (See page 18 of literature review). Hence, for this specific study four storey module diagrid is chosen.

4.2) Modeling of structural systems

4.2.1) Modeling description

For the analysis work, the models of high rise reinforced concrete frame building of 30 floors are made to know the realistic behavior of the building during earthquake. The length of the model building is 42m and width is 36m. Height of typical story is 3 m. Column sizes change every 10 story. Generally the following assumptions are taken.

1. Modal damping 5% is considered.
2. Beams and columns are modeled as frame element and joined node to nodes. While shear walls were represented by shell-type element.
3. The effect of soil structure interaction is ignored in analysis. The columns are assumed to be fixed at the ground level.
4. Plan dimension and beam size are kept similar to all Storey.
5. The same location of both bracings and shear walls is taken, to have the better seismic performance comparison.
6. Shear wall is continues and the same dimension throughout the height of the frames
7. Participating Components: Only the primary structural components are assumed to participate in the overall behavior. The effects of secondary structural components and nonstructural components are assumed to be negligible; these include staircases, partitions, cladding, and openings.
8. The beam, column and slab dimension of all models is kept similar to achieve a correct and reliable comparison among them.

4.2.2) Loading

All the structural systems are subjected to three types of primary loading cases as per the provisions of ESEN 1998-1; 2013 and other EBCS Codes. They are:

1. Dead Load: only dead load from the frames and slabs of the building has been considered for this thesis. The material properties are shown in table 4.2
2. Live Load: based on EBCS 1-1995 (old) for office buildings from the code category of building area D (D1), the imposed floor area load is 5kN/m2.
3. Seismic Load: this load is calculated based on ESEN 1998-1; 2013 from the seismic mass of the building as mentioned in section 4.1 of this chapter in detail.

Table 4. 2: Material properties

Grade of concrete	C-40 (as used in practical application of tall buildings)
Poisons ratio of concrete	0.2
Density of concrete	25kN/m3
Modulus of elasticity of concrete	35GPa for C-40
Coefficient of thermal expansion of concrete	10x10-6 per o C
Grade of steel(rebar)	S-420
Grade of steel(wide flange-section for bracing)	S-450
Density of steel(wide flange-section for bracing)	77KN/m3
Coefficient of thermal expansion of steel	10x10-6 per oC
Modulus of elasticity of steel	200GPa
Poisons ratio of steel	0.3

4.2.3) Studied structural configuration

The following four types of structural configurations are studied.

1. 30 storeys reinforced concrete framed structure without bracing and shear wall (Bare frame)
2. 30 storeys reinforced concrete framed structure braced with shear wall (200mm, 300mm and 400mm thick middle and corner shear wall)
3. 30 storeys reinforced concrete framed structure braced with different bracing patterns (X, V, and inverted V (chevron) middle and corner bracing)
4. 30 storeys reinforced concrete framed structure braced with four storeys module diagrid.

4.2.4) Details of the building plan and member size

a) Building Plan

Plan of the reinforced concrete building which is used for the study is shown in figure below.

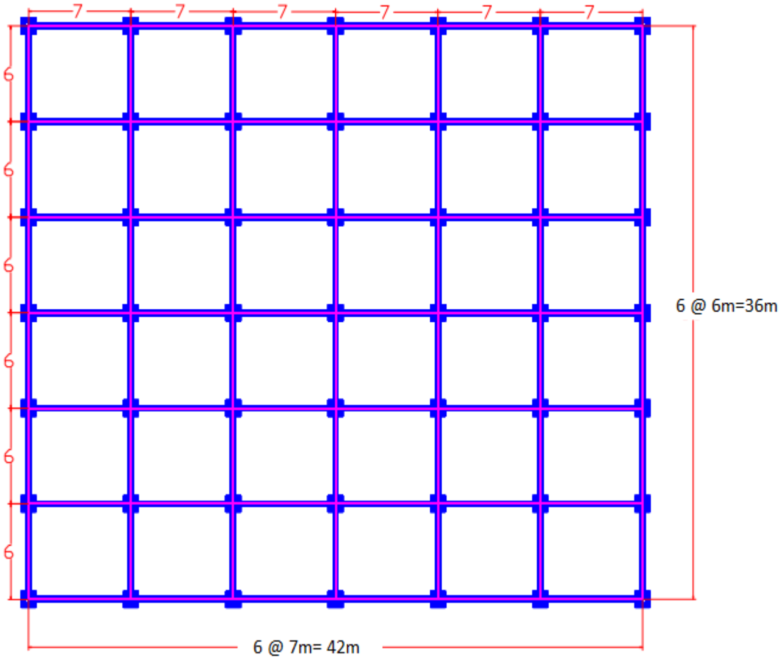


Figure 4. 1: plan of the model

b) Member size of the beams, columns, slabs and bracings

The beam, column and slab dimension of all models is kept similar to achieve a correct and reliable comparison among them. Similarly, for the frames braced with X, V, inverted V and chevron their bracing size is kept similar. Member size used for beams, columns, slabs and bracings is shown in Table 4.9 and Table 4.10

Table 4. 3: Size of Beams, Columns and Slabs

Story level	**Column schedule**		**Beam schedule**		**Slab schedule**	
	Column Name	**Dimension(mm)**	**Beam Name**	**Dimension(mm)**	**Slab Name**	**Thickness(mm)**
1 up to 5	C1000	1000x1000	B300x600	300x600	Slab150	150
6 up to 10	C900	900x900				
11 up to 15	C800	800x800				
16 up to 20	C700	700x700				
21 up to 25	C600	600x600				
26 up to 30	C500	500x500				

Table 4. 4: Size of Bracings

Story level	**Steel bracing schedule**	
	Bracing Name	**Dimension(mm)**
1 up to 10	BR1	Wide flange steel section 550x250x15
11 up to 20	BR2	Wide flange steel section 500x200x15
21 up to 30	BR3	Wide flange steel section 450x150x15

4.2.5) Type and location of bracing patterns and shear walls used in the study

Plans of the model braced with diagrid and other than diagrid (bare frame, shear wall and steel bracing) used in the study are shown in the figures 4.2 and 4.3.

I. Plan of the model braced with bare frame, shear wall or steel bracing

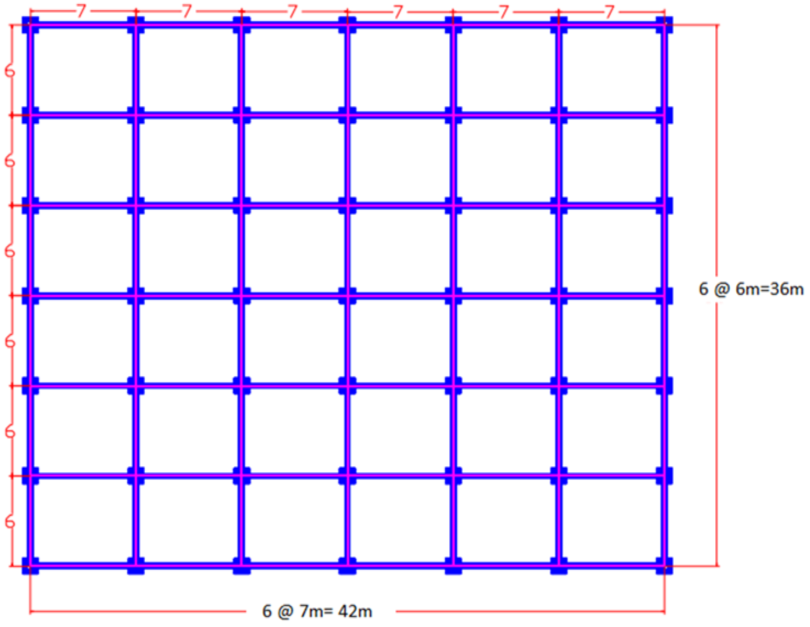


Figure 4. 2: Plan of the model braced with bare frame, shear wall or steel bracing

II. Plan of the model braced with diagrid

As it was discussed in chapter two and chapter four (section 4.2), diagrids contain triangular or diamond shaped module throughout exterior of the structure and they don’t have any external vertical columns. This is due to the extraordinary property of the diagonals of the diagrid which resist lateral load by axial action of the diagonals. Hence, in this research the diagrids are modeled without exterior columns as shown in the figure below.

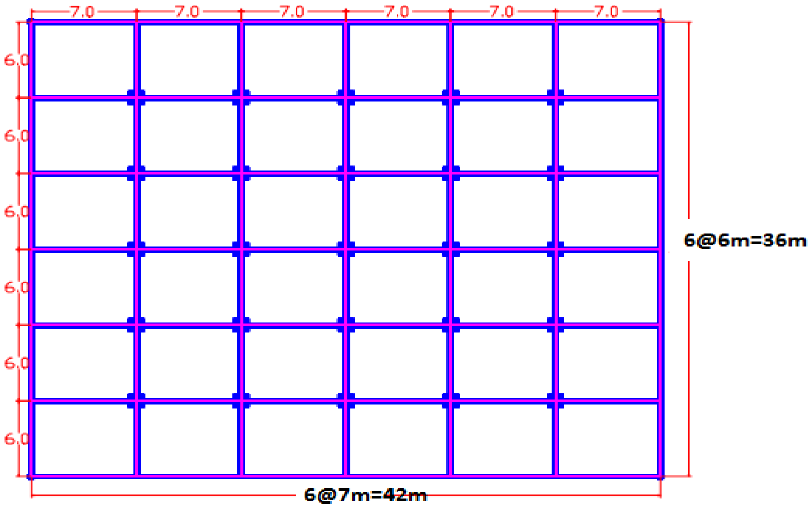
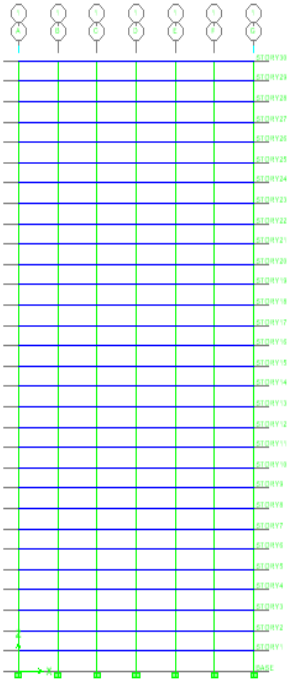


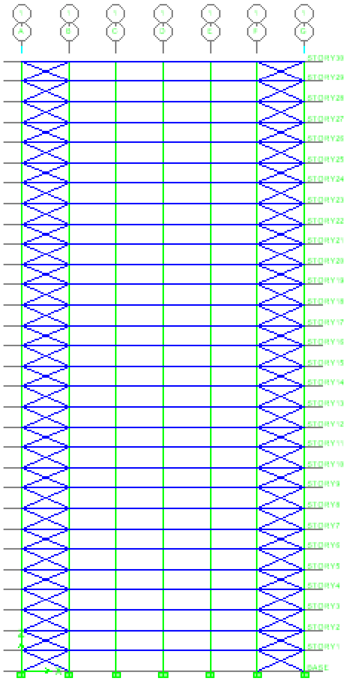
Figure 4. 3: Plan of the model braced with diagrid

Elevation of different types of bracing patterns, shear walls and diagrids used in the study are shown in the figures below.

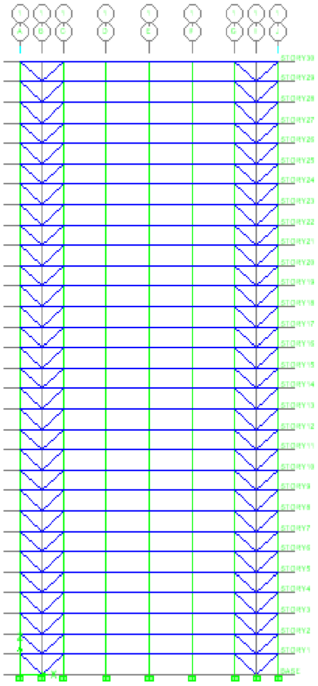
I. When the shear walls and bracings are provided at the corner



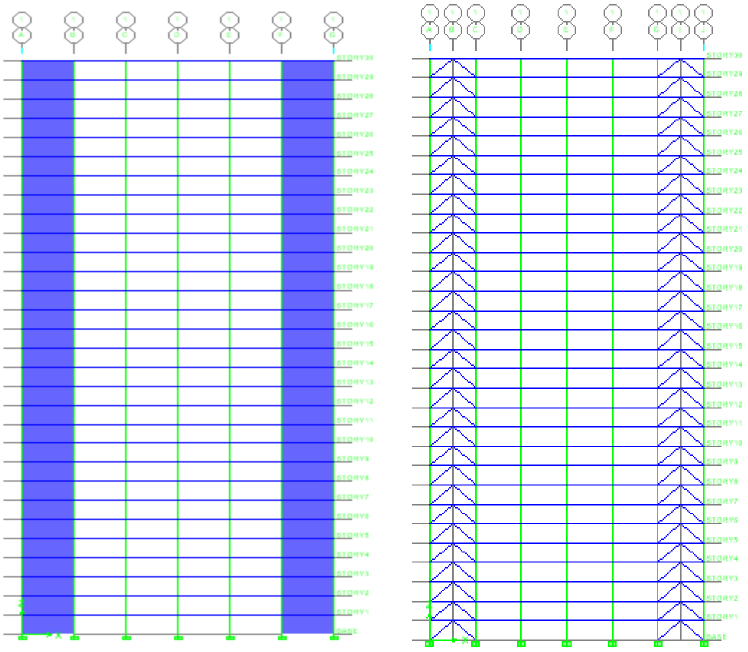
(A)



(B)



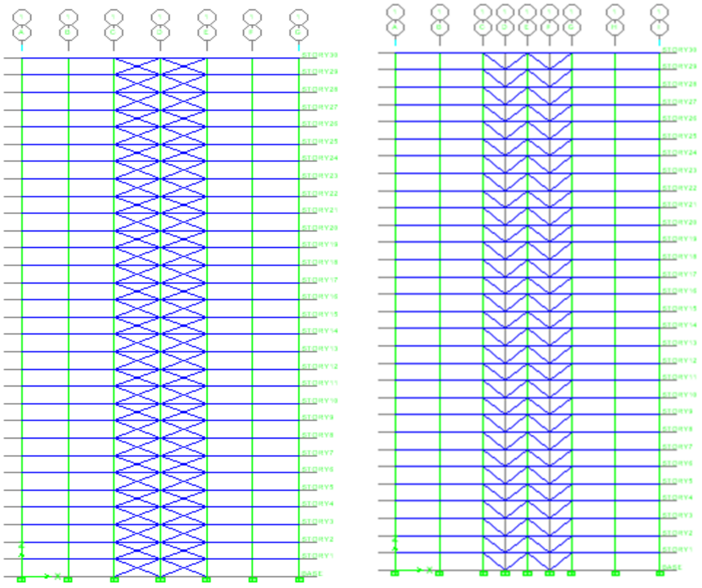
(C)



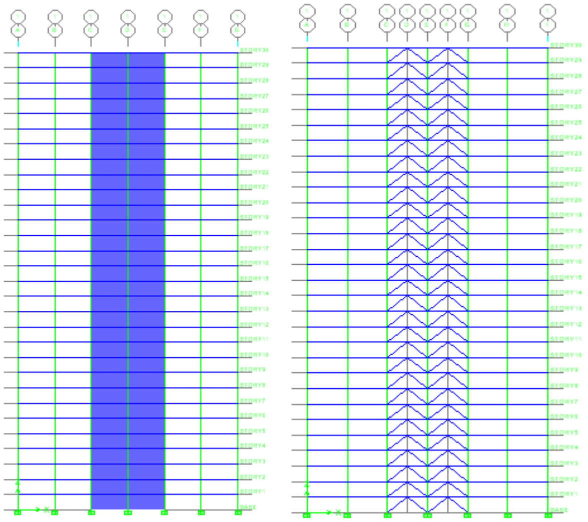
(D) **(E)**

Figure 4. 4: Elevation of Model of the Building with (A) bare frame, (B) corner X- braced frame, (C) corner V-braced frame (D) corner shear walled frame and (E) corner chevron braced frame

II. When the shear walls and bracings are provided at the middle



(A) **(B)**



(C) **(D)**

Figure 4. 5: Elevation of Model of the Building with (A) middle X- braced frame, (B) middle V-braced frame (C) middle shear walled frame and (E) middle inverted V braced (chevron) frame

III. When the Concrete Framed Model of the Building is braced with four storeys module diagrid.

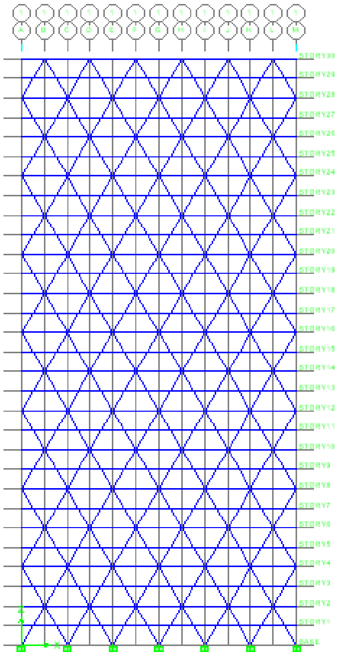
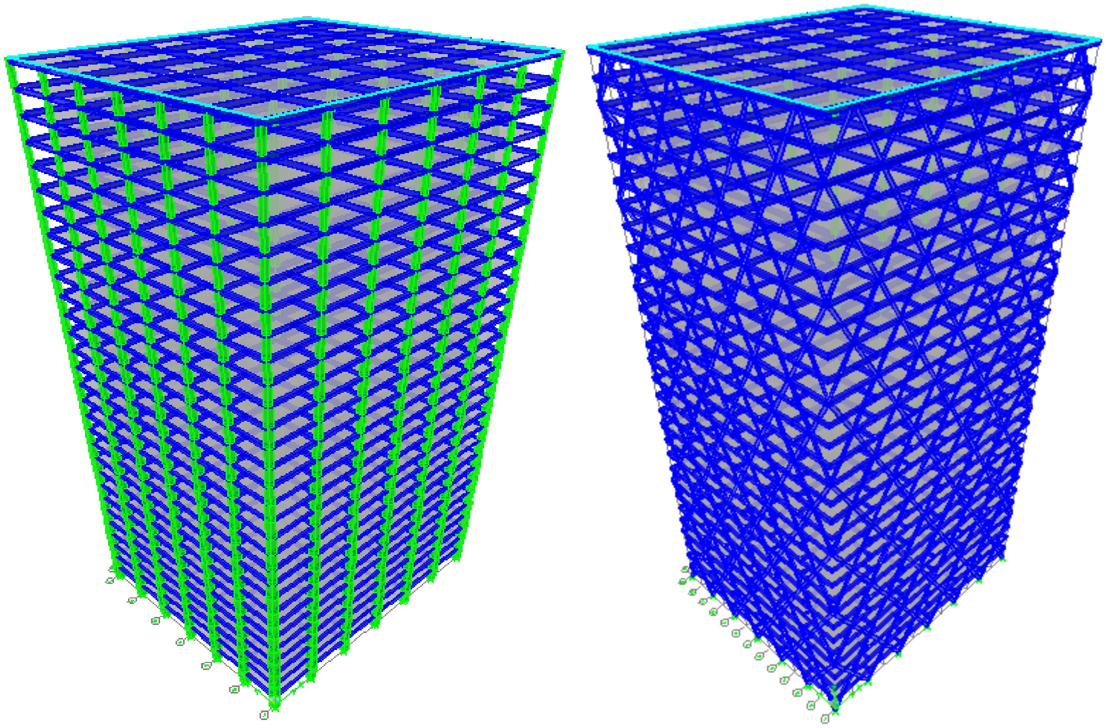
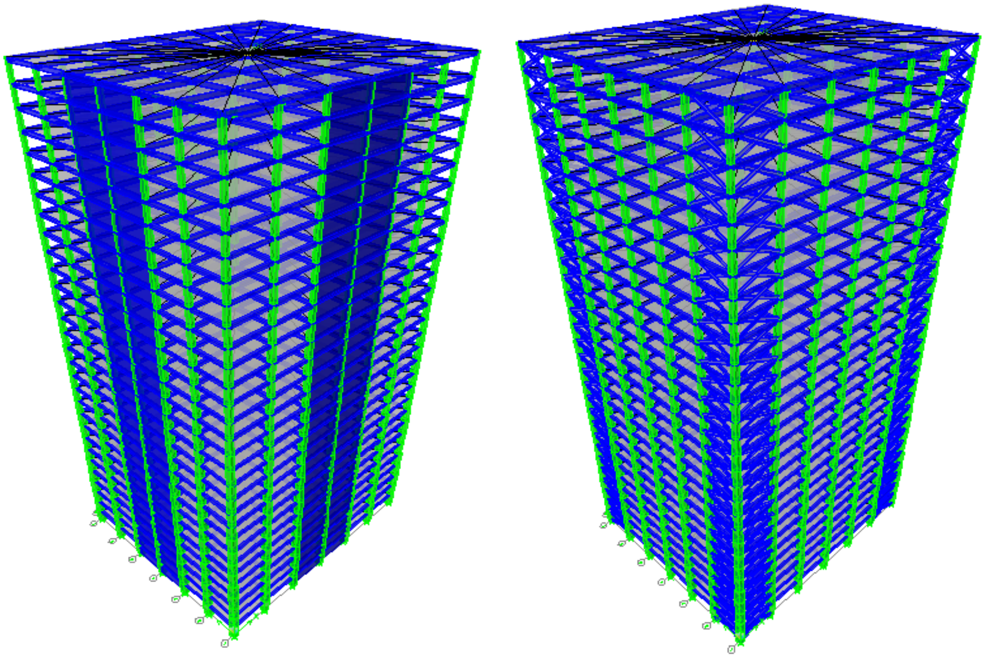


