ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

SEISMIC PERFORMANCE ASSESMNET OF STEEL DIAGRID STRUCTURES IN MULTI-STORY REINFORECED CONCRETE BUILDING

A Thesis to the School of Civil and Environmental Engineering of Addis Ababa University Institute of technology in partial fulfillment of the requirements of the degree of Master of Science in Civil (Structural) Engineering

By:

BEKALU TARIKU YIMER

October, 2020

Addis Ababa, Ethiopia

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Advisor : **Dr. Shifferaw Taye**

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Undersigned have examined the thesis entitled '**Seismic Performance Assessment of Steel Diagrid structures in Multi-Story Reinforced Concrete Building'** presented by **BEKALU TARIKU YIMER,** a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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AUTHOR’S DECLARATION

I, undersigned **Bekalu Tariku** hereby declare that this thesis work titled “**Seismic Performance Assessment of Steel Diagrid structures in Multi-Story Reinforced Concrete Building”** is my own work. To the best of my knowledge this thesis contains no material previously published by any other author except where due acknowledgement has been made in accordance with the standard referencing practices.

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ABSTRACT

The current trends of construction industry demand tall and lighter structures. These tall structures are very sensitive to Lateral loads induced by Earthquake, wind or ocean waves than that of the gravitation loads. To resist the lateral loads several techniques are available, out of the several techniques available diagrid structures are found as more structurally efficient over other type of lateral load resisting system in developed countries recently.

This type of lateral load resisting system (diagrid) has generated a good interest from architects on aesthetic aspect and structural Engineers by their structural efficiency. Diagrids or diagonal grids are a structural design approach 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. If this diagrid system constructed with optimal configuration, the material consumption will efficiently increase.

This research paper, base the study on the previous researches and accept the structural efficiency of diagrid structures than the other lateral load resisting system, mainly focused on the seismic performance evaluation of three different stories (G+10, G+16 and G+22) with different diagrid angle (53.13˚, 69.26˚, 75.57˚ & 79.22˚) located in two different ground type (A & C). the results from the twenty-four model cases were compared to verify the structural efficiency with different structural configuration using design response spectrum analysis in ETABS 2016 v16.2.1 software for steel diagrid in reinforced concrete building.

The analysis and design of these twenty-four (24) models of diagrid structures followed the basic steps and approaches that are operational and practical in real world. Proposed diagrid structure cases were to be situated in Hawassa, whose seismic zone is categorized under Zone IV according to the ES EN 1998-1:2015 annex D Table. The lateral load analysis of the study has been based on the new code ES EN 1998-1:2015. The analysis has been done using finite element software ETABS 2016 v16.2.1. The performance evaluation of these twenty-four case studies of diagrid buildings is mainly based on linear analysis parameters, such as Fundamental vibration period, story displacement and inter-story drift.

Based on the model cases considered in this study, Results has showed that Diagrid structure has difference fundamental vibration period, story displacement and inter-story drift based on their module angles considered for each case. From the linear analysis of twenty-four of G+10, G+16 and G+22 story buildings, in ground type A & C with four different module angles, a two story module or module diagrid angle 53.13˚ has shown a smaller top displacement, smaller inter-story drift and smaller fundamental time period for G+10 story building. Whereas module diagrid angle 69.26˚ and 79.22˚ has shown a smaller top displacement, smaller inter-story drift and smaller fundamental time period for G+16 and G+22 story buildings respectively.

Therefore, according to the linear analysis results and comparative study of this thesis, it can have concluded that for a better and significantly good performance, finding the optimal module angle with respect to height to width aspect ratio is very recommendable.

KEY WORDS: Diagrid Structure system, Module angles, Design response spectrum analysis,

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BEKALU TARIKU YIMER

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ABBEVERIBIATIONS

3D …………………………………………………………………. Three Dimensional

CSI ………………...…………………...…………. Computer and Structure Integrated

DCH ………………...…...……………………………………. Ductility Class High

EBCS ……………………………...……………. Ethiopian Building Code Standard

EC …………………………………………………….………………. Euro Code

ES …………………………………………………………………. Ethiopian Standard

EN ……………………………………………………………….………. European Norm

FEM ……………………………...……………………...…. Finite Element Method

RSX ……………………………………. Design Response Spectrum in the X - Direction

RSY ……………………………………. Design Response Spectrum in the Y - Direction

NOTATIONS

ag……………….……………………………………….……. design ground acceleration

dr ……………….…………………………………...…………………. inter-story drift

dr ……………….…………………………………...…………………. inter-story drift

E_c ……………….……………………..………………. modulus of elasticity of concrete

E_m ……………….……………………………...………………. initial young modulus

E_s ……………….………………………………………….……. modulus of elasticity of steel

f_{ck}……………….…………………………….….……. characteristic strength of concrete

f_y ……………….………………….……………...……….……. yield strength of steel

g ……………….…………………….…………………….……. acceleration due to gravity

GPa ……………….…………………………………………………….……. Giga Pascal

h ……………….………………………………………………………….……. inter-story height

I ……………….…………………………………………….…… Importance occupancy

kN ……………….……………………………………………………….……. Kilo Newton

m ……………….…………………….………………………………….……….……. meter

MPa ……………….…………………….……………….…………….……. Mega Pascal

q ……………….………………………………………………………………. behavior factor

S_d……………….…………………………………………….……. Spectral displacement

S_C……………….……………………………………….……. Chosen limit state capacity

S_D……………….……………………………………………………….……. chosen demand

T……………….…………………………...…………………………….……. period

GREEK SYMBOLS

δ ……………………………………………… lateral displacement

ε ……………………………………………… strain

σ ……………………………………………… stress

σ_y ……………………………………………… yield stress

ξ ……………………………………………… damping

ξ_n ……………………………………………… damping ratio

μ ……………………………………………… Poisson's ratio

η ……………………………………………… damping correction factor

CHAPTER ONE

INTRODUCTION

1.1 GENERAL BACKGROUND

The current rapid growth of urban population all over the world influenced the need for a residential development of city due to limited land space and Local topographic restriction. For this matter the construction industry make tall or high rise buildings feasible solution for housing needs.

The advance in construction technology techniques, high strength material, the use of light weight, structural systems and analysis and design software facilitated the rise of tall buildings. Understandably, as the height of building increases, these tall structures are very sensitive to Lateral loads induced by Earthquake, wind or ocean waves than that of the gravitation loads. This would cause unwanted vibrations to the structure, which would also cause large displacement, possible structural failure, occupant discomfort, and malfunction of equipment. Hence, it has become important to control the structural vibrations produced by earthquake or wind using various means such as lateral load resisting system (rigid frame, shear wall, braced frame, outrigger, braced tube and recently the Diagrids – Diagonal Grid structural system) or by providing passive, active or hybrid counter forces.

Among the Lateral load resisting system mentioned above, Diagrids – Diagonalized grid structures have emerged as one of the most innovative and adaptable approaches to most structural high-rise buildings (which can range anywhere from 20 – 100 stories high) and has generated a good interest from architects on esthetic aspect and structural Engineers by their structural effectiveness in this millennium.

The primary initiation behind the development of this diagrid system is to remove perimeter columns and saving all possible weight and cost.

From the vast researches has been done regarding diagrid structures over other lateral load resisting systems, it has been concluded that diagrid Structure overall performs better as lateral load resisting system than simple frame and shear wall system.

The main focus of the research is intended to verify the structural efficiency of steel diagrid in reinforced concrete building with different structural configuration using design response spectrum analysis from twenty-four (24) modeling gathered data in Finite element software (ETABS2016 V16.2.1)**.**

1.2 STATEMENT OF THE PROBLEM

Among the lateral load resisting systems used in the construction industry recently, diagrid system's structural efficiency is depending on how their module angles are close to or exactly fit to the optimal angle with respect to their height to width aspect ratio. Hence, choosing the right angle is a crucial question in designing of these diagrid structure, especially in during major earthquake or high seismic zones.

1.3 SIGNIFICANCE OF THE STUDY

As most architects and structural Engineers has generated a good interest on diagonal grid (diagrid) systems for the construction industry in many other countries due to their aesthetic and structural efficiency, this lateral load bearing system (diagrid structures) could be bring in Ethiopia; if its seismic performance is satisfactory.

1.4 OBJECTIVE AND QUESTIONS OF THE RESEARCH

1.4.1 General objective

The general objective of the study was to verify the structural efficiency of steel diagrid in reinforced concrete building with different structural configuration using design response spectrum analysis from twenty-four (24) modeling gathered data in Finite element software (ETABS2016 V16.2.1)**.**

1.4.2 Specific objective

- ❖ To study the effect of Gravity and Lateral loading on diagrid system of multi-story frame structure under seismic excitation.
- ❖ To verify the structural efficiency by using different parameters like angle of Module, Length of diagrid member of module, height of building and ground type.
- ❖ To establish the best overall performance of diagrids as lateral load resisting system with different structural configuration in Ethiopia.

1.4.3 Research questions

The research focused towards investigating how diagonal grid (diagrid) structures can be increase structurally efficient for Reinforced Concrete buildings? And in doing so, it tried to raise and answer the following questions.

- ❖ Why diagrid structure is most structurally efficient for high rise RC buildings?
- ❖ How to make the diagrid structure most effective by varying diagonal angles of module height of module?

- ❖ Which geometric pattern will increase the structural efficiency?
- ❖ How do diagrid structures perform under major seismic excitation load?
- ❖ How to evaluate seismic performance of diagarid structure?

1.4.4 Hypothesis

Diagrid structures are structurally efficient for high rises RC buildings, if they are designed for most effective Module angle and geometric pattern under major seismic areas.

1.5 SCOPE

The research has been limited to, three distinct symmetric five bays by four bays (G+10, G+16 and G+22) multi-stories Reinforced concrete buildings which are irregular in plan and regular in elevation. The frames were assumed firmly fixed at the bottom and the soil structure interaction has been neglected. Four different module angles of steel diagrid with fixed spacing has been applied as lateral load bearing system for each of G+10, G+16 and G+22 multi-story Reinforced concrete buildings, which is located in two different ground types locations (A and C). these a total of twenty-four (24) models has been analyzed with elastic response spectrum method and verified for their most structural efficiency based on lateral displacement, inter-story drift and time period excluding node design and cost comparison. The analysis has been performed by using Finite element software (ETABS 2016 v16.2.1).

The construction methodology of these structures is also not discussed.

1.6 METHODOLOGY

Among various methods of conducting researches, the research has been conducted based on quantitative nature (analytic study), aimed to gather data from twenty-four (24) modeling to verify the structural efficiency with different structural configuration in Finite element software (ETABS 2016 v16.2.1).

Three (3) symmetric, five bay by four bay with plan dimension 30m x 24m and story height 4m, multi-story Reinforced concrete building model cases for each design models (G+10, G+16 and G+22) has been modeled with four different structural configuration listed below (Model case I – IV) in two different ground type locations (A and C); Accordingly, a total of twenty-four (24) building model cases has been numerically modeled on Finite element software (ETABS 2016 v16.2.1);

Model case I: 53.13°angle of module

Model case II: 69.26° angle of module

Model case III: 75.57° angle of module

Model case IV: 79.22° angle of module

The later load analysis of the study will be based on the new code ES EN 1998-1:2015 (ES EN-8) design manual.

1.7 ORGANIZATION OF THE THESIS

This thesis consists of five chapters arranged carefully in order to make it clear and understandable.

The general background, statement of problem, significance of the study, objective and research questions, hypothesis, scope and methodology of the research are discussed in this introductory chapter.

Chapter two discusses the state of the art literature review on topics related to this study. An overview of the diagrid structure literatures by different authors were reviewed and discussed here.

Chapter three discusses a detailed methodology adapted for the overall work of the research. the method of analysis and the materials which have been used, the assumption has been taken, the procedures have been followed, the detail of the building plan and member sizes has been discussed in this chapter.

Chapter four discusses the result and discussions of the current study, this chapter present the response spectrum analysis of the diagrid system in Reinforced concrete building carried out to compare the seismic performance corresponding to the linear analysis.

Chapter five discusses the summary, conclusion and recommendations for future studies.

CHAPTER TWO

LITERATURE REVIEW

2.1. HISTORICAL DEVELOPMENT OF DIAGRID STRUCTURES

2.1.1. General Overview

The escalation of tall buildings is simplified by the help of construction technology techniques like, high strength material, the use of lightweight materials, structural systems and analysis and design software. Reasonably, tall structures are very sensitive to Lateral loads when they are induced by Earthquake, wind or ocean waves than that of the gravitation loads as the height of building increases. This results undesirable vibrations to the structure, which would also cause large displacement, likely structural failure, occupant discomfort, and malfunction of equipment. Hence, it has become necessary to control the structural vibrations produced by earthquake or wind using several means such as lateral load resisting system (rigid frame, shear wall, braced frame, outrigger, braced tube and recently the Diagrids – Diagonal Grid structural system) or by providing passive, active or hybrid control system.

Among the Lateral load resisting system mentioned above, Diagrids – Diagonalized grid structures have emerged as one of the most innovative and flexible approaches to most structural high-rise buildings (which can range anywhere from 20 – 100 stories high) and has generated a good interest from architects on esthetic characteristic and structural Engineers by their structural efficiency and cost reduction due to removal of boundary columns in this time.

Numerous engineers and researchers have been experimentally explored Diagrid Structures. Most of the studies are focused on comparing the effectiveness of diagrids structures with other types of lateral resisting system and optimal structural configuration. Some of these researches, past and recent, are documented. Terri Meyer Boake [2014]; Jinkoo Kim and Young-Ho Lee [2010]; Khushbu Jani and Paresh V. Patel [2012]; S.P. Sharma and J.P. Bhandari [2015]; K.Moon [2013]; Giovanni Maria Montuori, Elena Mele, Giuseppe Brandonisio and Antonello DeLuca [2014]; Curtis, N (1963).

2.1.2. Concept and Definition

The word - diagrid is somewhat misleading. Usually Diagrid is used to express a diagonal structural grid. The system is contained of diagonal members, normally made-up from structural steel, that are linked at nodal points. The diagonal grid, although often presented as the leading visual feature in the design of diagrid buildings, is by itself unstable. The diamond shaped system needs triangulation in order to create sufficiency in the structure. Diagrids or diagonal grids are a structural design approach for erecting buildings that combine the resistance to gravity and lateral loads into a triangulated system of members that excludes the need for vertical columns. This system is usually located on the perimeter of the building. Triangulation is normally attained where the floor edge beams link into the grid. The main idea behind the development of the diagrid system was the recognition of the savings likely removal of (most of) the vertical columns. Vertical columns, planned to carry gravity loads, are incapable of providing lateral stability. The diagonal grid, if appropriately 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 word - diagrid is a blending of the terms ―diagonal and ―grid and refers to a structural system that is single-thickness in nature and obtains 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 formed from the details of these three-dimensional systems. Boundary diagrids normally support the lateral and gravity loads of the building and are used to carry the floor edges. (Terri, 2014)

Usual words used in the analysis of diagrids are...

- ❖ The **module** refers to the number of floors that the diamond shape of the grid spans from peak to peak.
- ❖ The **node** is the point joining the diagonal members.
- ❖ A **horizontal bracing ring** is formed by linking the diagrid nodes to the floor edge beam.
- ❖ The **steepness of the angle** of the diagrid is measured as the angle bent between the diagonal and the floor. (Terri, 2014)

The first diagrid structure was presented by the excellent Russian engineer Vladimir Shukhov in the design of the world's first hyperboloid diagrid structure in Nizhny Novgorod, Russia in 1896. Though, it took sixty years after the introduction of the diagrid structure for the first diagrid building, known as the IBM building in Pittsburg to be constructed in 1963, [Curtis, 1963]

The technique used to build IBM building in Pittsburg was not truly used another time until several high profile projects were in their design phase around the year 2000. The IMB (now called Steelworkers) Building combined the diagrid with the glazing system resulting in oddly shaped windows. This would have created a far more costly option than the balance of curtain wall clad office buildings of the same period, and was likely the reason for its brief use." [Terri Meyer]

“Additional forty years passed before Diagrid based buildings started to appear in modern steel around the year 2003. All three of the first examples – London GLA, Swiss Re and the Hearst Tower- were in progress in the offices of Foster + partners at the same time and the engineering expertise of ARUP was part of all of the projects.” [Terri Meyer]

2.1.3. Why a diagrid structures are preferable?

Diagrids have arisen as an architectural preferable structures in the formation of modern buildings. The logical reasons for this are stated below,

There are various functional and economic benefits that inspire the system:

- Due to their triangulation nature, they increased the stability
- They are potentially efficient in Combined nature of the gravity and lateral load-bearing systems
- Their light weight nature reduced the load which transferred to the foundation
- In Comparison with conventional framed tubular structures without diagonals, diagrid structures are effective in carrying shear forces by axial action of their diagonal natured members on the perimeter of the building, hence, they are good in reducing shear deformations while conventional structures carry shear by bending of Vertical columns.

Some points that can be taken as difficulty of diagrid structure is;

- Designing the diagrid structures is complicated for a reason of a design procedure is not specifically included in any country design code.
- On the other side the construction difficulty can be also mentioned. Construction of node connections and formworks (for concrete diagrids) will demanded highly skilled manpower.

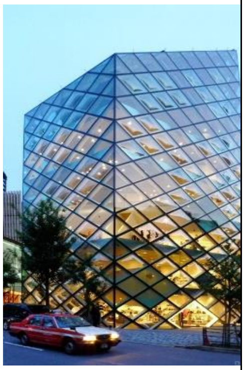
As Boake, 2014, stated one of the difference between a conventional braced – tube and diagrid structure is that diagrid structures eliminated the use of the perimeter columns for resisting lateral loads unlike the conventional braced –tube structure, because diagonal elements in the diagrid structural systems can carry gravity loads as well as horizontal loads thanks to their triangular configuration.

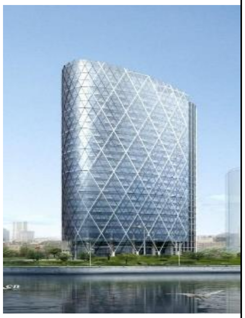
2.1.4. Samples of diagrid structures

The following table shows some sample examples of diagrid structures from the plenty of diagrid structures found in the world taken from the book “*The Evolutionary Process of Diagrid Structure Towards Architectural, Structural and Sustainability Concepts:*” written by Korsavi S, Maqhareh MR.

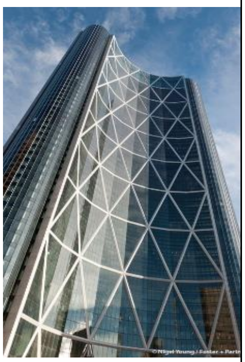
Table 2-1: Sample Diagrid High Rise Structures [Korsavi S, Maqhareh MR , 2014]

Building	**Location**	**Construction**	**Architect**	**Height/ No. of stories**	**Diagrid**	**Image**
Shukov Tower	Moscow	Completed in 1920-1922	Vladmir Shukov	350m	Steel Grid	
IBM building	Pittsburgh U.S.A	Completed in 1963	Curtis and Davis	13 stories 58m	Steel Grid	
Puerta De Europa	Madrid, Spain	1989-1996	Philip Johnson, John Burgee	115m and 26 stories	Steel Grid	
City Hall	London	Completed in 2002	Norman Foster	10 stories, 45m	Steel Grid	

PRADA Boutique	Tokyo Japan	2001-2003	Herzog and de Meuron	6 floors above ground, 2 floors underground, 28m	Steel Grid	
Swiss Re	London	2001-2003	Foster and Partners	40 floors, 180m	Steel Grid	
Hearst Tower	New York, USA	2003-2006	Foster and partners	46 stories, 183m	Steel Grid	
Atlas Building	Wageningen, Netherlands	Completed in 2006	Rafael Vinoly Architects	7 stories	Concrete Grid	
The Royal Ontario Museum	Toronto, Canada	Completed in 2006	Daniel Libeskind	6 stories	Steel Grid	

Poly Real Estate Headquarters	Guangzhou, China	2004-2007	S.O.M	34 stories, 150m	Composite	
Vivaldi Tower	Amsterdam	2004-2008	Foster and Partners	24 stories, 87m	Steel Grid	
SIPG Tower	Shanghai China	Completed in 2008	East China	29 stories above ground	Steel Grid	
Tornado Tower	Doha, Qatar	2006-2008	C.I.C.O	52 floors above ground, 3 floors undergr ound, 200m	Steel Grid	
Yellow Building	London, England	Completed in 2008	AHMM	7 stories above ground and 1 story under ground	Concrete Grid	

One Shelly Street Building	Sydney, Australia	2007-2009	Fitzpatrick Partners	7 and 11 stories	Steel Grid	
Guangzhou West Tower	Guangzhou, China	2005-2010	Wilkinson Eyre Architects	103 stories, 440m	Concrete Filled Steel Tube	
O-14 tower	Dubai, United Arab Emirates	Completed in 2010	Reiser Umemoto	22 stories, 106m	Concrete Grid	
Al Dar Headquarters	Abu Dhabi, United Arab Emirates	Completed in 2010	MZ Architects	23 floors above and 3 floors underground, 110m	Steel Grid	
Hong Kong Institute of Design	Hong Kong	Completed in 2010	CAAU	12 stories, 52.3m	Steel Grid	

Capital Gate	Dubai	2007-2011	RMJM	35 stories and 160m	Steel Grid	
CCTV Tower	China	2004-2012	Rem Koolhas-sand OMA	44 floors above and 3 floors underground, 234m	Steel Grid	
Doha Tower	Doha, Qatar	2005-2012	John Novel	45 floors above and 4 floors underground, 231m	R.C crossing diagrid column	
The Bow Tower	Canada	2007-2012	Norman Foster	59 stories, 238m	Steel Grid	

Dorobanti Tower	Bucharest, Romania	2008-2013	Zaha Hadid	57 floors above ground, 200m	Steel grid filled by concrete	
Cleveland Clinic	Abu Dhabi, UAE	Completed in 2013	HDR Architecture	99.6 m, 24 stories above ground	Steel Grid	
Manukau Institute of Technology	Auckland New Zealand	Completed in 2013	Warren and Mahoney Architects	5 stories	Steel Grid	
Technosphere	Abu Dhabi, UAE	Completed in 2013	James Law	More than 25 stories	Steel Grid	
Leadenhall Building	London	2014	Rogers StirkHarbour + Partners	225 m and 48 stories	Steel Grid	
Lotte Tower	Seoul, Korea	Completed on 2014	S.O.M	123 stories, 556m	Steel Grid	

West Bay Office Tower	Doha, Qatar	Completed in 2014	S.O.M	50 stories, 230m	Prefabricated steel and concrete ‘diagrid’ frame	
Poly International Plaza	Beijing, China	Completed in 2015	S.O.M	31 stories, 161.2m	Steel Grid	
Z15 Tower	Beijing, China	2011-2016	TFP Architects	108 stories, 528m	Steel Grid	

2.1.5. Structural importance of diagrid structures

From a structural viewpoint, the primary impression behind the development of the diagrid system was their structurally efficiency and architectural potential due to its triangular configuration, if properly placed by saving all possible vertical columns at the periphery.

Diagrid structures cantilevers become more susceptible to lateral forces as their height to base ratio increases since they perform like free vertical. The parameters take into consider while planning and designing a Diagrid Structure mostly are height of diagrid, angle made by diagonals, rate of twist, angle of tilt, angle of taper, degree of fluctuation of freeform, etc. Numerous studies have been conducted regarding the optimization of the module size as a function of the building height and angles of the inclined members. Module size is the number of floors that the diamond shape of the grid span from tip to tip, and this diagonal grid’s module sizes are arranged evenly dividing the height of the building. these diamond-shaped module sizes typically run six to eight floors tip to tip, even though shorter modules (two floors tip to tip) are used, if buildings are irregular in geometries or tighter curves.

According to Moon, K. (2018), Axial forces of the diagonal members on the web plane mainly represent the lateral shear force and with less degree represent overturning moment resisting mechanism through axial actions of the diagonal members. On the other side diagonal members on the flange planes primarily represent in the overturning moment resisting mechanism. The shear lag effect of diagrids structure is much lesser than that of conventional framed tube structures because of the triangular configurations.

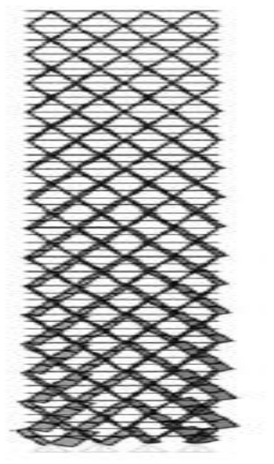


Figure 2-1: Axial force and bending moment diagrams of diagrid structures subjected to lateral loads (Moon,2018).

2.1.6. Parameters of Diagrid Structures

Parameters are circumstance that restrict how a design is done, which are subjected to change. The parameters take into consider while planning and designing a Diagrid Structure could be the diagrid angle, diagrid module and node. These parameters could also be different for each project and as these vary the optimal structural configuration also varies.

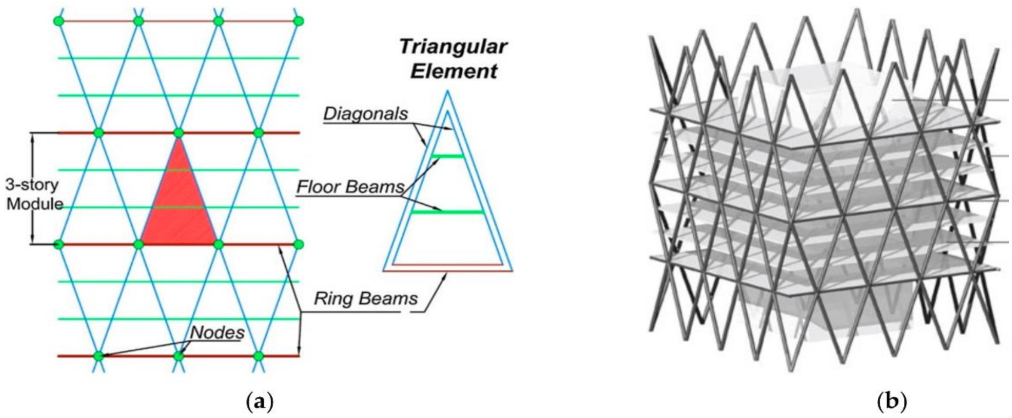


Figure 2-2: Basic diagrid module

I) Diagrid angles

Diagrid structure can be structurally designed with a uniform angle which satisfy architect's aesthetic perspective and Structural Engineering requirements. However, in subjective matter the aesthetic expression is decided by the selected angles in terms of structural performance.

