

Design and Analysis of Sustainable Building with Hexagonal Configuration

Submitted in partial fulfilment of the requirements for the award of
Bachelor of Engineering Degree in
Civil Engineering

by

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**DEPARTMENT OF CIVIL ENGINEERING
SCHOOL OF BUILDING AND ENVIRONMENT**

SATHYABAMA

INSTITUTE OF SCIENCE AND TECHNOLOGY

(DEEMED TO BE UNIVERSITY)

Accredited with Grade "A" by NAAC | 12B Status by UGC | Approved by AICTE

JEPPIAAR NAGAR, RAJIV GANDHI SALAI, CHENNAI - 600 119

May – 2022

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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the Bonafide work of **K. Janahan (38200012)**, **Swagatam Bardhan (38200035)**, carried out the project entitled "**DESIGN AND ANALYSIS OF SUSTAINABLE BUILDING WITH HEXAGONAL CONFIGURATION**" under our supervision from December 2021 to April 2022.



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DECLARATION

I **Swagatam Bardhan** and **K. Janahan** hereby declare that the Project Report entitled **Design and analysis of sustainable building with hexagonal configuration** done by us under the guidance of **Mrs. B. Priyadarshini** is submitted in partial fulfilment of the requirements for the award of **Bachelor of Engineering degree in Civil Engineering** at **Sathyabama Institute of Science and Technology**

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ABSTRACT

The purpose of this study is to design and analyse buildings with hexagonal configurations; an optimized 45° inclined column angle Hexagrid and a variable angle Hexagrid (40°,45°,50°,55°,60°,65°,70°) to determine the resistance to seismic loads and wind loads, and to compare the structural performance of these buildings with the conventional square building.

In this process, one can understand the sustainability and the structural reliability of using the hexagonal geometry to design the building, and the cost-performance value of using it.

This study is upon the design and analysis of G+20 structure with different Hexagrid topologies, optimized inclined column angle and variable angle design in & ETABS v.18 software. It primarily focuses on the biomimicry of the honeycomb pattern, forming the structural system, known as Hexagrid.

CONTENTS

CHAPTER No:	TITLE	PAGE No:
	ABSTRACT	V
	LIST OF ABBREVIATIONS	VIII
	LIST OF FIGURES	IX
	LIST OF TABLES	XII
1	INTRODUCTION	1
2	LITERATURE REVIEW	2
	2.1 General	2
	2.2 Literature survey	2
3	OBJECTIVE AND SCOPE OF THE INVESTIGATION	6
	3.1 Objective of the study	6
	3.2 Scope of the study	6
4	METHODOLOGY	7
	4.1 Methodology	7
	4.2 Hexagrid structural system	8
	4.3 Structure parameters	11
	4.4 Factor of influence	13
	4.5 Floor plan	17
	4.5.1 Conventional structure	17
	4.5.2 45° diagonal Hexagrid structure	19

	4.5.3 Varying angle Hexagrid structure	21
4	4.6 Structural modelling	23
	4.6.1 Conventional structure	23
	4.6.2 45° diagonal Hexagrid structure	26
	4.6.3 Varying angle Hexagrid structure	30
5	ANALYSIS	34
	5.1 Static analysis	34
	5.2 Dynamic analysis	38
6	RESULTS & DISCUSSION	43
	6.1 Static Responses	43
	6.1.1 Story drift	43
	6.1.2 Story displacement	44
	6.1.3 Story overturning moment	46
	6.1.4 Story stiffness	47
	6.1.5 Lateral load	48
	6.1.6 Quantity of steel	49
	6.2 Dynamic Responses	50
	6.2.1 Time period	50
7	CONCLUSIONS	52
8	REFERENCE	53

LIST OF ABBREVIATIONS

RCC	Reinforced Cement Concrete
MS	Mild Steel
ISWB	Indian Standard Wide Flange Beam
ETABS	Extended Three-Dimensional Analysis of Building System
RF	(Regular Frame) Conventional structure
VH	(Vertical Hexagrid) 45° diagonal angle Hexagrid structure
VAH	(Varying Angle Hexagrid) Varying angle Hexagrid structure
FEMA	Foreign Exchange Management Act
RSA	Response spectrum analysis
ABS	Algebraic sum
CQC	Complete Quadratic Combination
SRSS	Square root of sum of squares

LIST OF FIGURES

FIGURE No:	TITLE	PAGE No:
4.1	Methodology chart	7
4.2	Honeycomb structure in beehive	8
4.3	Elements in a hexagonal cell	9
4.4	Horizontal Hexagrid pattern, with hexagonal cell of 1-story	9
4.5	Vertical Hexagrid pattern, with hexagonal cell is 3-story height	10
4.6	Hexagrid building	11
4.7	Elevation view of RF VH & VAH structure	15
4.8	Floor plan of RF model	17
4.9	Details of the section used in the steel columns of the RF model perimeter	19
4.10	Floor plan of VH model	20
4.11	Floor plan of VAH model	22
4.12	Elevation view of RF model	24
4.13	Wireframe view of RF model	25
4.14	Extruded shell and frame overview of RF model	26
4.15	Elevation view of VH model	27
4.16	Dimensions of the 45° diagonal angle diagonal angle hexagonal cell in the VH model	27

FIGURE No:	TITLE	PAGE No:
4.17	Wireframe view of VH model	28
4.18	Extruded shell and frame overview of VH model	29
4.19	Elevation view of VAH model	30
4.20	Hexagrid models with varying diagonal angle used in each row of the Hexagrid frame in the VAH model.	31
4.21	Elevation view of VAH model	32
4.22	Extruded shell and frame overview of VAH model	33
5.1	Axial force diagrams from VH model	36
5.2	Natural frequencies of different structures with varying mass source and stiffness	38
5.3	Linear displacement spectra of 1986 North Palm Springs earthquake	39
5.4	Response spectra providing design acceleration coefficient (S_a/g) corresponding to 5% damping	40
5.5	Flowchart of the Response spectrum analysis in ETABS	41
5.6	Response spectrum function definition as per IS 1893:2016	42
6.1	Story drift vs Story plot for conventional structure, 43 45° diagonal Hexagrid structure and varying angle Hexagrid structure	

FIGURE No:	TITLE	PAGE No:
6.2	Story displacement vs Story plot for conventional structure, 45° diagonal Hexagrid structure and varying angle Hexagrid structure	44
6.3	Displacement for 5th, 10th, 15th & 20th story of varying angle Hexagrid structure	45
6.4	Story overturning moment vs Story for conventional structure, 45° diagonal Hexagrid structure and varying angle Hexagrid structure	46
6.5	Story stiffness vs Story plot for conventional structure, 45° diagonal Hexagrid structure and varying angle Hexagrid structure	47
6.6	Lateral load vs Story for conventional structure, 45° diagonal Hexagrid structure and varying angle Hexagrid structure	48
6.7	Steel quantity for conventional structure, 45° diagonal Hexagrid structure and varying angle Hexagrid structure	49
6.8	Time period vs mode for conventional structure, 45° diagonal Hexagrid structure and varying angle Hexagrid structure	50
6.9	Frequency, time period and the participation ratio of modes for varying angle Hexagrid structure	51

LIST OF TABLES

TABLE No:	TITLE	PAGE No:
4.1	Data for static analysis of Conventional, Hexagrid and Variable angle Hexagrid structural system	12
4.2	Details of conventional reference model	16
4.3	Details and configuration of Hexagrid structure models	16
4.4	Section properties of the conventional model (RF model)	18
4.5	Section properties of perimeter frame in the 45° diagonal angle model (VH model)	20
4.6	Section properties of the interior columns and beams	21
4.7	Section properties of the beams, floor slabs, and interior columns	22
5.1	Structure parameters for design and analysis	35
5.2	Loading and analysis parameters	37

CHAPTER 1

INTRODUCTION

As the population of the world keeps increasing significantly, there is a rise in the cost of construction materials, and the land required for construction. One of the solutions to this issue is creating tall and slender buildings in a smaller plot area. So, to meet demands, there is an increase in the construction of tall buildings in the past decade.

There are some challenges to be considered in tall buildings while designing them. The lateral forces acting upon the building is an important challenge, as the height of the building increases, the lateral load acting on it intensifies. This lateral load includes the wind forces on the windward side, and the seismic forces affecting the building in event of an earthquake.

To resist the lateral forces, many advancements in building design and methods of construction. The structural system utilized plays the main role in the building design, this can be influenced to make it more efficient, and sustainable. This need to increase the structural efficiency can be achieved through optimizing the structural elements, using efficient member design and positioning. Some of the existing structural systems for tall buildings focus on resisting lateral loads such as tube structural system, rigid frame system, shear wall system and the diagonal bracing system.

One of the comparatively recent structural systems being adopted is the hex-grid structural system. This Hexagrid system is based upon using the hexagon-shaped frame on the exterior perimeter of the building, the advantage of using this system is the ability of it to resist gravity loads and lateral loads with their inclined columns. Though there are plenty of structural systems that perform well, in this case the Hexagrid system, as the hexagonal shape occurring in nature within the honeycomb. These hexagonal cells perform exceptionally well in resisting and distributing the stresses uniformly.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

A study review's main goal is to provide a summary of the research as well as in-depth knowledge about the research that has been undertaken. This serves as the foundation for carrying out work and formulating project strategy. The research study on the design and analysis of sustainable buildings with hexagonal configuration was identified in the following literature survey.

2.2 LITERATURE SURVEY

Yasaman Memarzadeh Kiani et al., (2021), Seismic assessment of nature-inspired Hexagrid lateral load-resisting system. The study gives a general perspective of the seismic performance of Hexagrid under near-field ground motions. This is achieved by analysing and understanding the behaviour of two 20-storey buildings with Hexagrid skeleton and bundled-tube skeleton structural system.

Sooriya P and Bushra M, (2020), Performance assessment of Hexagrid structural system. The aim of the paper is to compare the various available Hexagrid structural systems with different patterns and to achieve an optimized pattern that will resist lateral loads in the Hexagrid structural system effectively.

Shajeea and Seethu Sunny, (2020), Seismic Performance of Soft Storey Behaviour in Irregular Steel Frames using Different Bracing Systems. This paper uses asymmetrically irregular and symmetrically irregular frames of different types; V, Octa, Hexa and Zipper frames are considered for dynamic analysis of a G+20-storey building, to understand the effect of soft storey in the steel frame.

Krishnan P A et al., (2019), A Study on Seismic Performance of Hexagrid Structures. The study is based upon the seismic performance of the Hexagrid structures, mainly considering an 18- and 24- storey structure of regular pattern Hexagrid and a 36- storey structure with varying angle and varying density of the modules in ETABS software. The structural performance is evaluated with different parameters like storey displacement, storey drift, and story shear.