Figure 4. 6: Elevation of the Concrete Framed Model of the Building braced with four storeys module diagrid



3D model of the bare frame building 3D model of the four module diagrid



3D model with shear wall at the middle 3D model with X bracing at the corner

Figure 4. 7: Sample 3D models

CHAPTER FIVE

RESULTS AND DISCUSSIONS

Finite element analyses were conducted using the software ETABS v9.6.0 to compare the performance of concrete structures under seismic loading with different lateral load resisting systems such as rigid frames, steel bracings, shear walls and diagrids. Results of Response Spectrum Analysis have been used to observe and compare floor response of all the models in terms of the following parameters.

1) Storey displacement
2) Storey drift
3) Modal time period
4) Storey shear

The above parameters of the RC framed building for the cases of seismic load have been analyzed in both X and Y directions. The comparison of results in terms of the above parameters was discussed in terms of tables (in the appendix) & graphs in the coming paragraphs.

5.1) Storey displacement

Lateral loading effects from wind and seismic sources usually dominates the structural design of tall buildings. As well as strength considerations, stiffness and its effect on deflection is usually the governing criteria which determines structural element size and cost.

5.1.1) Storey displacement in X-direction

Case-1) When the shear walls and steel bracings are provided at the corner

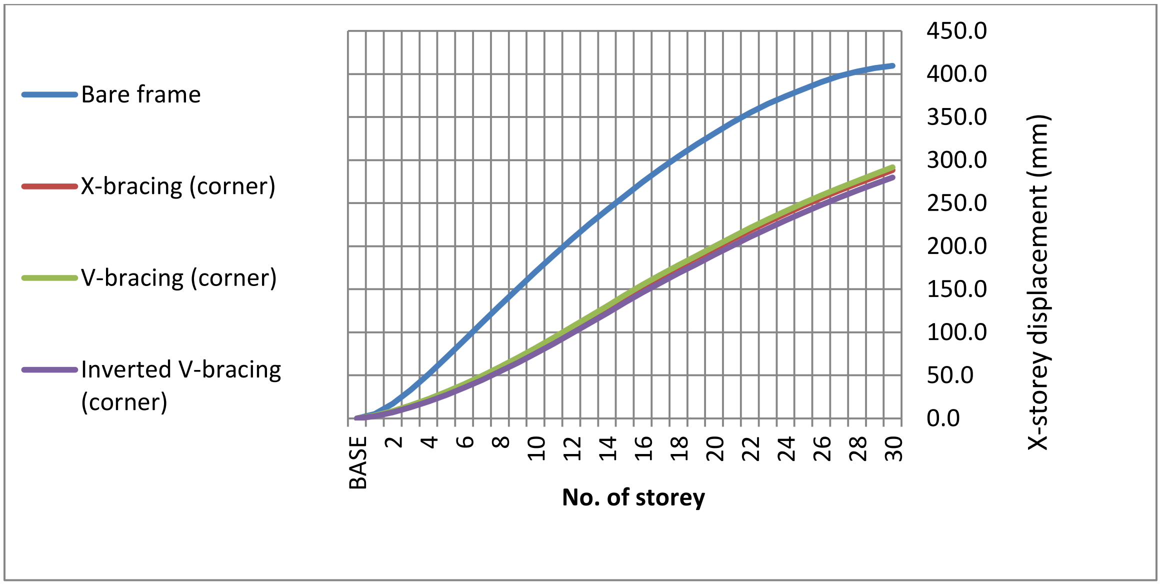


Figure 5. 1: Maximum Storey Displacement comparison of X, V and inverted V braced frame with bare frame in the X-direction (when the bracings are at the corner)

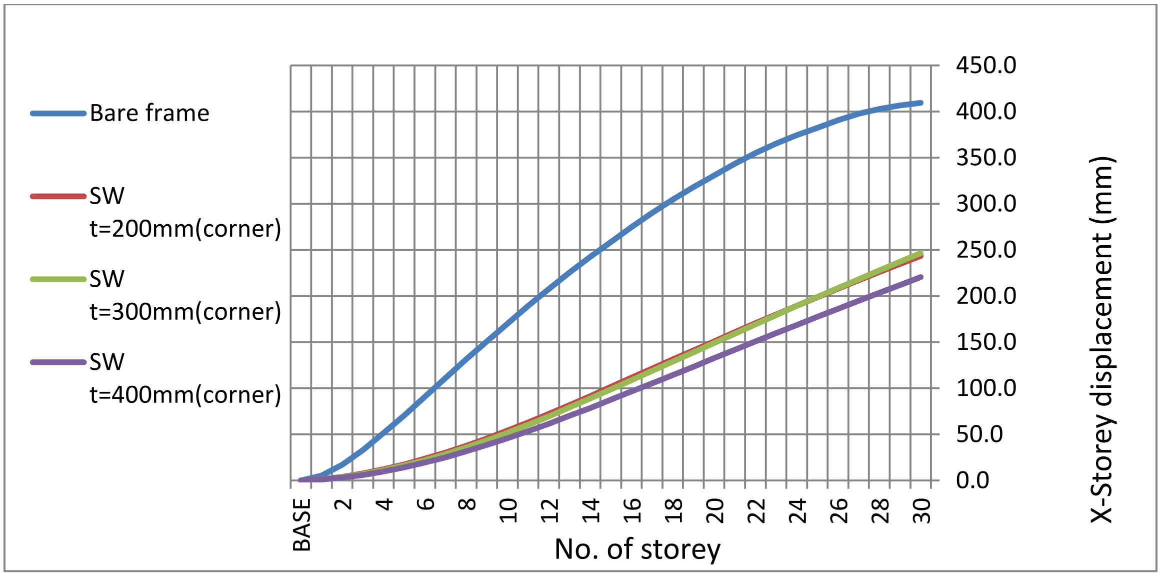


Figure 5. 2: Maximum Storey Displacement comparison of 200,300 and 400 mm thickness shear walled frame with bare frame in the X-direction (when the shear walls are at the corner)

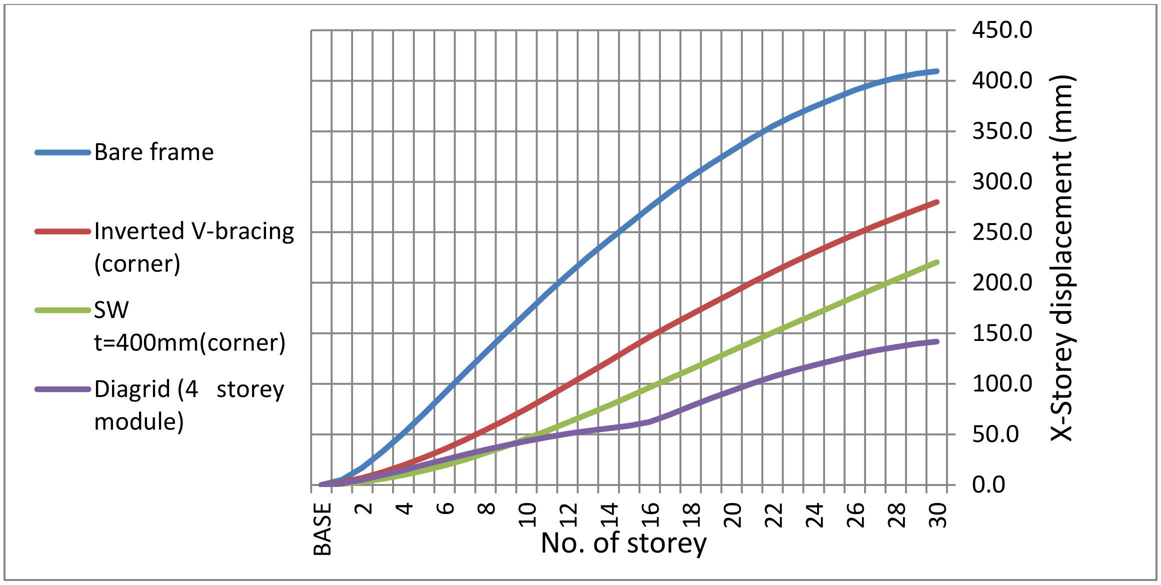


Figure 5. 3: Comparison of efficiency of diagrids with most efficient corner shear walled and steel braced RC frames based on maximum storey displacement in the X-direction (case-1)

Case-2) When the shear walls and bracings are provided at the middle

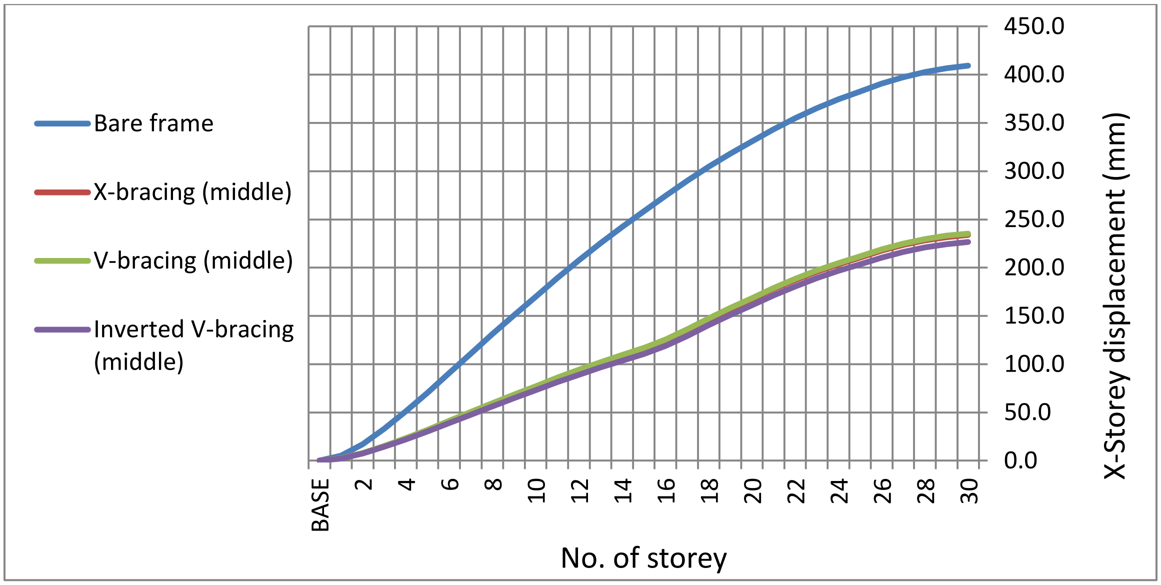


Figure 5. 4: Maximum Storey Displacement comparison of X, V and inverted V braced frame with bare frame in the X-direction (when the bracings are at the middle)

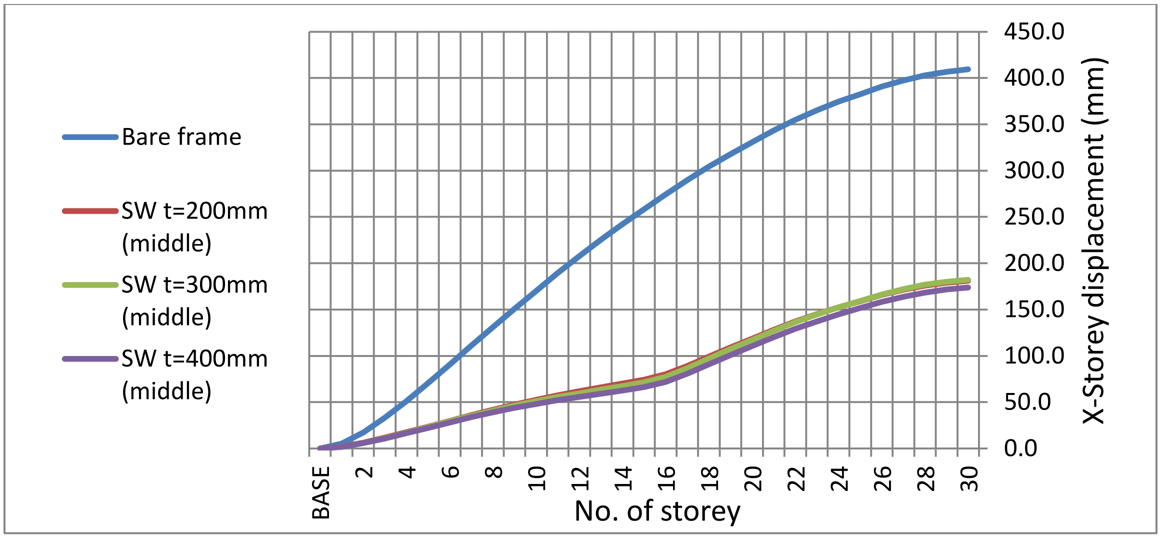


Figure 5. 5: Maximum Storey Displacement comparison of 200,300 and 400 mm thickness shear walled frame with bare frame in the X-direction (when the shear walls are at the middle)

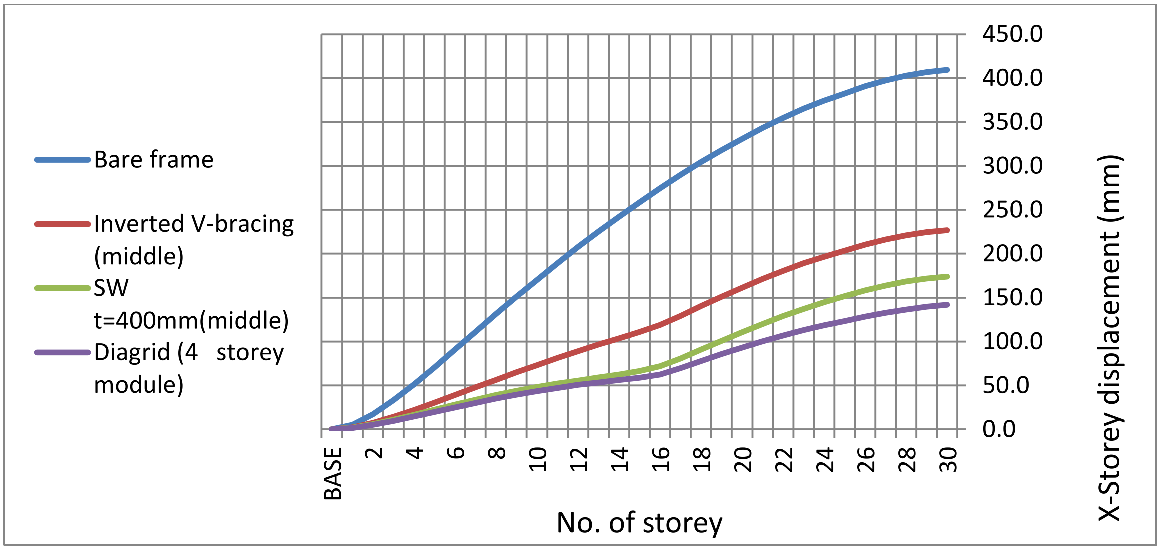


Figure 5. 6: Comparison of efficiency of diagrids with most efficient shear walled and steel braced RC frames based on maximum storey displacement in the X-direction (case-2)

Generally the following table compares the reduction of X- storey displacement in percentage as compared to the bare frame for the different lateral load resisting systems considered in this study.