The optimal angle of the columns for gravity and overturning moments is 90 degrees and that of the diagonals for maximum shear rigidity is about 35 degrees for most effective performance in conventional braced frame buildings. Based on this, it is expected that the optimal angle of the diagonal members in diagrid structures carrying all the combined loads will fall between these two angles (35 – 90 degree).

II) Diagrid Module

According to Moon, K. (2013), optimal diagrid structures configuration is stiffness-based methodology, Diagrid angles and modules play a great role in the structural, architectural and aesthetic concept of the design of these special structure. In the design of the diagrid construction, choosing the right angle is the important factor. If the chosen diagonal angle deviates from the optimal value, the required amount of material is significantly increased. High- rise buildings with a high ratio (height/width) behave like bent beams. Consequently, when a building's height rises, the optimum diagonal angle also increases and becomes steeper. The stiffness of bending and shearing of the diagrid module can be defined in the form of Equations (01) and (02).

$$K_b = (N_f + \delta)\frac{\left(B^2 A_{d,f} E\right)}{\left(2L_d\right)\sin^2\theta} \quad \text{(2-1)}$$

$$K_t = (2N_w)\frac{\left(A_{d,w} E\right)}{\left(L_d \cos^2\theta\right)} \quad \text{(2-2)}$$

Where: K_b = bending stiffness

K_t =shear stiffness

$A_{d,w}$=the area of each diagonal on the front side

$A_{d,f}$ =the area of each diagonal on the lateral side

E= the modulus of Elasticity of steel

Θ=the angle of diagonal member

δ=the contribution of front side diagonals for bending stiffness

B=Building width

L_d =Length of diagonal

N_f =the number of diagonals on each lateral side plane

N_w=the number of diagonals on each front side

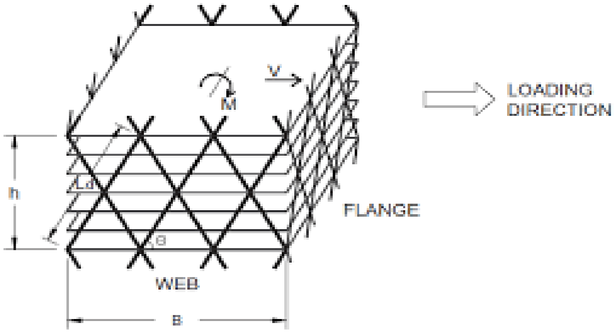


Figure 2-3: Diagrid structural system, module

III) Node

Diagrid structures normally use crossing diagonal members at the perimeter instead of conventional vertical columns. These members are used as a structural support system that gives the building a recognizable character and stability. Normally, there are two types of nodes in this system: the interior and corner. The interior nodes are planar and transfer the loads in two-dimensional space, whereas the corner nodes transfer the loads in three-dimensional space and thus form a more complicated arrangement. These nodes are joined to the other crossing diagonal members by welding or bolting. [Jerzy S. Hanna S. 2017]

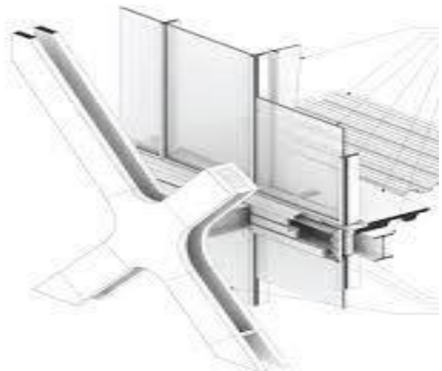


Figure 2-4: Detail of the Diagrid system, Node

2.1.7. Optimal Structural Configuration of Diagrid Structures

K. Moon has studied the optimal configuration of diagrid structures with uniform and variable angles in his published research in 2013. The optimal diagrid angle is dependent on the height-to-width aspect ratio of the building. when a building's height rises, the optimum diagonal angle also increases and becomes steeper, and vice versa, since a slender structure acts more like a bending beam and a shorter structure acts more like a shear beam.

In his study a hundred-story diagrid structure of five different angle configurations was considered. For each building plan dimensions were 54 meters by 54 meters and typical story height of 3.9 meters. Case I is a uniform angle diagrid structure. Cases II and III are diagrid structures of horizontal angle variations. Case IV is a diagrid structure of vertical angle variation with steeper angles towards the base. Case V combines horizontal and vertical angle variations of Case III and IV respectively. Structural design was performed for Case I first using the stiffness-based design methodology developed by Moon et al. (2007) to resist code defined wind loads in Chicago. The maximum lateral displacement of these five different diagrid structure are restricted to 1/500 of the building height.

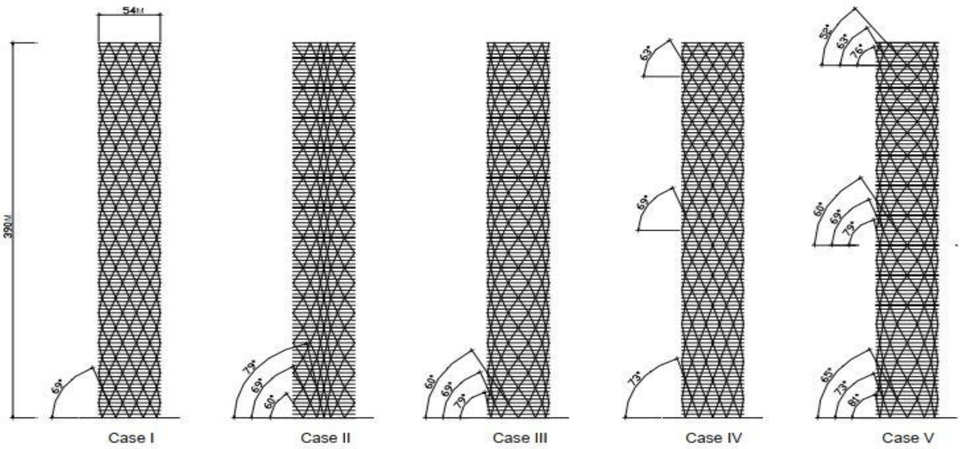


Figure 2-5: Diagrids of various angle configuration (Moon, 2013)

As the diagonal angle becomes stiffer toward the building corner, the web diagonals' (parallel to the wind direction) influence to the bending rigidity rises, and vice versa. Hence, the lateral stiffness of Case III is greater than Case I, while that of Case II is lesser than Case I. Since the design of the lower and upper level diagrid members is governed by overturning moments and shear forces respectively, diagrids configured with steeper angle diagonals toward the base of the building, such as Case IV, can be more efficient than uniform angle diagrids. By combining angle configurations of Cases III and IV, the lateral stiffness of the diagrids can be maximized. Maximum lateral displacements of Cases I, II, III, IV and V are 76.0, 90.1, 74.6, 72.7 and 71.9 cm respectively. Steel masses used for the five diagrid structures are very similar. In fact, Case V which produces the greatest lateral stiffness uses 0.6% less than Case I.

Based on the above study Moon, K. (2013), Concluded that, configuration substantially influence the efficiency of a particular structural system selected for a tall building. Structural efficiency of diagrids can be more increased for high rise building by changing diagrid angles. Incremental rates of shear forces and overturning moments towards the base of a tall building are not similar. While lateral shear forces increase nearly linearly, overturning moments increase drastically towards the base of the building. Thus, in appropriately designed diagrid structure, the design of the higher portion of the building is governed by shear, and the lower portion is governed by overturning moment.

2.1.8. Construction

I) Structural Material

Based on architectural, economical, site factors, local market preference/availability, project size/height, building form, design consideration, erection and lea time, site location/access and speed of the structure; the structural materials are chosen for high-rise buildings. These structural materials are usually one or a combination of (reinforced or pre-stressed) concrete, structural steel and composite systems.

The materials available for the construction of diagrids are:

- ❖ Steel Diagrid

Steel grids are more widely used due to its simplicity and faster construction, simpler joints and less expensive formwork. However, construction of steel diagrids is more challenging and complex when compared to conventional system for high buildings because of the joints of diagrid. [Boake, 2014]

- ❖ Concrete Diagrid

Currently several high rise buildings are in construction and the most challenging use of the diagrid structure is in conception model in different forms i.e. in twisted, tapered, tilted, free form, etc. Concrete is used widely as diagrid construction material to support the compression loads by carrying the gravity and lateral loads coming from the structure and lateral forces. In order to design the concrete core, further engineering to assure the structural integrity of the building is required. [Boake, 2014]

II) Constructability

Constructability is an important topic in diagrid structures. Both the engineering and fabrication of the joints of node to diagonal members are more complex than the conventional orthogonal structure, which requests extra costs. The accuracy of the geometry of the joining nodes is critical, for this matter, maximize shop fabrication to decrease complications related with site work and erection of the odd geometries associated with the design of the nodes is recommended.

According to Boake, 2013, there are two thoughts as to the rigidity of the construction of the nodes themselves. In theory, if designing a purely triangulated 'truss like' structure, the center of the node need not be rigid and be can constructed as a hinge or pin connection. Where this may work well for symmetrical structures having well balanced loads, eccentrically loaded structures will need some rigidity in the node to assist in self-support during the construction process.

In many of the diagrid projects constructed to date, the nodes have been fabricated in the shop as rigid elements allowing for incoming straight members to be either bolted or welded on site, more easily, and without need of temporary supports until the next node is attached. [Boake, 2013]

2.1.9. Recent Architectural Applications of the diagrid

"Now the most challenging use of the diagrid structural model is in the formation of "twisted forms". These can be seen in many high rise buildings presently under construction, particularly in Asia and the Middle East. The steel diagrid, in its ability to create a "mesh" is capable of conforming to nearly any shape that can be created using modern 3-D modeling software. The diamond shaped grids are simply further subdivided into triangulated shapes for curtain wall manufacture. Typically, the building will try to use a substantial vertical concrete core that can provide straight run elevator access through the building, and arrange the offsets to hang from the core. This requires additional engineering to ascertain the structural integrity of the building. There is also a substantial increase in fabrication and erection cost as a result of the decrease in repetitive design of the nodes. [Terri Meyer, 2014]

CHAPTER THREE

LINEAR ANALYSIS OF RC BUILDING WITH STEEL DIAGRID STRUCTURE

1.1. RESEARCH METHODOLOGY

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

1.1.1. Study Design

Among various methods of conducting researches, the research has been conducted based on quantitative nature (analytic study), aimed to gather data from twenty-four (24) modeling to examine the structural efficiency with different structural configuration in Finite element software (ETABS 2016 v16.2.1).

Three (3) symmetric five bay by four bay with plan dimension 30m x 24m and story height 4m multi-story Reinforced concrete building model cases for each design models (G+10, G+16 and G+22) has been modeled with four different structural configuration listed below (Model case I – IV) in two different ground types (ground type A & C); Accordingly, a total of twenty-four (24) building model cases has been numerically modeled on Finite element software ETABS 2016 v16.2.1;

- ❖ Model case I: 53.13° angle of module
- ❖ Model case II: 69.26° angle of module
- ❖ Model case III: 75.57° angle of module
- ❖ Model case IV: 79.22° angle of module

Seismic action is used as governing lateral force on the building structures and the analysis for the lateral action followed modal response spectrum method and based on the new code EBCS EN 1998-1:2015 (ES EN-8) design manual

1.1.2. Study variables

I) Dependent Variables

The dependent variables of the study were:

- ❖ Fundamental Natural vibration period
- ❖ Story displacement
- ❖ Inter Story drift

II) Independent Variables

Since major parameters has been kept constant except the type of lateral load resisting system, the independent variables of the study were:

- ❖ Angle of Module
- ❖ Length of diagonal member of module
- ❖ Height of building
- ❖ Ground type

1.1.3. Data Collection Procedure

A Seismic Performance study has been done by considering a G+10, G+16 and G+22 office high rise RC building with different module size (angle) diagrid laterally strengthened in four different degree arrangements for each stories in two different ground types. Aimed to compare their structural efficient in later and gravity load resisting. The twenty-four (24) lateral load resisting systems were stated as follows:

1. G+10 mid-rise building with diagrid module angle of 53.13°, ground type A
2. G+10 mid-rise building with diagrid module angle of 69.26°, ground type A
3. G+10 mid-rise building with diagrid module angle of 75.57°, ground type A
4. G+10 mid-rise building with diagrid module angle of 79.22°, ground type A
5. G+16 mid-rise building with diagrid module angle of 53.13°, ground type A
6. G+16 mid-rise building with diagrid module angle of 69.26°, ground type A
7. G+16 mid-rise building with diagrid module angle of 75.57°, ground type A
8. G+16 mid-rise building with diagrid module angle of 79.22°, ground type A
9. G+22 mid-rise building with diagrid module angle of 53.13°, ground type A
10. G+22 mid-rise building with diagrid module angle of 69.26°, ground type A

11. G+22 mid-rise building with diagrid module angle of 75.57°, ground type A
12. G+22 mid-rise building with diagrid module angle of 79.22°, ground type A
13. G+10 mid-rise building with diagrid module angle of 53.13°, ground type C
14. G+10 mid-rise building with diagrid module angle of 69.26°, ground type C
15. G+10 mid-rise building with diagrid module angle of 75.57°, ground type C
16. G+10 mid-rise building with diagrid module angle of 79.22°, ground type C
17. G+16 mid-rise building with diagrid module angle of 53.13°, ground type C
18. G+16 mid-rise building with diagrid module angle of 69.26°, ground type C
19. G+16 mid-rise building with diagrid module angle of 75.57°, ground type C
20. G+16 mid-rise building with diagrid module angle of 79.22°, ground type C
21. G+22 mid-rise building with diagrid module angle of 53.13°, ground type C
22. G+22 mid-rise building with diagrid module angle of 69.26°, ground type C
23. G+22 mid-rise building with diagrid module angle of 75.57°, ground type C
24. G+22 mid-rise building with diagrid module angle of 79.22°, ground type C

These twenty-four (24) lateral load resisting system's comparison has been modelled and analyzed using ETABS 2016 v16.2.1 software and the result has been discussed from the tabulating and graphing presentation in MS Excel.

1.1.4. Data quality Assurance

In order to assure the data quality, the following measures has been taken;

- The ETABS 2016 v16.2.1 software has been checked for a known single frame/simple structure systems, to check if the finite program is working properly or not.
- The structural modeling, the loading and the different connections of the frame system and diagrid system has been checked carefully before proceeding to analysis and design to remove errors.
- When unreliable results are shown due to some unobserved errors, the structure has been re-modeled and re-analyzed.

1.2. STRUCTURAL MODELING AND ANALYSIS

1.2.1. Methods of analysis

The lateral load analysis of the study has been based on the new code ES EN 1998-1:2015 which is the direct copy of Euro code 8 Design Manual. Relevant articles, figures and tables referred in this chapter are summarized in Appendix B. The analysis has been done using finite element software ETABS 2016 v16.2.1 to assess the seismic behavior of a G+10, G+16 and G+22 stories high rise building. The following sections describe the finite element ETABS 2016 v16.2.1 model and the material properties has been used in the analysis to achieve accurate and reliable results.

I) Methods of analysis

For this specific study Modal response spectrum analysis has been used due to the fact that the structure can ‘t satisfies the fundamental period criteria given in the code for applying the lateral force method of analysis due to its height in using this method it has been checked that the maximum number of modes specified meet the 90% mass participation requirement by the ES EN 1998-1:2015.

II) Behavior factor

The behavior 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.

$q = q_o k_w \geq 1.5$ ………..……………………………………………………… **(3-1)**

however, diagrid structures are not included in any of building code, for this mater as the provisions of the code ES EN-1998-1:2015, section 5.3.3, stated for buildings regardless of the structural system and the regularity in plan and elevation, a behavior factor q has been used ***1.5***.

III) Seismic Mass Source according to ESEN 1998-1:2015

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

$\Sigma G_{k,j} + \Sigma \psi_{E,i} \times Q_{k,i}$ ………..…………………………………………………….. **(3-2)**

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.

$\psi Ei = \phi . \psi 2i$ ………..…………………………………………………….. **(3-3)**

For this specific study our mass source coefficients have been calculated as follows

Φ=0.8 --------------- stories with correlated occupancies

$\psi 2$=0.3 -------------- office building

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

IV) Considering Effect of Cracking according to ESEN 1998-1:2015

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 un cracked 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 beams and columns has been reduced to 50%.

V) 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: $e_{ai} = \pm 0.05 L_i$ Where e_{ai} is the accidental eccentricity of story 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 2016 v16.2.1 software 5% has been specified in the eccentricity ratio to satisfy the above requirements regarding minimum accidental torsion effect.

VI) Response spectrum scale factor

In this research response spectrum scale factor has been calculated based on the ESEN 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 it found correct. The Scale factor is calculated by the formula Scale factor = I g / q, where I = occupancy factor, g=acceleration due to gravity and q=behavior factor of the system.

VII) Criterion of the Second Order effects

The criterion for taking into account the second order effect is based on the inter story drift sensitivity coefficient θ, which is defined with equation (ES EN 1998-4/4.4.2.2 (2))

$$\theta = \frac{P_{tot} * d_r}{V_{tot} * h} \quad \text{...} \quad \textbf{(3-4)}$$

Where d_r is the inter-story drift, h is the story height; V_{tot} is the total seismic story shear obtained by modal response spectrum analysis and P_{tot} is the total gravity load at and above the story considered in the seismic design situation.

- If $\theta \leq 0.1$- ignore Second order effect (P-Δ effects)
- If $0.1 < \theta \leq 0$ - Second order effect (P-Δ effects) is approximated to $\theta = \frac{1}{1-\theta}$
- If $0.2 < \theta \leq 0.3$ - Second order effect (P-Δ effects) analysis is required and
- If $\theta > 0.3$ – not acceptable

The 3D ETABS analysis was setup that it will take into account any P-Δ effects resulting from lateral loads. Therefore, the analysis results from ETABS 2016 v16.2.1 give both the first and second order effects of the loads.

1.2.2. Modeling of structural systems

I) Modeling description

For the analysis work, the models of high rise reinforced concrete frame building of G+10, G+16 and G+22 has been made to know the realistic behavior of the building during earthquake for diagrid structures. The length of the model buildings is 30m and width is 24m. Height of typical story is 4 m. Generally, the following assumptions has been taken.

1. Modal damping 5% has been considered.
2. Beams and columns has been modeled as frame element and joined node to nodes.
3. The effect of soil structure interaction has been ignored in analysis. The columns have been assumed to be fixed at the ground level.
4. Plan dimension has been kept similar to all Stories for all cases.
5. Wind load action has been ignored in the analysis.
6. Node analysis and Design has not been included in the research.

II) Loading

Beams and columns has been modeled with line or frame elements and floor slabs and roofs floors has been modeled with area element. all the structural systems have been subjected to three types of primary loading cases as per the provisions of ESEN 1998-1; 2015 and ES EN 1991:2015. Analysis and design of slab entirely followed coefficient method where the approach depends upon whether it is a two-way slab, support conditions and the loadings, accordingly, slabs are analyzed on spread sheets/excel sheets based on their support conditions and corresponding parameters as per ES EN 1992:2015. The calculated partition loads, floor finishes and live loads are then assigned on the modeled area elements on ETABS 2016 v16.2.1: so as to consider for their respective applied gravity loads

1. Dead Loads:
    - Finishing loads on floors:

    Floor Finish = 0.03 x 27 kN/m^3 = 0.81 kN/m^2

    Ceiling plaster = 0.02 x 23 kN/m^3 = 0.46 kN/m^2

    Cement Screed = 0.03 x 23 kN/m^3 = 0.69 kN/m^2

    Total = **1.96** kN/m^2

    - Partition load on floors (mean value):

    = 14 kN/m^3 x 3.5m*0.15m* 6 m/(6m*6m) = **1.2** kN/m^2
2. Live Loads: based on ESEN 1991-1-1-2015 for office buildings from the code category of building area B, the imposed floor area load is **3** kN/m^2 and the imposed roof floor **2** kN/m^2.
3. Seismic Load: this load has been calculated based on ESEN 1998-1; 2015 from the seismic mass of the building as mentioned in section 4.1 of this chapter in detail.

Table 3-1: Static loads case

Load Name	**Load Type**	**Details**	**Value**
Dead	Dead Load	Self-weight of structural members has been calculated automatically by ETABS using self-weight multiplier	-
		Floor Finish loads	1.96 kN/m^2
		Partition loads	1.2 kN/m^2
Live	Live Load	Floor area load	3 kN/m^2
		Roof floor area	2 kN/m^2
Seismic	Seismic Load	This load has been calculated based on ESEN 1998-1; 2015	-

III) Earthquake Parameters

Table 3-2: Geometric parameters of diagrid building

No.	Description	Data/Values
1	Building category	Office (Category B)
2	Number of Stories	G+10 , G+16 & G+22
3	Plan size	30m x 24m
4	Typical Story height	4
5	Story height at base of building	4
6	Dead load: a) floor finish b) Partition wall	1.96 KN/m^2 1.2 KN/ m^2
7	Live Load: a) roof b) other floors	2KN/m^2 3 KN/m^2
8	Seismic zone	Hawassa, a_g =0.15
10	Ground Type	A & C
11	Structure type	Reinforced concrete with steel diagrid
12	Diagrid Angle	53.13° , 69.26° , 75.57° & 79.22°
13	Diagrid Module	2 ,4, 6 & 8
14	Behavior Factor, q	1.5

IV) Material Properties

In computation of dead loads and associated loads on the structure, the following unit weight of material were used

Table 3-3: Material Properties

Grade of Concrete	C40/50
Poisons ration of concrete (cracked Section)	0
Density of concrete	25kN/m3
Modulus of elasticity of concrete	35.2GPa
Coefficient of thermal expansion	10x10-6
Grade of steel rebar	S-430
Grade of steel (Diagrid)	S-430
Density of steel	77kN/m3
Modulus of elasticity of steel	200GPa
Poisons ration of steel	0.3
Partial Safety factors	Dead load = 1.35
	Live load = 1.5

V) Load Combinations

1. Gravity=1.35 DL+1.5LL
2. Quasi =1DL+ψ_2LL
3. EQ 1-4=1Quasi ± 1EQXP ±0.3EQYP
4. EQ 5-8=1Quasi ± 1EQXN ± 0.3EQYP
5. EQ 9-12=1Quasi ± 1EQYP ± 0.3EQXP
6. EQ 13-16=1Quasi ± 1EQYN ± 0.3EQXP
7. EQ 17-20=1Quasi ± 1EQXP ± 0.3EQYN
8. EQ 21-24=1Quasi ± 1EQXN ± 0.3EQYN
9. EQ 25-28=1Quasi ± 1EQYP ± 0.3EQXN
10. EQ 29-32=1Quasi ± 1EQYN ± 0.3EQXN
11. RSMX 1-4=1Quasi ± RSX ± 0.3RSY
12. RSMY 1-4=1Quasi ± RSY ± 0.3RSX
13. Service= DL + LL

VI) Detail 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 the figure below.

Table 3-4: Building Geometry data

Building Geometry data				
Building Type	No of Bays in X-Direction	No of Bays in Y-Direction	Interior Bay width (m)	Exterior Bay width (m)
G+8	5	4	6	6
G+11	5	4	6	6
G+17	5	4	6	6

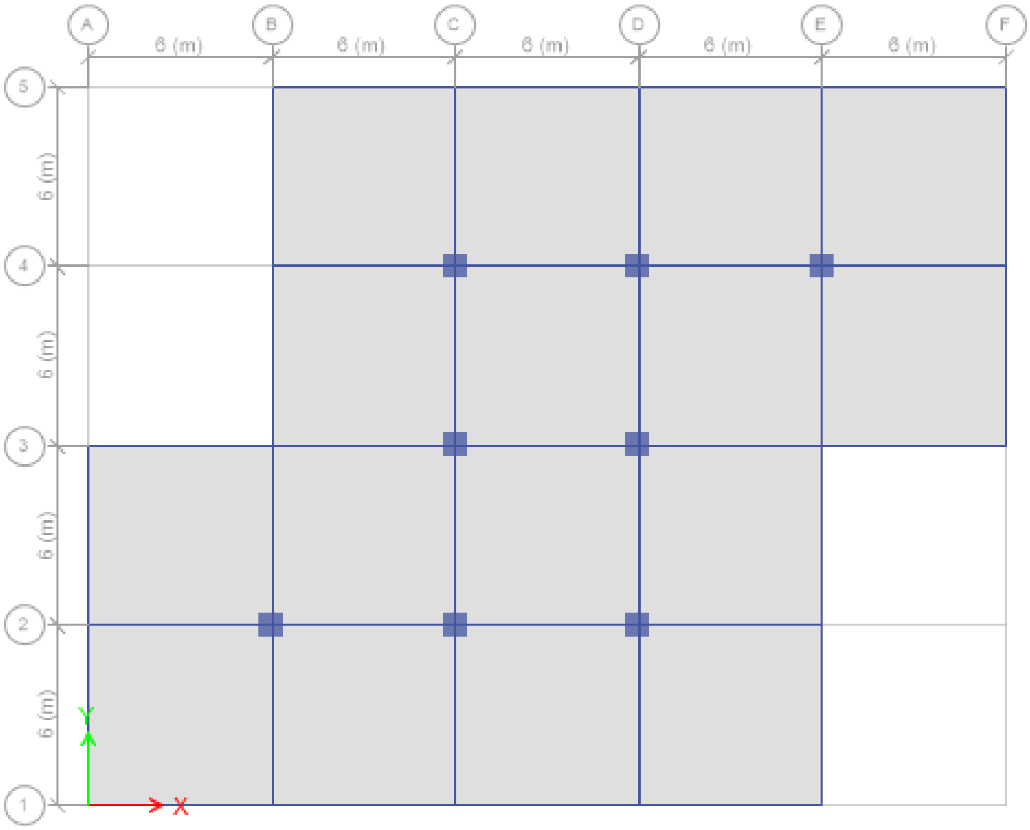


Figure 3-1: Typical Floor plans for all building model cases

b) Member size of the beams, columns, slab and diagrids

The beam, column and slab dimension of all models has been chosen to most relevant or similar to achieve a correct and reliable comparison among them. Member size used for beams, columns, slabs and Diagrids is shown as follows.