Niloufar Mashhadiali and Ali Kheyroddin, (2019), Quantification of the seismic performance factors of steel Hexagrid structures. The aim of this study is to assess the response modification factor, R , of Hexagrid structural system under seismic loading. Set of structure models with 3-, 9-, 21-storey with varying diagonal angles of 33° , 45° , and 53° are designed with an evaluated R factor using nonlinear static and dynamic analysis under FEMA P695 methodology.

Yash Bhardwaj, (2019), Structural Behaviour of Hexagrid & Diagrid Structural Systems in Multi Storey Buildings. The project focuses on the optimizing the diagonal angle and the topology of the diagonal members used in the horizontal Hexagrid frame using finite element analysis. The focus also extends to compare the efficiency of the achieved Hexagrid structural system with use of various parameters such as inter-storey drift, time period and displacement.

Elena Mele et al., (2019), Hexagrid-Voronoi transition in structural patterns for tall buildings. This study is based upon the non-conventional structural patterns and systems used for the design of tall buildings. The Hexagrid and Voronoi-inspired arrays. The mechanical properties of selected non-conventional structural patterns were studied and utilized with the help of Representative Volume Element (RVE) and stress-strain relationships to make them applicable effectively for tall buildings.

Vedprakash Maralapalle et al., (2019), Analysis & design of pile foundation for G+20 residential building, this paper is focused on the design and analysis of a G+20 building located in Mumbai and focuses mainly on foundation design.

Siva Rama Prasad C.V et al., (2019), Analysis and Design of G+20 Residential RCC Building by Using ETABS in Zone II. This paper is mainly focused on the design and analysis of a G+20-storey under seismic loads.

Niloufar Mashhadiali and Ali Kheyroddin, (2018), Seismic performance of concentrically braced frame with hexagonal pattern of braces to mitigate soft storey behaviour. This paper introduces the innovative hexa-braced frames. In these braces, the vertical structural elements connect the V and inverted-V bracings over three stories to form the hexagonal bracing configuration. The building models with 4-, 10-, and 20- storeys are used to evaluate the seismic performance with static and dynamic analyses.

Han-UI Lee and Young-Chan Kim, (2017), Preliminary design of tall building structures with a Hexagrid system. This study basically investigates the characteristics of tall buildings with Hexagrid tubular structural system, considering the pattern and size of the Hexagrid modules. It also focuses on a proposed sizing formula based on the stiffness criteria of the members.

Farhan Danish et al., (2017), Comparison of Hexagrid and Diagrid Structural System in Tall Buildings. The study involves the design and analysis of a 40-storey steel structure with both the Diagrid and Hexagrid systems in ETABS software to improve the structural performance.

Pooja Liz Isaac and Bennet Ipe A, (2017), Comparative Study of Performance of High-Rise Buildings with Diagrid, Hexagrid and Octagrid Systems under Dynamic Loading. Twelve models with exterior braced steel structure, Diagrid, Octagrid, and Hexagrid buildings with variation to their diagonal angles and module density are used to study their performances under equivalent static analysis and Response spectrum analysis.

Divya M.S and Saraswathy B, (2017), Comparative analysis of high-rise steel building with Hexagrid, Diagrid and Conventional structural system. The design and analysis of 48-storey steel structure with Diagrid and Hexagrid structural system is carried out using ETABS software. Hexagrid, Diagrid and Conventional system are compared based on their load resistance, story shear, time period and story drift.

Peyman Askari Nejad (2016), Beehive (Hexagrid), New Innovated Structural System for Tall Buildings, this paper introduces the Hexagrid structural system and optimized angle and topology of the structural system by analysis and modelling for an 80-storey tall building.

Giovanni Maria Montuori et al., (2014), Geometrical patterns for diagrid buildings: Exploring alternative design strategies from the structural point of view. The Diagrid structures characterized by regular patterns are compared to alternative geometrical configurations, obtained by changing the angle of diagonals for a 90-storey tall building.

Taranath S.D, (2014), Comparative Study of Pentagrid and Hexagrid Structural System for Tall Building. This study involves the study of efficiency of Pentagrid and Hexagrid bracing system and comparing them with the basic model (without bracing) at standard loading conditions. Three tall buildings of 40-, 50-, and 60-storey are considered for analysis and comparison of story drift, story shear of Pentagrid and Hexagrid structural system.

Khushbu Jania and Paresh Patel V, (2013), Analysis and Design of Diagrid Structural System for High Rise Steel Buildings. This paper focuses upon the Diagrid structures, mainly the analysis and design of 36-storey Diagrid steel structure. The Diagrid structural system is adopted in tall buildings due to its structural efficiency and flexibility in architectural planning. The structural performance of the 36-storey structure is compared along with Diagrid structures of 50-, 60-, 70- and 80-storey using ETABS software for design and analysis.

CHAPTER 3

OBJECTIVE AND SCOPE OF THE STUDY

3.1 OBJECTIVE OF THE STUDY

1. To design and analyse the Hexagrid structures; 45° diagonal angle Hexagrid structure & varying diagonal angle Hexagrid structure, along with a conventional structure model using Response Spectrum Analysis (RSA).
2. To compute the static and dynamic responses; story drift, story displacement, time period, story over-turning moment and story stiffness.
3. To compare the structural performance of the Hexagrid structures with the conventional model.

3.2 SCOPE OF THE STUDY

The main scope of the project is,

1. To compare the structural efficiency of these buildings against the conventional structure.
2. To understand the sustainability and the structural reliability of using the hexagonal geometry to design the structural system of the building, and the cost-performance value of using it.
3. To utilize this structural system in tall buildings to increase structural efficiency and also influence the architecture and sustainability of the structure.

CHAPTER 4

METHODOLOGY

4.1 METHODOLOGY

The methodology for the design and analysis of the Hexagrid structures and conventional structure is simplified using the ETABS v.16 software. The summary of the methodology followed is to begin with initializing the site and structure parameters. This includes site conditions, general structure parameters such as the dimensions, floor plan, story height, grade and specifications of material sections used, loading conditions and load case parameters. This is followed by 2-dimensional plan created using AutoCAD software, which consists of the floor plan of the structures. These structures are then modelled in the structural analysis software, ETABS v.16. The analysis is performed after considering the wind and seismic loads, as per IS 875-2015 Part – III & IS 1893: 2016 Part – I. The Response spectrum analysis is added along with it, according to IS 1893: 2016 Part – I. The analysis results are obtained in terms of various structure parameters such as story displacement, story drift, story stiffness, time period and story over-turning moment.

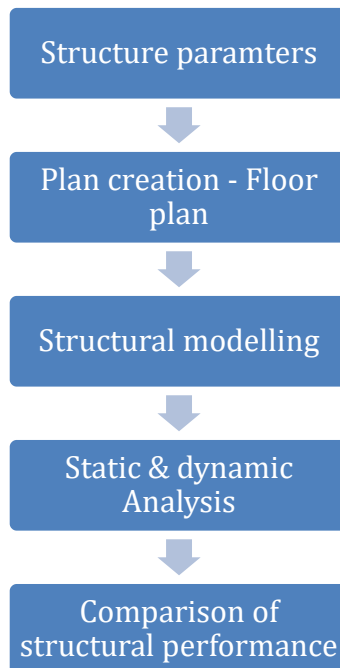


Figure. 4.1 Methodology chart

4.2 HEXAGRID STRUCTURAL SYSTEM

Apart from the conventional building, the Hexagrid buildings are designed with the variation in the inclined angle in the exterior of the structure. The Hexagrid can be defined as system of hexagonal grids in a pattern on the exterior of the structure. This pattern is identical to the honeycomb structure found in beehives; they are void of vertical columns as the inclined columns make up the structural integrity. The hexagon shape of the tightly packed honey comb cells ensures maximum utilization of area and also distribute any force acting upon it efficiently.

Since the Hexagrid pattern provides no vertical column, the inclined columns resist both the gravity load and lateral load, and also provide flexibility in architectural aspects such as view, lighting and aesthetic façade.



Figure 4.2 Honeycomb structure in a beehive

The honeycomb can be defined as a structure made of hexagonal cells bound together forming a pattern, these cells are used by the honeybees to brood and store honey. It has proven to be highly efficient in terms of space utilization and also capable of withstanding high compressive stress.

A single hexagonal cell is made up of inclined member and, vertical or horizontal member depending upon the orientation of the cell - 0° or 90° . The intersection of this inclined member and the vertical or horizontal member to form a six-sided structure when connected to one and another, forming the Hexagrid framework. This frame can be configured in two orientations, forming the horizontal Hexagrid depicted in **Figure 4.4** and the vertical Hexagrid shown in **Figure 4.5**.

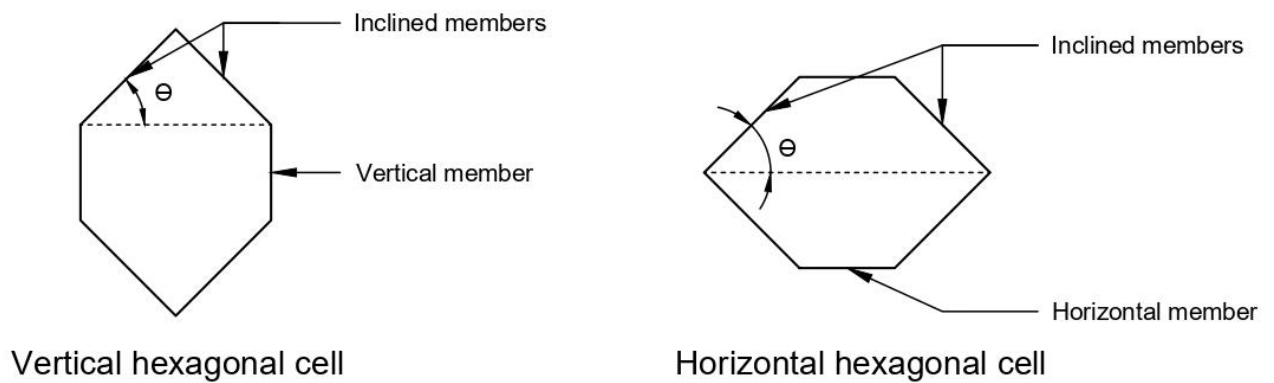


Figure 4.3 Elements of a hexagonal cell

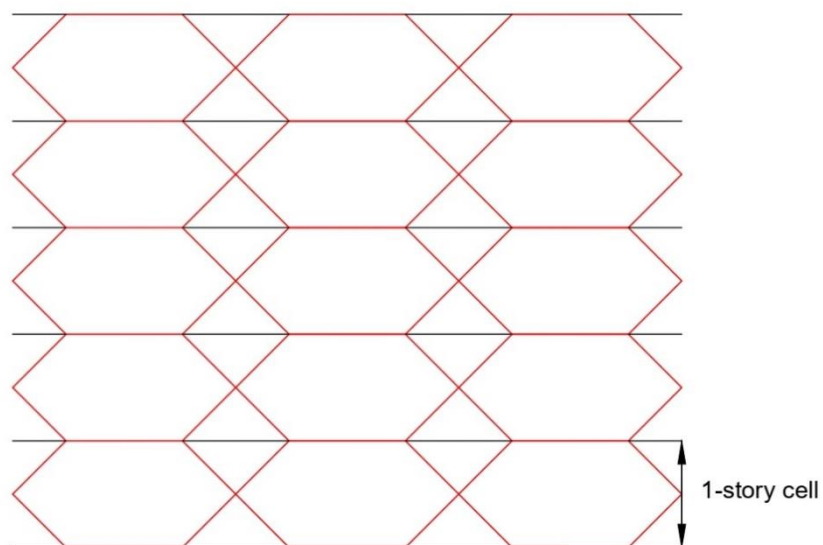


Figure 4.4 Horizontal Hexagrid pattern, with hexagonal cell of 1-story height

The Hexagrid pattern can be considered as a horizontal pattern, if the hexagonal cells do not possess any vertical columns and has only horizontal and inclined members. Similarly, vertical Hexagrid patterns consist of only vertical and inclined members as depicted in **Figure 4.4**.