Table 5. 1: Percentage reduction in top storey displacement of different lateral load resisting systems compared to bare frame (in the X-direction)

Model	Top storey displacement(mm)	% reduction in top storey displacement in X-dxn. compared to bare frame
Bare frame	409.5	0.00
X-bracing (corner)	288.2	29.61
X-bracing (middle)	234.0	42.85
V-bracing (corner)	291.6	28.78
V-bracing (middle)	235.4	42.51
Inverted V-bracing (corner)	279.8	31.68
Inverted V-bracing (middle)	226.6	44.66
SW with t=200mm (corner)	243.6	40.52
SW with t=200mm (middle)	181.0	55.81
SW with t=300mm (corner)	246.4	39.82
SW with t=300mm (middle)	182.2	55.50
SW with t=400mm (corner)	220.4	46.18
SW with t=400mm (middle)	173.9	57.54
four storey module diagrid	141.9	65.35

5.1.2) Storey displacement in Y-direction

Case-1) When the shear walls and steel bracings are provided at the corner

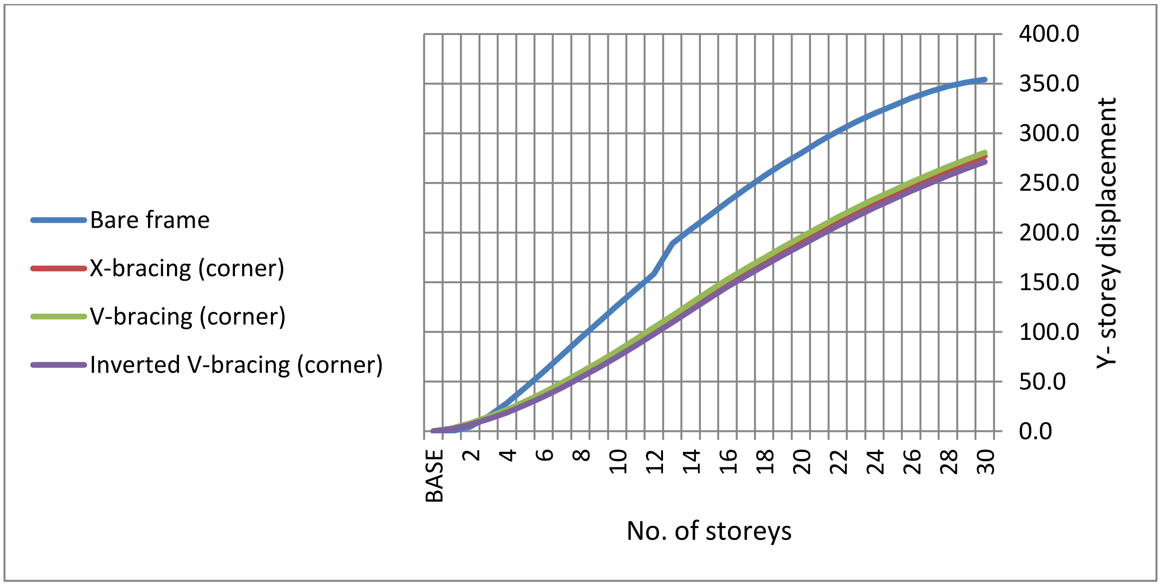


Figure 5. 7: Maximum Storey Displacement comparison of X, V and inverted V braced frame with bare frame in the Y-direction (when the bracings are at the corner)

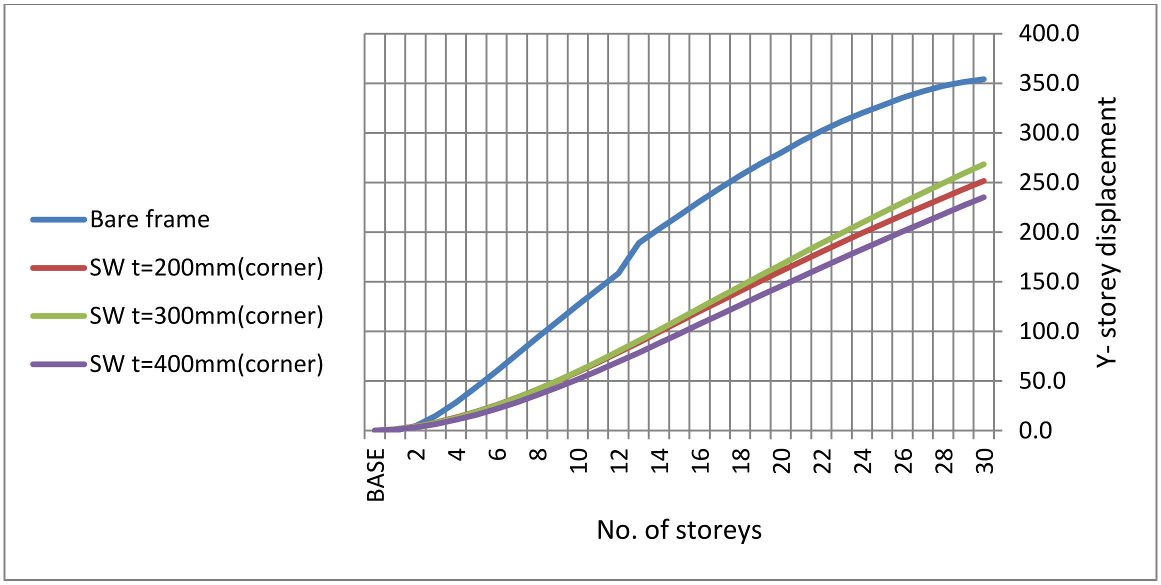


Figure 5. 8: Maximum Storey Displacement comparison of 200,300 and 400 mm thickness shear walled frame with bare frame in the Y-direction (when the shear walls are at the corner)

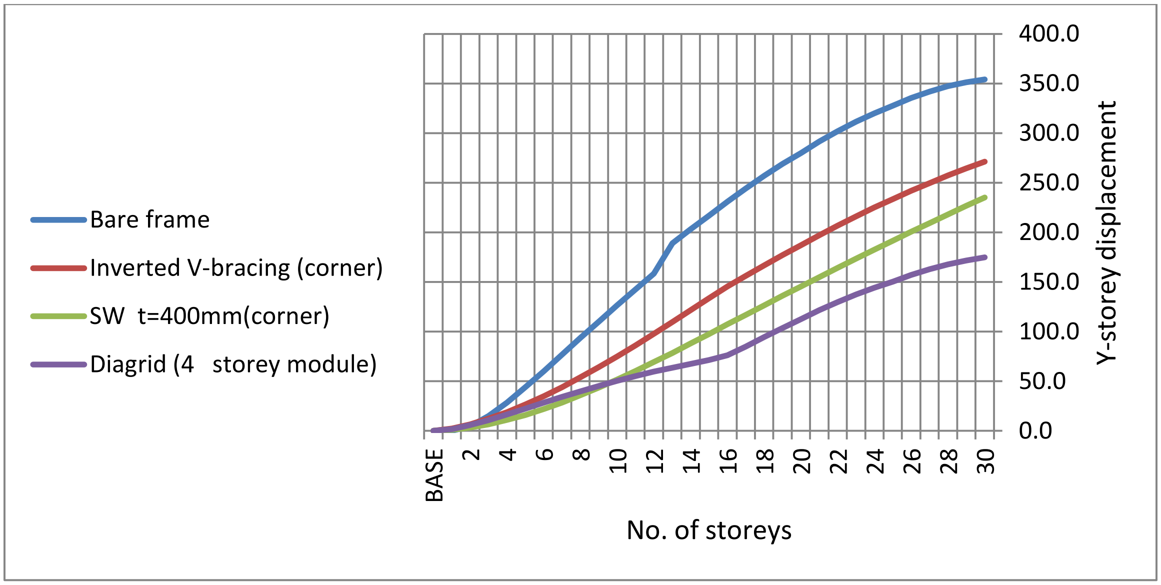


Figure 5. 9: Comparison of efficiency of diagrids with most efficient corner shear walled and steel braced RC frames based on maximum storey displacement in the Y-direction (case-1)

Case-2) When the shear walls and bracings are provided at the middle

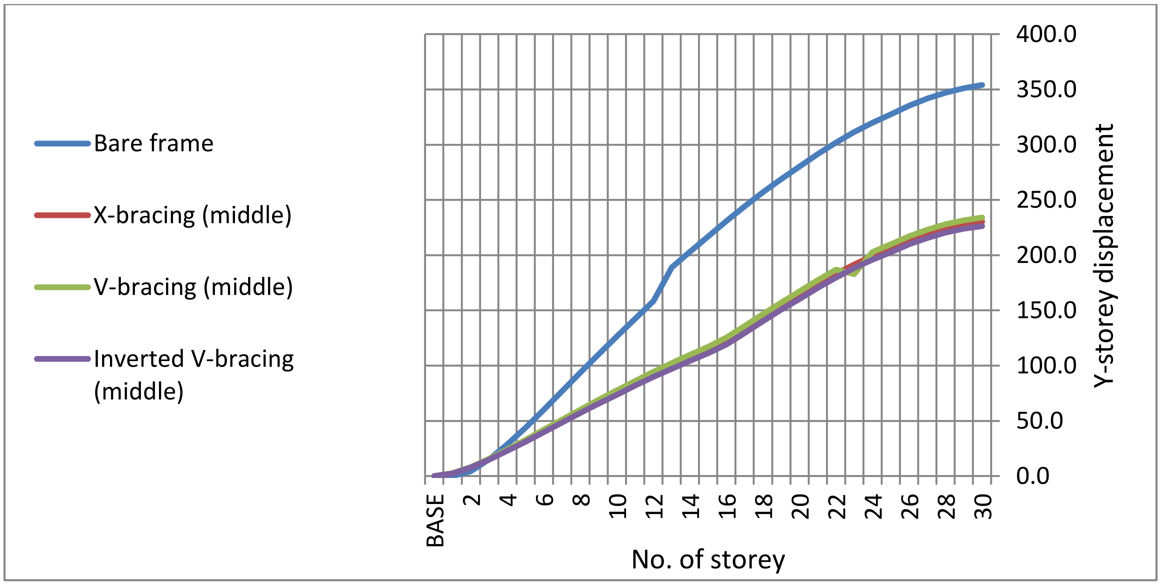


Figure 5. 10: Maximum Storey Displacement comparison of X, V and inverted V braced frame with bare frame in the Y-direction (when the bracings are at the middle)

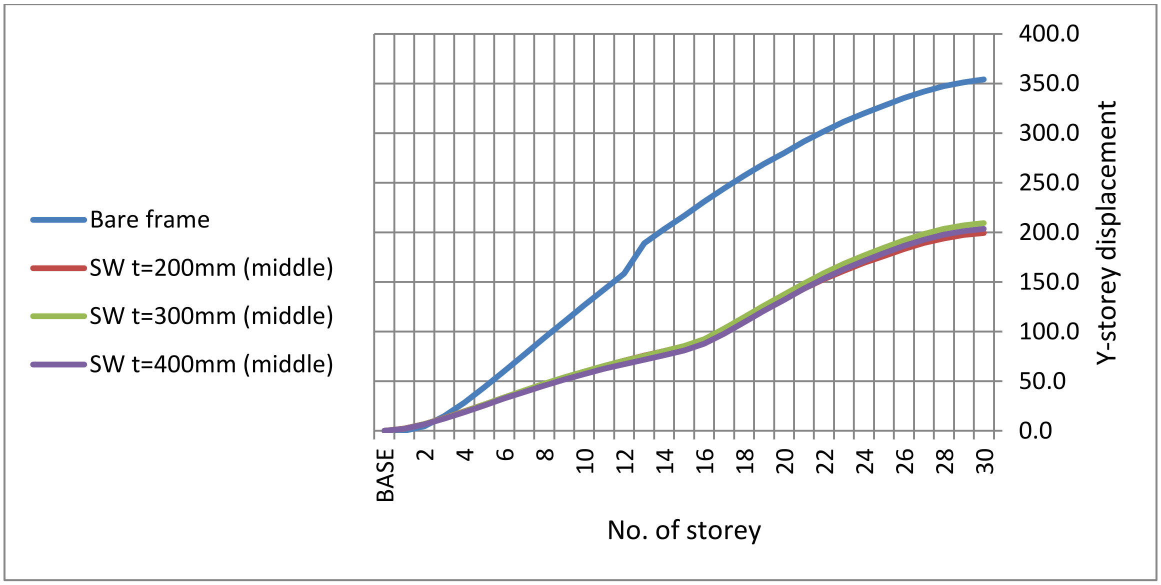


Figure 5. 11: Maximum Storey Displacement comparison of 200,300 and 400 mm thickness shear walled frame with bare frame in the Y-direction (when the shear walls are at the middle)

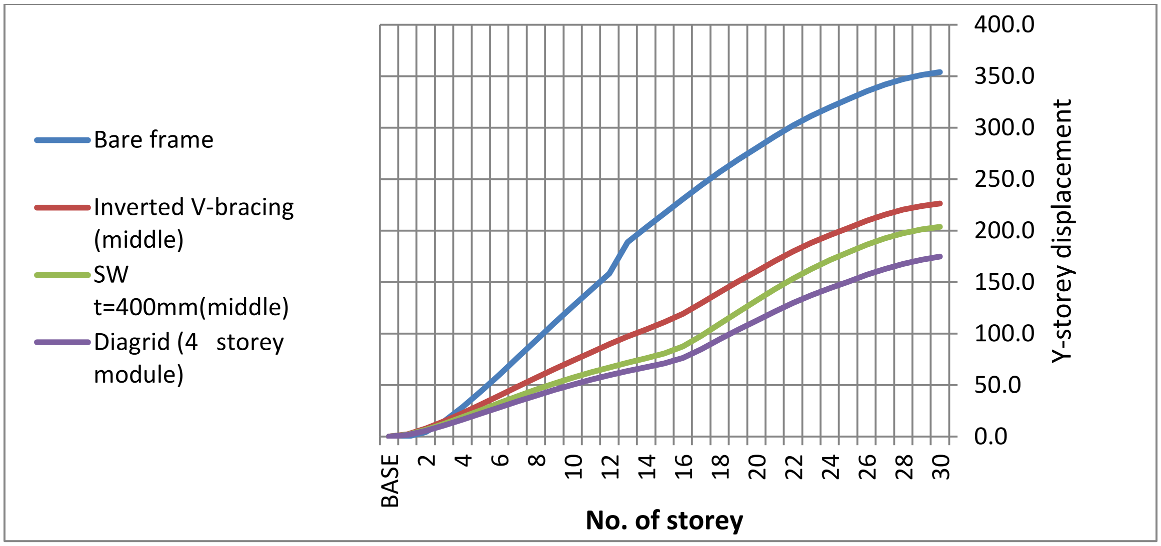


Figure 5. 12: Comparison of efficiency of diagrids with most efficient shear walled and steel braced RC frames based on maximum storey displacement in the Y-direction (case-2)

Generally the following table compares the reduction of Y- storey displacement in percentage as compared to the bare frame for the different lateral load resisting systems considered in this study.

Table 5. 2: Percentage reduction in top storey displacement of different lateral load resisting systems compared to bare frame (in the Y-direction)

Model	Top storey displacement	% reduction in top storey displacement in Y-dxn. compared to bare frame
Bare frame	354.1	0.0
X-bracing (corner)	276.9	21.8
X-bracing (middle)	230.3	35.0
V-bracing (corner)	280.6	20.8
V-bracing (middle)	234.0	33.9
Inverted V-bracing (corner)	271.3	23.4
Inverted V-bracing (middle)	226.4	36.1
SW with t=200mm (corner)	251.5	29.0
SW with t=200mm (middle)	199.4	43.7
SW with t=300mm (corner)	268.5	24.2
SW with t=300mm (middle)	209.3	40.9
SW with t=400mm (corner)	235.1	33.6
SW with t=400mm (middle)	203.7	42.5
four storey module diagrid	175.0	50.6

5.1.3) Summarized discussion on storey displacement

Rob (2011) stated that Current guidance on deflection limits in international design codes is very limited and is based primarily on experience with typical low and medium -rise buildings. The issues with lateral deflection in very tall buildings are different to those of low-rise buildings, and depend on structural form. Rational choice of deflection criteria for tall buildings therefore requires further consideration of the nature of the deformations and the effects they have on the functional aspects of the building. Many modern design codes (including EUROCODE) do not apply limits on lateral deflection of buildings.

As shown in Figures 5.1 to 5.12 the storey displacement was higher for the bare frame as compared to the frame with different lateral load resisting systems such as shear wall steel bracing and diagrid for both X and Y directions.

As shown in Figure 5.1, 5.4, 5.7 and 5.10 inverted-V braced frame showed the maximum reduction in storey displacement as compared to X and V- braced frame for both cases when the steel bracing is at the middle and corner; in the X and Y directions. X braced frame showed the maximum reduction in storey displacement for the whole storeys as compared to V- braced frame for both cases when the steel bracing is at the middle and corner; in the X and Y directions.

As shown in figures 5.2, 5.5, 5.8 and 5.11 the shear walled frame with thickness 400mm showed better reduction in storey displacement as compared to 200mm and 300mm thickness shear walled frame for both cases when the shear wall is at the corner and middle; in X and Y direction. Comparing the performance of 200mm and 300mm thickness shear walled frame in the X direction, although the 300mm thickness shear walled frame was performing well up to the 25 storey but, for the last five storeys the 200mm thickness shear walled frame showed a good performance than the 300mm thickness shear walled frame for both cases when the shear wall is at the middle and corner. In the Y direction, although the 300mm thickness shear walled frame was performing well up to the 25 storey when it is at the corner and up to the fifth story when it is at the middle but for the last remaining storeys the 200mm thickness shear walled frame showed a good performance than the 300mm thickness shear walled frame.

The 400mm thickness shear walled frame showed better reduction in storey displacement as compared to inverted-V braced frame for the whole storey, for both cases when the steel bracing is at the middle and corner; in the X and Y directions. (See figures 5.3, 5.6, 5.9 and 5.12).

As shown in figures 5.3, 5.6, 5.9 and 5.12 and table 5.2 and 5.2 four module diagrid braced frame showed the best reduction in storey displacement for every cases as compared to every lateral load resisting systems considered in this research. The maximum storey displacement of the diagrid in the X direction was 141.9mm where as for the bare frame it was 409.5mm. So there was 65.4 % reduction for this case. The maximum storey displacement of the diagrid in the Y direction was 175mm where as for the bare frame it was 354.1mm. So there was 50.6 % reduction for this case. From these values one can understand that there was a minimum of 7.8% displacement reduction difference in the X direction and 6.9% displacement reduction difference in the Y direction from the most efficient lateral load resisting system considered in this study (400mm thick shear wall in the X direction and 200mm thick shear wall in Y direction). Hence, diagrids have found the most efficient in terms of story displacement reduction and consequently resisting lateral loads from every lateral load resisting system considered in this study.

After the diagrids, the sequence of reduction in top storey displacement from the most efficient was 400mm thick shear wall, 200mm shear wall, 300mm shear wall, Inverted V-bracing, X-bracing and V-bracing respectively in both X and Y direction.

From the two cases studied in this paper the overall reduction of lateral displacement is better in the case of middle shear walled and steel braced frame.

The percentage displacement decrease in the longer direction (X-direction) is greater than the percentage decrease in the shorter direction (Y-direction).

5.2) Storey drift

Drift is a unitless quantity defined as the difference in horizontal displacement over one storey (floor) divided by the storey height. This is the most commonly used form of deformation criterion and many structural design standards refer to this.