Table 3-5: Member size of Beams, columns and diagrids

Member size of Beams, columns and diagrids						
	Reinforced Concrete					Steel
Floor Level	Column dimension (mm)	Beam			Slab (mm)	Diagrid
		Grade beam (mm)	Floor beam (mm)	Top tie beam (mm)		
1. G+10 RC building with diagrid angle 53.13^{o} in Ground type A						
Base up to 1^{st}	600x600	300x300	300x300	300x300	150	H400x237
2^{nd} up to 4^{th}	500x500					
5^{th} up to 10^{th}	400x400					
2. G+16 RC building with diagrid angle 53.13^{o} in Ground type A						
Base up to 1^{st}	750x750	300x300	300x400	300x300	150	H400x237
2^{nd} up to 5^{th}	700x700					
6^{th} up to 12^{th}	600x600					
13^{th} up to 16^{th}	500x500					
3. G+22 RC building with diagrid angle 53.13^{o} in Ground type A						
Base up to GF	950x950	300x300	400x400	300x300	150	H400x237
1^{st} up to 2^{nd}	900x900					
3^{rd} up to 4^{th}	850x850					
5^{th} up to 9^{th}	800x800					
10^{th} up to 16^{th}	750x750					
17^{th} up to 22^{nd}	600x600					
4. G+10 RC building with diagrid angle 69.26^{o} in Ground type A						
Base up to 1^{st}	600x600	300x300	300x300	300x300	150	H400x237
2^{nd} up to 4^{th}	500x500					
5^{th} up to 10^{th}	400x400					
5. G+16 RC building with diagrid angle 69.26^{o} in Ground type A						
Base up to 1^{st}	750x750	300x300	300x400	300x300	150	H400x237
2^{nd} up to 5^{th}	700x700					

Member size of Beams, columns and diagrids						
	Reinforced Concrete					Steel
Floor Level	Column dimension (mm)	Beam			Slab (mm)	Diagrid
		Grade beam (mm)	Floor beam (mm)	Top tie beam (mm)		
6th up to 12th	600x600					
13th up to 16th	500x500					
6. G+22 RC building with diagrid angle 69.26° in Ground type A						
Base up to GF	950x950	300x300	400x400	300x300	150	H400x237
1st up to 2nd	900x900					
3rd up to 4th	850x850					
5th up to 9th	800x800					
10th up to 16th	750x750					
17th up to 22nd	600x600					
7. G+10 RC building with diagrid angle 75.57° in Ground type A						
Base up to 1st	600x600	300x300	300x300	300x300	150	H400x237 H400x262
2nd up to 4th	500x500					
5th up to 10th	400x400					
8. G+16 RC building with diagrid angle 75.57° in Ground type A						
Base up to 1st	750x750	300x300	300x400	300x300	150	H400x237 H400x347 H400x393
2nd up to 5th	700x700					
6th up to 12th	600x600					
13th up to 16th	500x500					
9. G+22 RC building with diagrid angle 75.57° in Ground type A						
Base up to GF	950x950	300x300	400x400	300x300	150	H400x237 H400x347 H400x393 H400x467
1st up to 2nd	900x900					
3rd up to 4th	850x850					
5th up to 9th	800x800					
10th up to 16th	750x750					
17th up to 22nd	600x600					

Member size of Beams, columns and diagrids						
	Reinforced Concrete					Steel
Floor Level	Column dimension (mm)	Beam			Slab (mm)	Diagrid
		Grade beam (mm)	Floor beam (mm)	Top tie beam (mm)		
10. G+10 RC building with diagrid angle 79.22^{o} in Ground type A						
Base up to 1st	600x600	300x300	300x300	300x300	150	H400x237 H400x262 H400x288 H400x314 H400x340 H400x388 H400x422 H400x463
2nd up to 4th	500x500					
5th up to 10th	400x400					
11. G+16 RC building with diagrid angle 79.22^{o} in Ground type A						
Base up to 1st	750x750	300x300	300x400	300x300	150	H400x237 H400x347 H400x467 H400x593
2nd up to 5th	700x700					
6th up to 12th	600x600					
13th up to 16th	500x500					
12. G+22 RC building with diagrid angle 79.22^{o} in Ground type A						
Base up to GF	950x950	300x300	400x400	300x300	150	H400x237 H400x347 H400x467 H400x551 H400x634 H400x744 H400x818
1st up to 2nd	900x900					
3rd up to 4th	850x850					
5th up to 9th	800x800					
10th up to 16th	750x750					
17th up to 22nd	600x600					
13. G+10 RC building with diagrid angle 53.13^{o} in Ground type C						
Base up to 1st	600x600	300x300	300x300	300x300	150	H400x237
2nd up to 4th	500x500					
5th up to 10th	400x400					

Member size of Beams, columns and diagrids						
	Reinforced Concrete					Steel
Floor Level	Column dimension (mm)	Beam			Slab (mm)	Diagrid
		Grade beam (mm)	Floor beam (mm)	Top tie beam (mm)		
14. G+16 RC building with diagrid angle 53.13 º in Ground type C						
Base up to 1st	750x750	300x300	300x400	300x300	150	H400x237
2nd up to 5th	700x700					
6th up to 12th	600x600					
13th up to 16th	500x500					
15. G+22 RC building with diagrid angle 53.13 º in Ground type C						
Base up to GF	950x950	300x300	400x400	300x300	150	H400x237
1st up to 2nd	900x900					
3rd up to 4th	850x850					
5th up to 9th	800x800					
10th up to 16th	750x750					
17th up to 22nd	600x600					
16. G+10 RC building with diagrid angle 69.26 º in Ground type C						
Base up to 1st	600x600	300x300	300x300	300x300	150	H400x237
2nd up to 4th	500x500					
5th up to 10th	400x400					
17. G+16 RC building with diagrid angle 69.26 º in Ground type C						
Base up to 1st	750x750	300x400	300x400	300x300	150	H400x237 H400x288 H400x347
2nd up to 5th	700x700					
6th up to 12th	600x600					
13th up to 16th	500x500					
18. G+22 RC building with diagrid angle 69.26 º in Ground type C						
Base up to GF	950x950	300x300	400x400	300x300	150	H400x237 H400x347 H400x393
1st up to 2nd	900x900					
3rd up to 4th	850x850					
5th up to 9th	800x800					
10th up to 16th	750x750					
17th up to 22nd	600x600					

Member size of Beams, columns and diagrids						
	Reinforced Concrete					Steel
Floor Level	Column dimension (mm)	Beam			Slab (mm)	Diagrid
		Grade beam (mm)	Floor beam (mm)	Top tie beam (mm)		
19. G+10 RC building with diagrid angle 75.57 º in Ground type C						
Base up to 1st	600x600	300x300	300x300	300x300	150	H400x237 H400x288 H400x347 H400x422 H400x463
2nd up to 4th	500x500					
5th up to 10th	400x400					
20. G+16 RC building with diagrid angle 75.57 º in Ground type C						
Base up to 1st	750x750	300x300	300x400	300x300	150	H400x237 H400x393 H400x467 H400x593 H400x678
2nd up to 5th	700x700					
6th up to 12th	600x600					
13th up to 16th	500x500					
21. G+22 RC building with diagrid angle 75.57 º in Ground type C						
Base up to GF	950x950	300x300	400x400	300x300	150	H400x237 H400x347 H400x393 H400x467 H400x551 H400x634 H400x744
1st up to 2nd	900x900					
3rd up to 4th	850x850					
5th up to 9th	800x800					
10th up to 16th	750x750					
17th up to 22nd	600x600					
22. G+10 RC building with diagrid angle 79.22 º in Ground type C						
Base up to 1st	600x600	300x300	300x300	300x300	150	H400x237 H400x288 H400x347 H400x393 H400x463 H400x509 H400x593 H400x678 H400x744 H400x818 H400x900
2nd up to 4th	500x500					
5th up to 10th	400x400					

Member size of Beams, columns and diagrids						
	Reinforced Concrete					Steel
Floor Level	Column dimension (mm)	Beam			Slab (mm)	Diagrid
		Grade beam (mm)	Floor beam (mm)	Top tie beam (mm)		
23. G+16 RC building with diagrid angle 79.22 º in Ground type C						
Base up to 1st	750x750	300x300	300x400	300x300	150	H400x237 H400x467 H400x593 H400x678 H400x818 H400x900 H400x990
2nd up to 5th	700x700					
6th up to 12th	600x600					
13th up to 16th	500x500					
24. G+22 RC building with diagrid angle 79.22 º in Ground type C						
Base up to GF	950x950	300x300	400x400	300x300	150	H400x237 H400x347 H400x467 H400x634 H400x744 H400x900 H400x990
1st up to 2nd	900x900					
3rd up to 4th	850x850					
5th up to 9th	800x800					
10th up to 16th	750x750					
17th up to 22nd	600x600					
For all columns and beams= C-40/50, S-430 Shear reinforcement= S-430 Diagrid steel = S-430						

VII) 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, four types of diagrid module have been selected to get the optimum one.

Two stories module diagrid

X–Direction diagonal angle = $\tan^{-1}$(module height/base width) = $\tan^{-1}$(4m/3m) = **53.13º**

Y–Direction diagonal angle = $\tan^{-1}$(module height/base width) = $\tan^{-1}$(4m/3m) = **53.13º**

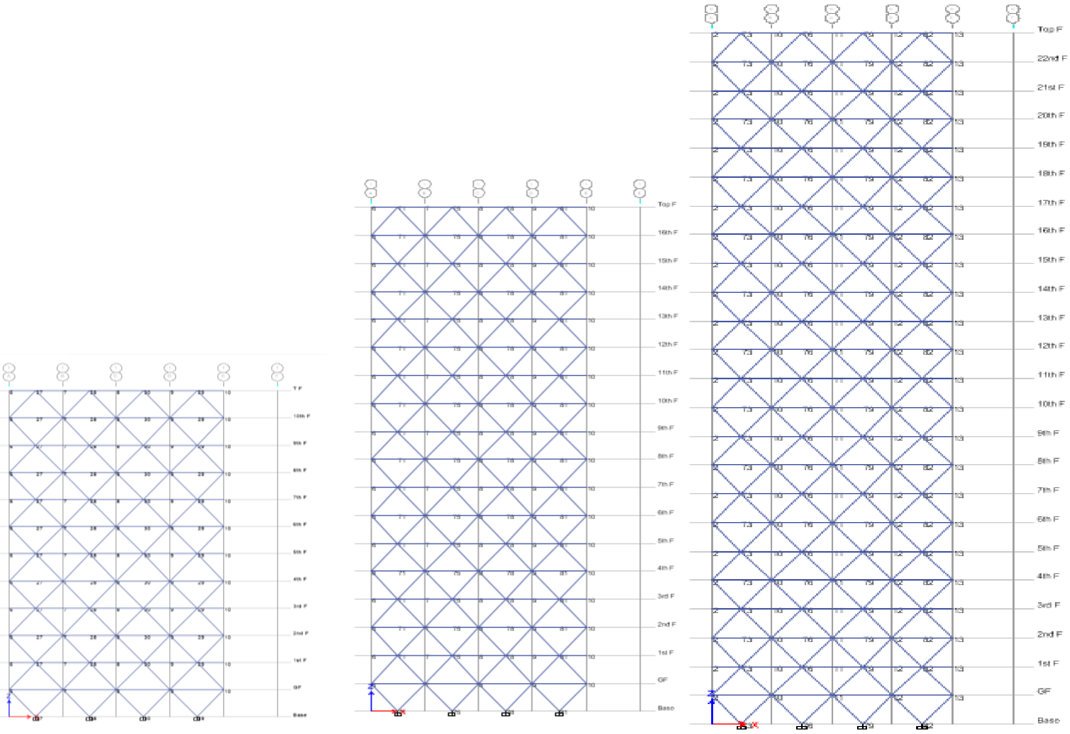


Figure 3-2: Two stories module diagrid structure for G+10, G+16 and G+22 Builings

Four stories module diagrid

X–Direction diagonal angle = $\tan^{-1}$(module height/base width) = $\tan^{-1}$(8m/3m) = **69.26º**

Y–Direction diagonal angle = $\tan^{-1}$(module height/base width) = $\tan^{-1}$(8m/3m) = **69.26º**

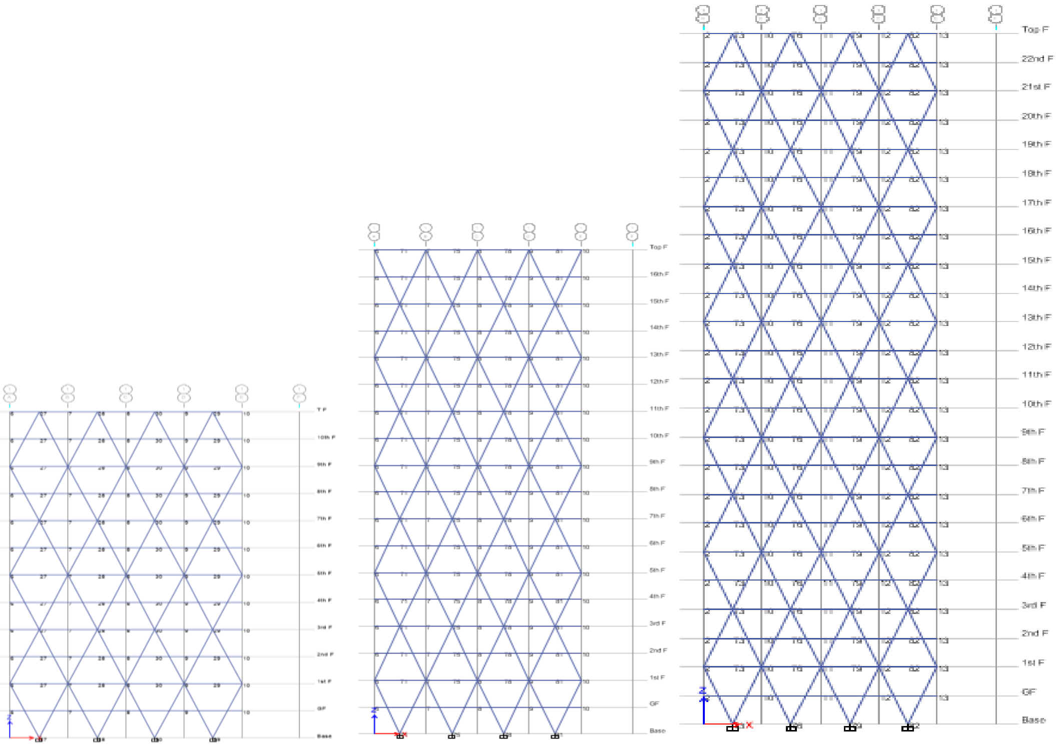


Figure 3-3: Four stories module diagrid structure for G+10, G+16 and G+22 Buildings

Six stories module diagrid

X–Direction diagonal angle = $\tan^{-1}$(module height/base width) = $\tan^{-1}$(12m/3m) = **75.57º**

Y–Direction diagonal angle = $\tan^{-1}$(module height/base width) = $\tan^{-1}$(12m/3m) = **75.57º**

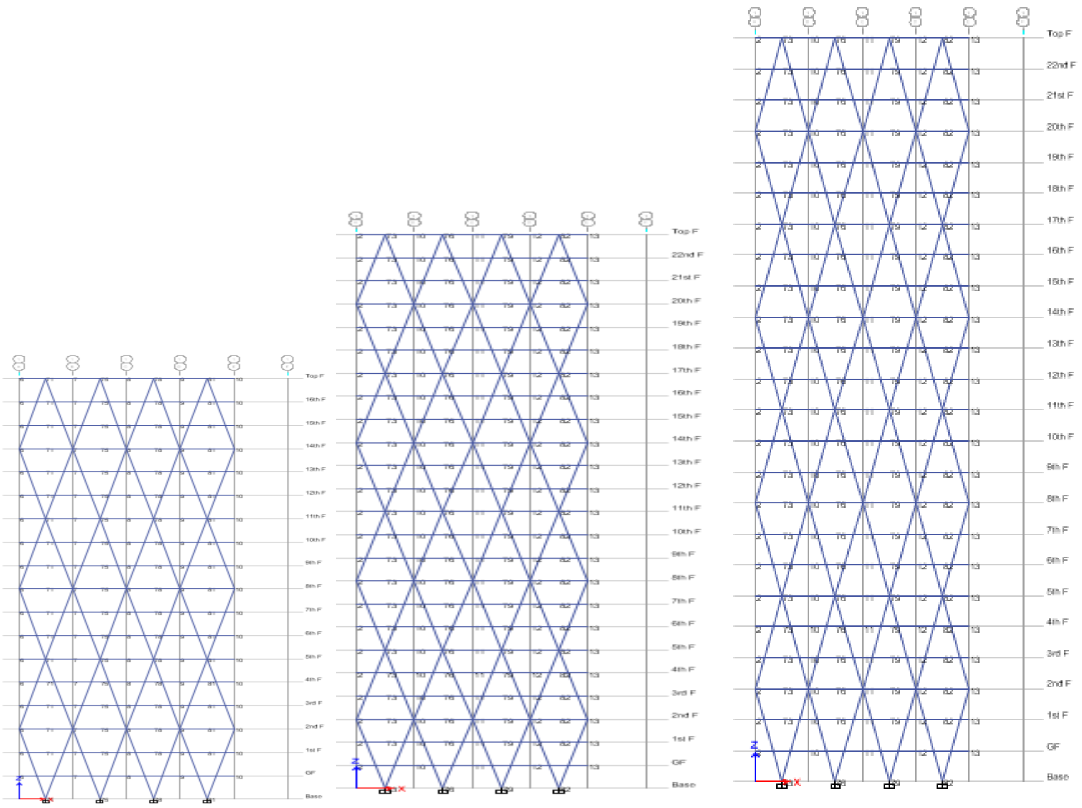


Figure 3-4: Six stories module diagrid structure for G+10, G+16 and G+22 Builings

Eight stories module diagrid

X–Direction diagonal angle = $\tan^{-1}$(module height/base width) = $\tan^{-1}$(16m/3m) = **79.22º**

Y–Direction diagonal angle = $\tan^{-1}$(module height/base width) = $\tan^{-1}$(16m/3m) = **79.22º**

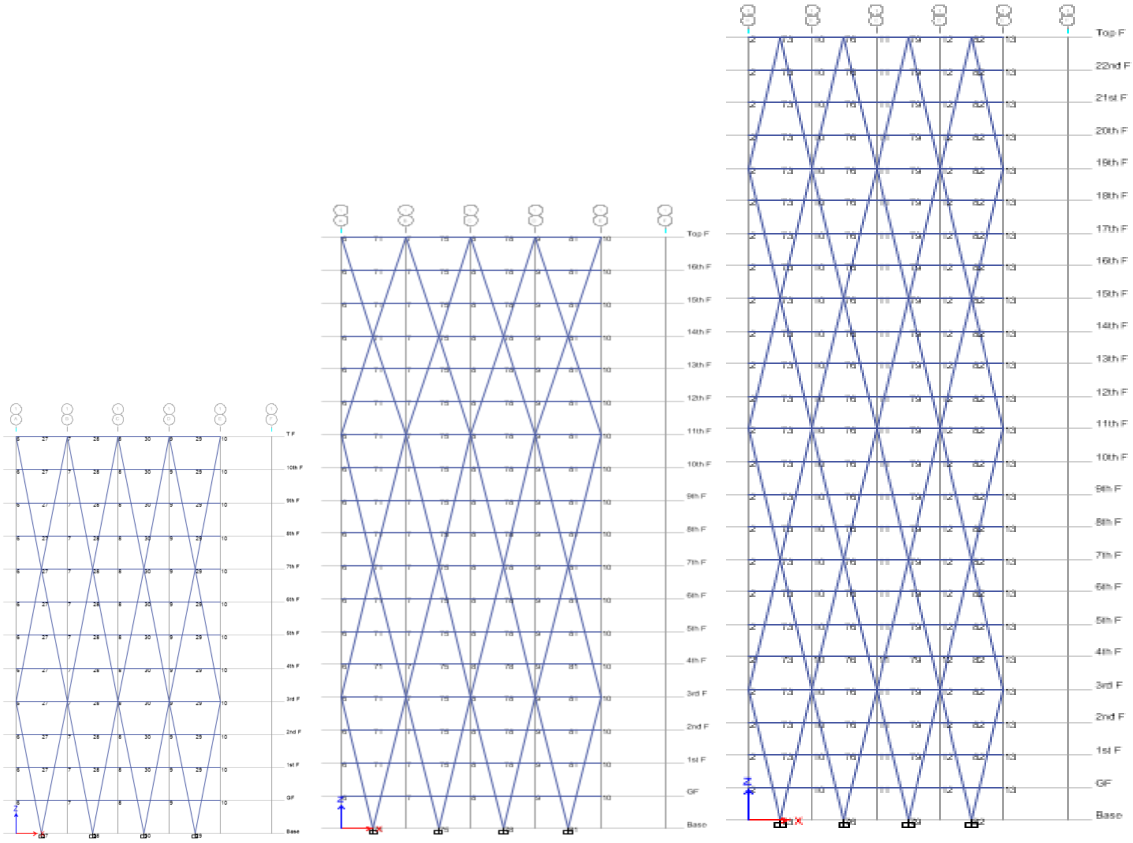
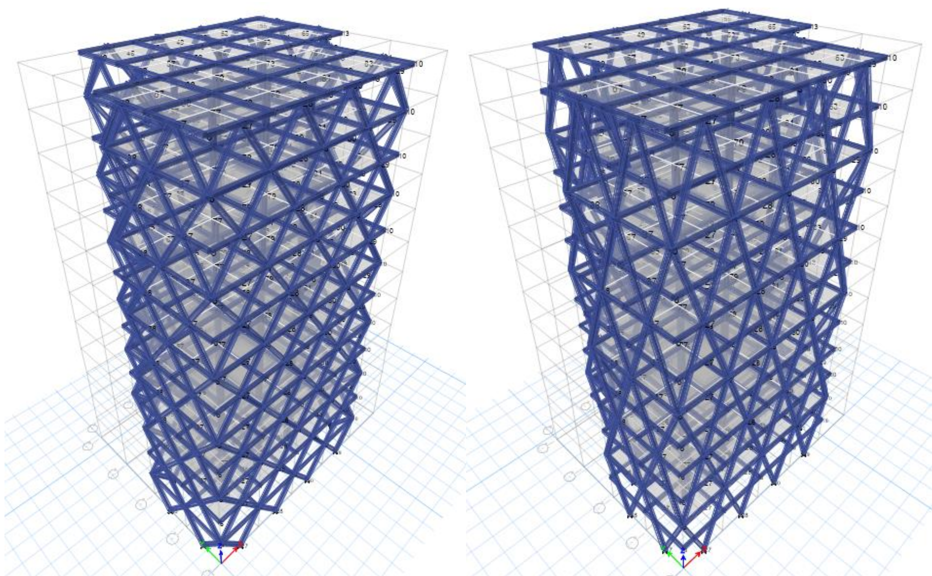
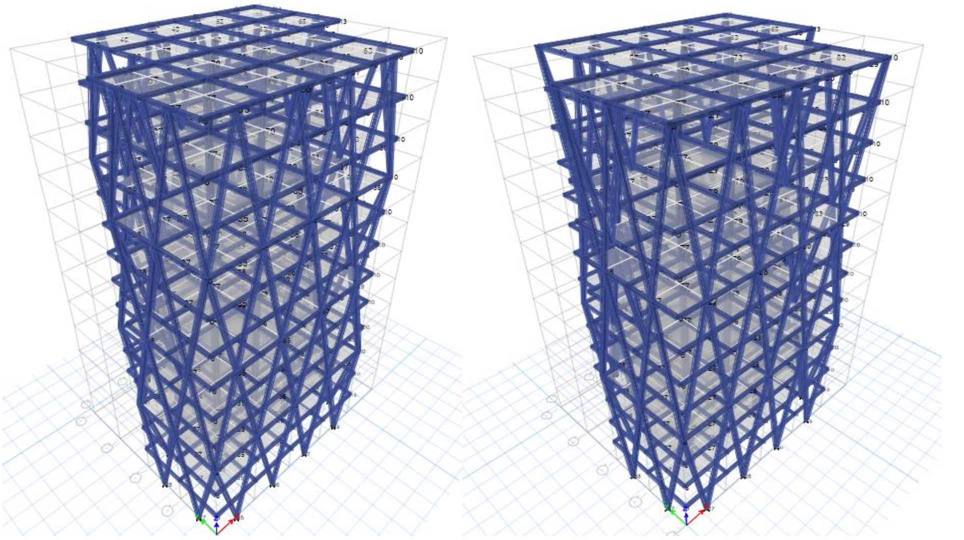