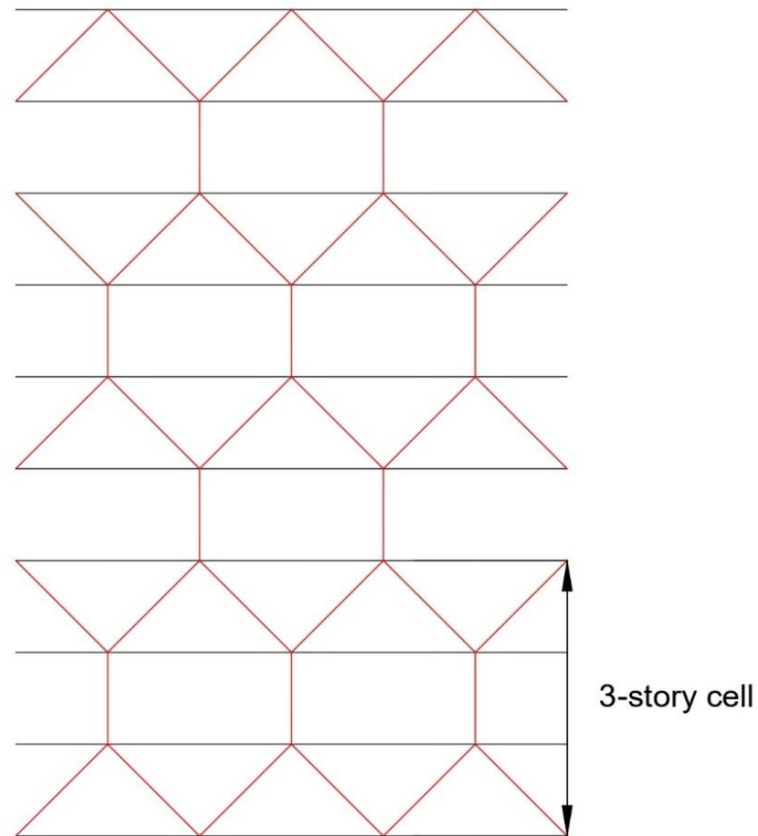


Figure 4.5 Vertical Hexagrid pattern, with hexagonal cell of 3-story height

These hexagonal cells connected together form a pattern, forming the Hexagrid structure. In our study only the vertical Hexagrid pattern is considered as it is known to be stiffer than the horizontal Hexagrid, for the structural system as depicted in **Figure 4.5**.

4.3 STRUCTURE PARAMETERS

A tall building model with a square plan of 18 * 18 m, with interior columns on the corners of a 6 * 6 m square in the centre of the plan is considered as the conventional model. After evaluating the geometrical parameters of the reference building, two different models are created with different hexagonal topology, namely an optimized 45° inclined column angle Hexagrid and a varying inclined column angle Hexagrid pattern of the exterior façade. The total height of the building is 63m, making it a G + 20 story building with floor height of 3m. The 45° inclined column angle Hexagrid structure is shown in the **Figure 4.6**.

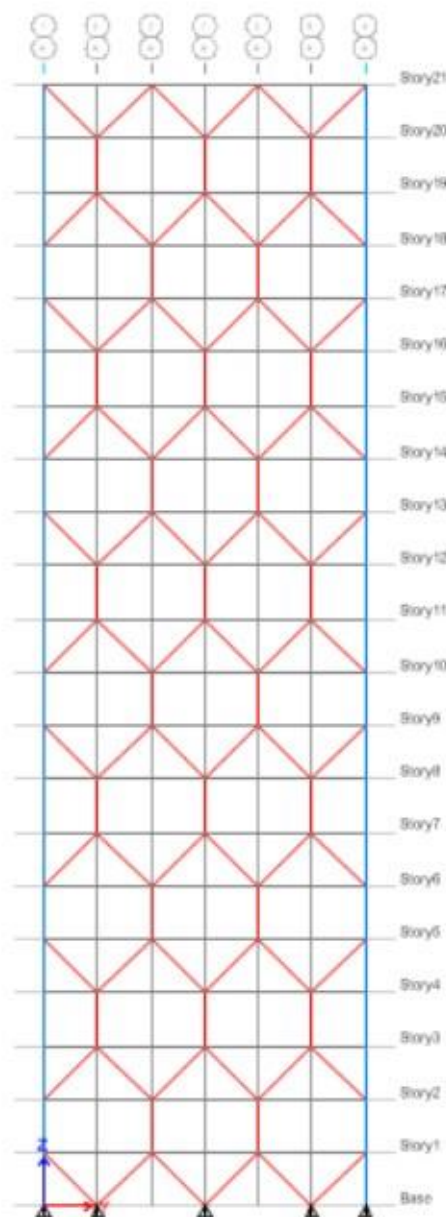


Figure 4.6 Hexagrid building

Table: 4.1 Data for static analysis of Conventional, Hexagrid and Variable angle Hexagrid structural system

S.No	Particulars	Conventional system	Hexagonal system	Variable angle system
1.	Dimension of Plan	18m * 18m	18m * 18m	18m * 18m
2.	Total height of the structure	63m	63m	63m
3.	Height of each storey	3m	3m	3m
4.	Section of beams	RCC-0.35m*0.3m	RCC-0.35m*0.3m	RCC-0.35m*0.3m
5.	Section of columns	RCC-0.45m*0.45m ISWB500	RCC-0.45m*0.45m ISWB500	RCC-0.45m*0.45m ISWB500
6.	Section of inclined columns	-	ISWB500	ISWB500
7.	Angle of inclined columns	-	45° (1 Hexagrid covers 3 story)	40°, 45°, 50°, 55°, 60°, 65°, 70° (1 Hexagrid covers 3 story)
8.	Grade of concrete Grade of steel	M30 FE500	M30 FE500	M30 FE500
9.	Section of slab	RCC-150mm	RCC-150mm	RCC-150mm
10.	Dead load	3.75 kN/m ²	3.75 kN/m ²	3.75 kN/m ²
11.	Live load	4.5 kN/m ²	4.5 kN/m ²	4.5 kN/m ²
12.	Seismic load - IS Code Seismic Zone Importance factor Zone factor Damping Ratio Response reduction factor	IS1893: 2016 (Part 1) IV 1 0.24 5% 5	IS1893-2016 (Part 1) IV 1 0.24 5% 5	IS1893-2016 (Part 1) IV 1 0.24 5% 5
13.	Wind load – IS Code Basic wind speed Terrain Category Structure Class Risk Coefficient (k1 factor) Topography (k3 factor) Windward coefficient Leeward coefficient	IS 875: 2015 (Part 3) 50 m/sec 3 B 1 1 0.8 0.5	IS 875: 2015 (Part 3) 50 m/sec 3 B 1 1 0.8 0.5	IS 875: 2015 (Part 3) 50 m/sec 3 B 1 1 0.8 0.5
14.	Soil condition	Medium soil (Type II)	Medium soil (Type II)	Medium soil (Type II)

4.4 FACTOR OF INFLUENCE

The parameters of the Hexagrid cell; The angle of the inclined members (Θ), length of the inclined/diagonal member (L_d), Length of horizontal member (L_h), length of the vertical member (L_v), height of the Hexagrid cell (h).

In respect to the Hexagrid frame, the module height, number of modules in a Hexagrid, and module density are some of the parameters of the Hexagrid system.

The design of the Hexagrid system can be based on different criteria such as the stiffness of the system. These criteria mainly depend upon the physical parameters of the Hexagrid system; diagonal angle of the Hexagrid is a significant part of it. Similarly, previous studies show that increase in the number of hexagonal cells or increase in the height of the building result in better efficiency of the Hexagrid structural system. The earlier researches indicate that the changes to the elements of the Hexagrid influences the physical properties and the structural performance. This influence of various parameters to increase the performance or efficiency of the Hexagrid system in terms of resistance to buckling, shear failure or progressive collapse and increased lateral stiffness of the Hexagrid, optimal diagonal angle, moment of inertia of individual member, module density result in the need to optimize and design the Hexagrid structural system accordingly.

In this study, the main focus is on the angle of the inclined/diagonal member, many studies have been upon the stiffness of the Hexagrid system, the numerical modelling of Hexagrid system based on the height, and diagonal angle. So, most of the work on the modelling of an efficient and optimized Hexagrid structural system has been with the different factors of influence; changes in diagonal angles, utilizing different member cross sections, module density.

From the various studies and work on the different configurations of the Hexagrid, one can arrive at the conclusion that there is limited work done upon varying diagonal angle Hexagrid structural system and about its potential in terms of structural performance, efficiency and sustainability compared to the conventional square building and an optimized diagonal angle Hexagrid system with fixed diagonal angle, module height and member lengths.

The modelling of the Hexagrid structures required for this study is more in a fundamental aspect in terms of the various configurations available to alter and study.

The methodology includes; the modelling of the conventional square building (**RF**) to be used as a reference model, the optimized diagonal angle Hexagrid model (**VH**) and the varying diagonal angle Hexagrid model (**VAH**).

RF (Regular Frame) - Conventional square building

This structure is a square G+20 building with the commonly used, rigid frame structural system. The rigid frame is composed of 0.45 * 0.45 m RCC columns and 0.35 * 0.3 m beams in the interior of the structure. The perimeter frame of the structure consists of a composite structural system with ISWB 500 steel columns connected with 0.35 * 0.3 m RCC beams.