5.2.1) Storey drift in X-direction

Case-1) When the shear walls and steel bracings are provided at the corner

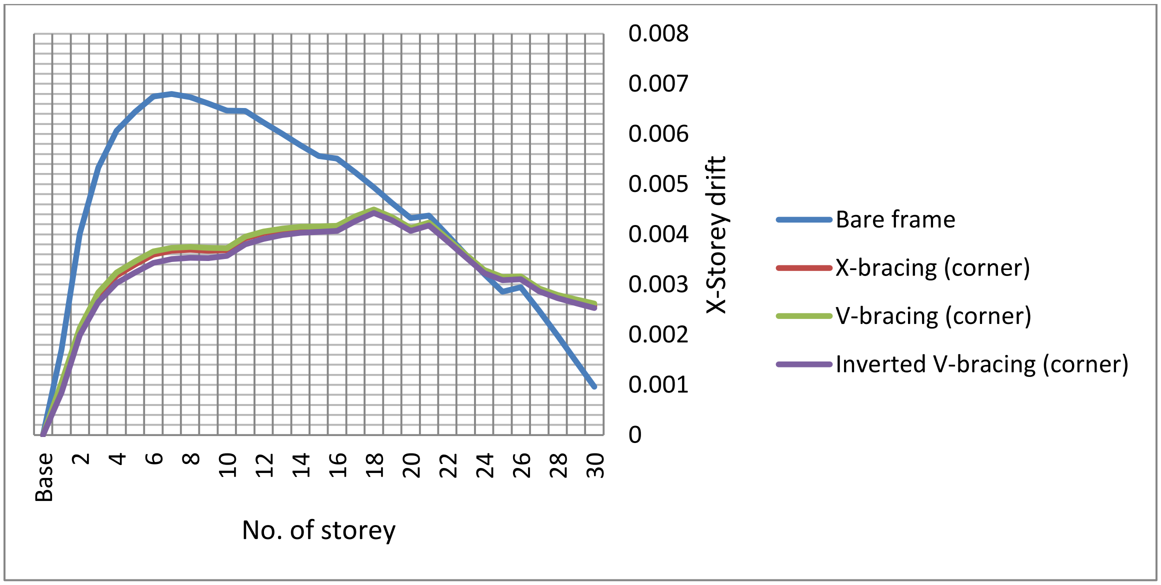


Figure 5. 13: Maximum Storey drift comparison of X, V and inverted V braced frame with bare frame in the X-direction (when the bracings are at the corner)

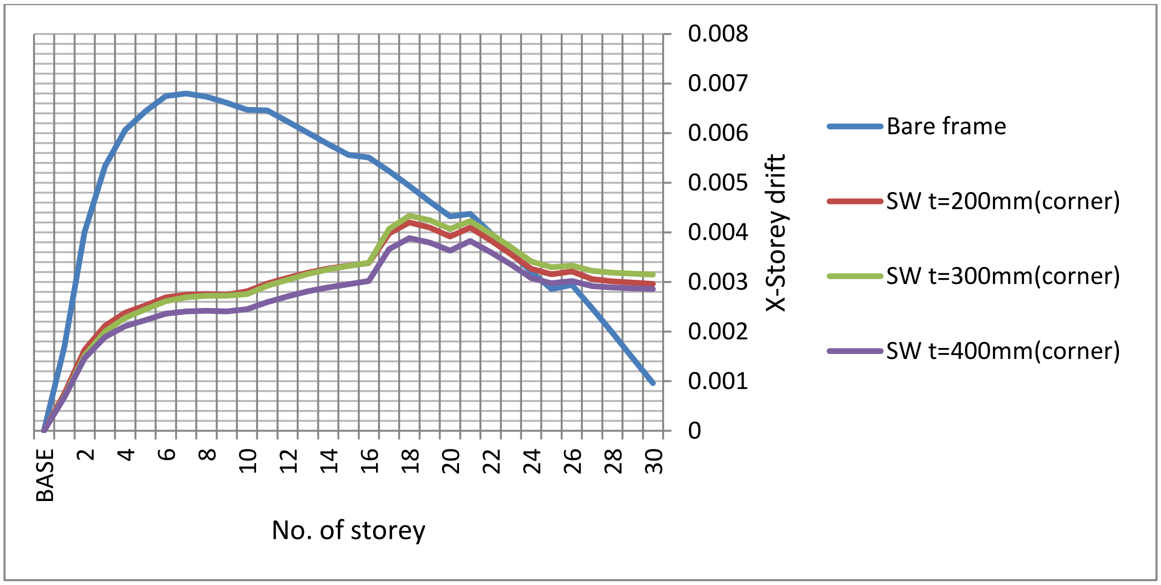


Figure 5. 14: Maximum Storey drift comparison of 200,300 and 400 mm thickness shear walled frame with bare frame in the X-direction (when the shear walls are at the corner)

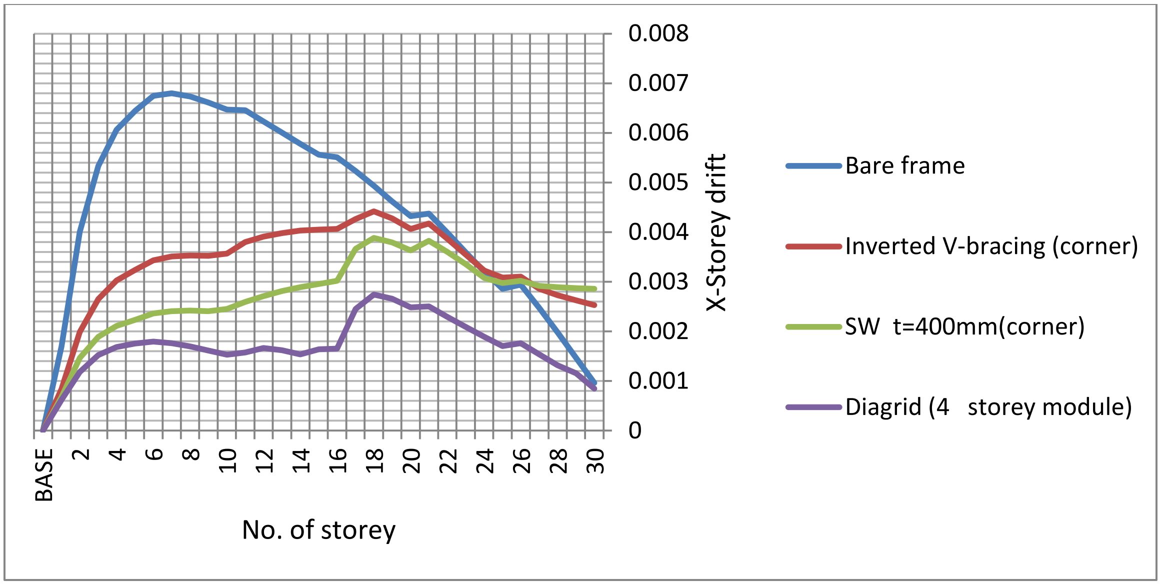


Figure 5. 15: Comparison of efficiency of diagrids with most efficient corner shear walled and steel braced RC frames based on maximum storey drift in the X-direction (case-1)

Case- 2) When the shear walls and steel bracings are provided at the middle

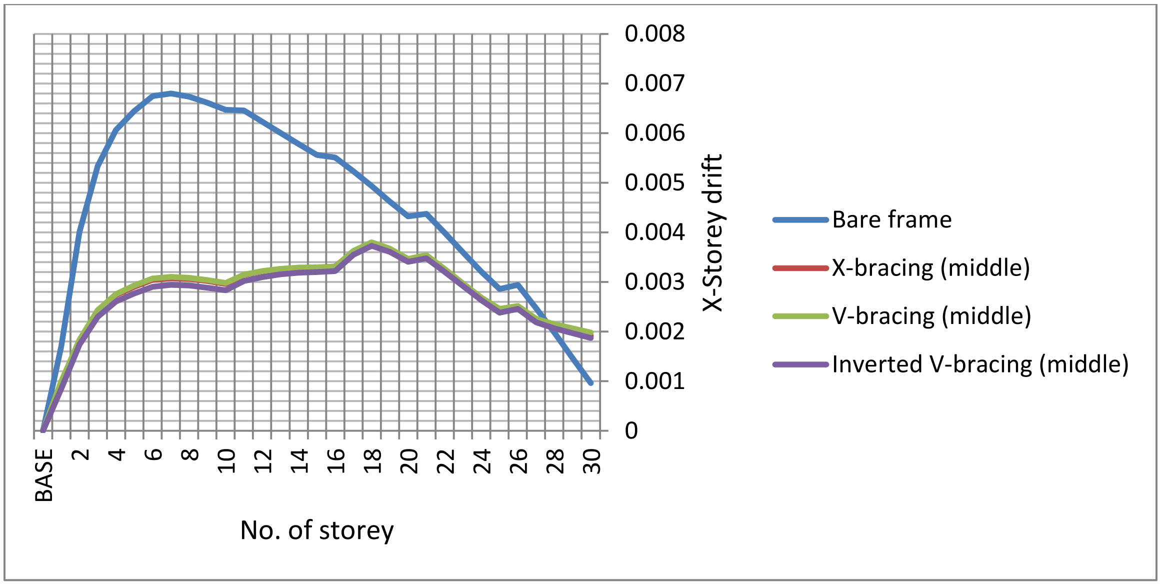


Figure 5. 16: Maximum Storey drift comparison of X, V and inverted V braced frame with bare frame in the X-direction (when the bracings are at the middle)

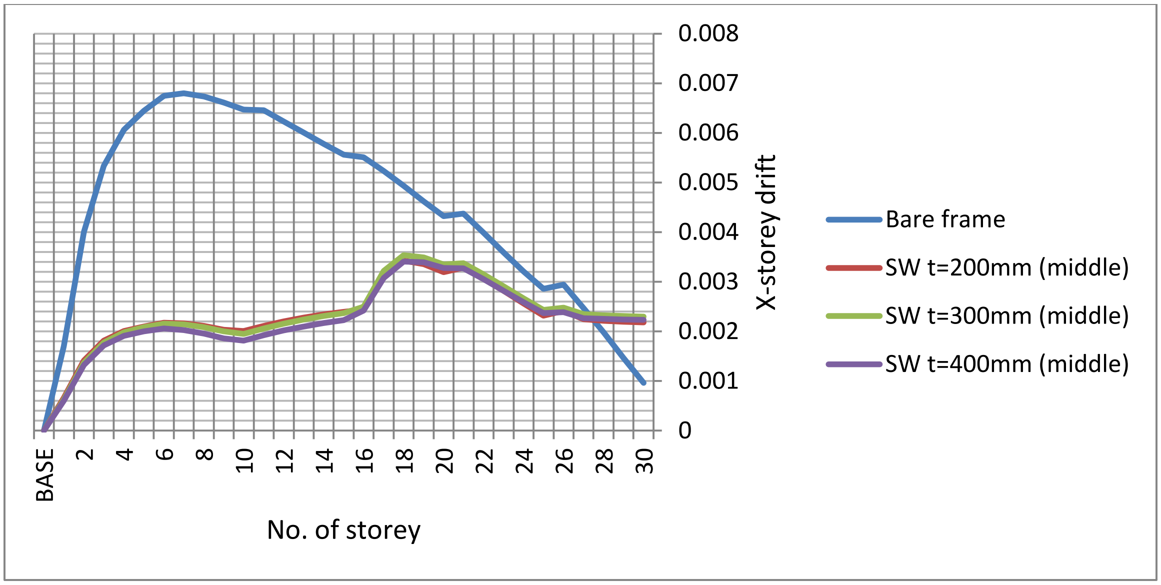


Figure 5. 17: Maximum Storey drift comparison of 200,300 and 400 mm thickness shear walled frame with bare frame in the X-direction (when the shear walls are at the middle)

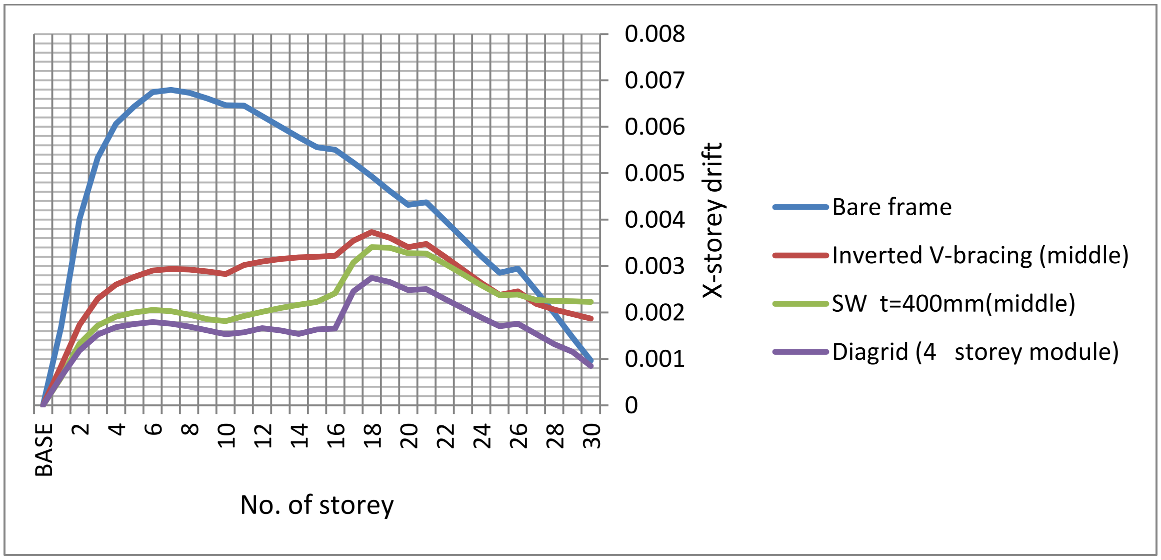


Figure 5. 18: Comparison of efficiency of diagrids with most efficient corner shear walled and steel braced RC frames based on maximum storey drift in the X-direction (case-2)

Generally the following table compares the reduction of X- storey drift in percentage as compared to the bare frame for the different lateral load resisting systems considered in this study.

Table 5. 3: Percentage reduction in maximum storey drift of different lateral load resisting systems compared to bare frame (in the X-direction)

Model	Max storey drift	% reduction in max. storey drift in X-dxn compared to bare frame	Storey at which the drift maximized
Bare frame	0.006796	0.00	7th
X-bracing (corner)	0.004475	34.15	18th
X-bracing (middle)	0.003789	44.25	18th
V-bracing (corner)	0.004494	33.87	18th
V-bracing (middle)	0.003798	44.11	18th
Inverted V-bracing (corner)	0.004422	34.93	18th
Inverted V-bracing (middle)	0.003731	45.10	18th
SW with t=200mm (corner)	0.004198	38.23	18th
SW with t=200mm (middle)	0.003429	49.54	18th
SW with t=300mm (corner)	0.004334	36.23	18th
SW with t=300mm (middle)	0.003535	47.98	18th
SW with t=400mm (corner)	0.003883	42.86	18th
SW with t=400mm (middle)	0.003406	49.88	18th
four storey module diagrid	0.002744	59.62	18th

5.2.2) Storey drift in Y-direction

Case-1) When the shear walls and steel bracings are provided at the corner

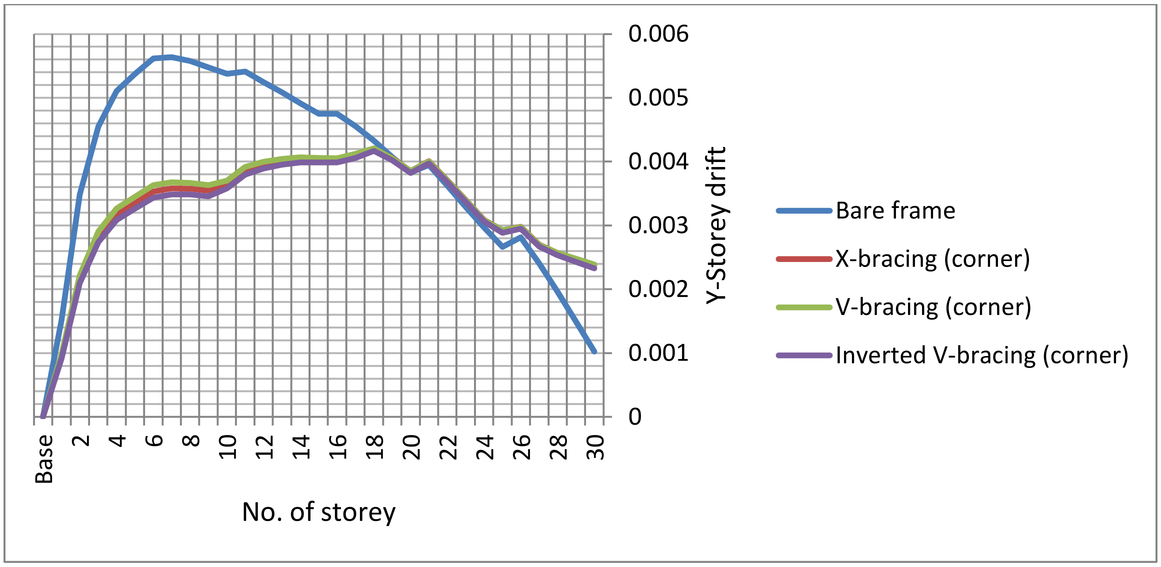


Figure 5. 19: Maximum Storey drift comparison of X, V and inverted V braced frame with bare frame in the Y-direction (when the bracings are at the corner)

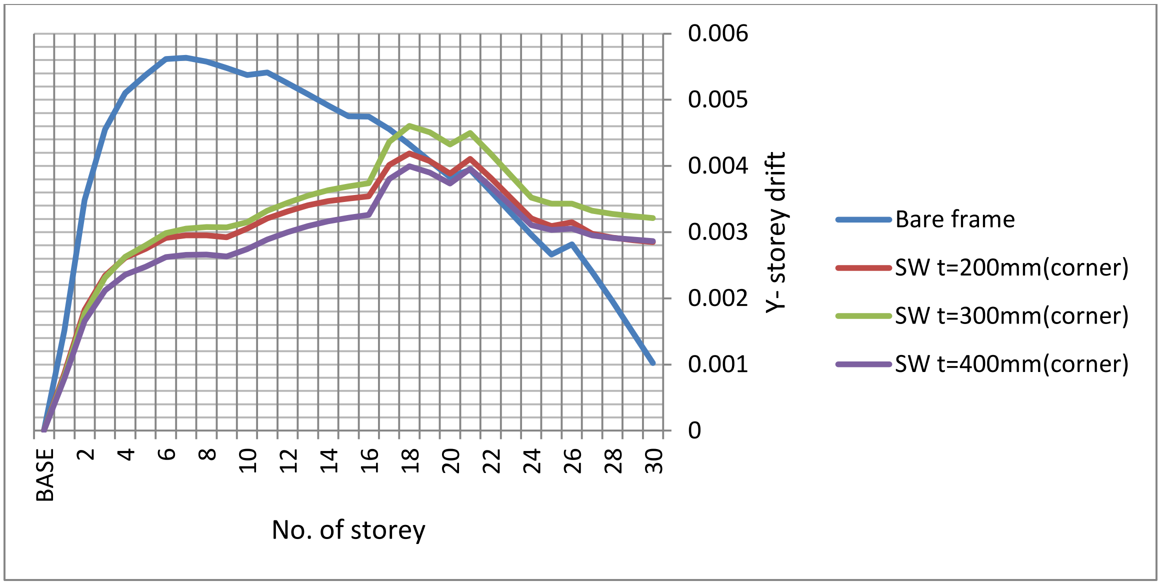


Figure 5. 20: Maximum Storey drift comparison of 200,300 and 400 mm thickness shear walled frame with bare frame in the Y-direction (when the shear walls are at the corner)