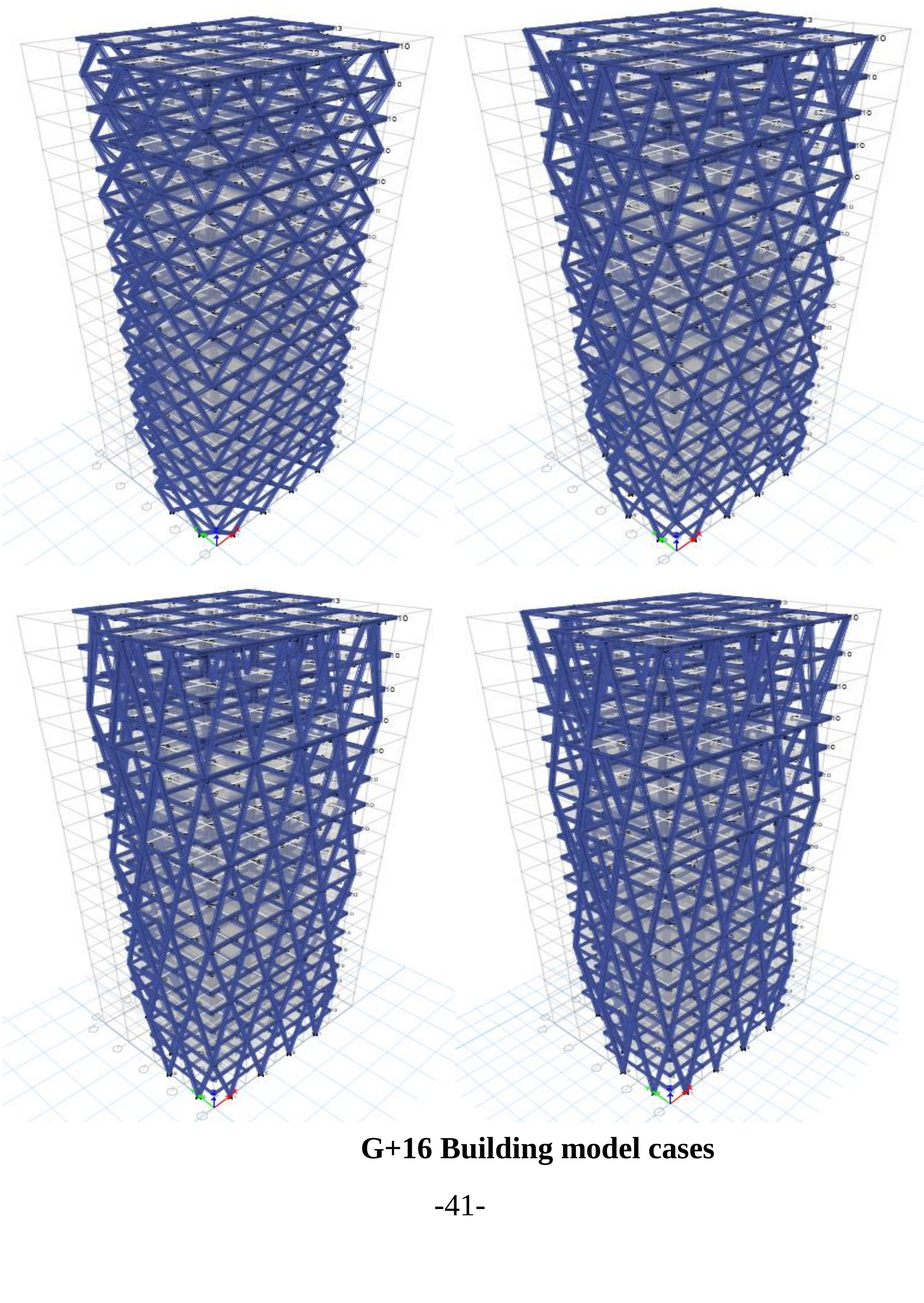
Figure 3-5: Eight stories module diagrid structure for G+10, G+16 and G+22 Builings

c) 3D Model

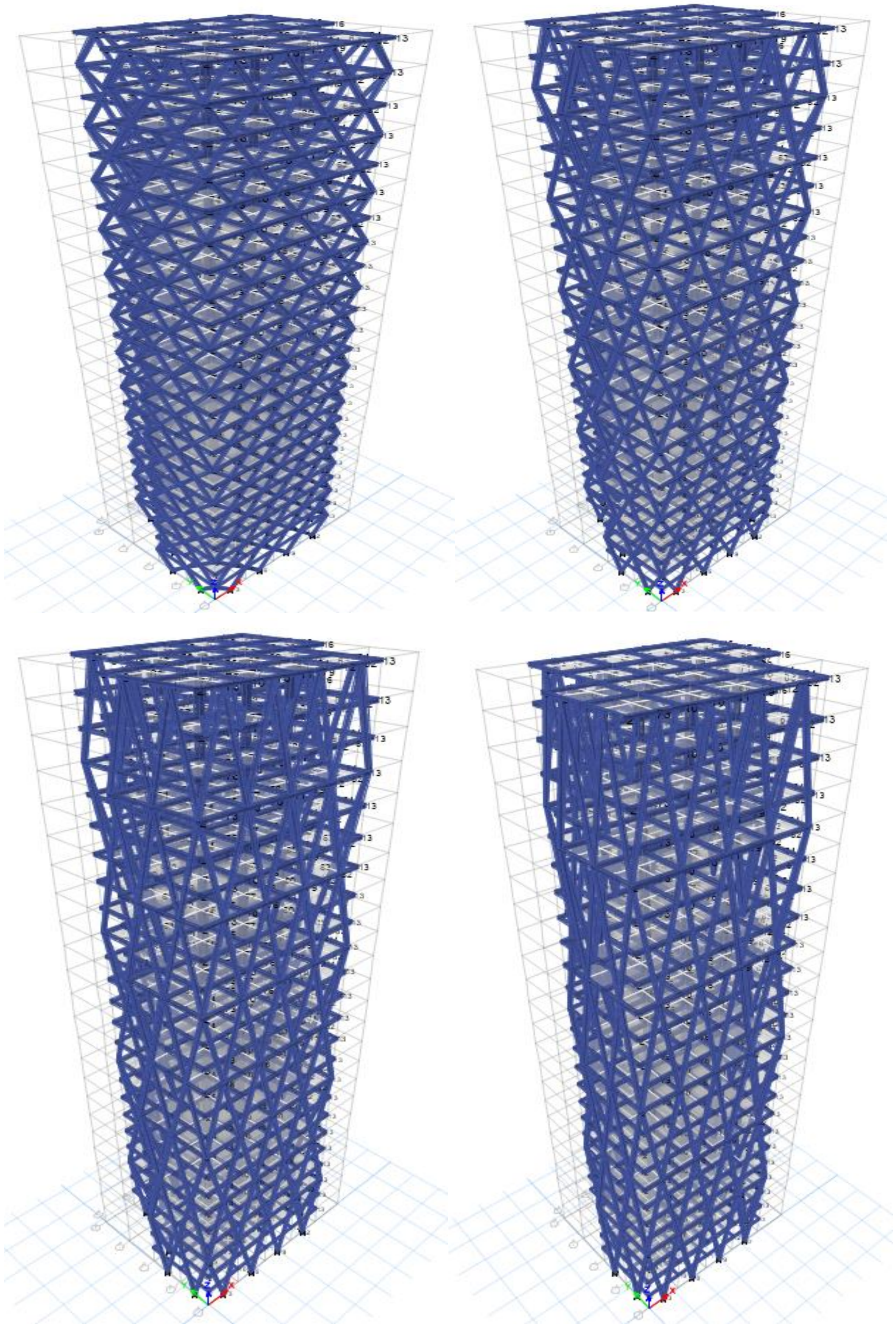




G+10 Building model cases



G+16 Building model cases



G+22 Building model cases

Figure 3-6: 3D models of Diagrid structure for G+10, G+16 and G+22 Buildings.

CHAPTER FOUR

RESULT, PERFORMANCE ASSESMENT AND DISCUSSION

Finite element analyses were conducted using the software ETABS 2016 v16.2.1 to compare the performance of concrete structures under seismic loading with four different module angle diagrid for three different Stories buildings (G+10, G+16 and G+22).

4.1. LINEAR ANALYSIS RESULT AND DISCUSSION

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. Fundamental Natural Vibration Period
2. Story displacement
3. Inter Story drift

The comparison of results in terms of the above parameters was discussed in terms of tables & graphs in the coming paragraphs.

4.1.1. Fundamental Natural Vibration Period

Structures will have multiple natural modes of vibration for which frequency will be higher and time period will be shorter that the fundamental period. The reliable and sufficient estimation of the natural period of vibration could play an essential role in the understanding of the global demands on the structure under an earthquake. Its evaluation is an essential step in estimating the seismic response both in seismic design and assessment. This important property of the building's seismic behavior is mainly dependent on mass, strength and stiffness and consequently on all the factors which affect them (dimensions in height and plan, morphology, irregularities, section properties, stiffness, cracking, etc.). In the current research the fundamental period of vibration is estimated for the different model cases of building and comparative study is made in the section follows.

a) G+10 Building (Ground type A) Model Cases

Table 4-1: Fundamental periods of G+10 Building (Ground type A) Models

Building Model Types	Case Designation	Fundamental Period (sec)	% reduction in time period is compared to 69.26 ˚
Diagrid angle - 53.13˚	Case -1	0.824	22 %
Diagrid angle - 69.26˚	Case -2	0.998	0 %
Diagrid angle - 75.57˚	Case -3	1.296	-23 %
Diagrid angle - 79.22˚	Case -4	1.395	-29 %

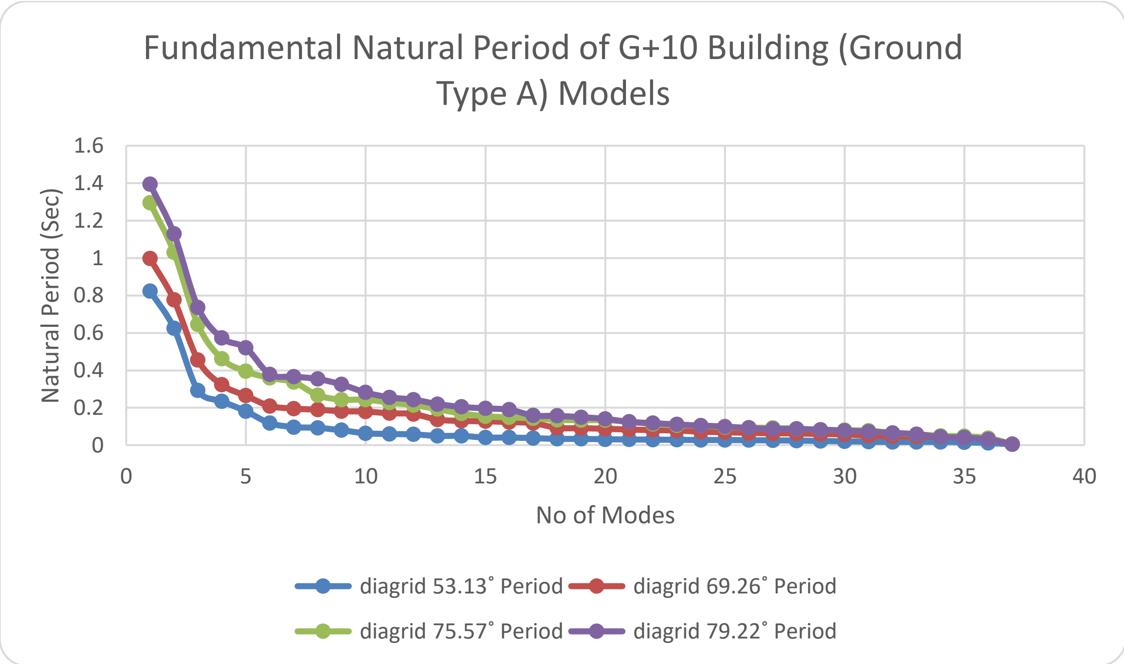


Figure 4-1: Fundamental periods of G+10 Building (Ground type A) Models

As shown in the table 4.1 and figure 4.1 the diagrid structure with module angle 79.57˚ model was found to have a highest fundamental natural period (i.e. 1.395 sec) compared to other building model cases. Highest fundamental natural vibration period corresponds to lowest natural frequency of vibration of structure and in turn corresponds to relatively lowest structural stiffness. Therefore, the diagrid structure with module angle 53.13˚ model was found to have a lowest fundamental natural vibration period (i.e. 0.824 sec) with 22% reduction from the fundamental natural period of 69.26˚ (i.e. 0.998 sec), which is between 60˚ - 70˚, a recommended diagonal angle as the most advantageous angle for most diagrid structure in Kim and Lee (2012) study and the 53.13˚ has showed that it is the stiffest one from the considered cases in the study.

b) G+16 Building (Ground type A) Model Cases

Table 4-2: Fundamental periods of G+16 Building (Ground type A) Models

Building Model Types	Case Designation	Fundamental Period (sec)	% reduction in time period is compared to 69.26 ˚
Diagrid angle - 53.13˚	Case -1	1.576	8 %
Diagrid angle - 69.26˚	Case -2	1.698	0 %
Diagrid angle - 75.57˚	Case -3	1.987	-15 %
Diagrid angle - 79.22˚	Case -4	1.883	-10 %

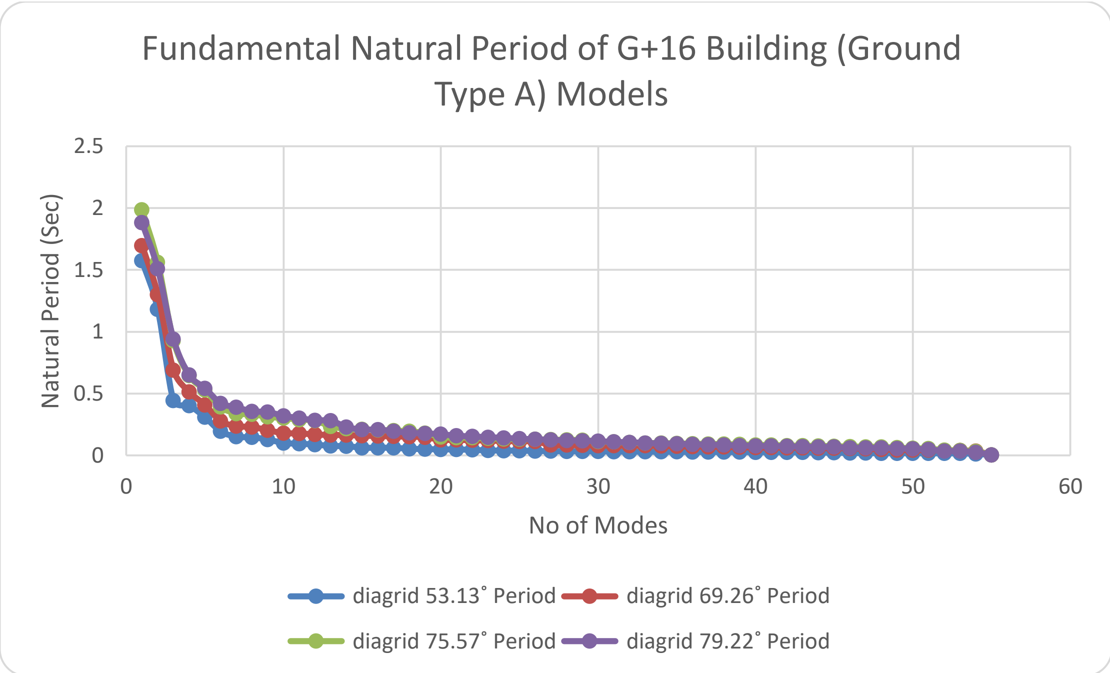


Figure 4-2: Fundamental periods of G+16 Building (Ground type A) Models

As shown in the table 4.2 and figure 4.2 the diagrid structure with module angle 75.57˚ model was found to have a highest fundamental natural period (i.e. 1.987 sec) compared to other building model cases. Highest fundamental natural vibration period corresponds to lowest natural frequency of vibration of structure and in turn corresponds to relatively lowest structural stiffness. Therefore, the diagrid structure with module angle 53.13˚ model was found to have a lowest fundamental natural vibration period (i.e. 1.576 sec) with 8% reduction from the fundamental natural period of 69.26˚ (i.e. 1.698 sec), which is between 60˚ - 70˚, a recommended diagonal angle as the most advantageous angle for most diagrid structure in Kim and Lee (2012) study and the 53.13˚ has showed that it is the stiffest one from the considered cases in the study.

c) G+22 Building (Ground type A) Model Cases

Table 4-3: Fundamental periods of G+22 Building (Ground type A) Models

Building Model Types	Case Designation	Fundamental Period (sec)	% reduction in time period is compared to 69.26˚
Diagrid angle - 53.13˚	Case -1	2.623	-1 %
Diagrid angle - 69.26˚	Case -2	2.613	0 %
Diagrid angle - 75.57˚	Case -3	2.754	-6 %
Diagrid angle - 79.22˚	Case -4	2.628	-1 %

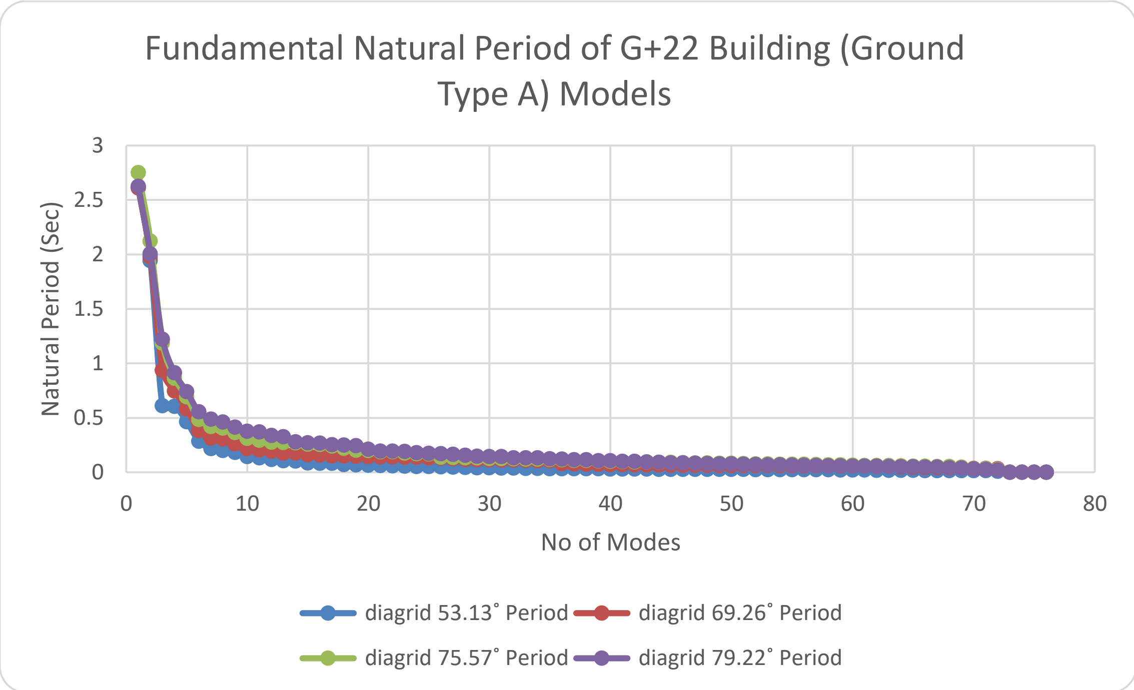


Figure 4-3: Fundamental periods of G+22 Building (Ground type A) Models

As shown in the table 4.3 and figure 4.3 the diagrid structure with module angle 75.57˚ model was found to have a highest fundamental natural period (i.e. 2.754 sec) compared to other building model cases. Highest fundamental natural vibration period corresponds to lowest natural frequency of vibration of structure and in turn corresponds to relatively lowest structural stiffness. Therefore, the diagrid structure with module angle 69.26˚ model was found to have a lowest fundamental natural vibration period (i.e. 2.613 sec), which is between 60˚ - 70˚, a recommended diagonal angle as the most advantageous angle for most diagrid structure in Kim and Lee (2012) study and it has showed that it is the stiffest one from the considered cases in the study.

d) G+10 Building (Ground type C) Model Cases

Table 4-4: Fundamental periods of G+10 Building (Ground type C) Models

Building Model Types	Case Designation	Fundamental Period (sec)	% reduction in time period is compared to 69.26˚
Diagrid angle - 53.13˚	Case -1	0.824	22 %
Diagrid angle - 69.26˚	Case -2	0.998	0 %
Diagrid angle - 75.57˚	Case -3	1.184	-16 %
Diagrid angle - 79.22˚	Case -4	1.488	33 %

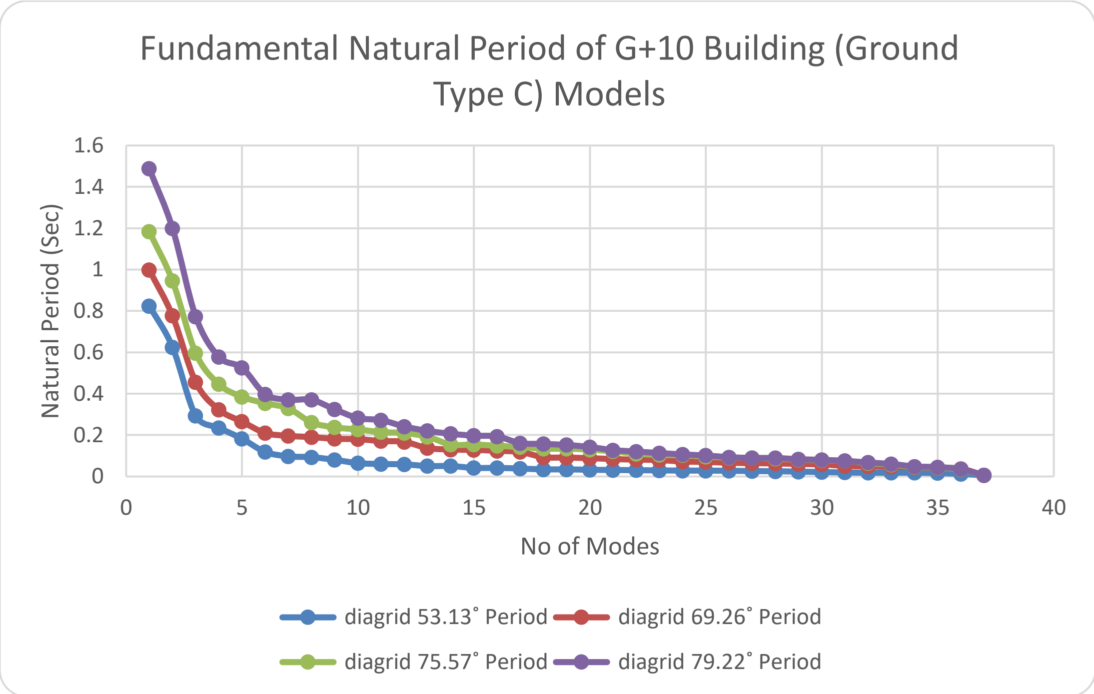


Figure 4-4: Fundamental periods of G+10 Building (Ground type C) Models

As shown in the table 4.4 and figure 4.4 the diagrid structure with module angle 79.22˚ model was found to have a highest fundamental natural period (i.e. 1.488 sec) compared to other building model cases. Highest fundamental natural vibration period corresponds to lowest natural frequency of vibration of structure and in turn corresponds to relatively lowest structural stiffness. Therefore, the diagrid structure with module angle 53.13˚ model was found to have a lowest fundamental natural vibration period (i.e. 0.824 sec) with 22% reduction from the fundamental natural period of 69.26˚ (i.e. 0.998 sec), which is between 60˚ - 70˚, a recommended diagonal angle as the most advantageous angle for most diagrid structure in Kim and Lee (2012) study and the 53.13˚ has showed that it is the stiffest one from the considered cases in the study.

e) G+16 Building (Ground type C) Model Cases

Table 4-5: Fundamental periods of G+16 Building (Ground type C) Models

Building Model Types	Case Designation	Fundamental Period (sec)	% reduction in time period is compared to 69.26˚
Diagrid angle - 53.13˚	Case -1	1.576	6 %
Diagrid angle - 69.26˚	Case -2	1.66	0 %
Diagrid angle - 75.57˚	Case -3	1.667	-1 %
Diagrid angle - 79.22˚	Case -4	1.607	4 %

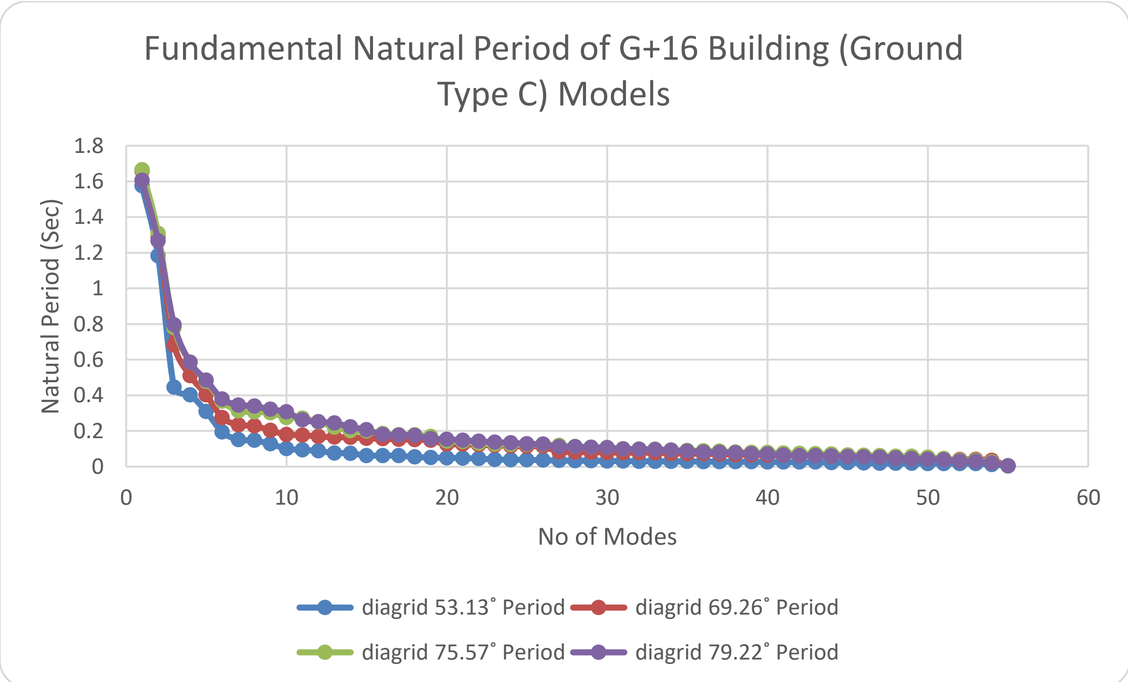


Figure 4-5: Fundamental periods of G+16 Building (Ground type C) Models

As shown in the table 4.5 and figure 4.5 the diagrid structure with module angle 75.57˚ model was found to have a highest fundamental natural period (i.e. 1.667 sec) compared to other building model cases. Highest fundamental natural vibration period corresponds to lowest natural frequency of vibration of structure and in turn corresponds to relatively lowest structural stiffness. Therefore, the diagrid structure with module angle 53.13˚ model was found to have a lowest fundamental natural vibration period (i.e. 1.576 sec) with 6% reduction from the fundamental natural period of 69.26˚ (i.e. 1.66 sec), which is between 60˚ - 70˚, a recommended diagonal angle as the most advantageous angle for most diagrid structure in Kim and Lee (2012) study and the 53.13˚ has showed that it is the stiffest one from the considered cases in the study.