VH (Vertical Hexagrid) - 45° diagonal angle Hexagrid structure

The Hexagrid structural system is utilized in the perimeter frame of this G+20 structure. Similar to the **RF** model, the interior of the structure consists of 0.45 * 0.45 m RCC columns and 0.35 * 0.3 m RCC beams as structural members along with 0.15 m thick RCC floor slabs. The exterior frame of the structural system consists of the ISWB 500 steel sections with vertical and 45° diagonal angle inclined columns, with 9 m module height hexagonal cells that make up the vertical pattern Hexagrid structural system.

VAH (Varying angle Hexagrid) – Varying diagonal angle Hexagrid structure

This structure is a G+20 Hexagrid structure with the varying diagonal angle of the inclined columns in the exterior frame of the structural system. The interior structural elements are identical to that of the **RF** and **VH** models, with 0.45 * 0.45 m RCC vertical columns and 0.35 * 0.3 m RCC beams along with 0.15 m thick RCC floor slabs. The perimeter skeleton however consists of the Hexagrid system with the diagonal angle having varying angles along the height of the structure. The diagonal angle starts at 40° and varies along the height of the structure with an increment of 5° after each row in the Hexagrid.

In the modelling of the two Hexagrid structures, the scope of the configurations such as the module density, varying material sections, story heights are not changed and kept constant as this would influence the effectiveness of the modelling technique since the increase in the number of factors will eventually increase the complexity of the structure and its performance. Only the angle of the inclined member is considered for the modelling and it is optimized for one Hexagrid model (**VH**) and varying for the second Hexagrid model (**VAH**).

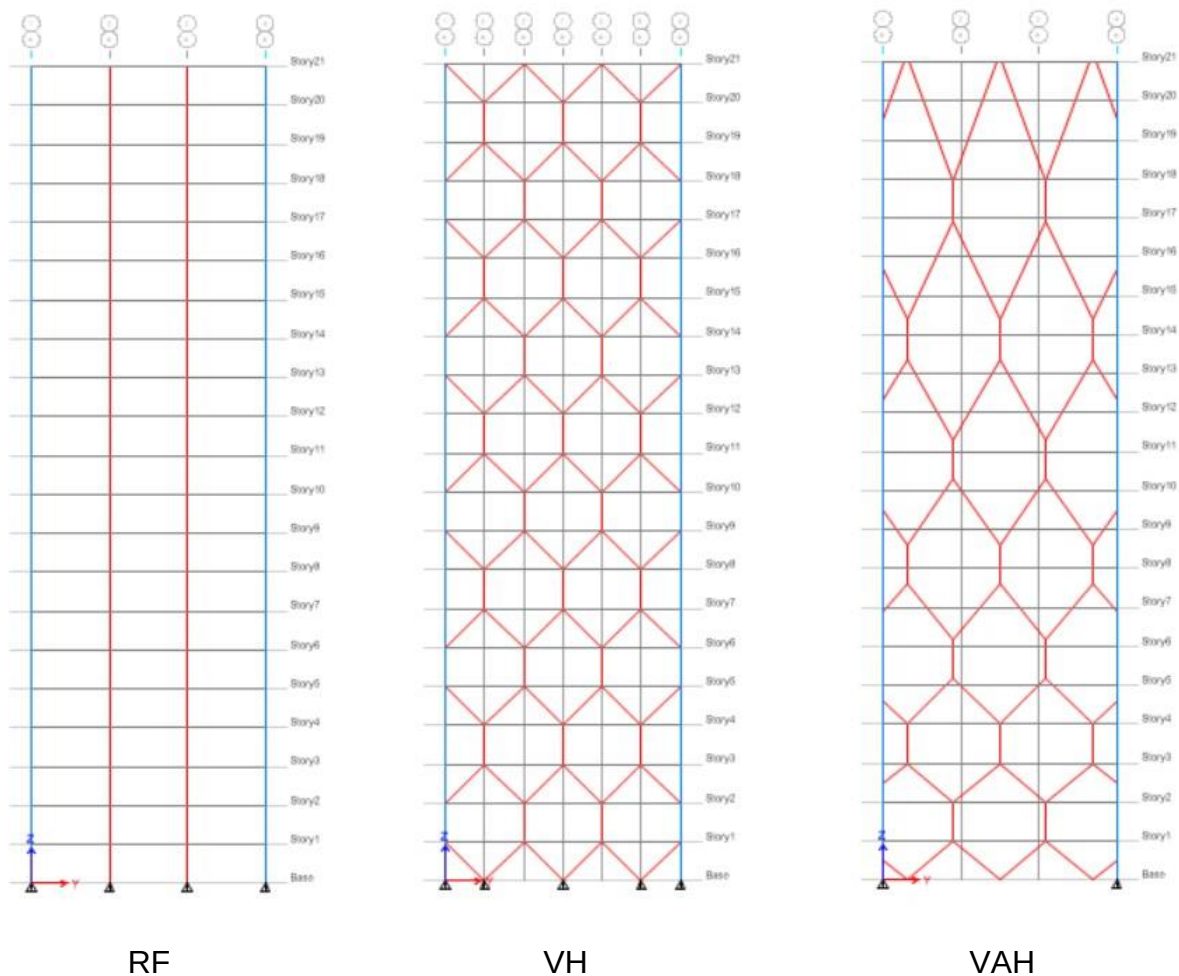


Figure.4.7 Elevation view of the RF, VH & VAH structure

Table 4.2 Details of conventional reference model

Model Pattern	Model name	Angle of members in the perimeter	Height of each story (m)	Total number of stories
Conventional square model	RF	Horizontal members - 0° Vertical members - 90°	3	G+20

Table 4.3 Details and configuration of Hexagrid structure models

Model Pattern	Model name	Angle of inclined columns	Height of module (m)	Total number of modules	Number of stories
Vertical Hexagrid	VH	45	9	140	G+20
Variable angle vertical Hexagrid	VAH	40° , 45° , 50° , 55° , 60° , 65° & 70°	40° - 9, 45° - 9.575, 50° - 10.836, 55° - 12.367, 60° - 14.209, 65° - 16.86 & 70° - 20.46	72	G+20

In the RF model, the height of the vertical columns is fixed. In the case of the VH model, with 45° diagonal angle model, the inclined column and vertical column heights are fixed, which results in a constant module height of 9m. Whereas in the VAH mode, with varying diagonal angle, the variation in the angle of the inclined column for every successive row of the Hexagrid results in increase in the increase of module height with increase in diagonal angle.

4.5 FLOOR PLAN

The square building plan of area 324m^2 , the basic dimension of the three models is identical, with $18\text{m} \times 18\text{m}$ square plan. Vertical columns are present in the corners of the perimeter and the interior $6\text{m} \times 6\text{m}$ square. While the members of the perimeter façade vary with each model.

4.5.1 Conventional model (RF)

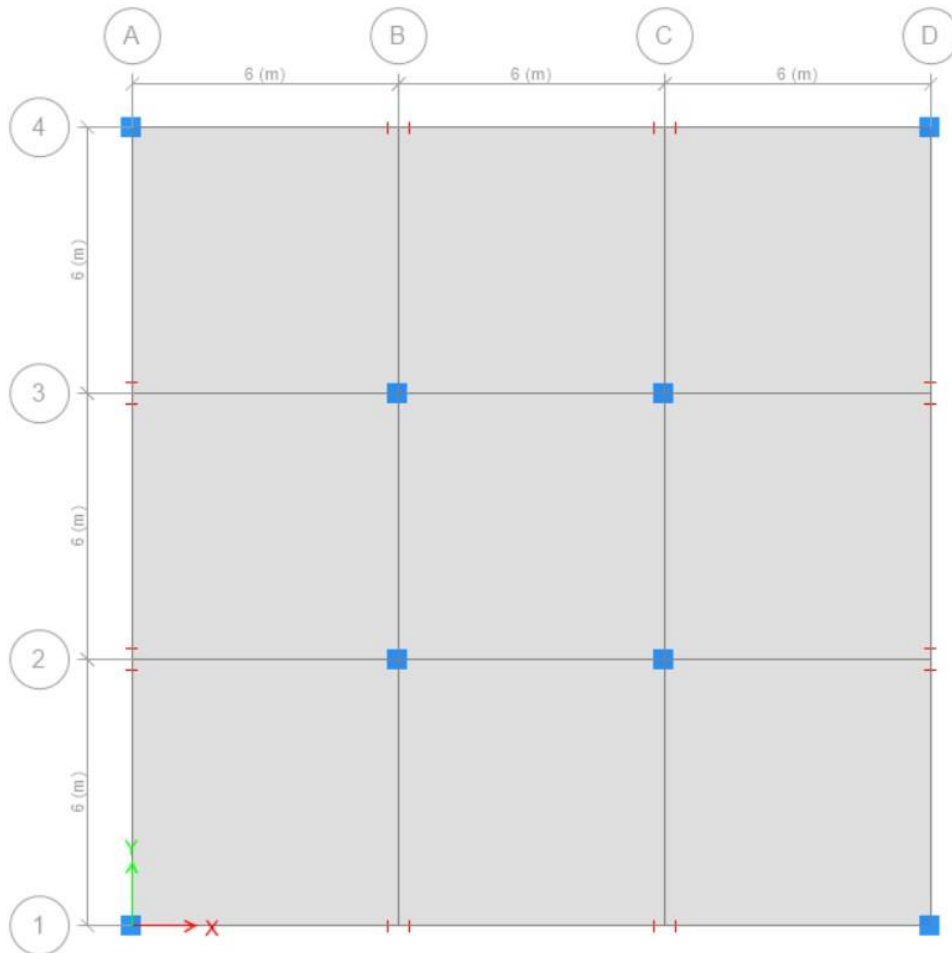


Figure.4.8 Floor plan of RF model

Number of exterior columns per floor: 4- RCC columns (Corners) & 8- Steel columns

Number of interior columns per floor: 4- RCC columns

Table 4.4 Section properties of the conventional model (RF model)

Story	Interior columns	Beams	Exterior columns
G + 20	RCC 0.45m * 0.45m	RCC 0.35m * 0.3m	ISWB500 RCC 0.45m * 0.45m (Corners of the perimeter)
Grade of concrete: M30		Grade of steel: FE500	Floor slab thickness: 150mm

The **figure.4.9** shows the details of the steel columns in the perimeter of the conventional model. The size of the members can be increased when a higher structural strength of steel is required.