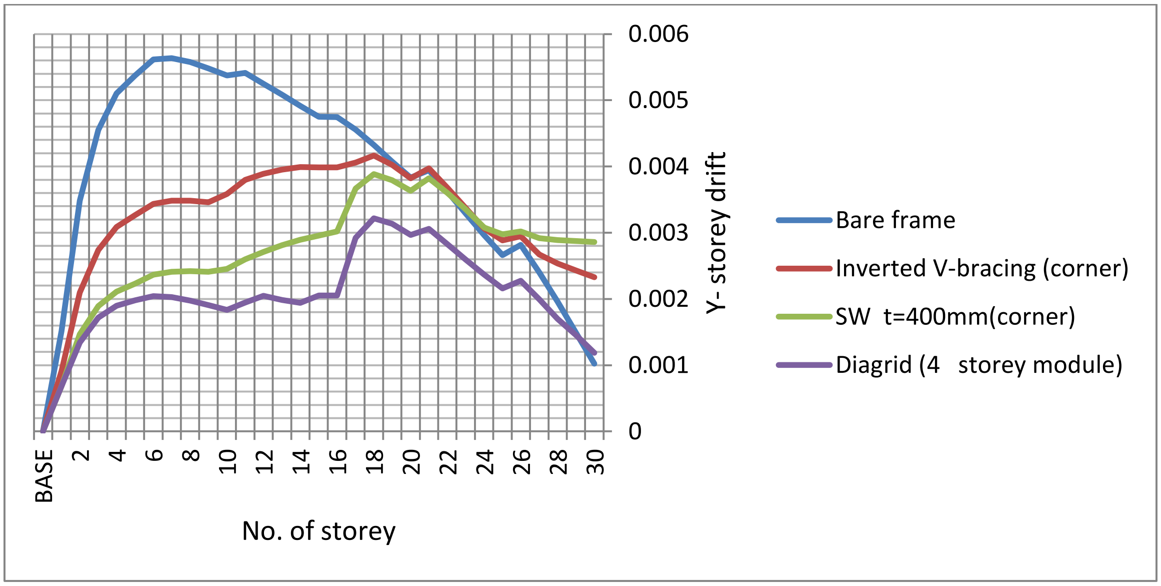


Figure 5. 21: Comparison of efficiency of diagrids with most efficient corner shear walled and steel braced RC frames based on maximum storey drift in the Y-direction (case-1)

Case-2) When the shear walls and steel bracings are provided at the middle

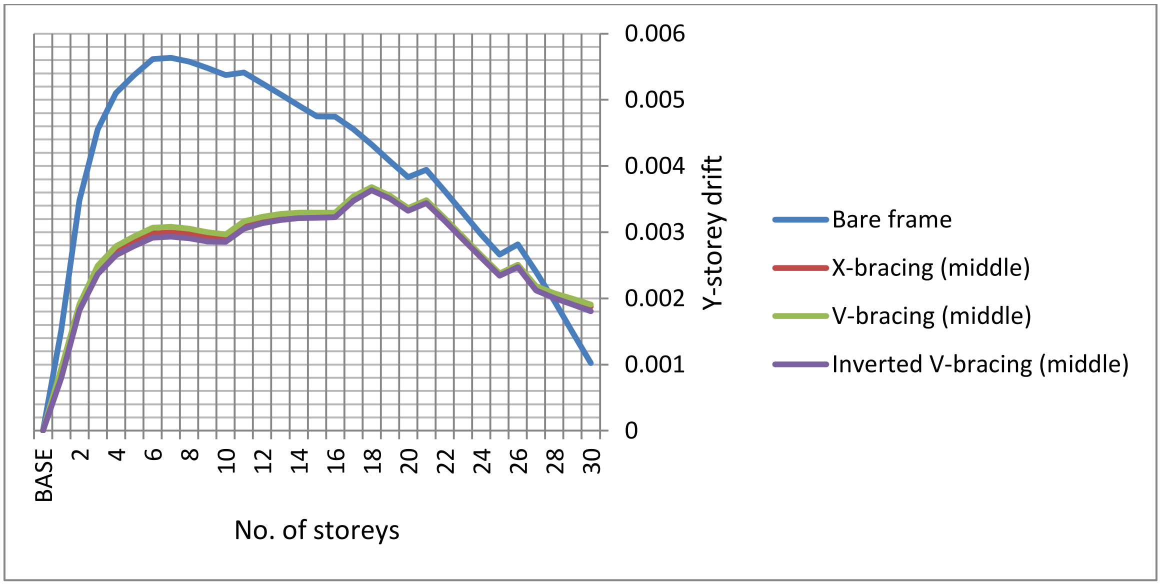


Figure 5. 22: Maximum Storey drift comparison of X, V and inverted V braced frame with bare frame in the Y-direction (when the bracings are at the middle)

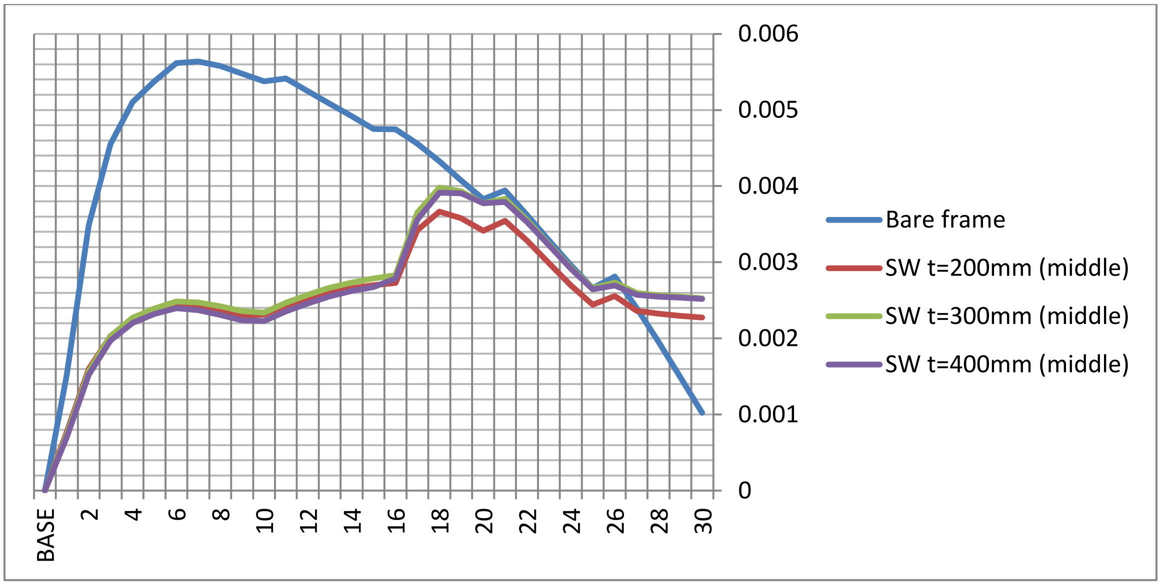


Figure 5. 23: Maximum Storey drift comparison of 200,300 and 400 mm thickness shear walled frame with bare frame in the Y-direction (when the shear walls are at the middle)

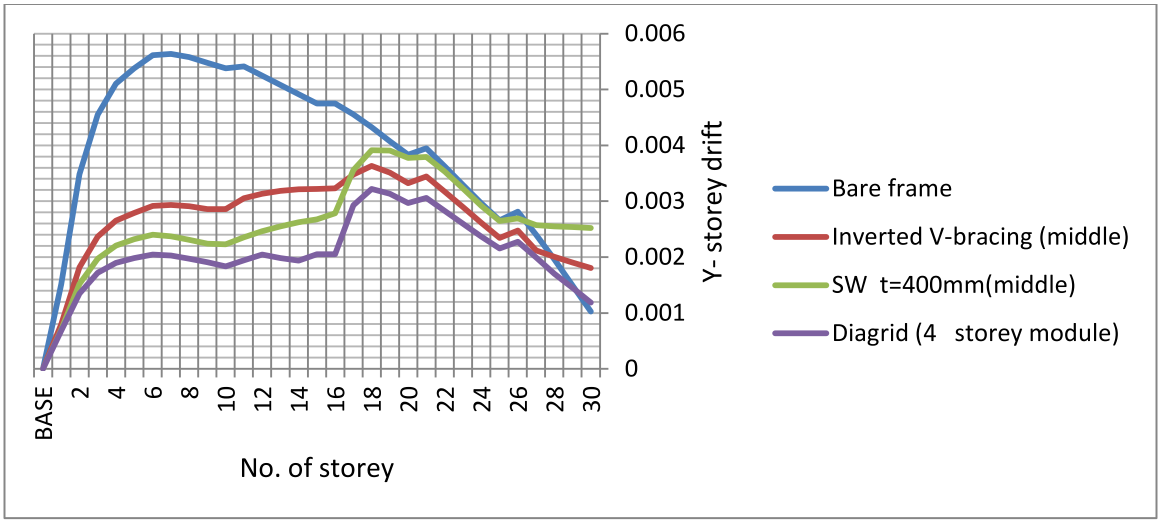


Figure 5. 24: Comparison of efficiency of diagrids with most efficient middle shear walled and steel braced RC frames based on maximum storey drift in the Y-direction (case-2)

Generally the following table compares the reduction of Y- storey drift in percentage as compared to the bare frame for the different lateral load resisting systems considered in this study.

Table 5. 4: Percentage reduction in maximum storey drift of different lateral load resisting systems compared to bare frame (in the Y-direction)

Model	Max storey drift	% reduction in max. storey drift in Y-dxn compared to bare frame	Storey at which the drift maximized
Bare frame	0.005636	0.00	7th
X-bracing (corner)	0.004204	25.41	18th
X-bracing (middle)	0.003673	34.83	18th
V-bracing (corner)	0.004206	25.37	18th
V-bracing (middle)	0.00368	34.71	18th
Inverted V-bracing (corner)	0.004167	26.06	18th
Inverted V-bracing (middle)	0.003631	35.57	18th
SW with t=200mm (corner)	0.004187	25.71	18th
SW with t=200mm (middle)	0.003667	34.94	18th
SW with t=300mm (corner)	0.003981	29.36	18th
SW with t=300mm (middle)	0.003981	29.36	18th
SW with t=400mm (corner)	0.003915	30.54	18th
SW with t=400mm (middle)	0.003915	30.54	18th
four storey module diagrid	0.003219	42.89	18th

5.2.3) Summarized discussion on Storey drifts

As per ESEN 1998-1:2013 interstorey drift is evaluated as the difference of the average lateral displacements ds at the top and bottom of the storey under consideration. For buildings having non-structural elements of brittle materials attached to the structure the code provides the following interstorey drift limit

$d_r .v \leq 0.005h$

Where, d_r is the design interstorey drift and h is the storey height

v is the reduction factor which takes into account the lower return period of the seismic action associated with the damage limitation requirement. The recommended values of ν are 0.4 for importance classes III and IV and ν = 0.5 for importance classes I and II.

Therefore, the drift limitation for the study will be

$d_r \leq 0.005h/0.4=0.0125h$

Based on the above criteria, for all the 14 models considered in the study, storey drift values are within the permissible limit.

As shown in figures 5.13 up to 5.24 the storey drift was higher for the bare frame as compared to the frame with different lateral load resisting systems such as shear wall, steel bracing and diagrid for all cases considered in this study.

As shown in figures 5.13, 5.16, 5.19 and 5.22 inverted-V braced frame showed the maximum reduction in storey drift in the X and Y direction as compared to X and V- braced frame for both cases; case-1 and case-2. X braced frame showed the maximum reduction in storey drift for the whole storeys as compared to V- braced frame for both cases; case-1 and case-2 in the X and Y directions.

As shown in figures 5.14, 5.17, 5.20 and 5.23 the shear walled frame with thickness 400mm showed better reduction in storey drift in the X and Y direction as compared to 200mm and 300mm thickness shear walled frame for both cases when the shear wall is at the corner and at the middle. Surprisingly, here is an exception for the drift in the Y direction when the shear walls are at the middle; the 200mm thick shear wall showed a better reduction in the maximum story drift and was performing well for the last fifteen storeys as compared to the 300mm and 400mm thick shear walls. Comparing the 200mm and 300mm thickness shear walled frame, the 200mm thickness shear walled frame was performing well as compared to the 300mm thick shear walled frame for the last more than fifteen storeys of the building in the X and Y axis and its maximum storey drift is less than that of the 300mm thick shear wall for both cases (when the shear wall is at the middle and at the corner).

As shown in figures 5.15, 5.18, 5.21 and 5.24 the 400mm thickness shear walled frame showed better reduction in maximum storey drift as compared to inverted-V braced frame in the X direction and the inverted V bracing showed better reduction in maximum storey drift as compared to the 400mm shear wall in the Y direction.

As shown in figures 5.15, 5.18, 5.21 and 5.24 and table 5.3 and 5.4, for the whole storeys, the four module diagrid braced frame showed big reduction in storey drift as compared to every lateral load resisting system considered in this research. The maximum storey drift of the diagrid in the X direction was 0.002744 where as for the bare frame it was 0.006796. So there was 59.62% reduction for this case. The maximum storey displacement of the diagrid in the Y direction was 0.003219 where as for the bare frame it was 0.005636. So there was 42.89% reduction for this case. From these values one can understand that there was a minimum of 9.74% displacement reduction difference in the X direction and 7.31% displacement reduction difference in the Y direction from the most efficient lateral load resisting system considered in this study (400mm thick shear wall in the X direction and inverted V bracing in the Y direction). Hence, diagrids have found the most efficient in terms of story drift reduction and consequently resisting lateral loads from every lateral load resisting system considered in this study.

After the diagrids, the sequence of reduction in maximum storey drift from the most efficient was 400mm thick shear wall, 200mm shear wall, 300mm shear wall, Inverted V-bracing, X-bracing and V-bracing respectively in the X direction and Inverted V-bracing, X-bracing, V-bracing, 200mm thick shear wall, 400mm shear wall and 300mm shear wall respectively in the Y direction.

A better drift reduction is observed when the bracings and shear walls are at the middle than when they are at the corner for both X and Y direction.

The percentage displacement decrease in the longer direction (X-direction) is greater than the percentage decrease in the shorter direction (Y-direction).

5.3) Modal time period

The time required to complete one complete cycle of vibration is called time period. Under free vibration the structure always vibrates in single mode called its fundamental mode and the corresponding time period is called fundamental period of the structure. The fundamental period is the longest period of the structure. The building's natural time period is obtained as:

$T=2\pi*\sqrt{(m/k)}$

Where, m = mass of the structure and k = stiffness of the building

From the above equation, it can be understood that period depends upon the mass and stiffness of the structure. The higher time period the heavier the modal mass and the less stiff the structure is and vice-versa.

By performing the Modal response spectrum analysis, time period is found out by considering 15 mode shapes for all models and their fundamental time period taken from ETABS is as shown below.

Table 5. 5: Fundamental time period comparison among different lateral load resisting system considered in the study

Model	Fundemental time period (S)	% reduction in time period compared to bare frame
Bare frame	6.246	0.00
X-bracing (corner)	4.858	22.23
X-bracing (middle)	4.389	29.73
V-bracing (corner)	4.889	21.72
V-bracing (middle)	4.413	29.36
Inverted V-bracing (corner)	4.775	23.55
Inverted V-bracing (middle)	4.323	30.79
SW with t=200mm (corner)	4.689	24.94
SW with t=200mm (middle)	4.198	32.80
SW with t=300mm (corner)	4.827	22.72
SW with t=300mm (middle)	4.284	31.41
SW with t=400mm (corner)	4.559	27.02
SW with t=400mm (middle)	4.224	32.38
four storey module diagrid	3.644	41.67

5.3.1) Summarized discussion on modal time period

As shown in Table 5.5 the fundamental time period was higher for the bare frame as compared to the frame with different lateral load resisting systems such as shear wall, steel bracing and diagrid.

Comparing the steel braced and shear walled frames, the inverted V-bracing showed the shortest fundamental time period from the rest steel bracings and the 400mm thick shear walled frame showed the shortest fundamental time period from rest shear walls.

The four storey module diagrid has shown the shortest time period as compared to every lateral load resisting system considered in this research as shown in table 5.5. The maximum time period (fundamental time period) of the diagrid was 3.644s where as for the bare frame it was 6.246s. So there was 41.67% reduction. From this value one can understand that there was a minimum of 8.87% fundamental time period reduction difference from the most efficient lateral load resisting system considered in this study (200mm thick middle shear walled frame). From the definition of modal time period it is known that “The lesser time period the lesser the modal mass the higher stiff the structure is. Hence, from the fundamental time period comparison one can conclude that, diagrids are the stiffest and lightest structure from all lateral load resisting systems considered in the study. This fact of diagrids is more clarified in the coming section. (i.e. Base shear comparison)

After the diagrids, the sequence of reduction in fundamental time period from the most efficient was 400mm thick shear wall, 200mm shear wall, 300mm shear wall, Inverted V-bracing, X-bracing and V-bracing respectively. A better time period reduction is observed when the bracings and shear walls are at the middle than when they are at the corner.

5.4) Base shear

Base shear is an estimate of the maximum expected lateral force that will occur due to seismic ground motion at the base of a structure. The following table summarizes base shear comparison both in the X and Y direction among different lateral load resisting systems considered in the study.(For further information refer appendix.C)

Table 5. 6: Base shear comparison among different lateral load resisting systems considered in the study

Model	Base shear (KN)(X-dxn)	Base shear (KN)(Y-dxn)
Bare frame	311071.48	311032.35
X-bracing (corner)	327075.74	323323.86
X-bracing (middle)	326209.08	322979.67
V-bracing (corner)	325678.1	321757.31
V-bracing (middle)	324842.11	321653.08
Inverted V-bracing (corner)	326041.4	322187.27
Inverted V-bracing (middle)	325288.58	321790.35
SW with t=200mm (corner)	322283.5	318885.83
SW with t=200mm (middle)	312108.21	313136.92
SW with t=300mm (corner)	326732.92	327600.41
SW with t=300mm (middle)	321050.19	322050.74
SW with t=400mm (corner)	333038.31	331238.28
SW with t=400mm (middle)	327753.95	330023.8
four storey module diagrid	302842.69	301614.1

5.4.1) Summarized discussion on Base shear

Base shear depends upon three things; building weight, building stiffness and distance from fault. Viraj (2017) assured that, a higher base shear indicates either of the three:

1) Highly Stiff Structure

2) Very Heavy Structure

3) Location near fault

The first factor depends on the natural period of the structure. The lower the natural period of the structure the more stiff the structure is. Since all the models are analyzed for same seismic zone the third factor is insignificant in our case. Surprisingly, the four storey module diagrid has shown the least base shear both in the X and Y direction as compared to every lateral load resisting system considered in this research including the bare frame as shown in table 5.6. In the X direction the base shear of the four module diagrid is 302842.69KN, whereas for the system with the least base shear, which is the bare frame, it is 311071.48KN. In the Y direction the base shear of the four module diagrid is 301614.1KN, whereas for the system with the least base shear, which is the bare frame, it is 311032.35KN. From these values one can understand that there was 8228.79KN of base shear reduction in the X direction and 9418.25KN of base shear reduction in the Y direction from the system with the least base shear considered in the study (bare frame). In the previous section, from the lower time period of diagrids, it has already been established that diagrids have higher stiffness. So, the lower base shear value indicates that the diagrid structures are light as compared to every structure considered in this study.

After the diagrids the bare frame showed the lowest base shear as compared to all models considered in this study. As shown in table 5.6 V braced frame showed the lowest X and Y base shear as compared to X and inverted V- braced frame for both cases when the bracing is at the corner and at the middle. Similarly, the shear walled frame with thickness 200mm showed the lowest X and Y base shear as compared to 300mm and 400mm thickness shear walled frame. A better base shear reduction is observed when the bracings and shear walls are at the middle than when they are at the corner. In the same way, the base shear in the Y-axis is lesser than the base shear in the X-axis.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1) Conclusion

From the analysis results and comparative study put forth in this paper following set of conclusions can be made:

The diagrids showed a reduction in maximum storey displacement 65.4% in the X direction and 50.6% in the Y direction as compared to the bare frame. They also showed a reduction in maximum storey displacement 7.8% in the X direction and 6.9% in the Y direction as compared to the most efficient lateral load resisting system considered in the study. Hence, diagrids have found the most efficient in terms of story displacement reduction and consequently resisting lateral loads from every lateral load resisting system considered in the study.