f) G+22 Building (Ground type C) Model Cases

Table 4-6: Fundamental periods of G+22 Building (Ground type C) Models

Building Model Types	Case Designation	Fundamental Period (sec)	% reduction in time period is compared to 69.26˚
Diagrid angle - 53.13˚	Case -1	2.62	-6 %
Diagrid angle - 69.26˚	Case -2	2.484	0 %
Diagrid angle - 75.57˚	Case -3	2.454	2 %
Diagrid angle - 79.22˚	Case -4	2.068	21 %

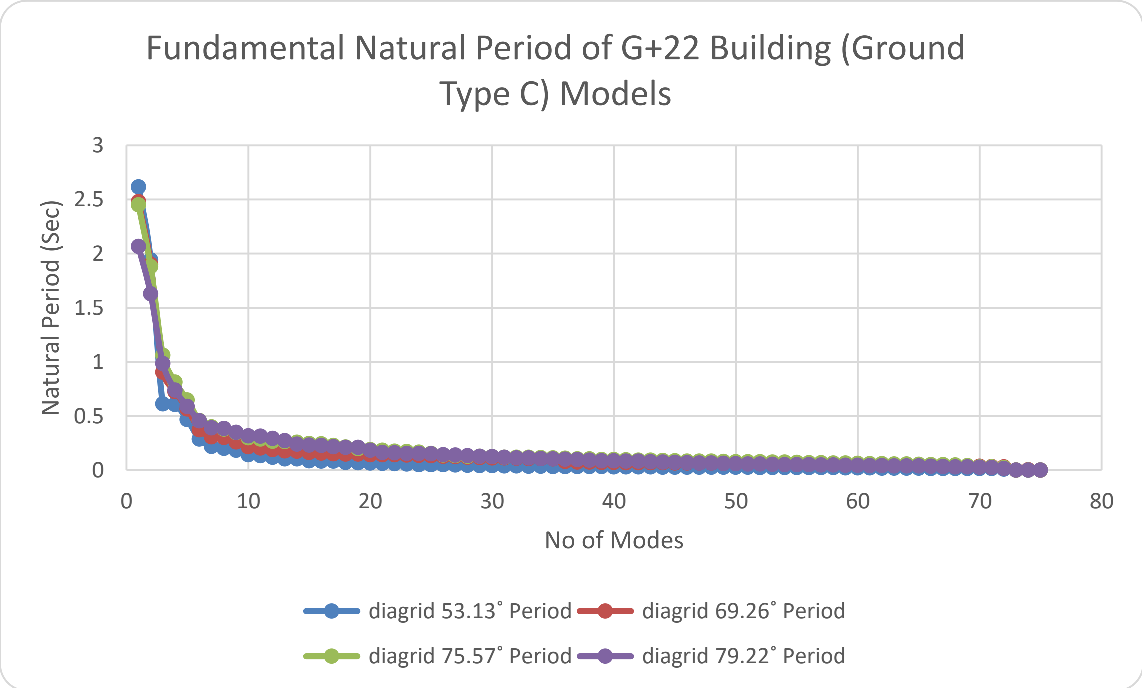


Figure 4-6: Fundamental periods of G+22 Building (Ground type C) Models

As shown in the table 4.6 and figure 4.6 the diagrid structure with module angle 53.13˚ model was found to have a highest fundamental natural period (i.e. 2.62 sec) compared to other building model cases. Highest fundamental natural vibration period corresponds to lowest natural frequency of vibration of structure and in turn corresponds to relatively lowest structural stiffness. Therefore, the diagrid structure with module angle 79.22˚ model was found to have a lowest fundamental natural vibration period (i.e. 2.068 sec) with 21% reduction from the fundamental natural period of 69.26˚ (i.e. 2.484 sec), which is between 60˚ - 70˚, a recommended diagonal angle as the most advantageous angle for most diagrid structure in Kim and Lee (2012) study and the 79.22˚ has showed that it is the stiffest one from the considered cases in the study.

g) Conclusion on Fundamental Periods

Generally speaking, based on Kim and Lee (2012) study regarding nonlinear static and time-history dynamic behavior of diagrids, this research considered their recommended a diagonal angle, which is, between 60˚ - 70˚ as the most advantageous angle for most diagrid structures and compared with other module angles taken in the study.

Hence, from a total of 24 models, a two story module or module diagrid angle 53.13˚ has shown a better time period reduction and higher stiffness for G+10 and G+16 stories for both ground types (A and C) and as the height of the building increased (G+22), diagrid angle 69.26 and 79.57˚ for ground type A and C respectively has shown a better time period reduction and higher stiffness than other type of cases considered in the study.

4.1.2. Story displacement

Story performance evaluation is directly related to displacement or deformation and thus estimation of seismic deformation demand is a primary or fundamental concern in performance evaluation of reinforced concrete structures under seismic excitation. The story displacement of the case study building models were studied to the selected earthquake.

a) **Story displacement in X – direction**

❖ G+10 building (Ground type A)

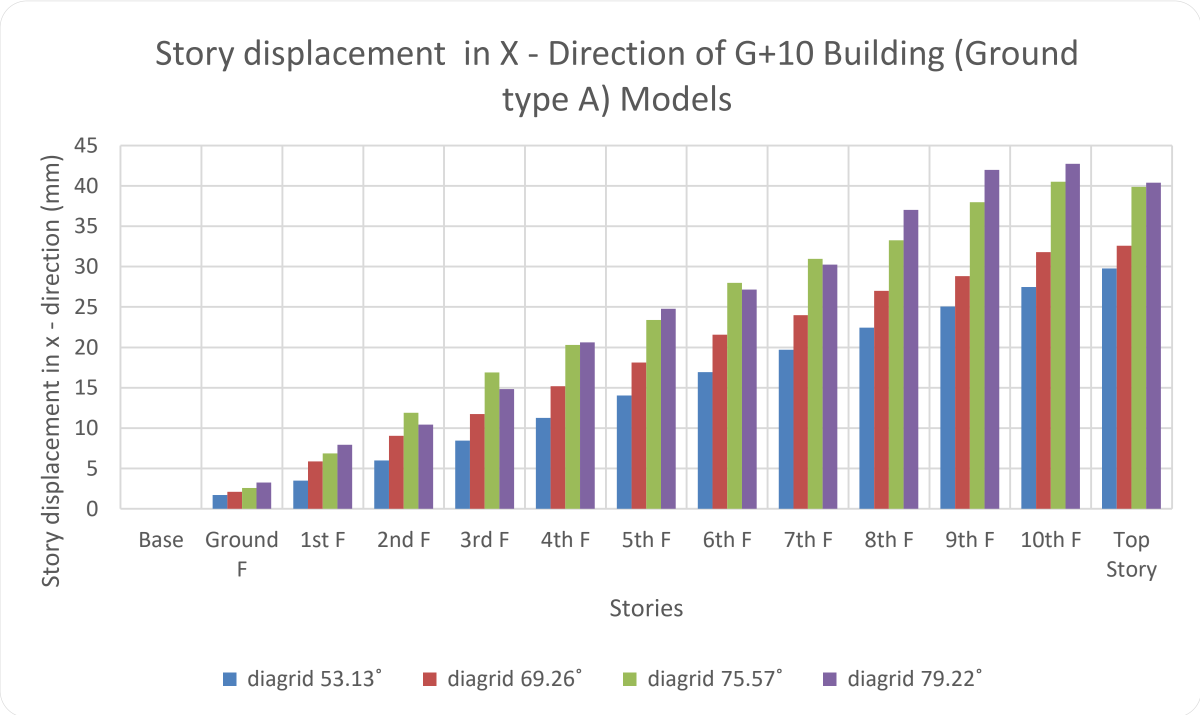


Figure 4-7: Story displacement of G+10 Building (Ground type A) Models in X – direction

❖ G+16 building (Ground type A)

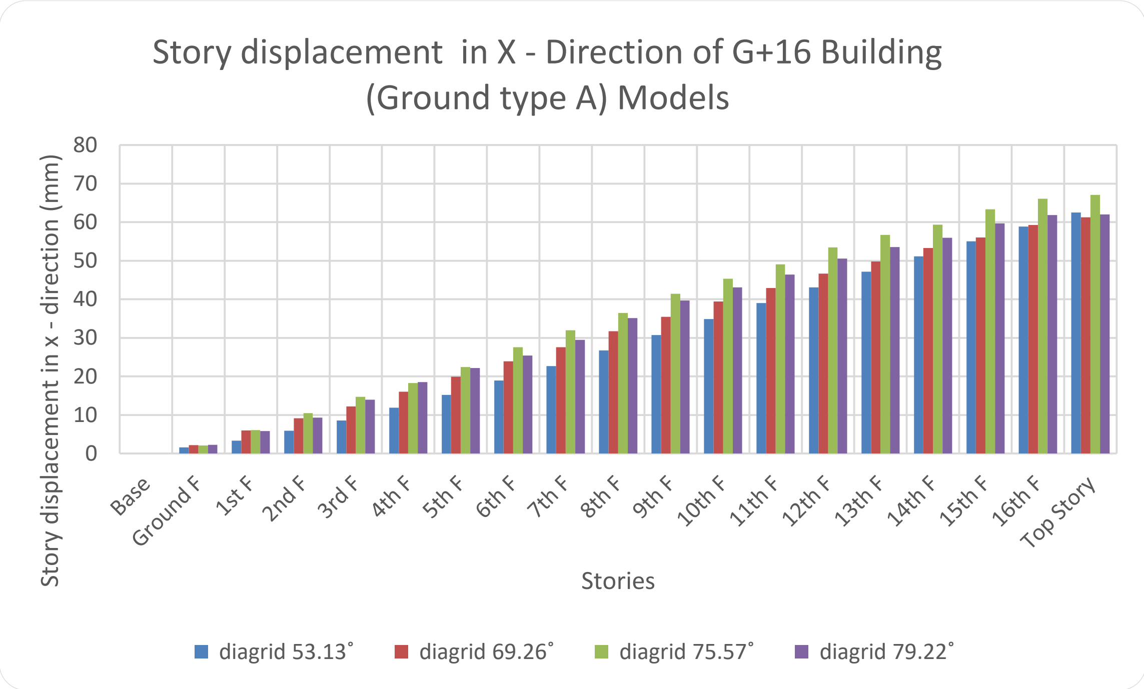


Figure 4-8: Story displacement of G+16 Building (Ground type A) Models in X - direction

❖ G+22 building (Ground type A)

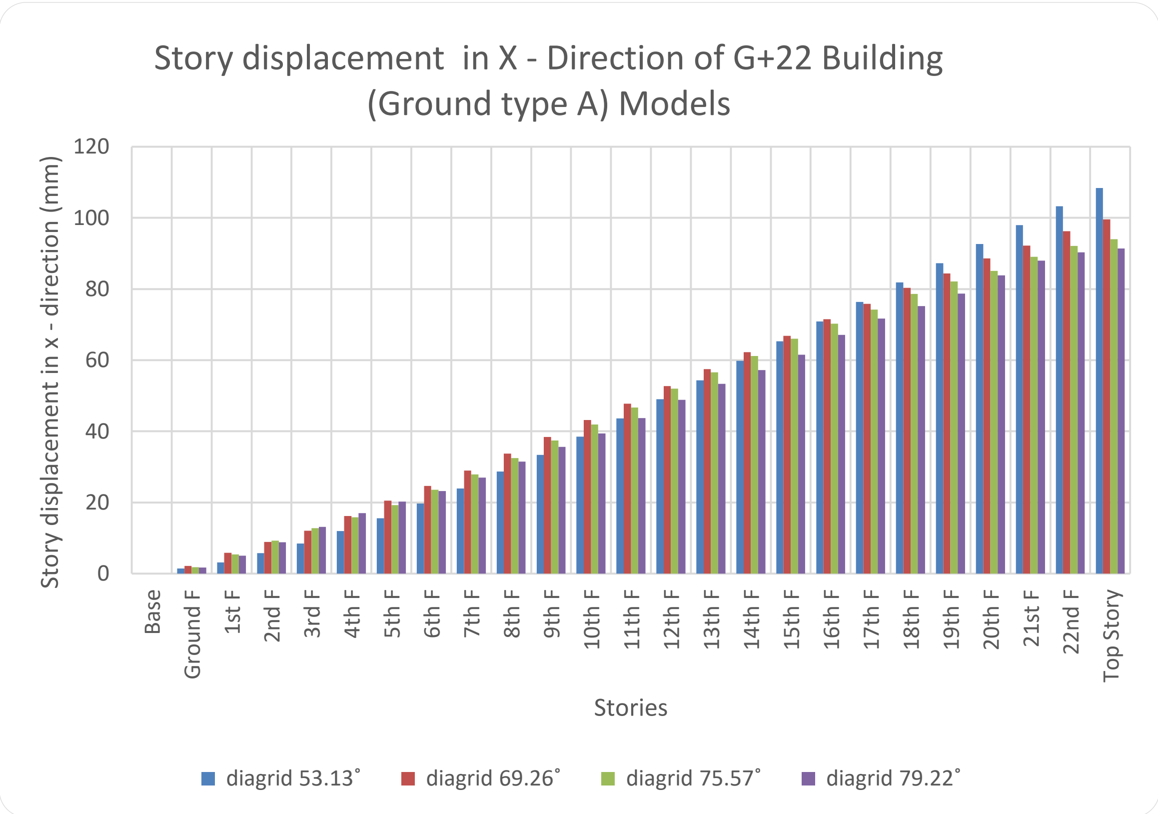


Figure 4-9: Story displacement of G+22 Building (Ground type A) Models in X – direction

❖ G+10 building (Ground type C)

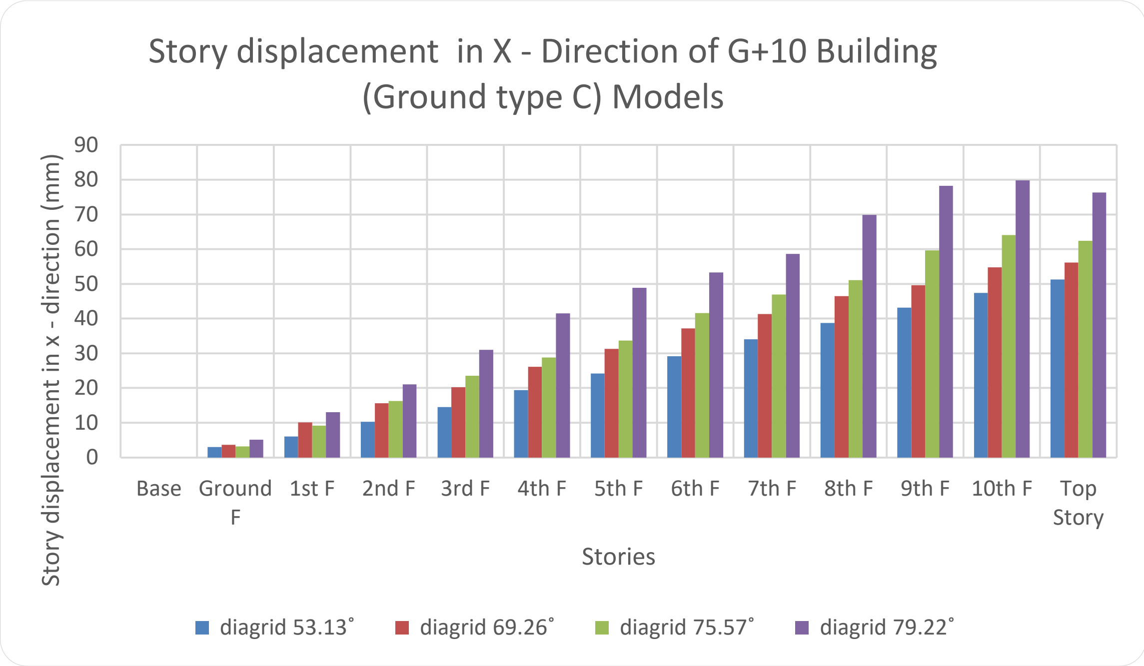


Figure 4-10: Story displacement of G+10 Building (Ground type C) Models in X - direction

❖ G+16 building (Ground type C)

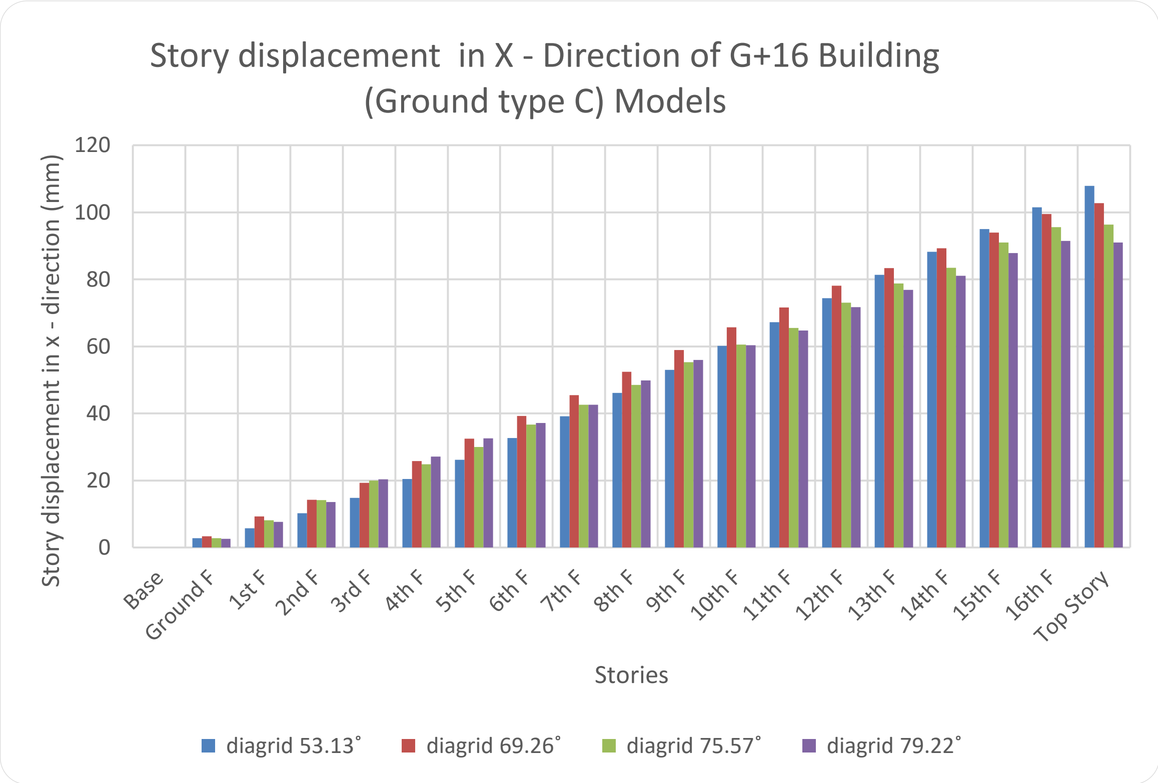


Figure 4-11: Story displacement of G+16 Building (Ground type C) Models in X – direction

❖ G+22 building (Ground type C)

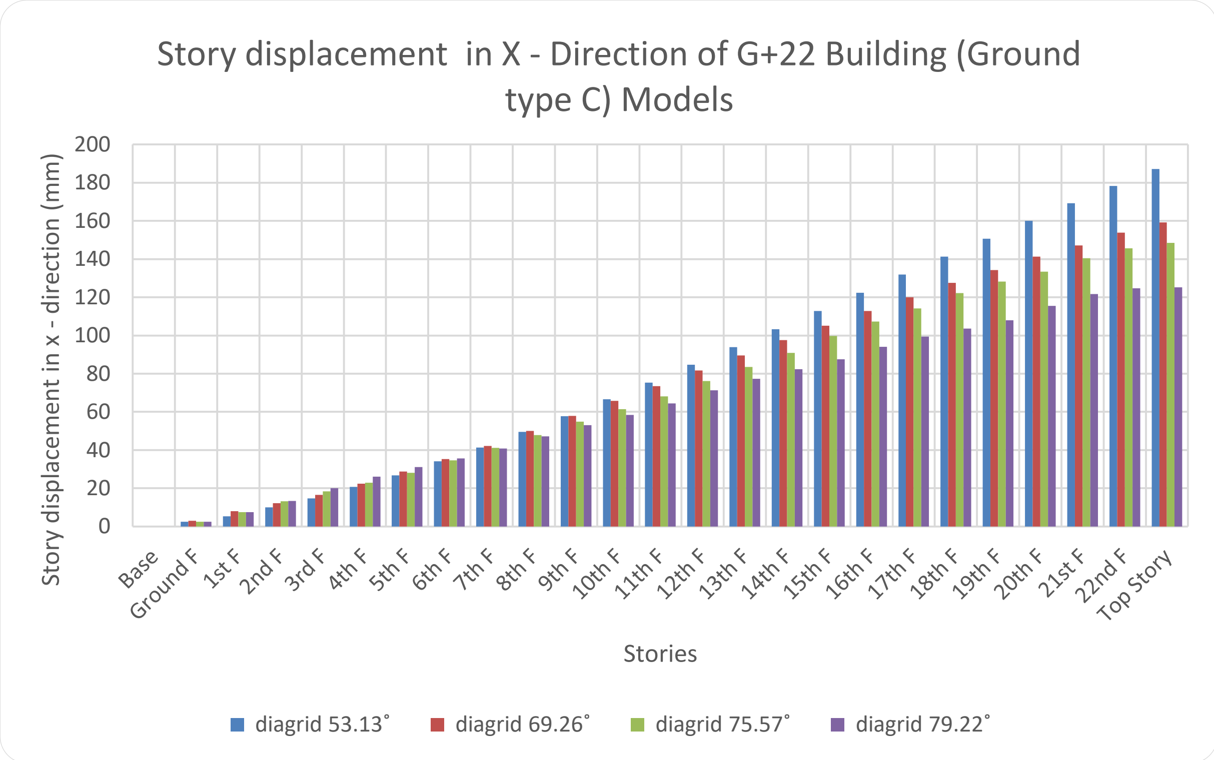


Figure 4-12: Story displacement of G+22 Building (Ground type C) Models in X – direction

❖ **Summarized discussion on story displacement in X - Direction**

Table 4-7: Top Story Displacement of G+10, G+16 and G+22 Building (Ground type A & C) Models in X – direction

Case	Model	Top Story displacement in X – direction (mm)	% reduction in top story displacement in X-dxn compared to 69.26˚
	G+10 Building (Ground type A)		
1	Diagrid with module angle 53.13˚	29.76	10
2	Diagrid with module angle 69.26˚	32.584	0
3	Diagrid with module angle 75.57˚	39.861	-19
4	Diagrid with module angle 79.22˚	40.398	-20
	G+16 Building (Ground type A)		
1	Diagrid with module angle 53.13˚	62.567	-3

2	Diagrid with module angle 69.26˚	61.243	0
3	Diagrid with module angle 75.57˚	67.061	-9
4	Diagrid with module angle 79.22˚	62.064	-2
	G+22 Building (Ground type A)		
1	Diagrid with module angle 53.13˚	108.436	-9
2	Diagrid with module angle 69.26˚	99.564	0
3	Diagrid with module angle 75.57˚	94.036	6
4	Diagrid with module angle 79.22˚	91.371	9
	G+10 Building (Ground type C)		
1	Diagrid with module angle 53.13˚	51.307	10
2	Diagrid with module angle 69.26˚	56.143	0
3	Diagrid with module angle 75.57˚	62.392	-11
4	Diagrid with module angle 79.22˚	76.348	-27
	G+16 Building (Ground type C)		
1	Diagrid with module angle 53.13˚	107.886	-5
2	Diagrid with module angle 69.26˚	102.764	0
3	Diagrid with module angle 75.57˚	96.366	7
4	Diagrid with module angle 79.22˚	91.023	13
	G+22 Building (Ground type C)		
1	Diagrid with module angle 53.13˚	187.253	-15
2	Diagrid with module angle 69.26˚	159.226	0
3	Diagrid with module angle 75.57˚	148.539	8
4	Diagrid with module angle 79.22˚	125.275	28

Referring to the above summary table 4.7. the right column has shown the compared percentage of each diagrid angle with diagrid angle 69.26˚, based on Kim and Lee (2012) study regarding nonlinear static and time-history dynamic behavior of diagrids, this research considered their recommended a diagonal angle, which is, between 60˚ - 70˚ as the most advantageous angle for most diagrid structures.