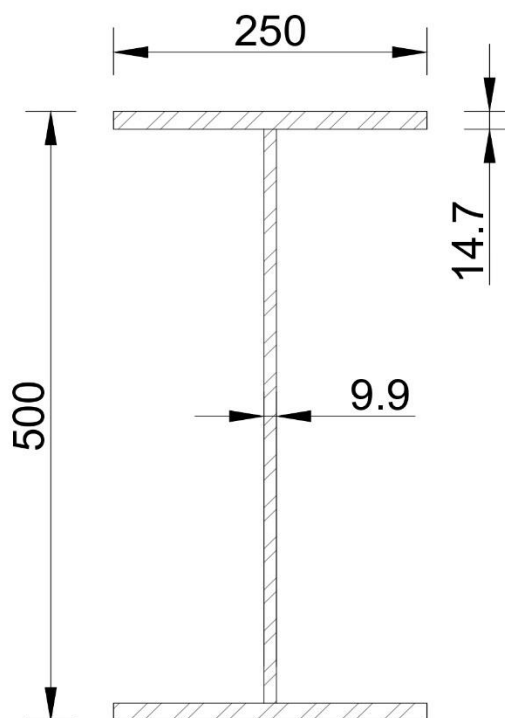


Figure.4.9 Details of the section used in the steel columns of the RF model perimeter (All dimensions are in mm)

The conditions for providing support for the interior columns and the exterior corner columns are fixed. The steel columns of the RF model are considered to be hinged.

The vertical steel columns are spaced 6m apart along the perimeter of the structure.

Load acting upon the floor slabs are the dead load of 3.75 kN/m^2 and the live load of 4.5 kN/m^2 .

4.5.2 45° Diagonal angle Hexagrid model (VH)

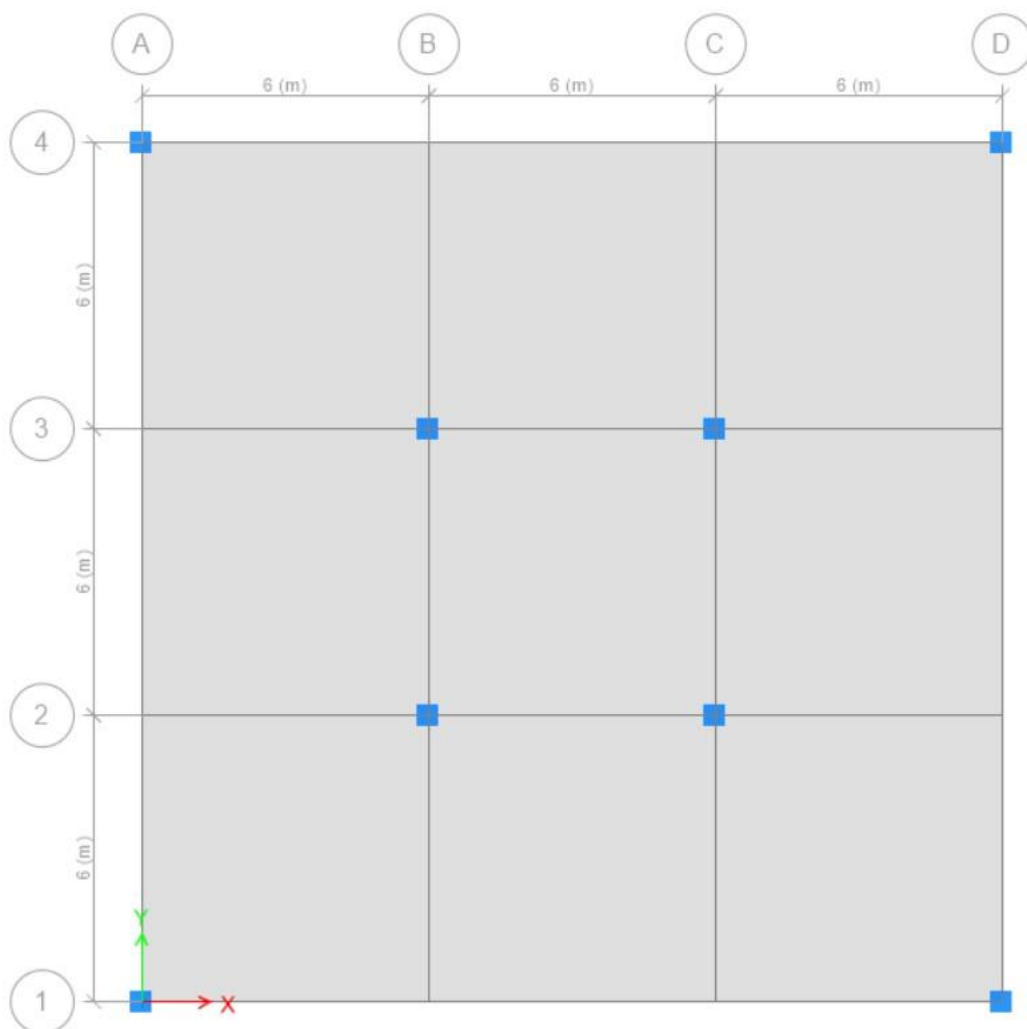


Figure.4.10 Floor plan of VH model

The floor plan of the VH model with 45° diagonal angle is identical to the RF model except for the structural framework in the perimeter. The RF model is made up of the vertical steel columns whereas the VH model consists of the Hexagrid frame in the exterior of the structure. The section properties of the interior columns, floor slabs, and the corner columns in the perimeter of the structure is the same for the RF model, VH model and VAH model.

As for the loading cases acting upon the floor, the live load of 4.5 kN/m² and dead load of 3.75 kN/m² are considered.

The spacing of the inclined columns are constant at 3m and the vertical steel columns are at 6m in the exterior.

Table.4.5 Section properties of perimeter frame in the 45° diagonal angle model (VH model)

Story	Diagonal columns	Vertical columns
GF, 2nd, 4 th , 6 th , 8th, 10 th , . . . 20 th story	ISWB500	Corner columns – RCC 0.45m * 0.45m
1 st , 3 rd , 5 th , 7 th , 9 th , . . . 19 th story		Corner columns – RCC 0.45m * 0.45m ISWB500

Grade of concrete: M30

Grade of steel: FE500

Floor slab thickness: 150mm

Table.4.6 Section properties of the interior columns and beams

Story	Interior columns	Beams	Floor slabs
G+20	RCC 0.45m * 0.45m	RCC 0.35m * 0.3m	RCC 150mm

Grade of concrete: M30

4.3.3 Varying diagonal angle Hexagrid model (VAH)

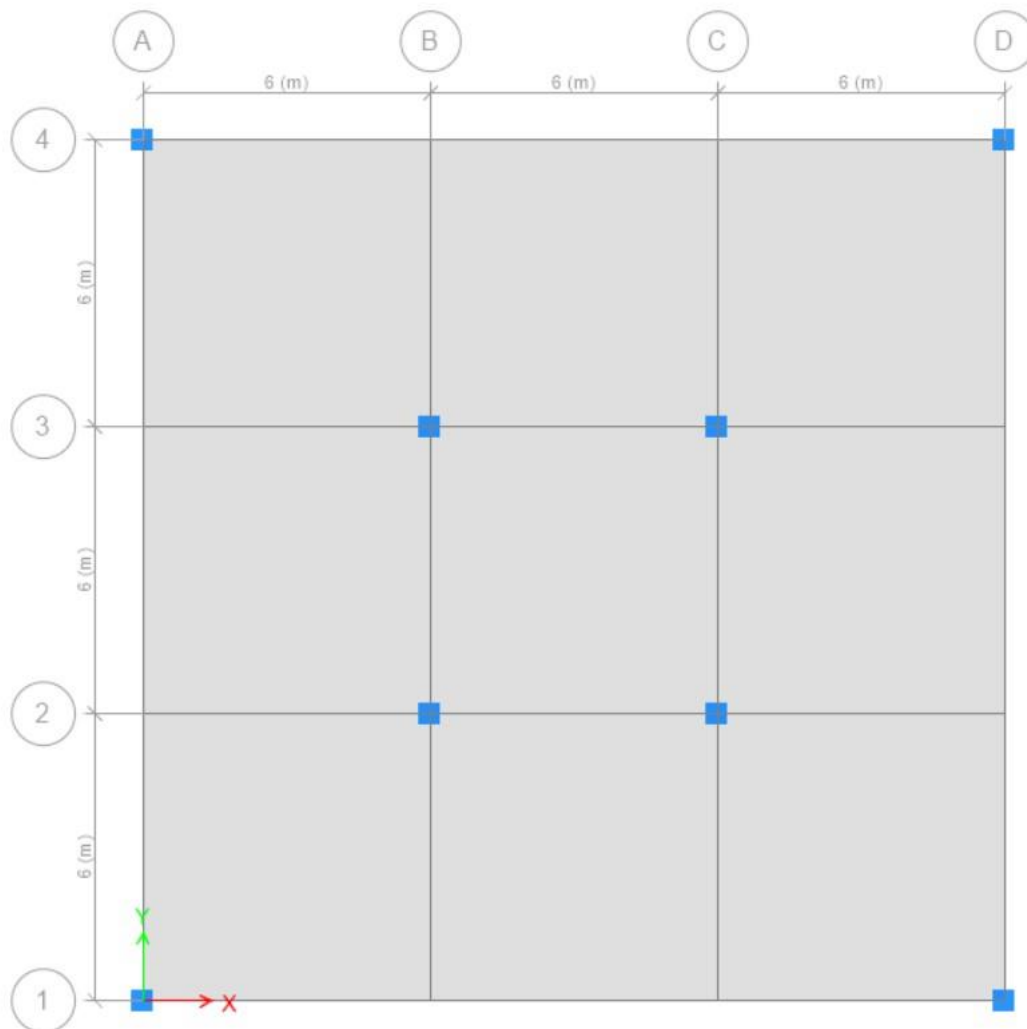


Figure.4.11 Floor plan of VAH model

Floor plan of the VAH models is identical to the RF, and VH model, with respect to the structure dimensions; 18 * 18m square plan made of 6 * 6m floor slabs. The section properties along with its sizes and positioning of the exterior corner columns, interior columns and the floor slabs are identical to that of the RF and the VH model.

Floor diaphragm for every model is considered with respect to the identical 6 * 6m floor slabs present in each floor, this is identical for every model as the dimensions of the structure do not vary.

In the perimeter Hexagrid frame, the spacing of the inclined columns and the vertical columns are 7.1m. Though the module height keeps increasing along with increase in diagonal angle, the length of the vertical member of the Hexagrid cells remain constant at 3m.

The support conditions of the interior columns and the exterior corner columns are considered to be fixed. The steel Hexagrid frame in the perimeter of the structure is hinged.

The loading cases are identical to that of the RF and VH model with 3.75kN/m² dead load and 4.5kN/m² live load acting upon the floor slabs.