They showed a reduction in maximum storey drift 59.62% in the X direction and 42.89% in the Y direction as compared to the bare frame. They also showed a reduction in maximum storey drift 9.74% in the X direction and 7.31% in the Y direction as compared to the most efficient lateral load resisting system considered in the study. Hence, diagrids have found the most efficient in terms of story drift reduction and consequently resisting lateral loads from every lateral load resisting system considered in the study.

They showed 41.67% reduction in fundamental time period as compared to the bare frame. They also showed 8.87% reduction in fundamental time period as compared to the most efficient lateral load resisting system considered in the study. From the definition of modal time period it is known that “The lesser time period the lesser the modal mass the higher stiff the structure is. Hence, from the fundamental time period comparison one can conclude that, diagrids are the stiffest structure from all lateral load resisting systems considered in the study.

Surprisingly, the diagrid model has shown the least base shear both in the X and Y direction as compared to every lateral load resisting system considered in this research including the bare frame. In the X direction there was 8228.79KN of base shear reduction and in the Y direction there was 9418.25KN of base shear reduction from the system with the least base shear considered in the study (bare frame). From the lower time period of diagrids, it has already been established that diagrids have higher stiffness. So, the lower base shear value indicates that the diagrid structures are the lightest as compared to every structure considered in this study.

Finally, diagrids, in addition to their inherent aesthetic quality and geometrical versatility, are the most efficient lateral load resisting systems in the range of many lateral load resisting systems known. Therefore, it is highly recommended for structural engineers and architects to use the advantage of these wonderful structures.

6.2) Recommendation

This thesis work is an inch towards the complex phenomena in analysis and design of diagrid structures. Among the possibilities for future study, the following are the main points that deserve attention.

1. Analytical and Experimental investigation in design of connections between the diagrid members and RC frames.
2. In this paper detail cost comparison is not included; for future study it is better to consider the cost of the systems in detail.
3. The structure considered in this study fulfills plan and elevation regularity, the behaviors for irregular structures under those bracing type can be considered for future study.
4. The modeling and analysis was carried out using a wide flange steel section as a bracing member. A study using composite sections such as steel tubular composite sections (filled with concrete) as a bracing member is left for future investigation.
5. The comparative study was carried out under seismic load, leaving a comparison under wind load for future researchers.

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Appendix-A: Storey displacement versus number of storeys tables

Table A. 1: Storey displacement in the X-direction versus number of storeys when the shear walls and steel bracings are at the corner

Story	Bare frame	Different steel bracings(at the corner)			Shear wall with different thickness(at the corner)			Four storey module diagrid
		X-bracing	V-bracing	Inverted V-bracing	Shear wall t=200m	Shear wall t=300m	Shear wall t=400m	
STORY30	409.5	288.2	291.6	279.8	243.6	246.4	220.4	141.9
STORY29	406.8	280.6	283.9	272.2	234.8	237.0	211.9	139.5
STORY28	402.9	272.8	275.9	264.5	225.9	227.7	203.4	136.5
STORY27	397.5	264.6	267.6	256.4	217.0	218.2	194.8	132.8
STORY26	390.7	256.0	259.0	248.0	207.9	208.6	186.1	128.4
STORY25	382.5	247.0	250.0	239.1	198.7	198.9	177.3	123.4
STORY24	374.4	237.8	240.6	230.0	189.4	189.1	168.5	118.5
STORY23	365.2	228.2	230.9	220.5	179.9	179.2	159.6	113.0
STORY22	354.9	218.2	220.9	210.6	170.3	169.3	150.6	107.0
STORY21	343.3	207.8	210.5	200.4	160.6	159.2	141.6	100.3
STORY20	330.6	197.1	199.7	189.8	150.8	149.1	132.5	93.0
STORY19	318.0	186.3	188.9	179.2	141.0	139.0	123.4	85.6
STORY18	304.4	175.4	177.8	168.5	131.1	128.8	114.4	77.7
STORY17	289.9	164.3	166.6	157.6	121.2	118.7	105.4	69.6
STORY16	274.5	152.9	155.2	146.5	111.4	108.7	96.4	62.4
STORY15	258.4	140.6	142.8	134.4	101.3	98.6	87.4	58.6
STORY14	242.2	128.2	130.4	122.3	91.4	88.7	78.6	56.0
STORY13	225.4	115.9	118.0	110.3	81.6	79.0	70.0	53.4
STORY12	207.7	103.6	105.7	98.4	72.1	69.6	61.6	50.5
STORY11	189.3	91.6	93.6	86.7	62.9	60.5	53.5	47.2
STORY10	170.1	79.9	81.7	75.3	54.0	51.8	45.7	43.5
STORY9	150.8	68.8	70.6	64.6	45.6	43.5	38.4	39.3
STORY8	131.1	58.2	59.8	54.4	37.7	35.8	31.5	34.9
STORY7	111.0	48.1	49.5	44.6	30.2	28.6	25.1	30.1
STORY6	90.7	38.5	39.7	35.5	23.4	22.0	19.3	25.0
STORY5	70.5	29.6	30.7	27.1	17.4	16.1	14.1	19.8
STORY4	51.2	21.6	22.4	19.5	12.1	11.1	9.6	14.6
STORY3	33.1	14.3	15.0	12.8	7.6	6.8	5.9	9.6
STORY2	17.1	8.0	8.4	7.0	4.0	3.5	3.0	5.1
STORY1	5.1	2.9	3.1	2.4	1.4	1.2	1.0	1.6
BASE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A. 2: Storey displacement in the X-direction versus number of storeys when the shear walls and steel bracings are at the middle

Story	Bare frame	Different steel bracings(at the middle)			Shear wall with different thickness(at the middle)			Four storey module diagrid
		X-bracing	V-bracing	Inverted V-bracing	Shear wall with t=200m	Shear wall with t=300m	Shear wall with t=400m	
STORY30	409.5	234.0	235.4	226.6	181.0	182.2	173.9	141.9
STORY29	406.8	231.7	233.1	224.4	179.1	180.1	171.6	139.5
STORY28	402.9	228.3	229.7	221.0	175.9	176.8	168.4	136.5
STORY27	397.5	223.6	224.9	216.4	171.4	172.2	163.9	132.8
STORY26	390.7	217.6	218.9	210.5	165.8	166.3	158.2	128.4
STORY25	382.5	210.5	211.7	203.5	159.0	159.4	151.6	123.4
STORY24	374.4	203.6	204.8	196.7	152.4	152.4	144.8	118.5
STORY23	365.2	195.8	197.0	189.0	145.1	144.7	137.3	113.0
STORY22	354.9	187.2	188.3	180.6	137.0	136.3	129.1	107.0
STORY21	343.3	177.8	178.8	171.2	128.2	127.1	120.1	100.3
STORY20	330.6	167.4	168.4	161.0	118.6	117.2	110.5	93.0
STORY19	318.0	157.2	158.2	150.9	109.2	107.3	100.8	85.6
STORY18	304.4	146.4	147.3	140.3	99.3	97.0	90.8	77.7
STORY17	289.9	135.2	136.1	129.2	89.2	86.6	80.7	69.6
STORY16	274.5	124.5	125.4	118.8	80.1	77.3	71.9	62.4
STORY15	258.4	116.1	117.0	110.7	74.3	71.4	66.2	58.6
STORY14	242.2	108.8	109.6	103.7	70.1	67.2	62.4	56.0
STORY13	225.4	101.3	102.1	96.6	66.0	63.4	59.0	53.4
STORY12	207.7	93.5	94.2	89.1	61.8	59.6	55.6	50.5
STORY11	189.3	85.3	85.9	81.3	57.4	55.5	52.1	47.2
STORY10	170.1	76.6	77.2	73.1	52.5	51.0	48.2	43.5
STORY9	150.8	68.0	68.5	64.8	47.3	46.2	43.8	39.3
STORY8	131.1	59.1	59.5	56.3	41.8	40.9	39.0	34.9
STORY7	111.0	50.0	50.4	47.6	36.0	35.2	33.7	30.1
STORY6	90.7	40.9	41.2	38.9	29.8	29.2	28.1	25.0
STORY5	70.5	31.8	32.1	30.3	23.6	23.1	22.2	19.8
STORY4	51.2	23.2	23.3	22.1	17.5	17.0	16.4	14.6
STORY3	33.1	15.0	15.1	14.3	11.6	11.2	10.8	9.6
STORY2	17.1	7.8	7.8	7.4	6.2	5.9	5.7	5.1
STORY1	5.1	2.3	2.3	2.2	2.0	1.9	1.8	1.6
BASE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A. 3: Storey displacement in the Y-direction versus number of storeys when the shear walls and steel bracings are at the corner

Story	Bare frame	Different steel bracings(at the corner)			Shear wall with different thickness(at the corner)			Four storey module diagrid
		X-bracing	V-bracing	Inverted V-bracing	Shear wall with t=200m	Shear wall with t=300m	Shear wall with t=400m	
STORY30	354.1	276.9	280.6	271.3	251.5	268.5	235.1	175.0
STORY29	351.3	269.9	273.6	264.4	243.0	258.9	226.6	171.8
STORY28	347.2	262.6	266.3	257.2	234.5	249.3	218.1	167.7
STORY27	341.9	255.0	258.7	249.8	225.9	239.6	209.4	162.8
STORY26	335.4	247.1	250.7	241.9	217.1	229.7	200.6	157.1
STORY25	327.5	238.7	242.3	233.6	208.1	219.7	191.7	150.5
STORY24	320.0	230.0	233.7	225.0	199.0	209.5	182.7	144.2
STORY23	311.5	221.0	224.7	216.1	189.6	199.1	173.6	137.4
STORY22	302.0	211.6	215.3	206.9	180.1	188.7	164.4	129.8
STORY21	291.5	201.9	205.6	197.2	170.5	178.0	155.0	121.5
STORY20	280.1	191.7	195.4	187.2	160.6	167.3	145.6	112.5
STORY19	268.9	181.5	185.2	177.1	150.7	156.4	136.1	103.8
STORY18	257.0	171.0	174.7	166.8	140.6	145.5	126.5	94.5
STORY17	244.2	160.3	164.0	156.3	130.5	134.6	116.9	84.9
STORY16	230.8	149.3	153.0	145.5	120.3	123.6	107.4	76.4
STORY15	216.9	137.3	140.9	133.6	109.8	112.5	97.7	71.3
STORY14	203.2	125.3	128.8	121.7	99.3	101.5	88.1	67.5
STORY13	188.9	113.2	116.6	109.8	88.9	90.6	78.6	63.8
STORY12	158.6	101.2	104.5	97.9	78.7	80.0	69.4	59.7
STORY11	142.5	89.3	92.6	86.3	68.8	69.7	60.4	55.3
STORY10	126.5	77.8	80.9	74.9	59.3	59.8	51.8	50.4
STORY9	110.2	66.8	69.8	64.2	50.1	50.3	43.5	45.3
STORY8	93.6	56.3	59.1	53.9	41.4	41.4	35.8	39.9
STORY7	76.7	46.3	48.8	44.1	33.3	33.1	28.6	34.3
STORY6	60.0	36.8	39.1	34.9	25.8	25.5	22.0	28.4
STORY5	43.9	28.1	30.1	26.5	19.1	18.8	16.1	22.4
STORY4	28.6	20.3	21.9	19.0	13.3	12.9	11.0	16.6
STORY3	15.0	13.3	14.5	12.3	8.3	7.9	6.7	10.9
STORY2	4.5	7.3	8.1	6.6	4.3	4.0	3.4	5.8
STORY1	0.0	2.6	2.9	2.3	1.5	1.3	1.1	1.8
BASE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A. 4: Storey displacement in the Y-direction versus number of storeys when the shear walls and steel bracings are at the middle

Story	Bare frame	Different steel bracings(at the middle)			Shear wall with different thickness(at the middle)			Four storey module diagrid
		X-bracing	V-bracing	Inverted V-bracing	Shear wall with t=200m	Shear wall with t=300m	Shear wall with t=400m	
STORY30	354.1	230.3	234.0	226.4	199.4	209.3	203.7	175.0
STORY29	351.3	227.9	231.6	224.0	197.3	207.0	201.2	171.8
STORY28	347.2	224.2	227.9	220.4	194.0	203.4	197.6	167.7
STORY27	341.9	219.4	223.1	215.6	189.3	198.4	192.7	162.8
STORY26	335.4	213.3	217.0	209.6	183.3	192.0	186.4	157.1
STORY25	327.5	206.2	209.8	202.5	176.2	184.5	179.1	150.5
STORY24	320.0	199.3	203.0	195.8	169.2	176.8	171.4	144.2
STORY23	311.5	191.6	183.0	188.2	161.5	168.3	162.9	137.4
STORY22	302.0	183.1	186.8	179.8	152.8	158.9	153.5	129.8
STORY21	291.5	173.7	177.4	170.5	143.3	148.6	143.2	121.5
STORY20	280.1	163.5	167.1	160.4	133.0	137.4	132.1	112.5
STORY19	268.9	153.6	157.2	150.6	123.0	126.3	121.0	103.8
STORY18	257.0	143.1	146.7	140.2	112.5	114.6	109.4	94.5
STORY17	244.2	132.2	135.8	129.5	101.7	102.9	97.9	84.9
STORY16	230.8	121.8	125.4	119.2	91.8	92.4	87.7	76.4
STORY15	216.9	113.7	117.0	111.2	85.4	85.5	81.0	71.3
STORY14	203.2	106.5	109.7	104.2	80.5	80.5	76.1	67.5
STORY13	188.9	99.3	102.2	97.1	75.8	75.7	71.7	63.8
STORY12	158.6	91.7	94.4	89.7	70.8	70.9	67.3	59.7
STORY11	142.5	83.7	86.2	81.9	65.4	65.6	62.5	55.3
STORY10	126.5	75.3	77.6	73.7	59.6	59.9	57.3	50.4
STORY9	110.2	66.9	68.9	65.5	53.5	53.9	51.7	45.3
STORY8	93.6	58.3	60.1	57.1	47.1	47.5	45.7	39.9
STORY7	76.7	49.6	51.0	48.5	40.4	40.7	39.3	34.3
STORY6	60.0	40.7	41.9	39.8	33.5	33.7	32.6	28.4
STORY5	43.9	31.8	32.8	31.1	26.5	26.5	25.7	22.4
STORY4	28.6	23.3	24.0	22.8	19.7	19.6	18.9	16.6
STORY3	15.0	15.2	15.7	14.9	13.1	12.9	12.4	10.9
STORY2	4.5	8.0	8.2	7.8	7.0	6.8	6.6	5.8
STORY1	0.0	2.4	2.5	2.4	2.3	2.2	2.1	1.8
BASE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Appendix-B: Storey drift versus number of storeys tables

Table B. 1: Storey drift in the X-direction versus number of storeys when the shear walls and steel bracings are at the corner

Story	Bare frame	Different steel bracings(at the corner)			Shear wall with different thickness(at the corner)			Four storey module diagrid
		X-bracing	V-bracing	Inverted V-bracing	Shear wall t=200mm	Shear wall t=300mm	Shear wall t=400mm	
STORY30	0.000964	0.002567	0.002617	0.00253	0.002965	0.003147	0.002858	0.000849
STORY29	0.001467	0.002664	0.002704	0.002627	0.002987	0.003168	0.002874	0.001156
STORY28	0.001983	0.002761	0.002793	0.002729	0.003016	0.003188	0.00289	0.001319
STORY27	0.002474	0.002895	0.002918	0.002862	0.003061	0.003225	0.002918	0.00154
STORY26	0.002944	0.003142	0.00316	0.003107	0.003211	0.003332	0.003019	0.00176
STORY25	0.002856	0.003126	0.003152	0.003085	0.003153	0.003299	0.002975	0.001705
STORY24	0.003209	0.003267	0.003288	0.003226	0.003266	0.003416	0.003077	0.001891
STORY23	0.003593	0.003582	0.003597	0.003546	0.003564	0.003705	0.003353	0.002091
STORY22	0.003984	0.003901	0.003917	0.003862	0.00384	0.003972	0.0036	0.002293
STORY21	0.004375	0.004217	0.004234	0.004174	0.004099	0.004224	0.003824	0.002507
STORY20	0.004322	0.004109	0.004125	0.004067	0.003913	0.004073	0.003635	0.002487
STORY19	0.00462	0.004326	0.004343	0.00428	0.004095	0.004248	0.003795	0.002659
STORY18	0.004935	0.004475	0.004494	0.004422	0.004198	0.004334	0.003883	0.002744
STORY17	0.005231	0.004337	0.004359	0.004267	0.003981	0.004074	0.003667	0.002454
STORY16	0.005507	0.004154	0.004168	0.004066	0.003383	0.003387	0.003018	0.001656
STORY15	0.00556	0.004138	0.004158	0.00405	0.003327	0.003321	0.002958	0.001638
STORY14	0.005778	0.004127	0.004149	0.004031	0.003269	0.003249	0.002893	0.001539
STORY13	0.006004	0.004087	0.004112	0.003982	0.00319	0.003159	0.002811	0.001619
STORY12	0.00623	0.004024	0.004054	0.003908	0.003087	0.003046	0.00271	0.001666
STORY11	0.006459	0.00392	0.003956	0.003798	0.002971	0.002922	0.002597	0.001576
STORY10	0.006466	0.003684	0.003725	0.003571	0.002815	0.002759	0.002453	0.001531
STORY9	0.006608	0.003675	0.003729	0.003524	0.002746	0.002721	0.002409	0.001616
STORY8	0.006731	0.003689	0.003747	0.003532	0.002758	0.002723	0.002422	0.001697
STORY7	0.006796	0.00367	0.003732	0.003509	0.002743	0.002692	0.00241	0.001763
STORY6	0.006748	0.003595	0.003659	0.003431	0.002689	0.002617	0.002365	0.001797
STORY5	0.006441	0.003398	0.003461	0.003238	0.002529	0.00245	0.002232	0.001757
STORY4	0.006062	0.003177	0.003238	0.003026	0.00238	0.002282	0.00211	0.001686
STORY3	0.005332	0.002786	0.00284	0.002652	0.00212	0.002004	0.001891	0.001525
STORY2	0.004008	0.002091	0.002132	0.001991	0.001633	0.001521	0.001467	0.001183
STORY1	0.0017	0.000952	0.001047	0.000844	0.000753	0.000692	0.000682	0.00062

Table B. 2: Storey drift in the X-direction versus number of storeys when the shear walls and steel bracings are at the middle