Hence, for the total of 24 models top story displacement of G+10, G+16 and G+22 story buildings, for ground type A & C in X – direction, a two story module or module diagrid angle 53.13˚ has shown a better top displacement reduction for G+10 story building for both ground type (A and C). whereas, diagrid angle 69.26˚ has shown a better top displacement reduction for G+16 story building for ground type A and diagrid angle 79.22˚ has shown a better top displacement reduction for G+22 story building in both ground types (A & C) and G+16 story building in ground type C.

b) **Story displacement in Y – direction**

❖ G+10 building (Ground type A)

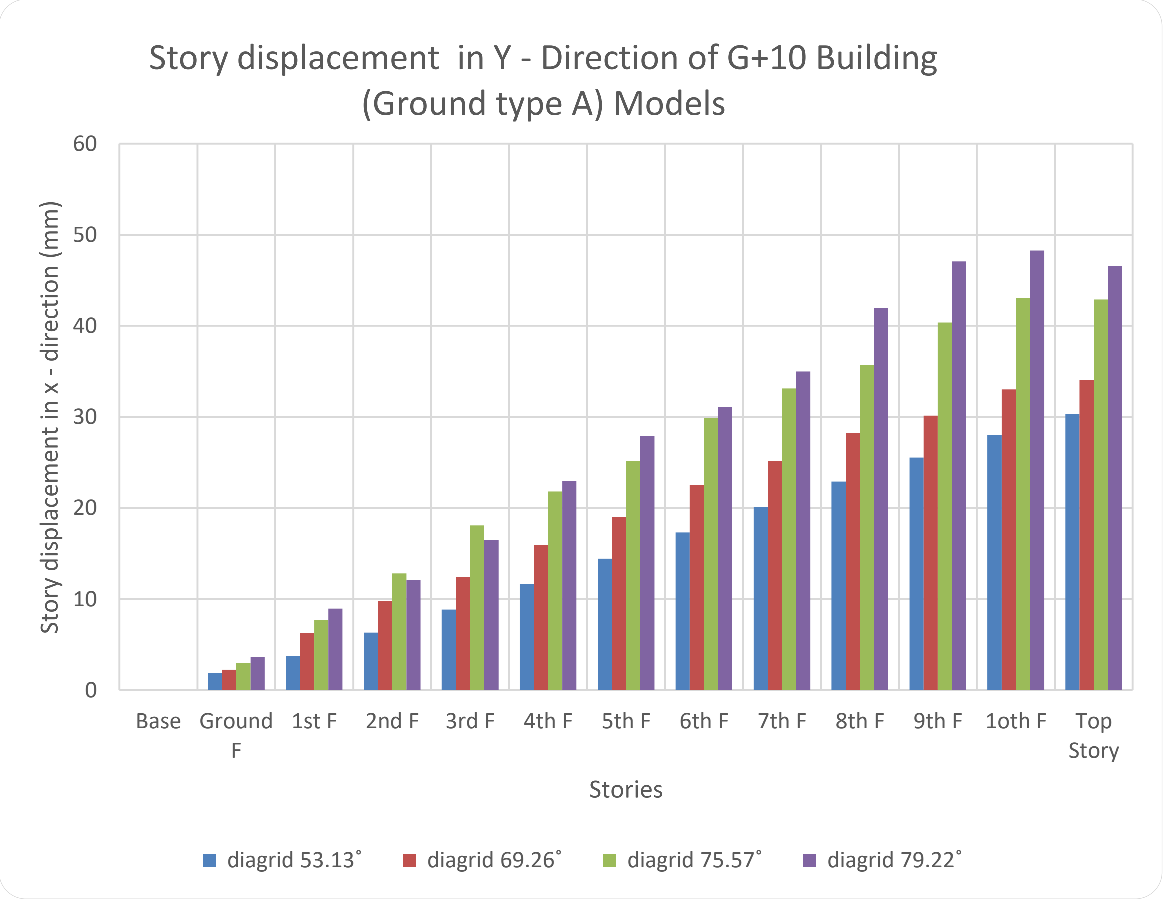


Figure 4-13: Story displacement of G+10 Building (Ground type A) Models in Y - direction

❖ G+16 building (Ground type A)

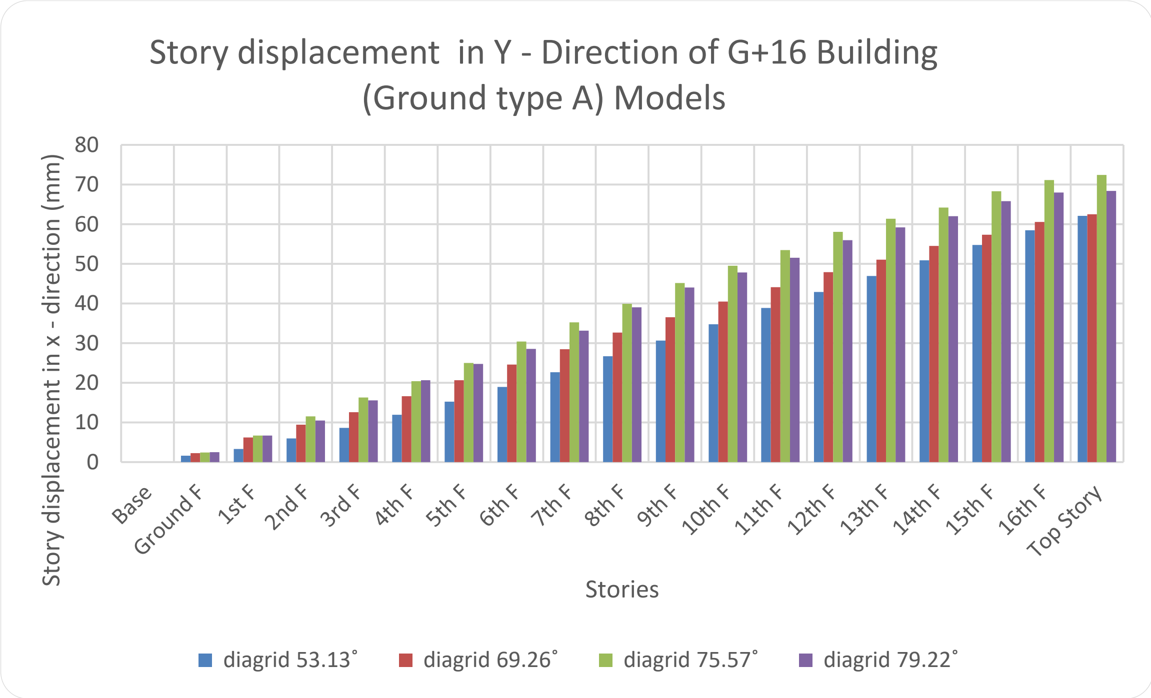


Figure 4-14: Story displacement of G+16 Building (Ground type A) Models in Y – direction

❖ G+22 building (Ground type A)

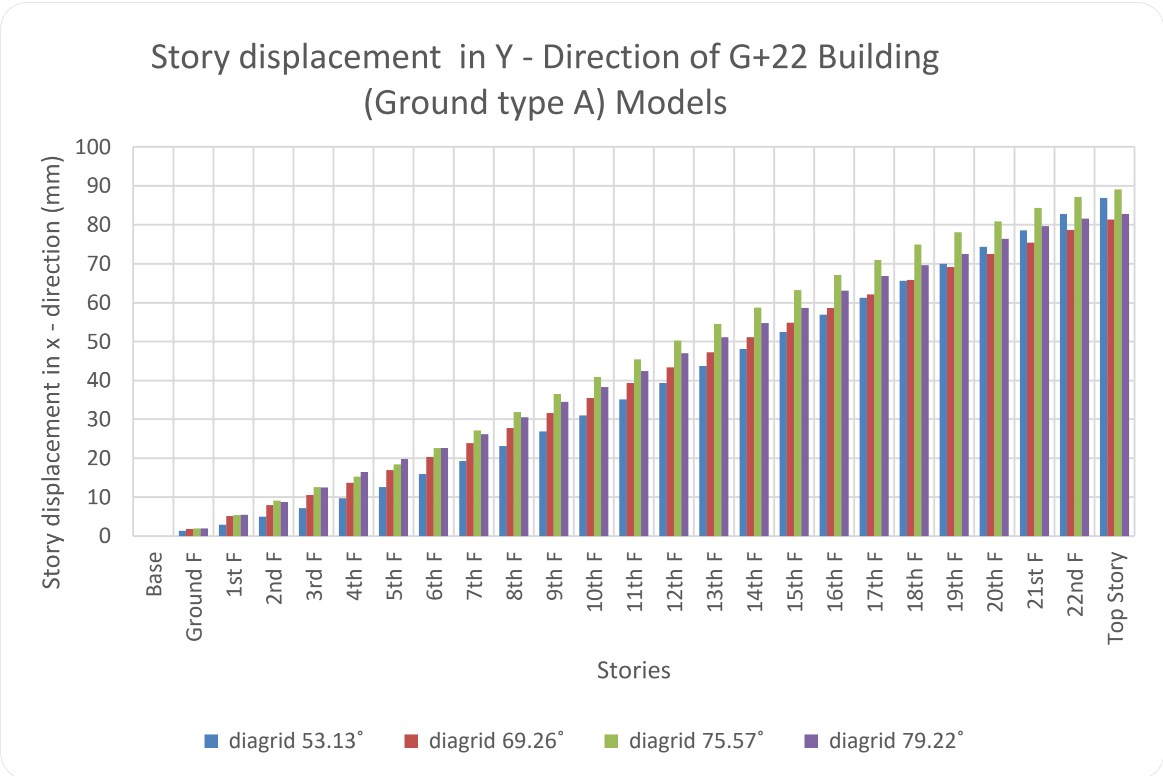


Figure 4-15: Story displacement of G+22 Building (Ground type A) Models in Y – direction

❖ G+10 building (Ground type C)

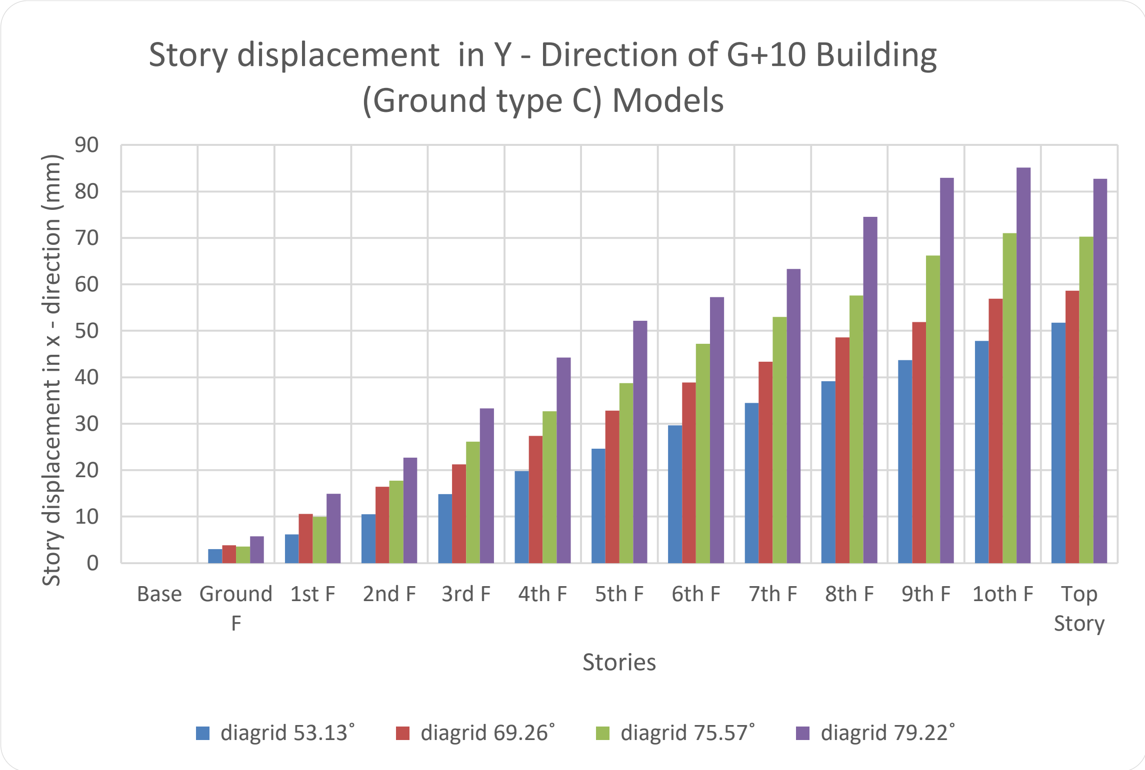


Figure 4-16: Story displacement of G+10 Building (Ground type C) Models in Y – direction

❖ G+16 building (Ground type C)

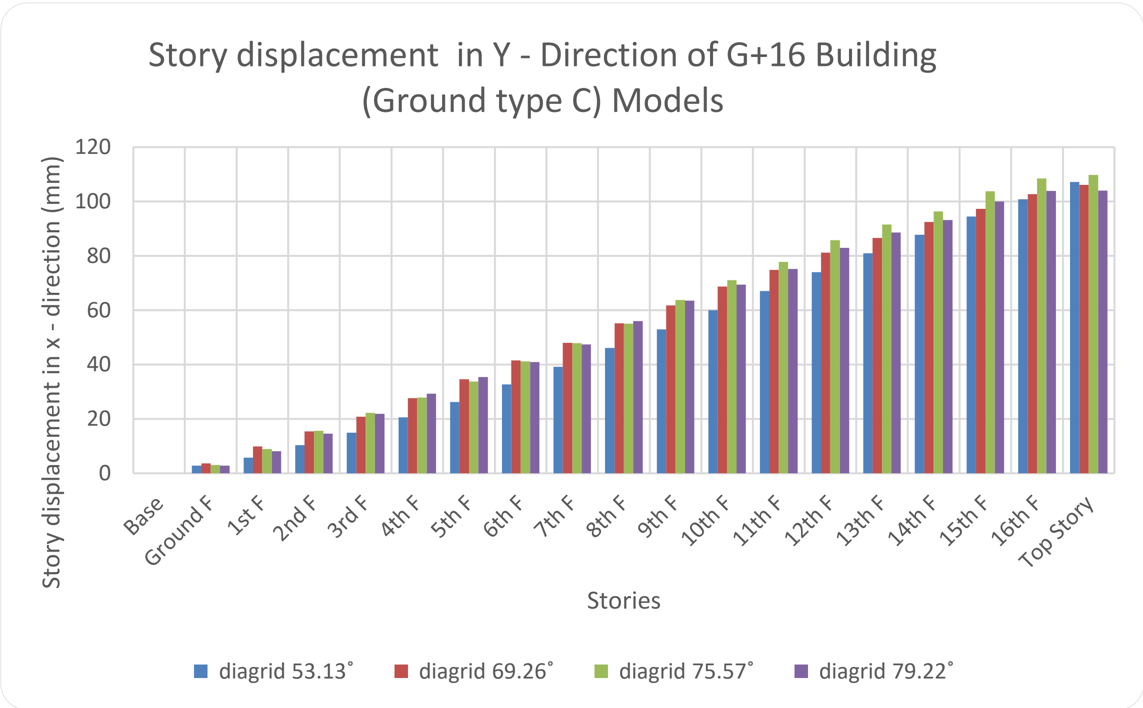


Figure 4-17: Story displacement of G+16 Building (Ground type C) Models in Y – direction

❖ G+22 building (Ground type C)

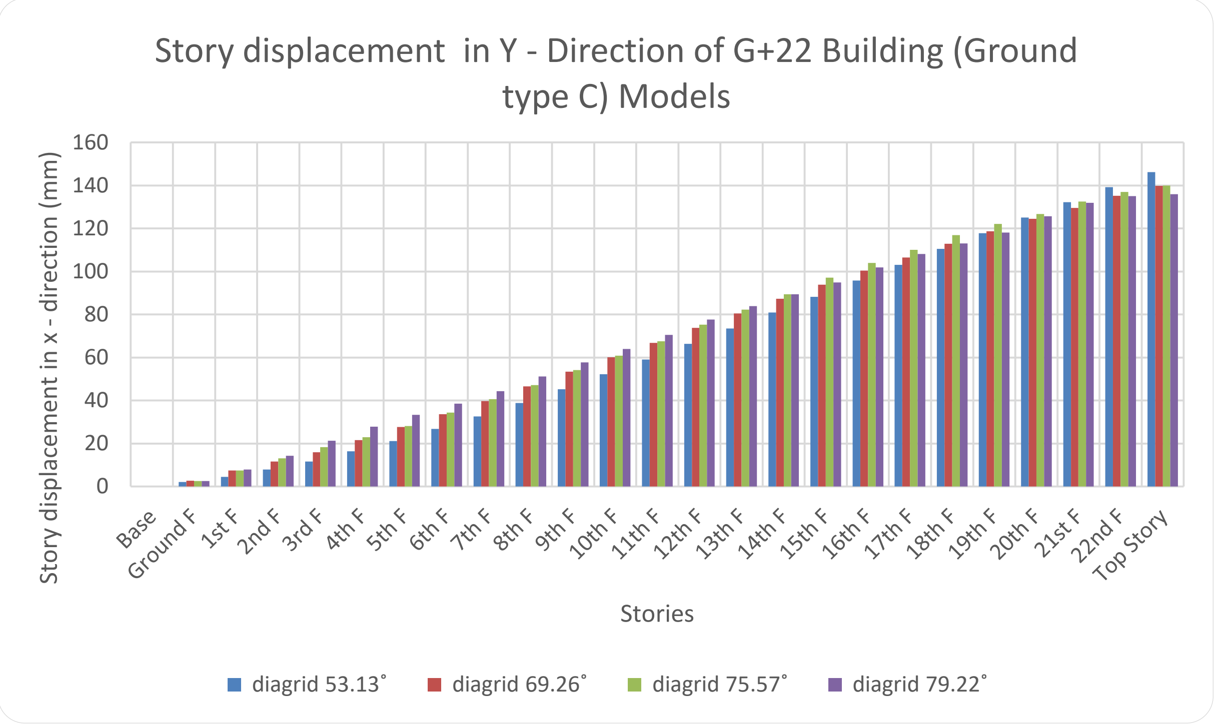


Figure 4-18: Story displacement of G+22 Building (Ground type C) Models in Y – direction

❖ **Summarized discussion on story displacement in Y - Direction**

Table 4-8: Top Story Displacement of G+10, G+16 and G+22 Building (Ground type A & C) Models in Y – direction

Case	Model	Top Story displacement in Y - direction	% reduction in top story displacement in Y - dxn compared to 69.26˚
	G+10 Building (Ground type A)		
1	Diagrid with module angle 53.13˚	30.309	13
2	Diagrid with module angle 69.26˚	34.042	0
3	Diagrid with module angle 75.57˚	42.904	-21
4	Diagrid with module angle 79.22˚	46.602	-27
	G+16 Building (Ground type A)		
1	Diagrid with module angle 53.13˚	62.151	1

2	Diagrid with module angle 69.26˚	62.563	0
3	Diagrid with module angle 75.57˚	72.435	-14
4	Diagrid with module angle 79.22˚	68.434	-9
	G+22 Building (Ground type A)		
1	Diagrid with module angle 53.13˚	86.908	-7
2	Diagrid with module angle 69.26˚	81.368	0
3	Diagrid with module angle 75.57˚	89.119	-9
4	Diagrid with module angle 79.22˚	82.733	-2
	G+10 Building (Ground type C)		
1	Diagrid with module angle 53.13˚	51.727	14
2	Diagrid with module angle 69.26˚	58.626	0
3	Diagrid with module angle 75.57˚	70.268	-17
4	Diagrid with module angle 79.22˚	82.765	-30
	G+16 Building (Ground type C)		
1	Diagrid with module angle 53.13˚	107.147	-1
2	Diagrid with module angle 69.26˚	106.089	0
3	Diagrid with module angle 75.57˚	109.807	-4
4	Diagrid with module angle 79.22˚	104.059	2
	G+22 Building (Ground type C)		
1	Diagrid with module angle 53.13˚	146.264	-5
2	Diagrid with module angle 69.26˚	139.826	0
3	Diagrid with module angle 75.57˚	139.946	-1
4	Diagrid with module angle 79.22˚	135.988	3

Referring to the above summary table 4.8. the right column has shown the compared percentage of each diagrid angle with diagrid angle 69.26˚, based on Kim and Lee (2012) study regarding nonlinear static and time-history dynamic behavior of diagrids, this research considered their recommended a diagonal angle, which is, between 60˚ - 70˚ as the most advantageous angle for most diagrid structures.

Hence, for the total of 24 model's top story displacement of G+10, G+16 and G+22 story buildings, for ground type A & C in Y – direction, a two story module or module diagrid angle 53.13˚ has shown a better top displacement reduction for G+10 story building for both ground type (A and C). whereas, diagrid angle 69.26˚ has shown a better top displacement reduction for G+16 story building for ground type A and diagrid angle 79.22˚ has shown a better top displacement reduction for G+22 story building in both ground types (A & C) and G+16 story building in ground type C.

4.1.3. Inter story drift

Lateral deflection is the predicted movement of a structure under lateral loads: and story drift is defined as the difference in lateral deflection between two adjacent stories. During an earthquake. If proper consideration is not taken during the design process, large deflections and drifts can have adverse effects on structural elements, nonstructural elements and adjacent structures.

The system performance levels of multistory building are evaluated on the basis of inter-story drift values along the height of the building under different levels of earthquake motion. Inter-story drift is defined as the ratio of relative horizontal displacement of two adjacent floors (δ) and corresponding story height (h).

$$\text{Inter-story drift} = \frac{\delta_i - \delta_{i-1}}{h}$$

As per ESEN1998-1:2015 inter-story drift is evaluated as the difference of the average lateral displacement δ at the top and bottom of the story under consideration. For building having non-structural elements of brittle materials attached to the structure the code provides the following inter-story drift limit.

$d_r\, v \leq 0.005h$, Where, d_r is the design inter-story drift and h is the story 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 v are 0.4 for important classes III and IV and v = 0.5 for importance classes I and II.

Therefore, the drift limitation for this study has been used,

$d_r \leq 0.005h/0.5 = 0.01h$

For the G+10 story, the drift limitation, d_r has been used = 0.48

For the G+16 story, the drift limitation, d_r has been used = 0.72

For the G+22 story, the drift limitation, d_r has been used = 0.96

a) Inter-story drift in X – direction

❖ G+10 building (Ground type A)

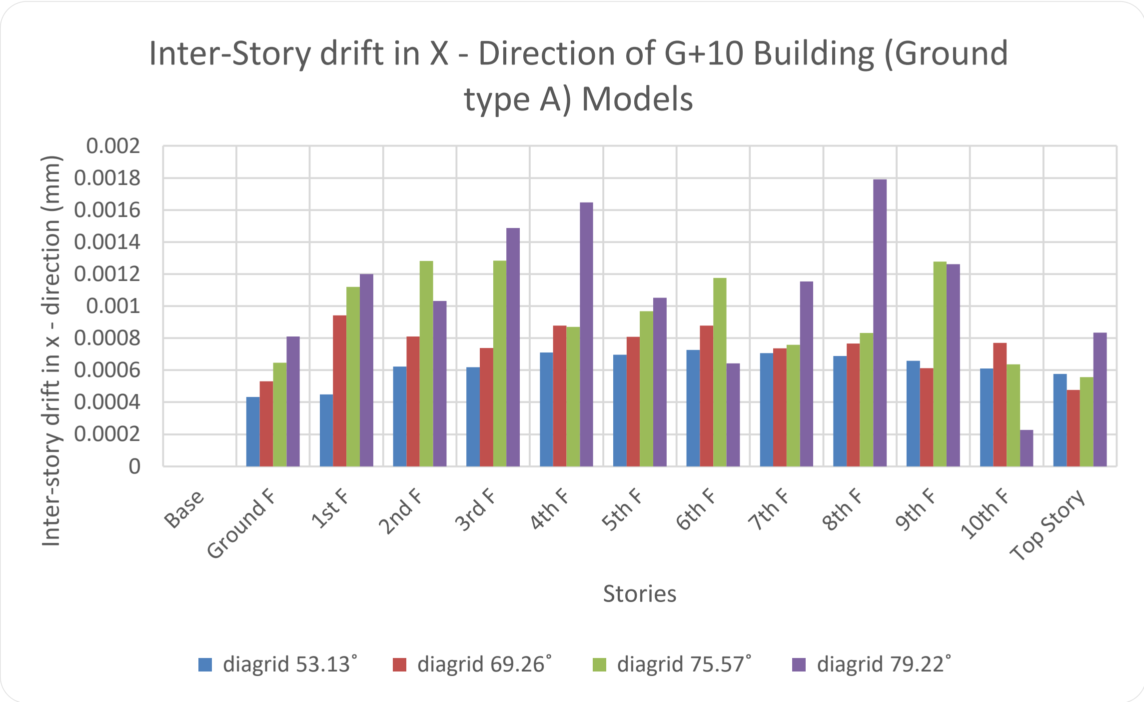


Figure 4-19: Inter-story drift of G+10 Building (Ground type A) Models in X – direction

❖ G+16 building (Ground type A)

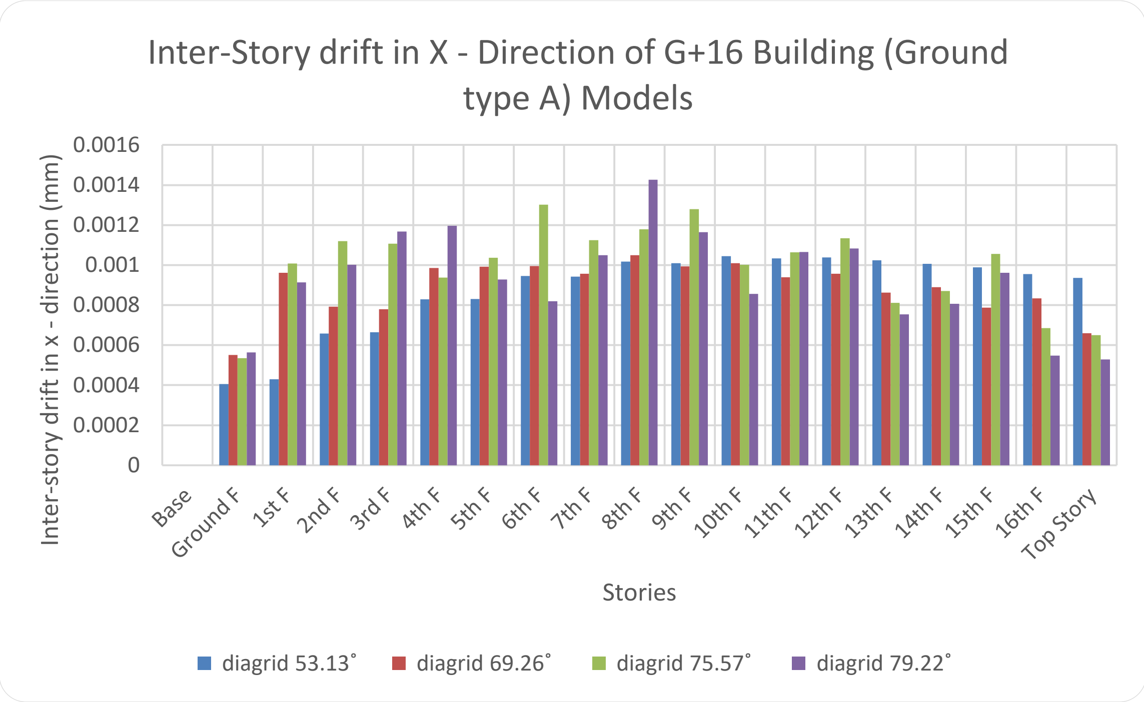


Figure 4-20: Inter-story drift of G+16 Building (Ground type A) Models in X – direction