Table.4.7 Section properties of the beams, floor slabs, and interior columns

Story	Interior columns	Beams	Floor slabs
G+20	RCC 0.45m * 0.45m	RCC 0.35m * 0.3m	RCC 150mm

Grade of concrete: M30

4.6 Structural modelling

4.6.1 Conventional model (RF model)

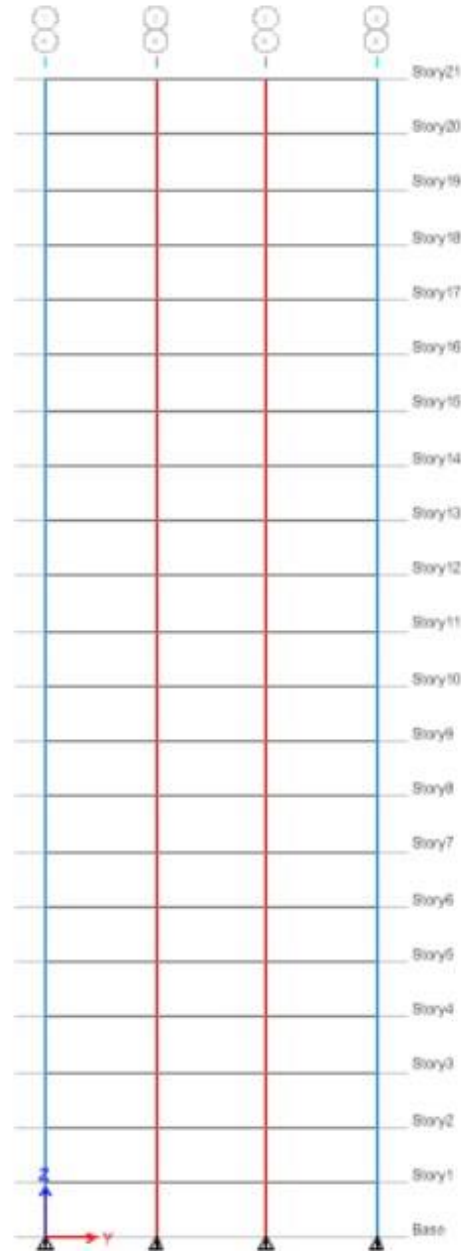


Figure.4.12 Elevation view of RF model (Red; ISWB500 steel section and the blue; 0.45 * 0.45m RCC section)

As described in the floor plan of the conventional model, the RF model consists of RCC 0.45 * 0.45m columns in the interior and the exterior corners, to resist gravity loads and transfer the loads effectively from the interior.

The 150mm RCC floor slabs along with the 0.35 * 0.3m RCC beams resist the gravity loads and mainly transfer them to the interior columns and to the exterior frame of the structure. The elevation of the RF model in **Figure.4.12** shows the two columns of vertical steel columns designed in the outer skeleton of the structure at 6m spacing for every floor with a story height of 3m.

The loading cases of the RF model are as follows;

Dead load: 3.75 kN/m² and live load: 4.5 kN/m² acting upon the floor slabs

Wind load; Basic wind speed (**V_b**): 50m/s, Structure Class: B, Terrain Category: 3, Risk coefficient (**k₁**): 1, Topography (**k₃**): 1 as per IS875: 2015 Part 3.

Seismic load; Seismic zone factor (**Z**): 0.24, Site type: II, Importance factor (**I**): 1, Response reduction factor (**R**): 5 and soil type: Medium soil.

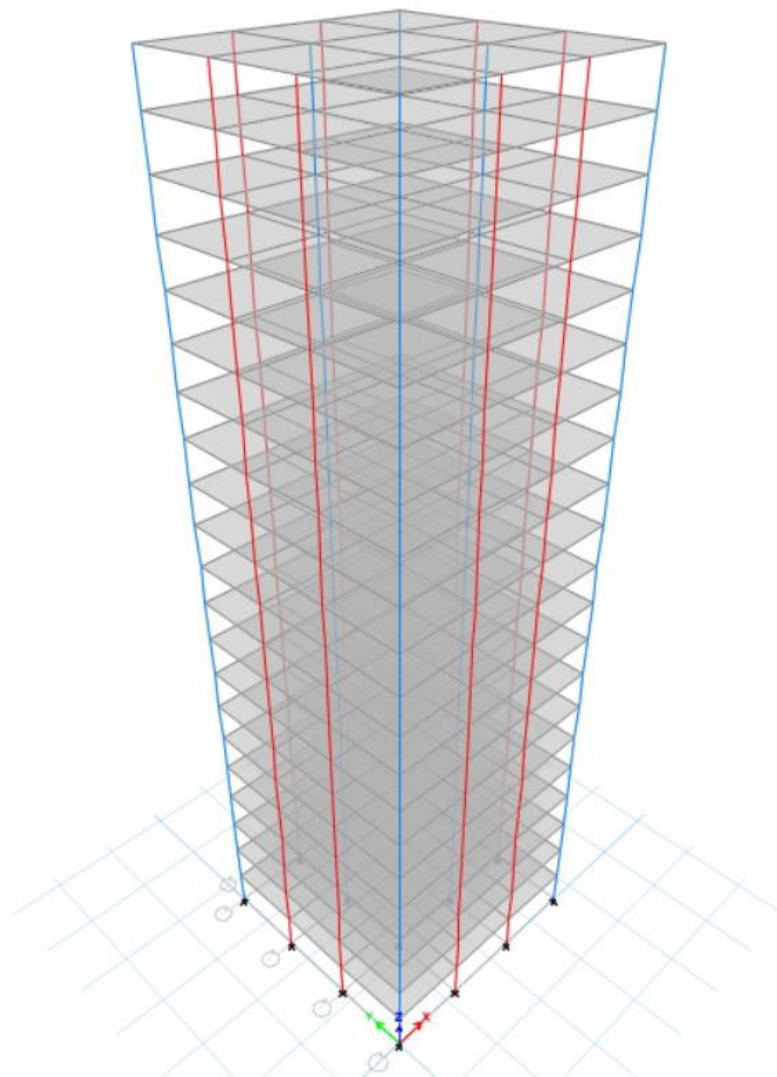


Figure.4.13 Wireframe view of RF model

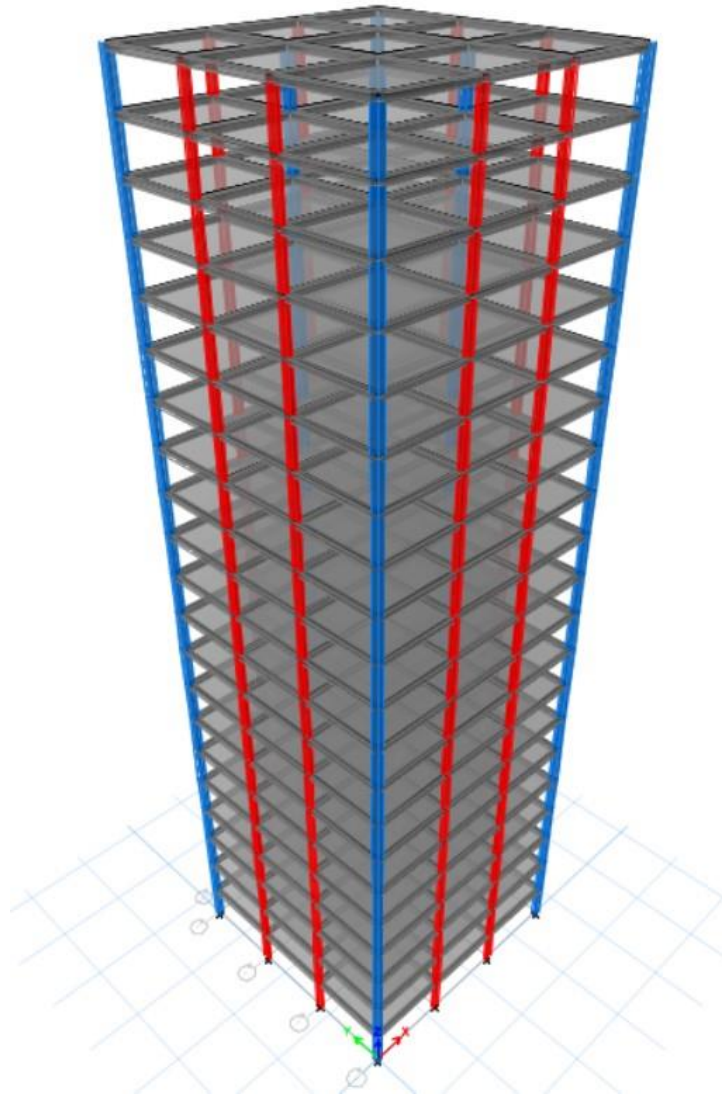


Figure.4.14 Extruded shell and frame overview of RF model

This conventional building is the reference model, RF used as the base model to compare with the Hexagrid building models. This vertical columns in the exterior frame and interior together create the commonly used structural system known as Rigid frame system.

4.6.2 45° diagonal angle Hexagrid model (VH model)

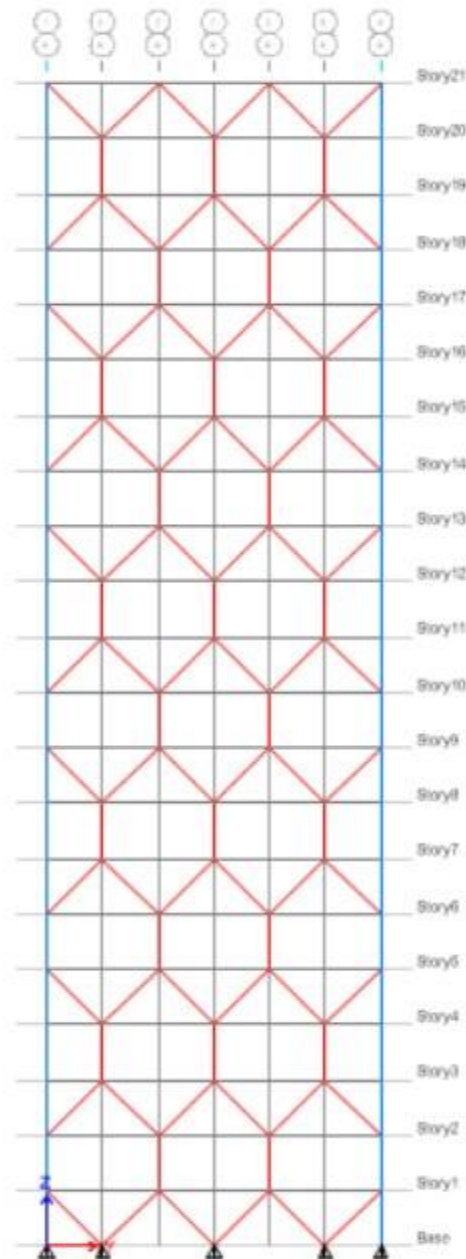


Figure.4.15 Elevation view of VH model

The basic dimensions and floor plan of the VH model are identical to that of the RF model, with an exception in the exterior skeleton comprising of the Hexagrid. The Hexagrid consists of the inclined and vertical columns at constant spacing of 3m and 6m respectively due to the fixed 45° diagonal angle of the Hexagrid.