Story	Bare frame	Different steel bracings(in the middle)			Shear wall with different thickness(in the middle)			Four storey module diagrid
		X-bracing	V-bracing	Inverted V-bracing	Shear wall with t=200mm	Shear wall with t=300mm	Shear wall with t=400mm	
STORY30	0.000964	0.001915	0.001982	0.001871	0.00218	0.0023	0.002232	0.000849
STORY29	0.001467	0.002014	0.002067	0.001968	0.002197	0.002314	0.002243	0.001156
STORY28	0.001983	0.002109	0.002152	0.002067	0.002217	0.002327	0.002252	0.001319
STORY27	0.002474	0.002228	0.002262	0.002187	0.002248	0.00235	0.002269	0.00154
STORY26	0.002944	0.002496	0.002518	0.002457	0.002411	0.002479	0.002388	0.00176
STORY25	0.002856	0.00243	0.002457	0.002383	0.002316	0.002431	0.002372	0.001705
STORY24	0.003209	0.00267	0.002684	0.002634	0.002565	0.002665	0.002591	0.001891
STORY23	0.003593	0.002958	0.002971	0.002918	0.002823	0.002911	0.002822	0.002091
STORY22	0.003984	0.003243	0.003256	0.0032	0.003063	0.00315	0.003052	0.002293
STORY21	0.004375	0.003528	0.00354	0.00348	0.003285	0.003377	0.00327	0.002507
STORY20	0.004322	0.003457	0.003468	0.00341	0.003193	0.003347	0.003276	0.002487
STORY19	0.00462	0.003659	0.003669	0.003607	0.003353	0.003493	0.003397	0.002659
STORY18	0.004935	0.003789	0.003798	0.003731	0.003429	0.003535	0.003406	0.002744
STORY17	0.005231	0.003618	0.003627	0.003546	0.003174	0.003222	0.003079	0.002454
STORY16	0.005507	0.00331	0.003306	0.003221	0.002442	0.002497	0.002418	0.001656
STORY15	0.00556	0.003294	0.003296	0.003202	0.002392	0.002367	0.002227	0.001638
STORY14	0.005778	0.003287	0.003289	0.003189	0.002343	0.002311	0.00217	0.001539
STORY13	0.006004	0.003259	0.003262	0.003154	0.002282	0.002241	0.002101	0.001619
STORY12	0.00623	0.003215	0.003219	0.0031	0.002204	0.002157	0.002019	0.001666
STORY11	0.006459	0.00314	0.003148	0.003021	0.002114	0.00206	0.001924	0.001576
STORY10	0.006466	0.002961	0.002979	0.002831	0.002005	0.001947	0.001817	0.001531
STORY9	0.006608	0.003021	0.003041	0.002887	0.002037	0.001999	0.001859	0.001616
STORY8	0.006731	0.003065	0.003086	0.002927	0.002109	0.002083	0.001955	0.001697
STORY7	0.006796	0.003081	0.003103	0.00294	0.002161	0.002142	0.002029	0.001763
STORY6	0.006748	0.003048	0.003072	0.002907	0.002178	0.002157	0.002058	0.001797
STORY5	0.006441	0.002905	0.002928	0.002768	0.002097	0.002083	0.002002	0.001757
STORY4	0.006062	0.002734	0.002756	0.002605	0.002005	0.00198	0.00191	0.001686
STORY3	0.005332	0.002413	0.002432	0.002299	0.001815	0.001774	0.001716	0.001525
STORY2	0.004008	0.001821	0.001835	0.001736	0.001416	0.001369	0.001325	0.001183
STORY1	0.0017	0.000937	0.000997	0.000848	0.000662	0.000627	0.000602	0.00062

Table B. 3: Storey drift in the Y-direction versus number of storeys when the shear walls and steel bracings are at the corner

Story	Bare frame	Different steel bracings(in the corner)			Shear wall with different thickness(in the corner)			Four storey module diagrid
		X-bracing	V-bracing	Inverted V-bracing	Shear wall with t=200mm	Shear wall with t=300mm	Shear wall with t=400mm	
STORY30	0.001024	0.002378	0.002386	0.002329	0.002848	0.003214	0.002867	0.001187
STORY29	0.001488	0.002473	0.002477	0.00243	0.002879	0.003244	0.002889	0.001451
STORY28	0.00196	0.00257	0.00257	0.002534	0.002917	0.003274	0.002913	0.001699
STORY27	0.002402	0.002699	0.002695	0.002669	0.002974	0.003325	0.002952	0.001992
STORY26	0.002814	0.002978	0.002973	0.002947	0.003148	0.003431	0.003054	0.002273
STORY25	0.002661	0.002924	0.002924	0.002886	0.003093	0.003432	0.003035	0.002157
STORY24	0.002962	0.003087	0.003082	0.003062	0.003206	0.003521	0.003107	0.002366
STORY23	0.003288	0.0034	0.003394	0.003372	0.003518	0.003854	0.003402	0.002593
STORY22	0.003619	0.003708	0.003702	0.003678	0.003821	0.004184	0.003688	0.002824
STORY21	0.003945	0.004006	0.004001	0.003974	0.004107	0.0045	0.003957	0.003057
STORY20	0.00383	0.003854	0.00385	0.003823	0.003887	0.004323	0.003735	0.002968
STORY19	0.004074	0.004057	0.004054	0.004023	0.004072	0.00451	0.003901	0.003136
STORY18	0.004327	0.004204	0.004206	0.004167	0.004187	0.004607	0.003996	0.003219
STORY17	0.004555	0.004105	0.00412	0.004059	0.004013	0.004365	0.003803	0.002925
STORY16	0.004747	0.004038	0.004051	0.003987	0.003543	0.003742	0.003261	0.00205
STORY15	0.004749	0.004036	0.004055	0.003988	0.003508	0.00369	0.003216	0.002052
STORY14	0.004916	0.004041	0.004066	0.003989	0.00347	0.003633	0.003166	0.001939
STORY13	0.005083	0.004012	0.004043	0.003954	0.003406	0.003552	0.003094	0.001984
STORY12	0.005247	0.003957	0.003997	0.003892	0.003316	0.003445	0.003	0.002047
STORY11	0.005412	0.003868	0.003915	0.003797	0.00321	0.003322	0.002891	0.001944
STORY10	0.005376	0.003651	0.003702	0.003583	0.003055	0.003151	0.002744	0.001836
STORY9	0.005478	0.003547	0.003633	0.003458	0.002925	0.003072	0.002633	0.001909
STORY8	0.005577	0.003577	0.003667	0.003485	0.002953	0.003079	0.00266	0.001973
STORY7	0.005636	0.003579	0.003674	0.003485	0.002954	0.003054	0.002659	0.002026
STORY6	0.005616	0.003532	0.00363	0.003437	0.002914	0.002985	0.002622	0.002045
STORY5	0.005376	0.003357	0.003453	0.003265	0.002751	0.002804	0.002477	0.00198
STORY4	0.005104	0.003172	0.003266	0.003085	0.002611	0.002626	0.002355	0.001899
STORY3	0.004551	0.002819	0.002903	0.002741	0.002341	0.002315	0.002119	0.00172
STORY2	0.003484	0.002155	0.002219	0.002096	0.001823	0.001767	0.001657	0.001344
STORY1	0.001514	0.000938	0.000984	0.000913	0.000869	0.000822	0.000792	0.000682

Table B. 4: Storey drift in the Y-direction versus number of storeys when the shear walls and steel bracings are at the middle

Story	Bare frame	Different steel bracings(in the middle)			Shear wall with different thickness(in the middle)			Four storey module diagrid
		X-bracing	V-bracing	Inverted V-bracing	Shear wall with t=200mm	Shear wall with t=300mm	Shear wall with t=400mm	
STORY30	0.001024	0.001876	0.001906	0.001805	0.002275	0.002528	0.00252	0.001187
STORY29	0.001488	0.001969	0.001992	0.001905	0.002298	0.002548	0.002536	0.001451
STORY28	0.00196	0.002057	0.002075	0.002003	0.002324	0.002566	0.002549	0.001699
STORY27	0.002402	0.002168	0.002182	0.002121	0.002363	0.002597	0.002574	0.001992
STORY26	0.002814	0.002505	0.002508	0.002474	0.002556	0.002733	0.002694	0.002273
STORY25	0.002661	0.002373	0.002376	0.002344	0.002442	0.002662	0.002645	0.002157
STORY24	0.002962	0.002643	0.002646	0.002612	0.002697	0.002925	0.002915	0.002366
STORY23	0.003288	0.002925	0.002928	0.002891	0.00299	0.003239	0.003223	0.002593
STORY22	0.003619	0.003205	0.003207	0.003169	0.003282	0.003554	0.003527	0.002824
STORY21	0.003945	0.00348	0.003482	0.003441	0.003543	0.003835	0.003793	0.003057
STORY20	0.00383	0.003361	0.003364	0.003324	0.003412	0.003775	0.003775	0.002968
STORY19	0.004074	0.003548	0.003552	0.003509	0.003577	0.003931	0.003905	0.003136
STORY18	0.004327	0.003673	0.00368	0.003631	0.003667	0.003981	0.003915	0.003219
STORY17	0.004555	0.003521	0.003541	0.003476	0.003423	0.003652	0.00356	0.002925
STORY16	0.004747	0.003266	0.003294	0.003229	0.002729	0.002831	0.002786	0.00205
STORY15	0.004749	0.00326	0.003293	0.00322	0.002698	0.002786	0.002676	0.002052
STORY14	0.004916	0.003258	0.003296	0.003215	0.002659	0.002734	0.002622	0.001939
STORY13	0.005083	0.003231	0.003274	0.003184	0.002602	0.002665	0.002551	0.001984
STORY12	0.005247	0.003184	0.003234	0.003133	0.002525	0.002575	0.002461	0.002047
STORY11	0.005412	0.003108	0.003164	0.003054	0.002433	0.00247	0.002356	0.001944
STORY10	0.005376	0.002904	0.002966	0.002857	0.002312	0.00234	0.002229	0.001836
STORY9	0.005478	0.002919	0.003001	0.002859	0.002296	0.002359	0.002238	0.001909
STORY8	0.005577	0.00297	0.003055	0.002908	0.002366	0.002422	0.002308	0.001973
STORY7	0.005636	0.002997	0.003084	0.002934	0.002416	0.002472	0.002371	0.002026
STORY6	0.005616	0.00298	0.003068	0.002917	0.002429	0.002487	0.002398	0.002045
STORY5	0.005376	0.002851	0.002936	0.00279	0.002331	0.002393	0.002321	0.00198
STORY4	0.005104	0.002708	0.002789	0.002651	0.002236	0.002271	0.002205	0.001899
STORY3	0.004551	0.002419	0.002491	0.002367	0.00203	0.002031	0.001972	0.00172
STORY2	0.003484	0.001857	0.001911	0.001818	0.001597	0.00157	0.001521	0.001344
STORY1	0.001514	0.000846	0.000941	0.000795	0.000766	0.000731	0.0007	0.000682

Appendix-C: Storey and base shear versus number of storeys tables

Table C. 1: Storey shear in the X-direction versus number of storeys when the shear walls and steel bracings are at the corner

Story	Bare frame	Different steel bracings(at the corner)			Shear wall with different thickness(at the corner)			Four storey module diagrid
		X-bracing	V-bracing	Inverted V-bracing	Shear wall t=200mm	Shear wall t=300mm	Shear wall t=400mm	
STORY30	952.5	1018.2	1014.2	1021.7	1094.5	1098.6	1111.2	975.2
STORY29	1904.1	2058.8	2048.6	2063.7	2236.6	2269.8	2312.9	1949.7
STORY28	2784.5	3054.8	3038.6	3060.9	3287.1	3345.1	3407.6	2879.1
STORY27	3591.8	3999.9	3977.9	4006.6	4246.0	4324.9	4400.6	3764.4
STORY26	4344.8	4892.8	4865.4	4899.6	5129.9	5226.2	5316.1	4608.8
STORY25	5081.9	5748.1	5715.9	5754.7	5967.5	6079.4	6188.7	5423.4
STORY24	5828.7	6576.4	6540.1	6582.2	6772.3	6897.4	7029.2	6211.7
STORY23	6565.3	7359.9	7319.9	7364.1	7518.0	7654.0	7805.4	6960.3
STORY22	7279.3	8099.0	8056.0	8100.9	8198.2	8342.0	8504.6	7664.5
STORY21	7961.2	8796.5	8750.8	8795.4	8820.1	8967.9	9133.4	8324.2
STORY20	8623.5	9468.7	9420.5	9463.5	9408.7	9556.5	9721.4	8944.7
STORY19	9277.7	10119.8	10069.4	10109.4	9976.1	10119.7	10286.2	9527.3
STORY18	9910.7	10729.3	10677.1	10712.8	10504.4	10641.7	10813.9	10058.8
STORY17	10517.6	11293.7	11240.1	11270.6	10986.0	11115.8	11295.0	10537.8
STORY16	11090.3	11815.8	11761.3	11786.1	11420.9	11542.1	11727.6	10969.0
STORY15	11637.6	12314.2	12259.3	12278.3	11843.1	11953.5	12145.1	11375.2
STORY14	12167.4	12795.3	12740.1	12753.3	12265.8	12369.0	12563.6	11773.3
STORY13	12671.3	13247.5	13191.8	13198.7	12667.4	12770.2	12966.1	12157.9
STORY12	13145.1	13671.0	13614.7	13615.1	13043.5	13149.8	13349.1	12520.6
STORY11	13575.1	14065.1	14008.5	14003.2	13411.9	13524.4	13731.9	12861.5
STORY10	13963.4	14435.2	14378.6	14368.9	13795.8	13918.9	14140.4	13193.2
STORY9	14323.9	14776.3	14719.8	14706.3	14181.8	14320.2	14560.9	13516.6
STORY8	14664.2	15077.1	15020.7	15003.4	14530.3	14687.5	14948.5	13813.0
STORY7	14971.6	15344.2	15287.3	15266.3	14837.2	15017.3	15294.9	14078.5
STORY6	15207.2	15577.4	15519.9	15496.2	15123.5	15332.9	15624.8	14317.8
STORY5	15380.4	15772.1	15714.3	15689.9	15402.1	15641.6	15955.3	14527.1
STORY4	15565.6	15950.3	15892.0	15868.8	15686.5	15938.3	16287.5	14703.8
STORY3	15753.8	16132.3	16072.4	16051.2	16000.6	16253.7	16644.3	14864.3
STORY2	15857.0	16248.1	16187.5	16168.7	16354.8	16674.2	17120.4	14991.1
STORY1	16474.2	16638.3	16575.5	16581.1	17573.1	18000.2	18651.8	15350.0
BASE SHEAR	**311071.5**	**327075.7**	**325678.1**	**326041.4**	**322283.5**	**326732.9**	**333038.3**	**302842.7**

Table C. 2: Storey shear in the X-direction versus number of storeys when the shear walls and steel bracings are at the middle

Story	Bare frame	Different steel bracings(at the middle)			Shear wall with different thickness(at the middle)			Four storey module diagrid
		X-bracing	V-bracing	Inverted V-bracing	Shear wall t=200mm	Shear wall t=300mm	Shear wall t=400mm	
STORY30	952.5	1001.4	999.4	1005.2	1034.3	1035.2	1039.8	975.2
STORY29	1904.1	2026.4	2020.2	2031.7	2115.8	2142.8	2171.8	1949.7
STORY28	2784.5	3008.7	2998.0	3014.6	3110.2	3166.6	3214.4	2879.1
STORY27	3591.8	3943.0	3927.8	3948.8	4021.6	4111.3	4176.0	3764.4
STORY26	4344.8	4829.7	4810.1	4835.3	4871.1	4994.5	5077.2	4608.8
STORY25	5081.9	5684.7	5660.8	5690.1	5688.7	5843.1	5945.3	5423.4
STORY24	5828.7	6517.0	6489.1	6522.2	6484.1	6665.7	6788.8	6211.7
STORY23	6565.3	7306.3	7274.7	7310.8	7230.0	7439.8	7586.8	6960.3
STORY22	7279.3	8050.7	8015.6	8053.5	7918.2	8160.3	8333.5	7664.5
STORY21	7961.2	8751.8	8713.6	8752.1	8550.5	8824.7	9021.8	8324.2
STORY20	8623.5	9426.4	9385.1	9423.1	9140.7	9438.7	9651.7	8944.7
STORY19	9277.7	10079.5	10035.1	10071.7	9692.9	10002.1	10221.9	9527.3
STORY18	9910.7	10690.3	10643.1	10677.2	10191.3	10502.0	10722.9	10058.8
STORY17	10517.6	11254.4	11204.7	11235.3	10634.5	10941.8	11161.8	10537.8
STORY16	11090.3	11774.1	11722.4	11748.5	11030.8	11335.7	11556.9	10969.0
STORY15	11637.6	12269.9	12216.7	12237.9	11420.4	11719.6	11945.4	11375.2
STORY14	12167.4	12750.1	12695.6	12712.1	11824.2	12122.0	12356.8	11773.3
STORY13	12671.3	13203.4	13147.4	13159.5	12215.7	12522.2	12769.3	12157.9
STORY12	13145.1	13629.6	13571.8	13579.7	12575.8	12893.5	13148.2	12520.6
STORY11	13575.1	14027.9	13968.5	13972.5	12920.1	13243.3	13496.0	12861.5
STORY10	13963.4	14404.4	14344.0	14344.7	13285.3	13610.5	13856.8	13193.2
STORY9	14323.9	14754.1	14692.8	14690.9	13669.7	14000.8	14244.4	13516.6
STORY8	14664.2	15064.3	15002.0	14997.8	14033.8	14381.3	14630.6	13813.0
STORY7	14971.6	15340.0	15276.3	15270.3	14370.0	14748.7	15013.8	14078.5
STORY6	15207.2	15581.3	15516.4	15509.2	14696.3	15122.4	15415.2	14317.8
STORY5	15380.4	15784.7	15719.2	15711.9	15013.5	15493.0	15822.4	14527.1
STORY4	15565.6	15971.8	15906.0	15900.2	15316.1	15829.9	16194.1	14703.8
STORY3	15753.8	16163.3	16096.2	16093.1	15635.0	16163.1	16557.2	14864.3
STORY2	15857.0	16281.7	16214.3	16213.2	16033.5	16622.6	17076.3	14991.1
STORY1	16474.2	16638.5	16575.5	16575.5	17384.2	17973.1	18556.9	15350.0
BASE SHEAR	**311071.5**	**326209.1**	**324842.1**	**325288.6**	**312108.2**	**321050.2**	**327754.0**	**302842.7**

Table C. 3: Storey shear in the Y-direction versus number of storeys when the shear walls and steel bracings are at the corner