❖ G+22 building (Ground type A)

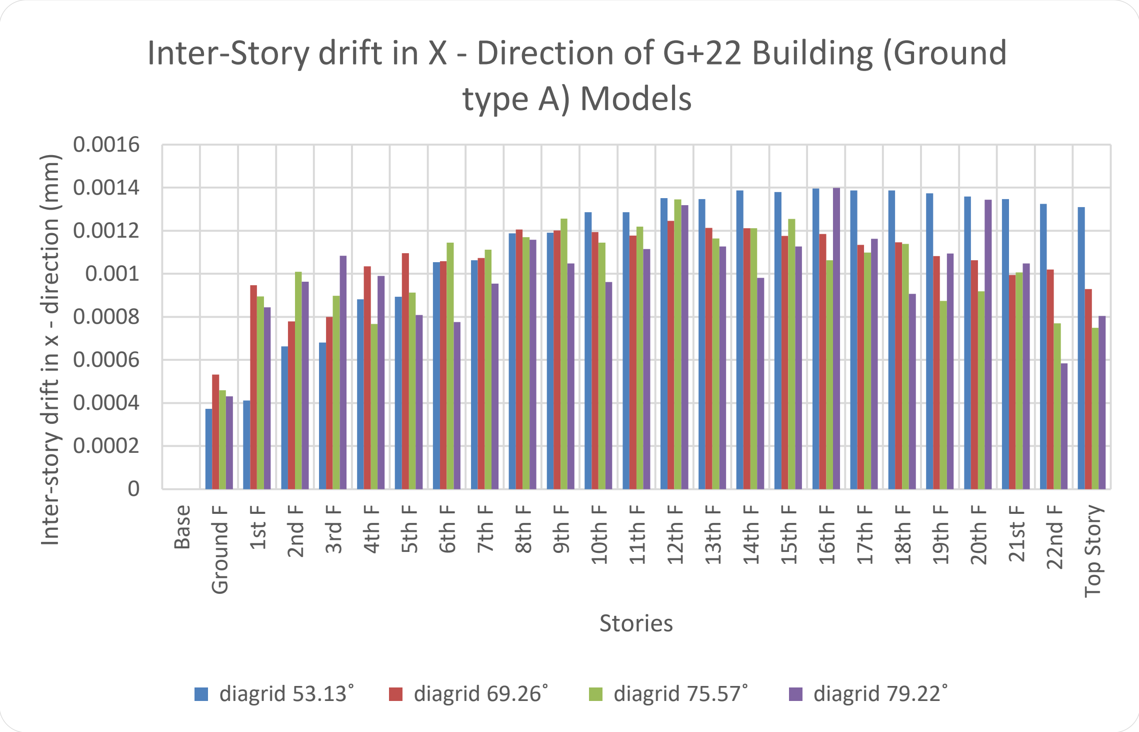


Figure 4-21. Inter-story drift of G+22 Building (Ground type A) Models in X – direction

❖ G+10 building (Ground type C)

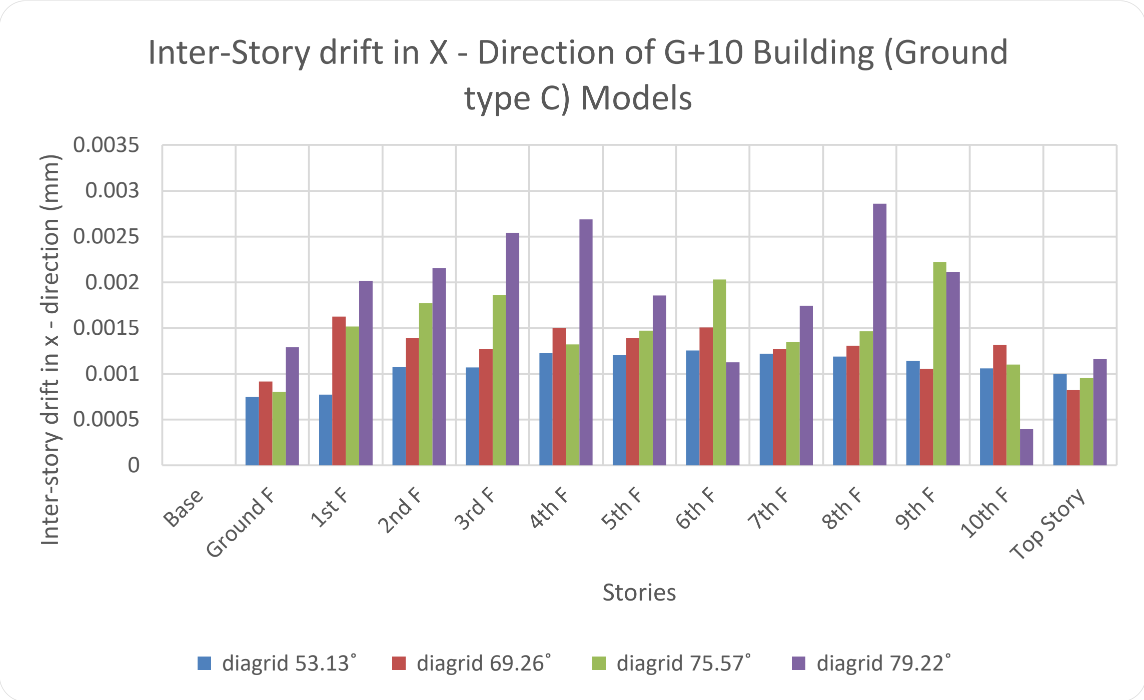


Figure 4-22: Inter-story drift of G+10 Building (Ground type C) Models in X – direction

❖ G+16 building (Ground type C)

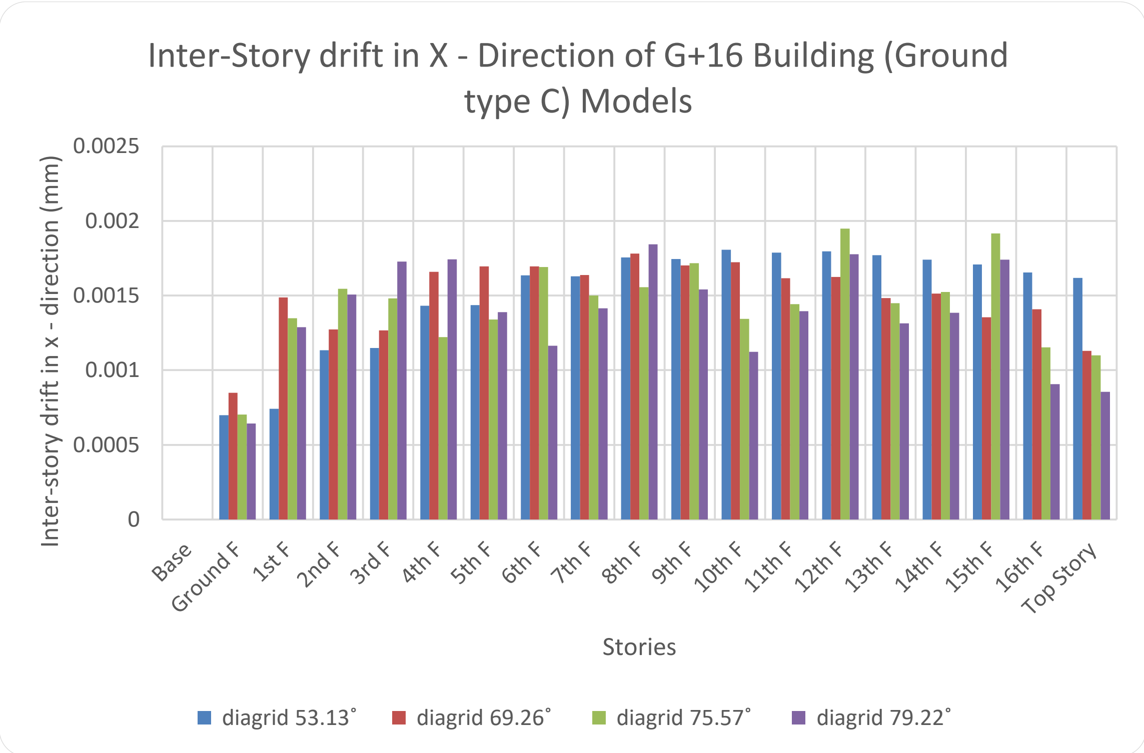


Figure 4-23: Inter-story drift of G+16 Building (Ground type C) Models in X – direction

❖ G+22 building (Ground type C)

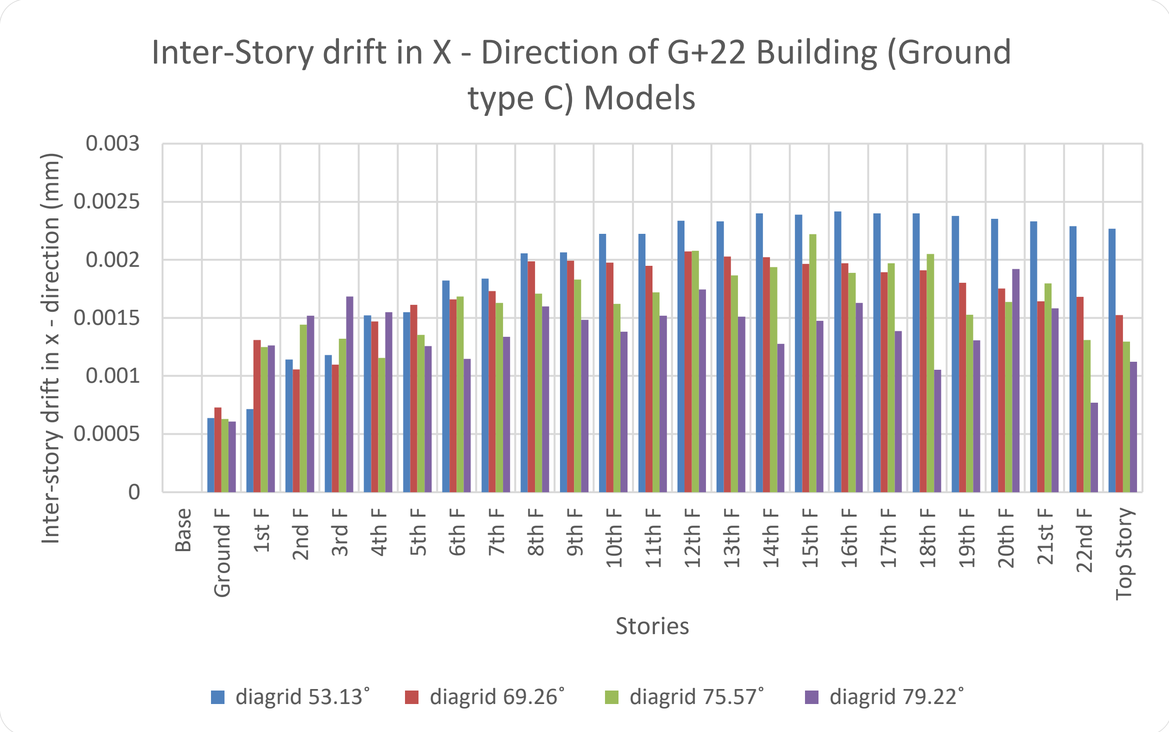


Figure 4-24: Inter-story drift of G+22 Building (Ground type C) Models in X – direction

❖ **Summarized discussion on Inter-story drift in X - Direction**

Table 4-9: Maximum Inter-story drift of G+10, G+16 and G+22 Building (Ground type A & C) Models in X - direction

Case	Model	MAX Inter-story drift in X -direction	% reduction in max inter-story drift in X-dxn compared to 69.26˚
	G+10 Building (Ground type A)		
1	Diagrid with module angle 53.13˚	0.000727	30
2	Diagrid with module angle 69.26˚	0.000943	0
3	Diagrid with module angle 75.57˚	0.001284	-27
4	Diagrid with module angle 79.22˚	0.001791	-48
	G+16 Building (Ground type A)		

1	Diagrid with module angle 53.13˚	0.001045	1
2	Diagrid with module angle 69.26˚	0.001049	0
3	Diagrid with module angle 75.57˚	0.001302	-20
4	Diagrid with module angle 79.22˚	0.001427	-27
	G+22 Building (Ground type A)		
1	Diagrid with module angle 53.13˚	0.001396	-11
2	Diagrid with module angle 69.26˚	0.001246	0
3	Diagrid with module angle 75.57˚	0.001345	-8
4	Diagrid with module angle 79.22˚	0.001398	-11
	G+10 Building (Ground type C)		
1	Diagrid with module angle 53.13˚	0.001255	30
2	Diagrid with module angle 69.26˚	0.001626	0
3	Diagrid with module angle 75.57˚	0.002221	-27
4	Diagrid with module angle 79.22˚	0.00286	-44
	G+16 Building (Ground type C)		
1	Diagrid with module angle 53.13˚	0.001807	-2
2	Diagrid with module angle 69.26˚	0.001782	0
3	Diagrid with module angle 75.57˚	0.001948	-9
4	Diagrid with module angle 79.22˚	0.001843	-4
	G+22 Building (Ground type C)		
1	Diagrid with module angle 53.13˚	0.002416	-15
2	Diagrid with module angle 69.26˚	0.002073	0
3	Diagrid with module angle 75.57˚	0.002222	-7
4	Diagrid with module angle 79.22˚	0.00192	8

Referring to the above summary table 4.9. the right column has shown the compared percentage of each diagrid angle with diagrid angle 69.26˚, based on Kim and Lee (2012) study regarding nonlinear static and time-history dynamic behavior of diagrids, this research considered their recommended a diagonal angle, which is, between 60˚ - 70˚ as the most advantageous angle for most diagrid structures.

Hence, for the total of 24 model's Inter-story drift of G+10, G+16 and G+22 story buildings, for ground type A & C in X – direction, a two story module or module diagrid angle 53.13˚ has shown a better Inter-story drift reduction for G+10 story building for both ground type (A and C) and for G+16 story building for ground type A. whereas, diagrid angle 69.26˚ has shown a better top displacement reduction for G+22 story building for ground type A and for G+16 story building for ground type C. diagrid angle 79.22˚ has also shown a better top displacement reduction for G+22 story building for ground type C.

b) Inter-story drift in Y – direction

❖ G+10 building (Ground type A)

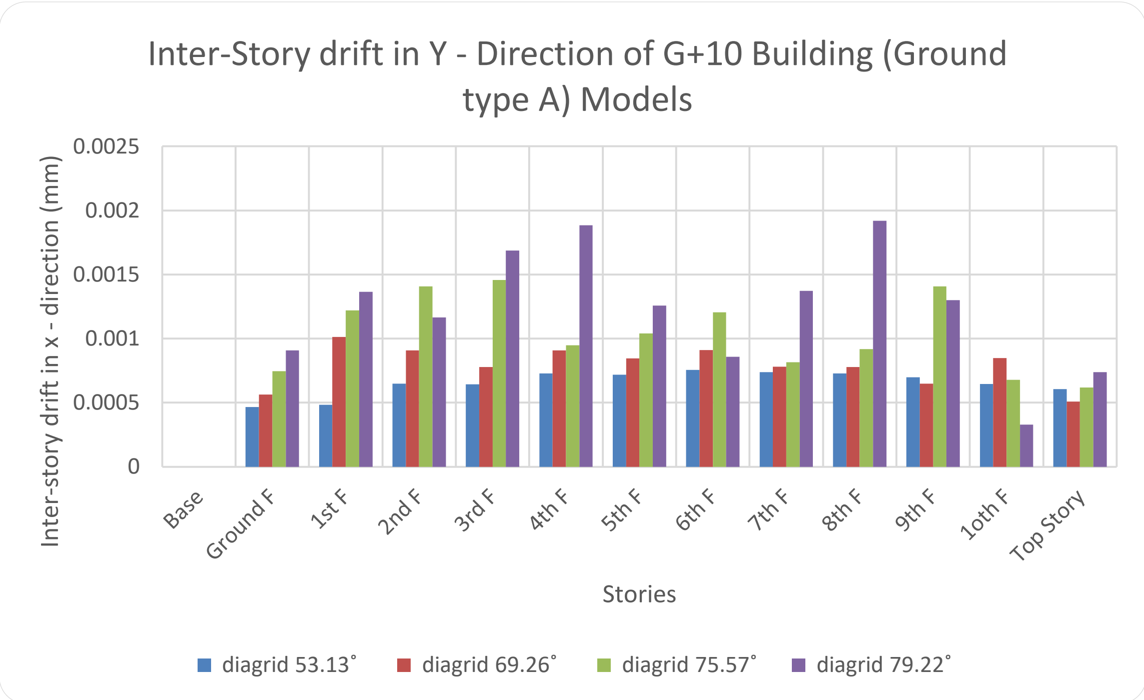


Figure 4-25: Inter-story drift of G+10 Building (Ground type A) Models in Y – direction

❖ G+16 building (Ground type A)

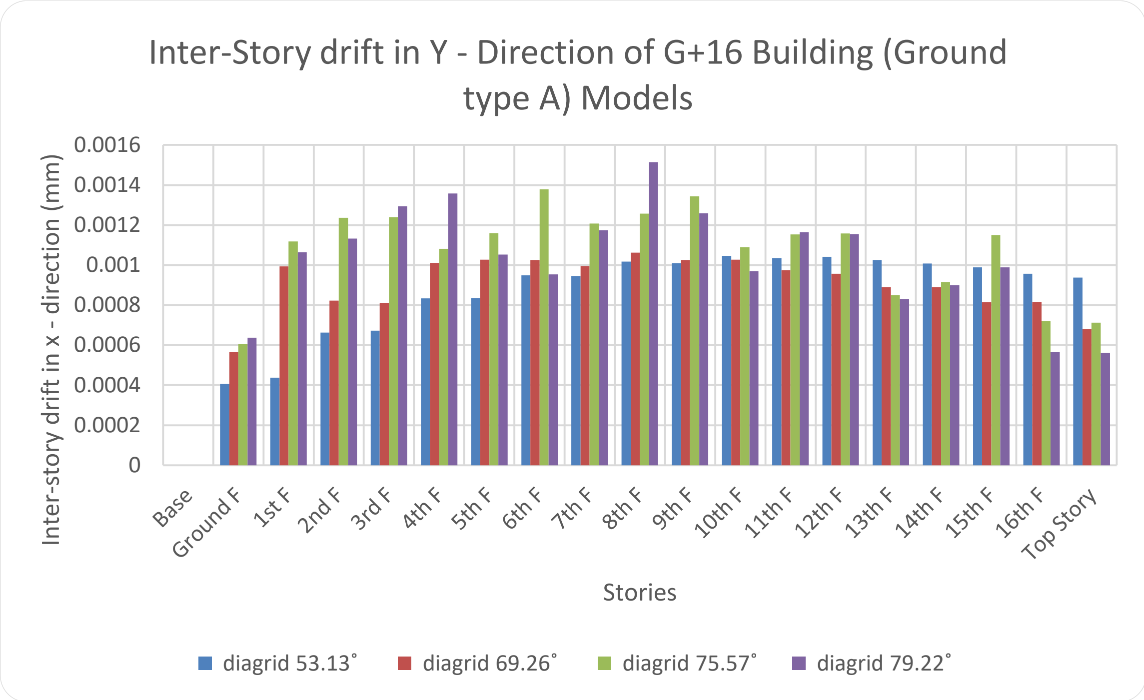


Figure 4-26: Inter-story drift of G+16 Building (Ground type A) Models in Y – direction

❖ G+22 building (Ground type A)

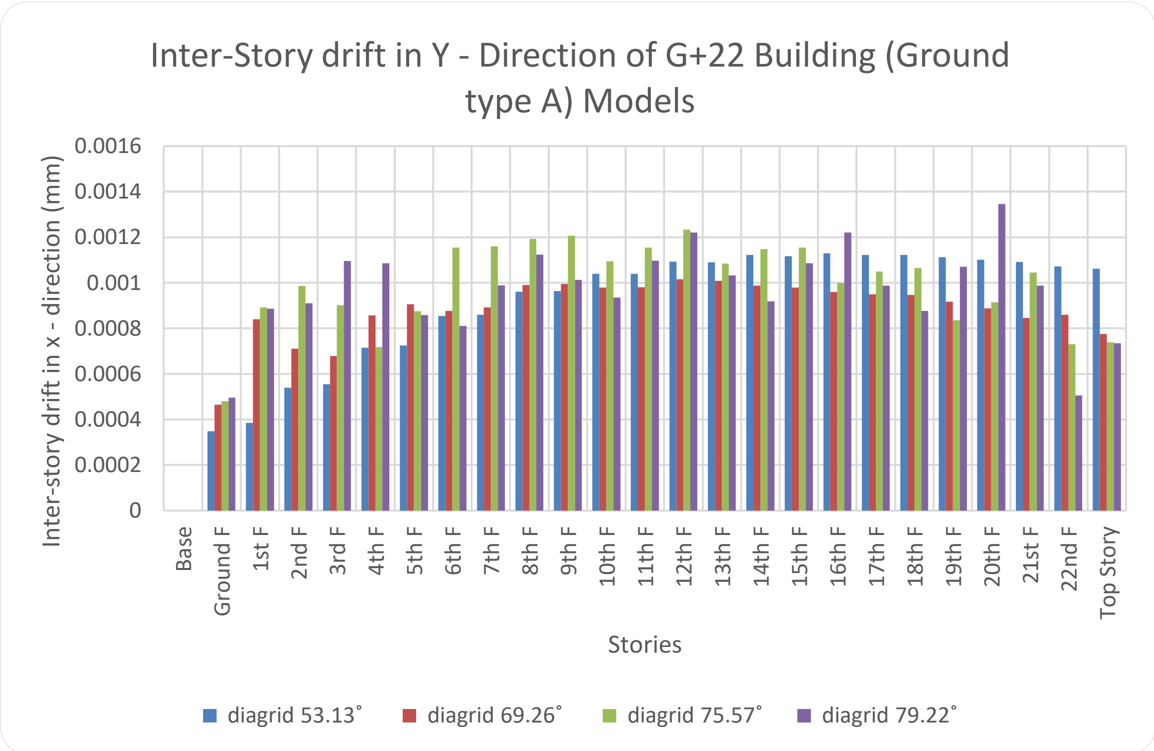


Figure 4-27: Inter-story drift of G+22 Building (Ground type A) Models in Y – direction

❖ G+10 building (Ground type C)

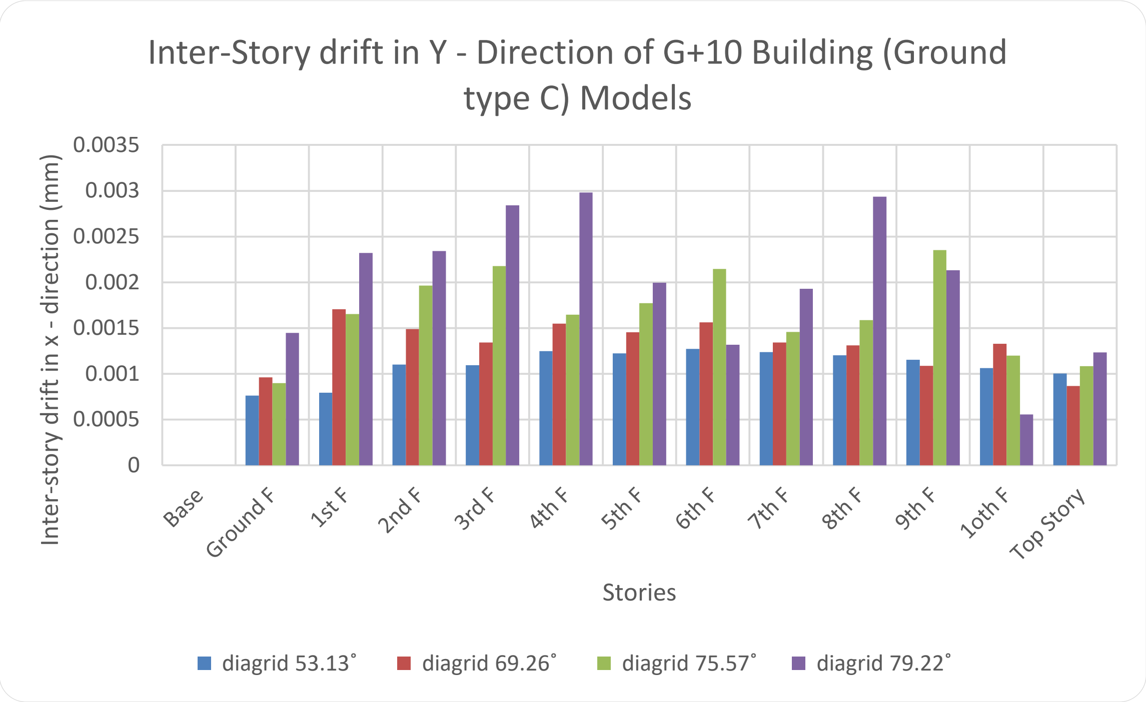


Figure 4-28: Inter-story drift of G+10 Building (Ground type C) Models in Y – direction

❖ G+16 building (Ground type C)