The sections used in the interior and the exterior corner and its dimensions are identical to that of the RF model; 0.45 * 0.45m RCC vertical columns in the interior and corners of the perimeter, 0.35 * 0.3m RCC beams and 150mm RCC floor slabs. All the structural members are designed as per IS800:2007.

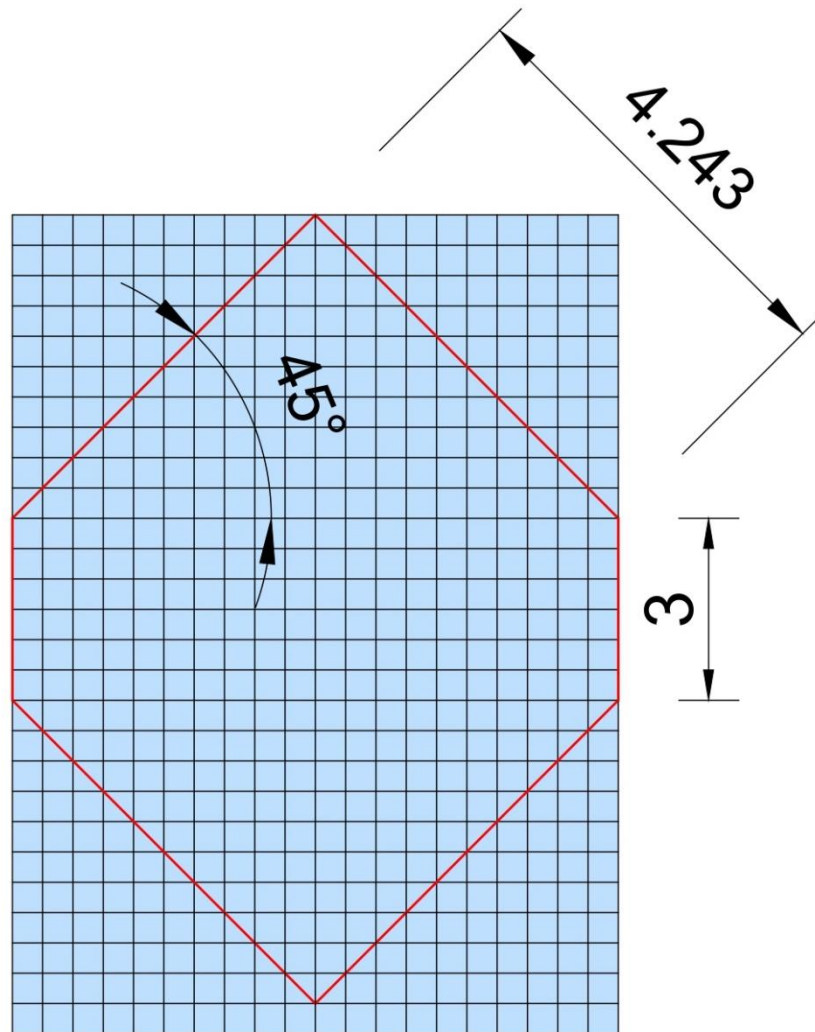


Figure.4.16 Dimensions of the 45° diagonal angle hexagonal cell in the VH model (Linear dimensions are in m)

The length of the diagonal member (**L_d**) is 4.243m, length of the vertical member (**L_v**) is 3m and the angle of the inclined/diagonal column (**Θ**) is 45°.

The module height is 9m, as seen in the **Figure.4.16** and is constant throughout the height of the structure. The diagonal angle is constant at an optimized at 45° that creates a regular Hexagrid frame. This is depicted in the **Figure.4.17**, the optimized diagonal angle Hexagrid covering the perimeter in all sides of the structure.

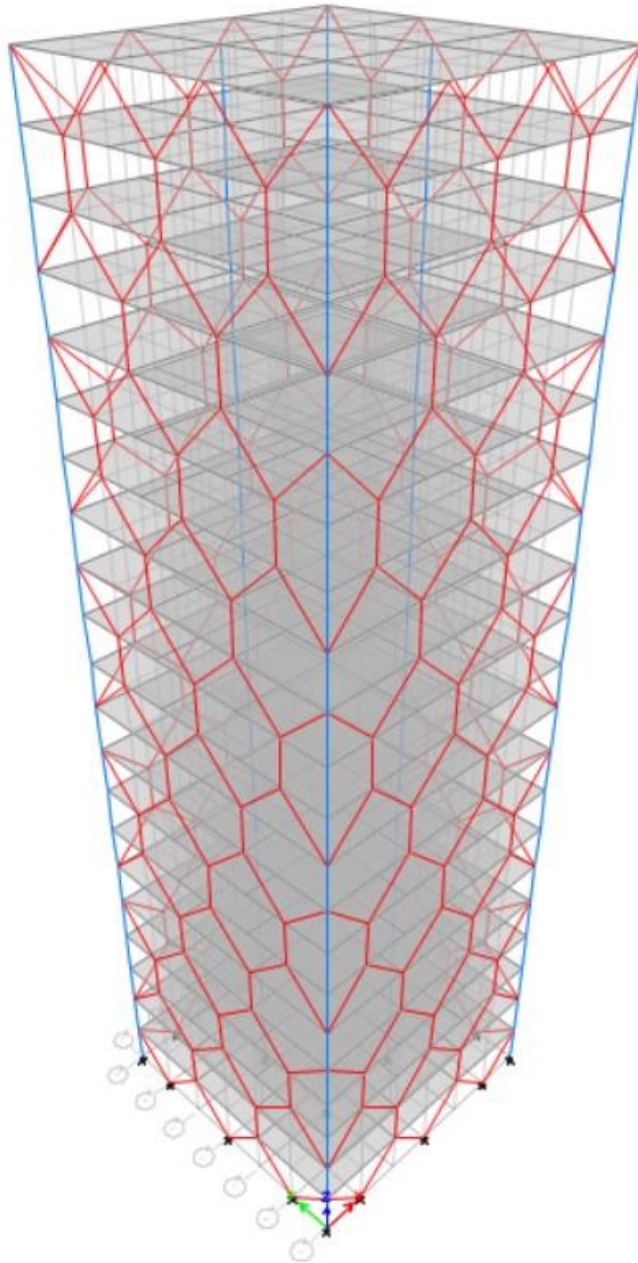


Figure.4.17 Wireframe view of VH model (Red; ISWB500 steel section and blue; 0.45 * 0.45m RCC section)

The loading cases of the VH model are as follows;

Dead load: 3.75 kN/m^2 and live load: 4.5 kN/m^2 acting upon the floor slabs

Wind load; Basic wind speed (**V_b**): 50m/s, Structure Class: B, Terrain Category: 3, Risk coefficient (**k₁**): 1, Topography (**k₃**): 1 as per IS875: 2015 Part 3.

Seismic load; Seismic zone factor (**Z**): 0.24, Site type: II, Importance factor (**I**): 1, Response reduction factor (**R**): 5 and soil type: Medium soil.

The inclined columns of the Hexagrid help in taking up the axial load, and the gravity loads efficiently and the moment transfer in the members of the Hexagrid is avoided.