Story	Bare frame	Different steel bracings(at the corner)			Shear wall with different thickness(at the corner)			Four storey module diagrid
		X-bracing	V-bracing	Inverted V-bracing	Shear wall t=200m	Shear wall t=300m	Shear wall t=400m	
STORY30	969.2	990.1	982.7	990.4	1012.8	1028.1	1024.9	969.55
STORY29	1936.1	2006.1	1989.6	2005.2	2092.3	2147.5	2162.9	1943.66
STORY28	2829.1	2984.9	2959.8	2982.7	3119.7	3210.9	3244.2	2881.48
STORY27	3645.3	3918.7	3885.7	3915.2	4084.2	4207.7	4258.2	3778.35
STORY26	4402.2	4802.4	4762.3	4797.5	4980.1	5133.6	5199.8	4630.19
STORY25	5137.4	5647.5	5601.3	5641.0	5819.2	6003.0	6081.2	5443.73
STORY24	5879.1	6464.8	6413.4	6456.5	6615.4	6829.2	6915.4	6225.84
STORY23	6609.0	7238.4	7182.7	7227.9	7354.3	7597.0	7687.1	6966.19
STORY22	7316.8	7969.5	7910.5	7956.7	8037.6	8304.6	8396.4	7661.22
STORY21	7994.0	8659.8	8598.4	8644.2	8669.9	8952.9	9046.7	8309.37
STORY20	8652.1	9324.1	9260.9	9305.2	9270.8	9560.9	9657.9	8917.64
STORY19	9301.2	9968.4	9903.8	9945.7	9855.0	10147.2	10246.5	9491.76
STORY18	9927.0	10575.8	10510.3	10548.8	10407.5	10703.0	10800.2	10020.23
STORY17	10525.1	11143.3	11077.7	11111.7	10913.1	11214.6	11305.7	10498.92
STORY16	11089.4	11668.0	11603.2	11631.7	11362.2	11667.8	11756.9	10930.73
STORY15	11629.8	12163.8	12100.4	12122.8	11781.8	12094.2	12183.6	11337.04
STORY14	12154.0	12640.6	12579.2	12595.2	12184.3	12499.6	12594.3	11727.12
STORY13	12651.6	13094.3	13034.9	13044.6	12579.2	12890.9	12994.6	12101.05
STORY12	13116.8	13526.5	13468.8	13472.9	12984.2	13290.4	13402.0	12463.3
STORY11	13536.8	13929.0	13872.3	13871.7	13393.3	13699.6	13815.4	12813
STORY10	13916.2	14298.8	14243.2	14238.2	13784.9	14098.9	14218.5	13144.92
STORY9	14271.8	14632.9	14578.7	14569.3	14135.1	14461.1	14589.4	13453.43
STORY8	14611.0	14926.7	14874.6	14860.6	14436.7	14777.5	14918.5	13733.43
STORY7	14919.1	15185.4	15135.3	15117.1	14710.3	15071.2	15224.7	13989.99
STORY6	15154.2	15409.2	15360.0	15338.9	14968.6	15352.6	15519.3	14218.4
STORY5	15326.1	15611.6	15561.8	15539.7	15224.4	15623.8	15811.1	14414.25
STORY4	15518.1	15810.1	15758.8	15737.9	15502.1	15904.5	16120.8	14591.34
STORY3	15721.6	15977.6	15924.2	15905.9	15802.1	16221.6	16470.2	14754.8
STORY2	15822.3	16106.3	16048.0	16034.4	16212.3	16708.3	17008.1	14891.94
STORY1	16469.9	16649.1	16574.7	16577.6	17592.8	18198.5	18584.1	15311.23
BASE SHEAR	**311032.4**	**323323.9**	**321757.3**	**322187.3**	**318885.8**	**327600.4**	**331238.3**	**301614.1**

Table C. 4: Storey shear in the Y-direction versus number of storeys when the shear walls and steel bracings are at the middle

Story	Bare frame	Different steel bracings(at the middle)			Shear wall with different thickness(at the middle)			Four storey module diagrid
		X-bracing	V-bracing	Inverted V-bracing	Shear wall t=200m	Shear wall t=300m	Shear wall t=400m	
STORY30	969.2	977.7	972.0	976.4	968.4	973.8	980.7	969.55
STORY29	1936.1	1984.1	1970.9	1979.8	2010.8	2049.5	2088.7	1943.66
STORY28	2829.1	2957.2	2936.6	2950.1	3007.1	3074.7	3139.4	2881.48
STORY27	3645.3	3888.9	3861.4	3879.3	3947.6	4040.5	4126.3	3778.35
STORY26	4402.2	4774.0	4740.1	4761.9	4828.7	4947.2	5053.7	4630.19
STORY25	5137.4	5623.2	5583.5	5608.8	5664.4	5813.7	5944.5	5443.73
STORY24	5879.1	6446.1	6401.3	6429.4	6466.9	6652.1	6810.6	6225.84
STORY23	6609.0	7225.4	7176.3	7206.4	7217.6	7441.7	7628.6	6966.19
STORY22	7316.8	7961.5	7909.1	7940.1	7911.8	8171.3	8383.7	7661.22
STORY21	7994.0	8655.1	8600.3	8631.3	8548.2	8834.4	9068.2	8309.37
STORY20	8652.1	9320.7	9264.3	9294.1	9144.2	9448.9	9701.4	8917.64
STORY19	9301.2	9964.7	9907.3	9934.9	9715.0	10032.7	10301.1	9491.76
STORY18	9927.0	10570.3	10512.5	10537.0	10245.5	10572.0	10850.4	10020.23
STORY17	10525.1	11133.9	11076.6	11097.0	10721.6	11050.4	11331.0	10498.92
STORY16	11089.4	11652.9	11597.1	11612.5	11142.4	11467.8	11748.6	10930.73
STORY15	11629.8	12142.3	12088.7	12098.6	11544.6	11871.9	12157.7	11337.04
STORY14	12154.0	12612.4	12561.4	12565.6	11935.0	12266.9	12561.7	11727.12
STORY13	12651.6	13060.5	13012.1	13010.9	12314.0	12648.5	12952.5	12101.05
STORY12	13116.8	13490.6	13444.4	13438.4	12696.3	13029.9	13340.0	12463.3
STORY11	13536.8	13896.0	13851.3	13841.1	13082.9	13415.0	13727.3	12813
STORY10	13916.2	14272.8	14228.8	14215.2	13462.3	13794.3	14106.3	13144.92
STORY9	14271.8	14615.1	14571.8	14555.0	13816.9	14150.9	14463.4	13453.43
STORY8	14611.0	14916.0	14873.8	14854.1	14139.4	14482.6	14800.2	13733.43
STORY7	14919.1	15181.4	15140.0	15117.9	14445.2	14811.0	15141.0	13989.99
STORY6	15154.2	15412.4	15371.3	15347.5	14736.1	15133.2	15482.2	14218.4
STORY5	15326.1	15622.7	15580.7	15556.7	15013.2	15433.2	15803.9	14414.25
STORY4	15518.1	15829.8	15786.0	15763.3	15301.3	15729.4	16123.0	14591.34
STORY3	15721.6	16006.7	15960.5	15940.3	15622.1	16072.0	16497.2	14754.8
STORY2	15822.3	16137.0	16086.8	16069.3	16070.4	16594.7	17080.0	14891.94
STORY1	16469.9	16648.4	16586.5	16577.5	17417.4	18046.5	18630.6	15311.23
BASE SHEAR	**311032.4**	**322979.7**	**321653.1**	**321790.4**	**313136.9**	**322050.7**	**330023.8**	**301614.1**

Appendix-D: Articles, graphs and tables referred in the paper from ESEN 1998-1:2013

D.1 Methods of analysis

There are four methods that can be used to analyze the response of a structure subjected to an earthquake. The choice of the method depends on the structure and on the objectives of the analysis.

1) Linear-elastic analysis
    a) Lateral force method of analysis (Static)
    b) Modal response spectrum analysis (Dynamic)
2) Non-linear analysis
    c) Non-linear static (pushover) analysis
    d) Non-linear time history (dynamic) analysis

For non-base-isolated buildings, linear methods of analysis may always be used.

a) Lateral force method of analysis

This type of analysis may be applied to buildings whose response is not significantly affected by contributions from modes of vibration higher than the fundamental mode in each principal direction. This requirement is deemed to be satisfied in buildings which fulfill both of the following two conditions.

a) They have fundamental periods of vibration *T*1 in the two main directions which are smaller than the following values

$$T_1 \le \begin{cases} 4 \cdot T_C \\ 2.0\text{s} \end{cases}$$

Where *T*C is given in Table 3.2 or Table 3.3 of the code

b) They meet the criteria for regularity in elevation given in 4.2.3.3 of the code

b) Modal response spectrum analysis

This type of analysis shall be applied to buildings which do not satisfy the conditions given above for applying the lateral force method of analysis. The response of all modes of vibration contributing significantly to the global response shall be taken into account. These requirements may be deemed to be satisfied if either of the following can be demonstrated:

- The sum of the effective modal masses for the modes taken into account amounts to at least 90% of the total mass of the structure
- All modes with effective modal masses greater than 5% of the total mass are taken into account.

c) Non-linear static (pushover) analysis

Pushover analysis is a non-linear static analysis carried out under conditions of constant gravity loads and monotonically increasing horizontal loads. It may be applied to verify the structural performance of newly designed and of existing buildings.

d) Non-linear time-history analysis

In this method the time-dependent response of the structure may be obtained through direct numerical integration of its differential equations of motion, using the accelerograms defined in 3.2.3.1 of the code to represent the ground motions.

D.2 Ground types, Seismic zones and Importance classes

Ground types A, B, C, D, and E described by the stratigraphic profiles and parameters given in Table 3.1 of EBCS EN 1998 may be used to account for the influence of local ground conditions on the seismic action.

According to Ethiopian building code EBCS EN 1998-1,2014 the seismic hazard map is divided into 5 zones, where the ratio of the design bedrock acceleration to the acceleration of gravity g =αo for the respective zone is described in table below.

Table D. 1: Bedrock Acceleration Ratio αo

Zone	5	4	3	2	1	0
αo =ag/g	0.2	0.15	0.1	0.07	0.04	0

Source: Table D1 of EBCS EN 1998-1, 2014

Buildings are classified in 4 importance classes, depending on the consequences of collapse for human life, on their importance for public safety and civil protection in the immediate post-earthquake period, and on the social and economic consequences of collapse.

Table D. 2: Importance classes for buildings

Importance class	Buildings
I	Buildings of minor importance for public safety, e.g. agricultural buildings,etc.
II	Ordinary buildings, not belonging in the other categories.
III	Buildings whose seismic resistance is of importance in view of the consequences associated with a collapse, e.g. schools, assembly halls, cultural institutions etc.
IV	Buildings whose integrity during earthquakes is of vital importance for civil protection, e.g. hospitals, fire stations, power plants, etc.

The value of γI for importance class II shall be, by definition, equal to 1.0. The recommended values of γI for importance classes I, III and IV are equal to 0.8, 1.2 and 1.4, respectively.

D.3 Design spectrum for elastic analysis and Behaviour factor

If the earthquakes that contribute most to the seismic hazard defined for the site for the purpose of probabilistic hazard assessment have a surface-wave magnitude, Ms, not greater than 5.5, it is recommended that the Type 2 spectrum is adopted. Otherwise type 1 spectrum will be used.

For the horizontal components of the seismic action the design spectrum, Sd(T), shall be defined by the following expressions:

$$0 \le T \le T_B: \quad S_d(T) = a_g \cdot S \cdot \left[\frac{2}{3} + \frac{T}{T_B} \cdot \left(\frac{2.5}{q} - \frac{2}{3}\right)\right]$$

$$T_B \le T \le T_C: \quad S_d(T) = a_g \cdot S \cdot \eta \cdot \frac{2.5}{q}$$

$$T_B \le T \le T_C: \quad S_d(T) = \begin{cases} = a_g \cdot S \cdot \dfrac{2.5}{q} \cdot \left[\dfrac{T_C}{T}\right] \\ \ge \beta \cdot a_g \end{cases}$$

$$T_D \le T: \quad S_d(T) = \begin{cases} = a_g \cdot S \cdot \dfrac{2.5}{q} \cdot \left[\dfrac{T_C \cdot T_D}{T^2}\right] \\ \ge \beta \cdot a_g \end{cases}$$

Where

*S*d(T) is the design spectrum

q is the behaviour factor

T is the vibration period of a linear single-degree-of-freedom system

*a*g is the design ground acceleration on type A ground (*a*g = γI·*a*gR)

*T*B is the lower limit of the period of the constant spectral acceleration branch;

*T*C is the upper limit of the period of the constant spectral acceleration branch;

*T*D is the value defining the beginning of the constant displacement response range of the spectrum;

S is the soil factor;

η is the damping correction factor with a reference value of η = 1 for 5% viscous damping

β is the lower bound factor for the horizontal design spectrum.

NOTE: The value to be ascribed to β for use is found in the National Annex. The recommended value for β is 0.2.

Table D. 3: Values of the parameters describing the recommended Type 1 elastic response spectra

Ground type	*S*	*T*B(s)	*T*C(s)	*T*D(s)
A	1	0.05	0.25	1.2
B	1.35	0.05	0.25	1.2
C	1.5	0.1	0.25	1.2
D	1.8	0.1	0.3	1.2
E	1.6	0.05	0.25	1.2

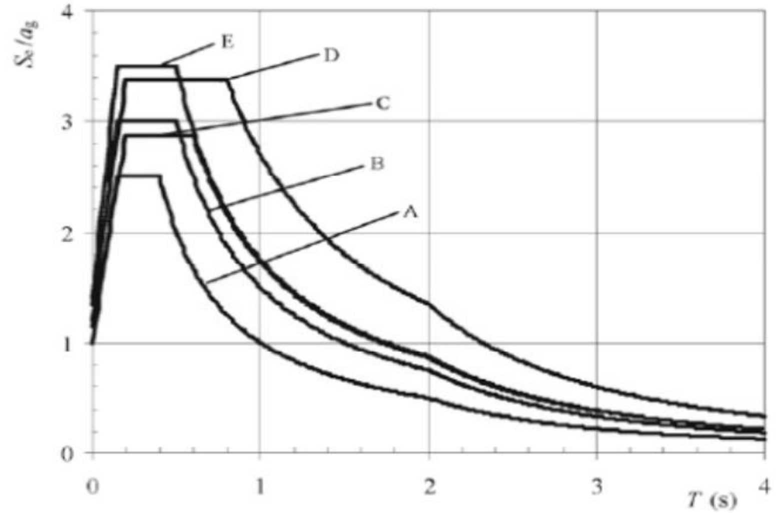

Figure D. 1: Recommended Type 1 elastic response spectra for ground types A to E (5% damping)

Structural types

a) **Frame system**

Structural system in which both the vertical and lateral loads are mainly resisted by spatial frames whose shear resistance at the building base exceeds 65% of the total shear resistance of the whole structural system

b) **Dual system**

Structural system in which support for the vertical loads is mainly provided by a spatial frame and resistance to lateral loads is contributed to in part by the frame system and in part by structural walls, coupled or uncoupled

Frame-equivalent dual system

Dual system in which the shear resistance of the frame system at the building base is greater than 50% of the total shear resistance of the whole structural system

Wall –equivalent dual system

Dual system in which the shear resistance of the walls at the building base is higher than 50% of the total seismic resistance of the whole structural system

c) **Ductile wall system (coupled or uncoupled)**

d) **System of large lightly reinforced walls**

e) **Inverted pendulum system**

f) **Torsionally flexible system**

Behaviour factors

To avoid explicit inelastic structural analysis in design, the capacity of the structure to dissipate energy, through mainly ductile behaviour of its elements and/or other mechanisms, is taken into account by performing an elastic analysis based on a response spectrum reduced with respect to the elastic one, henceforth called a "design spectrum". This reduction is accomplished by introducing the behaviour factor q.

The behaviour factor q is an approximation of the ratio of the seismic forces that the structure would experience if its response was completely elastic with 5% viscous damping, to the seismic forces that may be used in the design, with a conventional elastic analysis model, still ensuring a satisfactory response of the structure.

The upper limit value of the behaviour factor q, to account for energy dissipation capacity, shall be derived for each design direction as follows:

$q= q_o k_w \geq 1.5$

Where qo is the basic value of the behaviour factor, dependent on the type of the structural system and on its regularity in elevation

kw is the factor reflecting the prevailing failure mode in structural systems with walls

For buildings that are regular in elevation the basic values of *qo* for the various structural types are given in the following table. For buildings which are not regular in elevation, the value of *q*o should be reduced by 20%.

Table D. 4: Basic value of the behaviour factor, *q*o, for systems regular in elevation

STRUCTURAL TYPE	DCM	DCH
Frame system, dual system, coupled wall system	3.0αu/α1	4.5αu/α1
Uncoupled wall system	3.0	4.0αu/α1
Torsionally flexible system	2.0	3.0
Inverted pendulum system	1.5	2.0

The maximum value of αu/α1 that may be used in the design is equal to 1.5, even when the analysis based on pushover analysis results in higher values.

When the multiplication factor αu/α1 has not been evaluated through an explicit calculation, for buildings which are regular in plan the following approximate values of αu/α1 may be used.

a) Frames or frame-equivalent dual systems.

- One-storey buildings: αu/α1=1.1;
- Multistorey, one-bay frames: αu/α1=1.2;
- Multistorey, multi-bay frames or frame-equivalent dual structures: αu/α1=1.3.

b) - Wall- or wall-equivalent dual systems.

- Wall systems with only two uncoupled walls per horizontal direction: αu/αl =1.0;
- Other uncoupled wall systems: αu/α1=1.1;
- Wall-equivalent dual, or coupled wall systems: αu/α1=1.2.

The factor *k*w reflecting the prevailing failure mode in structural systems with walls shall be taken as follows:

$$k_w = \left\{ \begin{array}{l} 1.00, \text{ for frame and frame-equivalentdual systems} \\ (1+\alpha_0)/3 \leq 1, \text{ but not less than 0.5, for wall-equivalent and torsionally} \\ \text{ flexible systems} \end{array} \right\}$$

Where αo is the prevailing aspect ratio of the walls of the structural system.

$\alpha_o = \sum h_{wi} / \sum l_{wi}$

Where: h_{wi} is the height of wall *i*; And l_{wi} is the length of the section of wall *i*.

D.4 Base shear force

The seismic base shear force F_b, for each horizontal direction in which the building is analysed, shall be determined using the following expression.

$F_b = S_d(T_1) \cdot m \cdot \lambda$

Where

$S_d(T_1)$ is the ordinate of the design spectrum at period T_1;

T1 is the fundamental period of vibration of the building for lateral motion in the direction considered;

m is the total mass of the building, above the foundation or above the top of a rigid basement,

λ is the correction factor, the value of which is equal to: $\lambda = 0.85$ if $T1 < 2$ TC and the building has more than two storeys, or $\lambda = 1.0$ otherwise.

NOTE The effective modal mass m_k, corresponding to a mode *k*, is determined so that the base shear force F_{bk}, acting in the direction of application of the seismic action, may be expressed as $F_{bk} = S_d(T_k)\, m_k$.

It can be shown that the sum of the effective modal masses (for all modes and a given direction) is equal to the mass of the structure.

The inertial effects of the design seismic action, which is represented by m in the base shear formula, shall be evaluated by taking into account the presence of the masses associated with all gravity loads appearing in the following combination of actions:

$$\sum G_{k,j} + \sum \psi_{E,i} \, x Q_{k,i}$$

Where $\psi_{E,i}$ is the combination coefficient for variable action i

The combination coefficients $\psi_{E,i}$ take into account the likelihood of the loads $Q_{k,i}$ not being present over the entire structure during the earthquake.

$\psi_{Ei} = \phi . \psi_{2i}$

Table D. 5: Values of ϕ (Load type coefficient) for calculating ψEi

Type of variable action	Storey	ϕ
Categories A-C*	Roof Storeys with correlated occupancies Independently occupied storeys	1.0 0.8 0.5
Categories D-F* and Archives		1.0

* Categories as defined in EBCS EN1991-1-1:2013.

Table D. 6: Recommended values of ψ factors for buildings. Source: EN 1990:2002(E) Annex A1 Table A1.1

occupancy type	ψ2
Category A: areas in residential buildings	0.3
Category B: office areas	0.3
Category C: congregation areas	0.3
Category D: shopping areas	0.6
Category E: storage areas	0.8