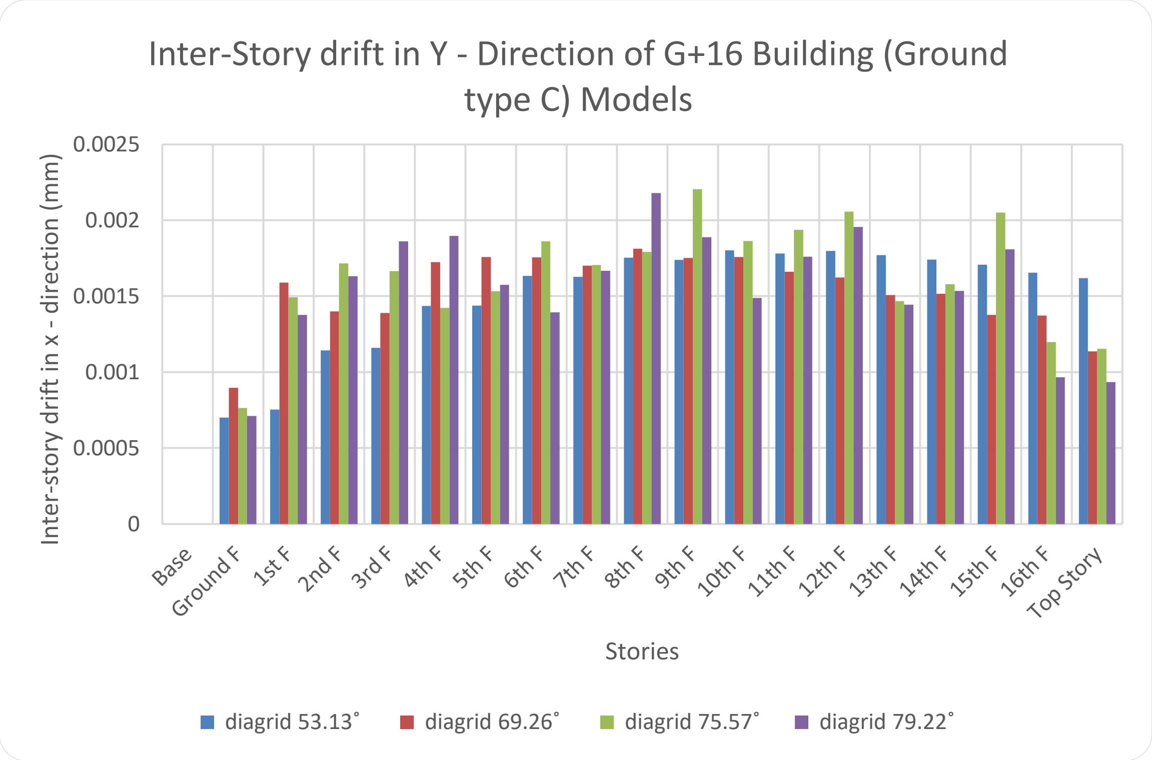


Figure 4-29: Inter-story drift of G+16 Building (Ground type C) Models in Y – direction

❖ G+22 building (Ground type C)

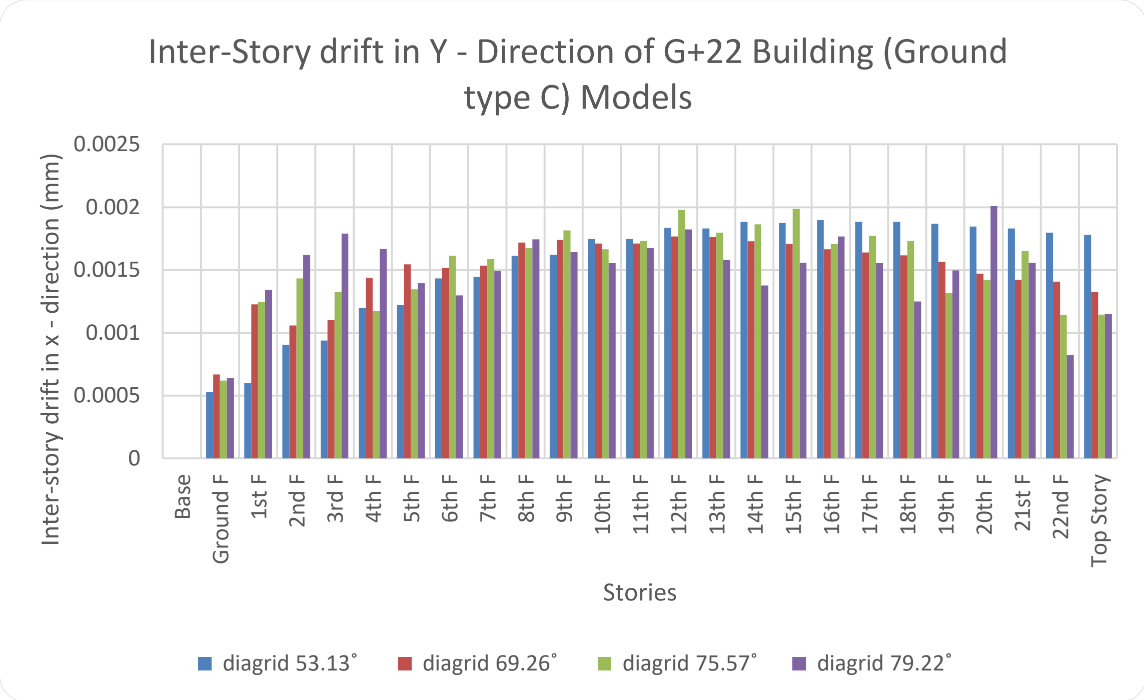


Figure 4-30: Inter-story drift of G+22 Building (Ground type C) Models in Y – direction

❖ Summarized discussion on Inter-story drift in Y - Direction

Table 4-10: Maximum Inter-story drift of G+10, G+16 and G+22 Building (Ground type A & C) Models in Y - direction

Case	Model	MAX Inter-story drift in Y -direction	% reduction in max inter-story drift in Y-dxn compared to 69.26˚
	G+10 Building (Ground type A)		
1	Diagrid with module angle 53.13˚	0.000756	35
2	Diagrid with module angle 69.26˚	0.001014	0
3	Diagrid with module angle 75.57˚	0.001458	-31
4	Diagrid with module angle 79.22˚	0.00192	-48
	G+16 Building (Ground type A)		
1	Diagrid with module angle 53.13˚	0.001047	2

2	Diagrid with module angle 69.26˚	0.001063	0
3	Diagrid with module angle 75.57˚	0.001378	-23
4	Diagrid with module angle 79.22˚	0.001514	-30
	G+22 Building (Ground type A)		
1	Diagrid with module angle 53.13˚	0.00113	-11
2	Diagrid with module angle 69.26˚	0.001015	0
3	Diagrid with module angle 75.57˚	0.001233	-18
4	Diagrid with module angle 79.22˚	0.001346	-25
	G+10 Building (Ground type C)		
1	Diagrid with module angle 53.13˚	0.001271	35
2	Diagrid with module angle 69.26˚	0.001706	0
3	Diagrid with module angle 75.57˚	0.002352	-28
4	Diagrid with module angle 79.22˚	0.002982	-43
	G+16 Building (Ground type C)		
1	Diagrid with module angle 53.13˚	0.001802	1
2	Diagrid with module angle 69.26˚	0.001813	0
3	Diagrid with module angle 75.57˚	0.002205	-18
4	Diagrid with module angle 79.22˚	0.002178	-17
	G+22 Building (Ground type C)		
1	Diagrid with module angle 53.13˚	0.001897	-7
2	Diagrid with module angle 69.26˚	0.001767	0
3	Diagrid with module angle 75.57˚	0.001987	-12
4	Diagrid with module angle 79.22˚	0.002009	-13

Referring to the above summary table 4.10. the right column has shown the compared percentage of each diagrid angle with diagrid angle 69.26˚, based on Kim and Lee (2012) study regarding nonlinear static and time-history dynamic behavior of diagrids, this research considered their recommended a diagonal angle, which is, between 60˚ - 70˚ as the most advantageous angle for most diagrid structures.

Hence, for the total of 24 model's Maximum Inter-story drift of G+10, G+16 and G+22 story buildings, for ground type A & C in Y – direction, a two story module or module diagrid angle 53.13˚ has shown a better Inter-story drift reduction for G+10 and G+16 story buildings for both ground type (A & C). whereas, diagrid angle 69.26˚ has shown a better top displacement reduction for G+22 story building for both ground types A and C.

CHAPTER FIVE

CONCLUSSION AND RECOMENDATIONS

5.1. Summary of the work

This research paper mainly focused on the seismic performance of three different stories (G+10, G+16 and G+22) with different diagrid angle (53.13˚, 69.26˚, 75.57˚ & 79.22˚) in two ground type (A & C). the results from the twenty-four model cases were compared to verify the structural efficiency with different structural configuration using design response spectrum analysis in ETABS 2016 v16.2.1 software for steel diagrid in reinforced concrete building.

The analysis and design of these twenty-four (24) models of diagrid structures followed the basic steps and approaches that are operational and practical in real world. Proposed diagrid structure cases were to be situated in Hawassa, whose seismic zone is categorized under Zone IV according to the ES EN 1998-1:2015 annex D Table. The lateral load analysis of the study has been based on the new code ES EN 1998-1:2015. The analysis has been done using finite element software ETABS 2016 v16.2.1. The performance evaluation of these twenty-four case studies of diagrid buildings is mainly based on linear analysis parameters, such as Fundamental vibration period, story displacement and inter-story drift.

5.2. Conclusion

Based on the model building cases considered in this study the following specific conclusions has been made according to the linear (response spectrum) analysis results and comparative study,

- Results from the linear analysis showed that Diagrid structure has difference fundamental vibration period, story displacement and inter-story drift based on their module angles considered in this study. From the total of twenty-four of G+10, G+16 and G+22 story buildings, for ground type A & C with four different module angles, a two story module or module diagrid angle 53.13˚ has shown a smaller top displacement, smaller inter-story drift and smaller fundamental time period for G+10 story building. Whereas module diagrid angle 69.26˚ and79.22˚ has shown a smaller top displacement, smaller inter-story drift and smaller fundamental time period for G+16 and G+22 story buildings respectively.

Therefore, according to the linear analysis results and comparative study of this thesis can concluded that for a better and significantly good performance, finding the optimal module angle with respect to height to width aspect ratio is very recommendable.

5.3. Recommendation

This case study of three different story (G+10, G+16 and G+22) diagrid buildings are a good start point for further researches that will cover uncertainties traced in this study. The following recommendations are given based on the results of the study that has been carried out;

- ❖ In this study design and detailing of Nodes is not included, a detail analytical and Experimental study should consideration further investigation.

- ❖ The diagrid structure used in this study is steel H-Sections; however Concrete diagrid structures also could be investigated in future study.

- ❖ Behavior factors for these diagrid structures are not suggested in any countries of building code; future studies are needed to investigate the behavior factor of these structures. Behavior factors based on nonlinear analysis can be considered as one of the options.

- ❖ Soil – structure interaction effects are neglected in this study. Future study could include this Soil – structure interaction effects.

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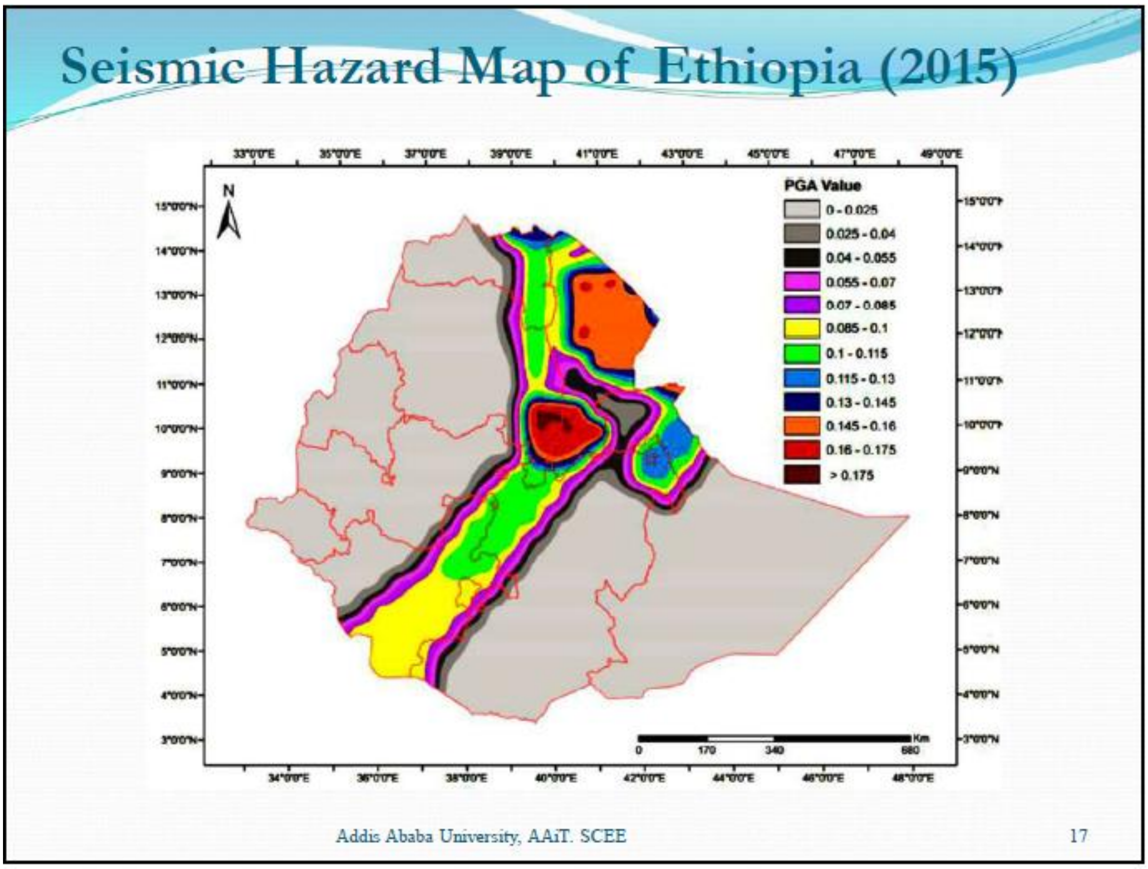
APPENDIXES

Appendixes A: Articles, graphs and tables referred in the thesis research from ES EN

A.1. Seismic Zones, Importance Classes and Ground Types

According to Ethiopian building code ES EN 1998-1:2015 the seismic hazard map is divided into 5 zones as shown below,

Figure A.1.1: Seismic Hazard Map of Ethiopia (ES EN 1998-1:2015 – Annex D – Figure D2)



And, the ratio of the design bedrock acceleration to the acceleration of gravity g= α_o for the respective zone is described in following table,

Table A.1.1: Bedrock Acceleration Ratio (ES EN 1998-1:2015 – Annex D – Table D1)

Zone	5	4	3	2	1	0
$\alpha_o = \alpha_g / g$	0.2	0.15	0.1	0.07	0.04	0

According to the new Ethiopian building code ES EN 1998-1:2015, based on the consequence of collapse human life, importance for public safety and civil protection in the immediate earthquake period and the social and economic consequences of collapse, Buildings are classified in to 4 importance classes.

Table A.1.2: Importance classes for buildings (ES EN 1998-1:2015 – table 4.3)

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

Importance Factor (defined in ES EN 1990:2015, Annex B)

Class	I	II	III	IV
I	0.8	1	1.2	1.4

Ground types are described by the stratigraphic profile and parameters given in Table 3.1 of ES EN 1998-1: 2015 as shown below, and this may use to account for the influence of local ground condition on the seismic action,

Table A.1.3: Ground types (ES EN 1998-1: 2015 – table 3.1)

Ground type	Description of stratigraphic	Parameters		
		v_s,30 (m/s)	N_{SPT} (blow/30cm)	C_u (kPa)
A	Rock or other rock-like geological formation, including at most 5m of weaker material at the surface.	>800	-	-

B	Deposits of Very dense sand, gravel or very stiff clay, at least several tens of meters in thickness, characterized by a gradual increase of mechanical properties with depth.	360 - 800	>50	>250
C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of meters.	180 - 360	15 - 50	70 - 250
D	Deposits of loose-to-medium cohesion less soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil	<180	<15	<70
E	A soil profile consisting of a surface alluvium layer with v_s values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with v_s > 800 m/s			
S_1	Deposits consisting, or containing a layer at least 10m thick, of soft clays/silts with a high plasticity index (PI>40) and high water content	<100 (indicative)	-	10 - 20
S_2	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in types A – E or S_1			

A.2. Structural Type, Behavioral factor and Design Spectrum

Structural type is the property of the building classification based on their response/behavior under horizontal seismic actions. These are namely;

- **a) Frame system:** frames take > 65% of seismic base shear, V_{base}
- **b) Dual system:**
  - ❖ (frame equivalent) – frames take 50 – 65% of seismic base shear
  - ❖ (wall equivalent) – wall take 50 – 65% of seismic base shear, V_{base}
- c) **Ductile wall system (coupled or uncoupled):** wall take > 65% of seismic base shear, V_{base}
- d) **System of large lightly reinforced walls;**
- e) **Inverted pendulum system;**
- f) **torsional flexible system.**

Design Spectrum is a reduced spectrum by energy dissipation capacity of the structure system through mainly the ductile behavior of its elements in performing a linear analysis. In which the capacity of structural system to resist seismic actions in the non-linear range permits their design for resistance to seismic forces smaller than those corresponding to a linear elastic response. This reduction is accomplished by introducing the behavior factor q.

The Behavior 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. Or in other words the behavior factor corresponds to the reduction in the level of seismic forces due to nonlinear behavior as compared with the expected elastic forces levels.

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

$q= qokw \geq 1.5$

where: qo - is the basic value of the behavior factor, dependent on the type of the structural system and its regularity in elevation;

kw - is the factor reflecting the prevailing failure mode in structural systems with walls shall be taken as follows;

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

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

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

where: h_{wi} is the height of wall i; and l_{wi} is the length of the section of wall i.

A behavior factor q of up to 1.5 may be used in deriving the seismic actions, regardless of the structural system and the regularity in elevation.

Table A.2.1: Basic value of the behavior factor q_o, for systems regular in elevation (ES EN 1998-1:2015)

Structural Type	DCM	DCH
Frame system, dual system, coupled wall system	$3.0\alpha u/\alpha 1$	$4.5\alpha u/\alpha 1$
Uncoupled wall system	3.0	$4.0\alpha u/\alpha 1$
Torsionally flexible system	2.0	3.0
Inverted pendulum system	1.5	2.0

For buildings which are not regular in elevation, the value of *q*o should be reduced by 20%.

If the seismic hazard defined for specific site have a surface-wave magnitude, Ms, is greater than 5.5 then it is recommended that Type -1 spectrum is adopted. Otherwise Type-2 Spectrum will be used.

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

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

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

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

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

Where: S_d (T) = Design Spectrum

q = behavior factor

β = lower bound factor for horizontal design spectrum (recommended value is 0.2)

T = Vibration period of a linear single-degree of freedom system

$\alpha_{\mathbf{g}}$ = design ground acceleration on type A ground (ag = $\gamma \alpha_{gR}$)

T_B = the lower limit of the period of the constant spectral acceleration branch

T_C = the Upper limit of the period of the constant spectral acceleration branch

T_D = the value defining the beginning of the constant displacement response range of the spectrum

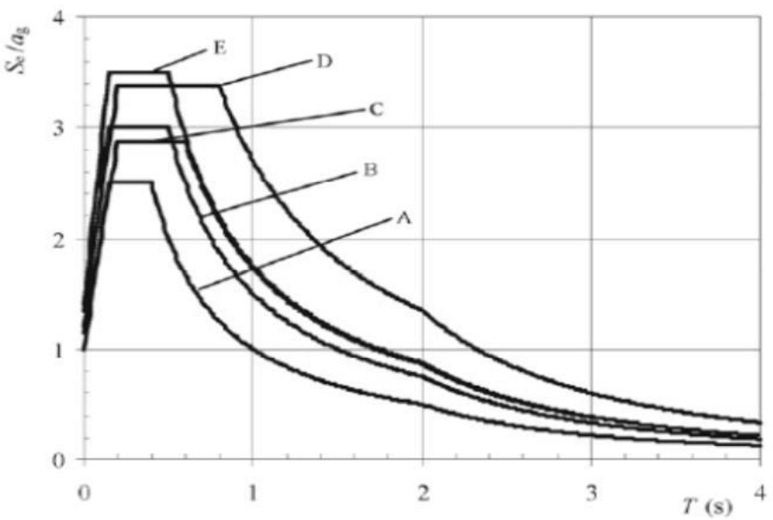
S = Soil factor

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

Table A.2.2: Values of the parameters describing the recommended Type-1 elastic response spectra (ES EN 1998-1:2015-table 3.2)

Ground type	S	T_B (s)	T_C (s)	T_D (s)
A	1.0	0.05	0.25	1.2
B	1.35	0.05	0.25	1.2
C	1.5	0.10	0.25	1.2
D	1.8	0.10	0.30	1.2
E	1.6	0.05	0.25	1.2

Figure A.2.1: Recommended Type-1 elastic response spectra for ground types A to E (5 % Damping) (ES EN 1998-1:2015- figure 3.2)



The ***seismic base shear force F_b,*** for each horizontal direction in which the building is analyzed, shall be determined using the following equation***;***

$F_b = S_d(T1) \times m \times \lambda$

Where: $S_d(T1)$ = the ordinate of Design spectrum at T1;

T1 = Fundamental period of vibration of the building for lateral motion in the direction considered;

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

λ= correction factor, the value of which is equal to 0.85 if $T1 < 2Tc$ and the building has more than two story, or equal to 1 otherwise.

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

$\Sigma G_{k,j} + \Sigma \psi_{E,i} \times Q_{k,i}$

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.

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

Table A.2.3: Value of ϕ for calculating ψEi (ES EN 1991-1-1:2015 – table 4.2)

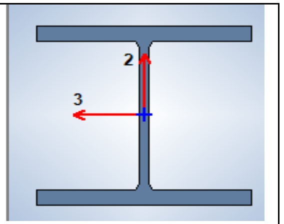
Type of Variable action	Story	ϕ
Categories A-C*	Roof Story with correlated occupancies Independency occupied story	1.0 0.8 0.5
Categories D-F* and Archives		1.0

Table A.2.4: Recommended values of ψ factors for building. (ES EN 1990:2015 Annex A – 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

Appendixes B: H Cross Section Steel Profile used in the thesis research for diagrid structure from Euro Steel /Wide Flange Source

B.1. H Cross Section Steel Properties



H cross Section Steel Profile Properties

Section designation	**Second moment of Area**		**Radius of Gyration**		**Elastic Module**		**Plastic Module**		**Warping Constant**	**Torsional Constant**	**Area of Section**	**Shear area**	
	Axis 3 – 3 Iy cm^4	Axis 2 – 2 Iy cm^4	Axis 3 – 3 Iy cm	Axis 2 – 2 Iy cm	Axis 3 – 3 Iy cm^3	Axis 2 – 2 Iy cm^3	Axis 3 – 3 Iy cm^3	Axis 2 – 2 Iy cm^3	Iw cm^6	It cm^4	A cm^2	Av3 cm^2	Av2 cm^2
H400x237	79710	31350	16.25	10.19	4184.3	1587.3	4727	2409	9621791.2	840	302	241	70.5
H400x288	99620	38680	16.48	10.27	5069.7	1938.8	5811	2951	12277767	1464	367	291	90.4
H400x314	111300	42710	16.68	10.33	5565	2135.5	6417	3251	13824000	1903	400	320	98
H400x340	122600	46850	16.83	10.4	6039.4	2325.1	6997	3543	15424592	2367	433	346	108
H400x347	124600	47870	16.81	10.42	6122.9	2369.8	7122	3614	15791774	2492	441	351.5	111.9
H400x393	146900	55370	17.12	10.51	7011.9	2710.9	8225	4154	18900396	3592	501	400.5	128.2
H400x422	159400	59970	17.23	10.57	7501.2	2932.5	8874	4482	20766846	4388	537	430	140
H400x467	183200	67930	17.55	10.68	8384.4	3297.6	10010	5040	24276542	5905	595	478	157

H400x551	226100	82380	17.95	10.83	9938.5	3941.6	12050	6046	30843581	9423	702	564	193
H400x593	250400	90410	18.21	10.94	10769.9	4295	13150	6588	34725809	11590	755	611	207
H400x634	275600	98050	18.47	11.02	11604.2	4635.9	14260	7115	38617649	14100	808	656	224
H400x678	301100	106800	18.67	11.12	12442.2	5002.3	15400	7685	42987119	16910	864	700	245
H400x744	343900	119900	19.05	11.25	13783.6	5563.8	17200	8556	50066982	21970	948	771.5	272
H400x818	392200	135500	19.39	11.4	15260.7	6201.4	19260	9561	58651202	28510	1043	847.8	311
H400x900	450200	153300	19.79	11.55	16957	6937	21620	10710	68887320	37350	1149	937	350
H400x990	518900	173400	20.28	11.72	18869.1	7741.1	24280	11960	81526567	48210	1262	1030.4	395.5

B.2. H Cross Section Steel Dimension

H Cross Section Steel Dimension							
Section Designation	**Total Depth of Section h (mm)**	**Web thickness t_w (mm)**	**Top Flange**		**Bottom Flange**		**Fillet Radius d (mm)**
			Width t_w (mm)	**Thickness t_f (mm)**	**Width t_w (mm)**	**Thickness t_f (mm)**	
H400x237	381	18.5	395	30.5	395	30.5	15
H400x288	393	23	399	36.5	399	36.5	15
H400x314	400	24.5	400	40	400	40	15
H400x340	406	26.5	403	42.9	403	42.9	15.2
H400x347	407	27.5	404	43.5	404	43.5	15
H400x393	419	30.6	407	49.5	407	49.5	15.2
H400x422	425	33	409	52.5	409	52.5	15
H400x467	437	35.9	412	58	412	58	15.2

H400x551	455	42.5	418	67.5	418	67.5	15
H400x593	465	44.5	421	72.5	421	72.5	15
H400x634	475	47	423	77.5	423	77.5	15
H400x678	484	50.5	427	82	427	82	15
H400x744	499	54.5	431	89.5	431	89.5	15
H400x818	514	60.5	437	97	437	97	15
H400x900	531	65.9	442	106	442	106	15
H400x990	550	71.9	448	115	448	115	15