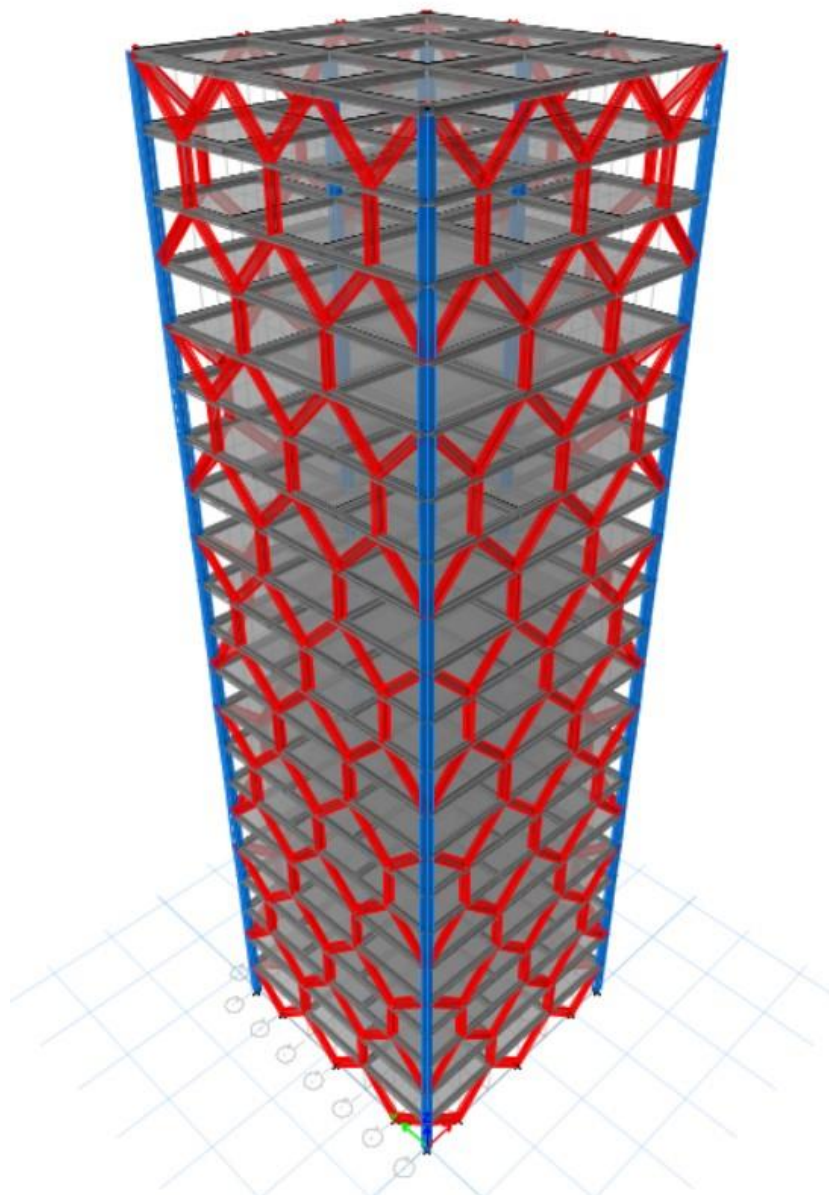


Figure.4.18 Extruded shell and frame overview of VH model

4.6.3 Varying diagonal angle Hexagrid model (VAH model)

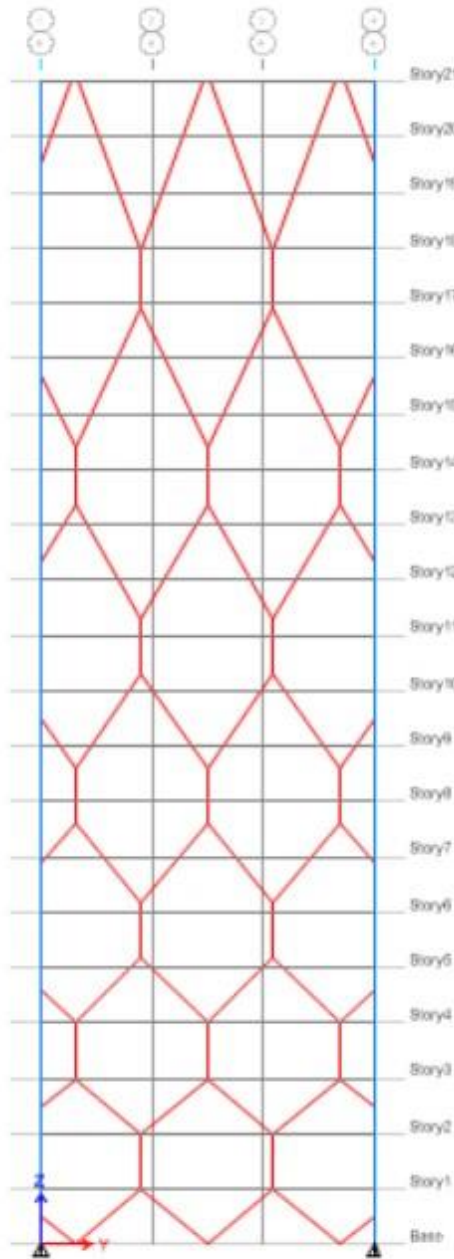


Figure.4.19 Elevation view of VAH model

The basic dimensions of the structure in terms of the floor plan, story height, interior column positioning and the exterior corner columns are identical to that of the RF model and the VH model. The varying diagonal angle Hexagrid can be seen in the figure.15.

The spacing between the vertical columns of the Hexagrid is 7.1m, with the height of the vertical members (**L_v**) in the Hexagrid remaining constant at 3m. The angle of the inclined columns varies with each row of the Hexagrid frame.

The diagonal angle (Θ) begins with 40° at the bottom, with the next Hexagrid row at 45° diagonal angle. This continues for every successive row in the Hexagrid frame, with each row having a 5° increment in the inclined column angle than the row below. The ISWB500 steel columns are utilized in the diagonal columns and the vertical columns of the Hexagrid frame.

Though the length of vertical member (**L_v**) and the spacing of the columns are constant, the increase in the angle of the diagonal column results in increase in the module height in the Hexagrid which is depicted in the **Figure.4.20** of the VAH model.

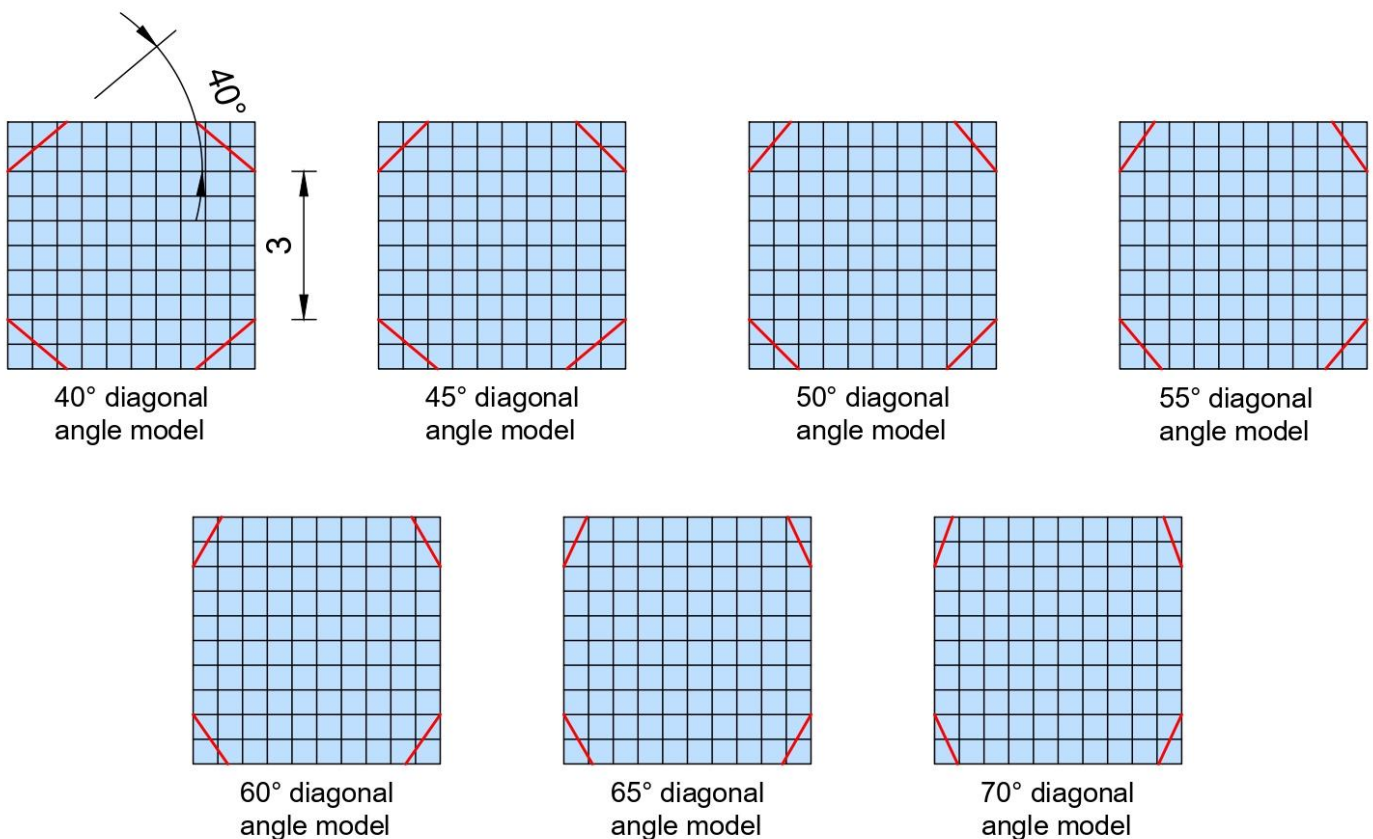


Figure.4.20 Hexagrid models with varying diagonal angle used in each row of the Hexagrid frame in the VAH model. (All linear dimensions are in m and angular dimensions are in degree)

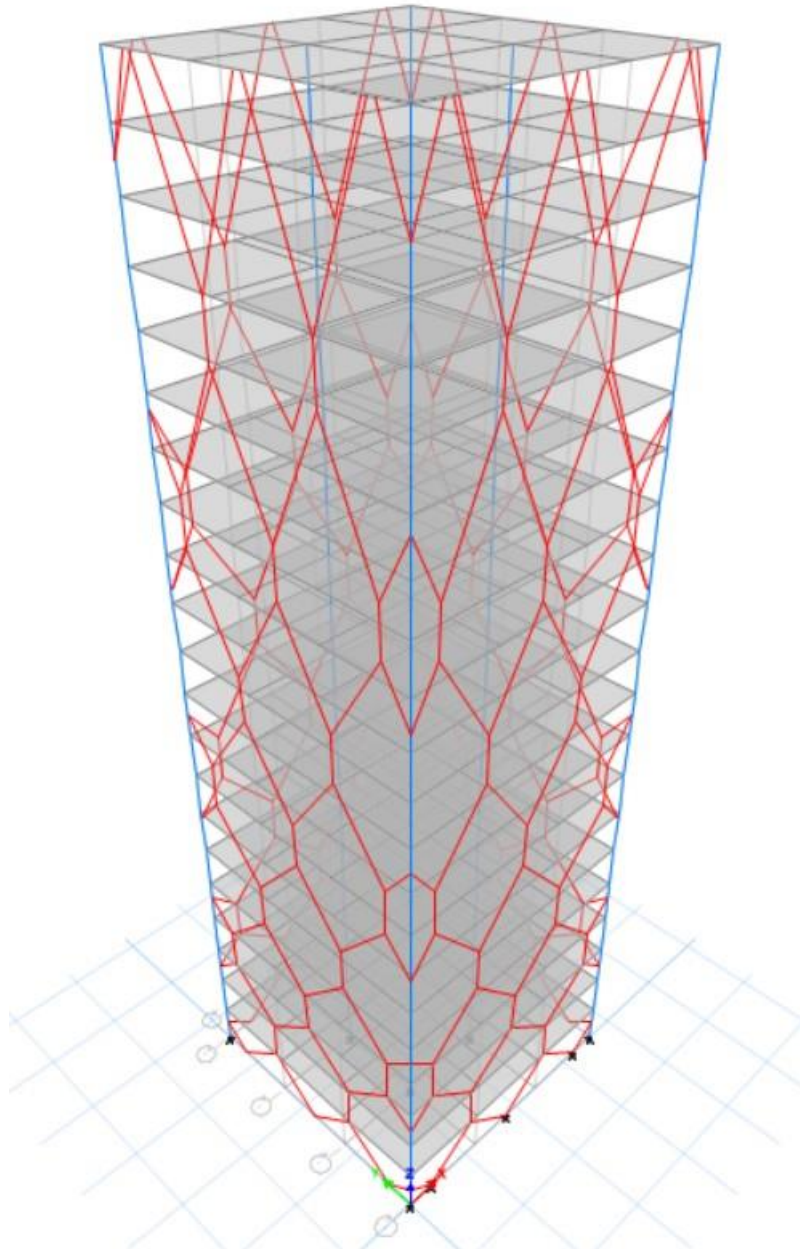


Figure.4.21 Elevation view of VAH model (Red; ISWB500 steel section and blue; 0.45 * 0.45m RCC section)

The loading cases of the VAH model are as follows;

Dead load: 3.75 kN/m² and live load: 4.5 kN/m² acting upon the floor slabs

Wind load; Basic wind speed (V_b): 50m/s, Structure Class: B, Terrain Category: 3, Risk coefficient (k_1): 1, Topography (k_3): 1 as per IS875: 2015 Part 3.

Seismic load; Seismic zone factor (Z): 0.24, Site type: II, Importance factor (I): 1, Response reduction factor (R): 5 and soil type: Medium soil.

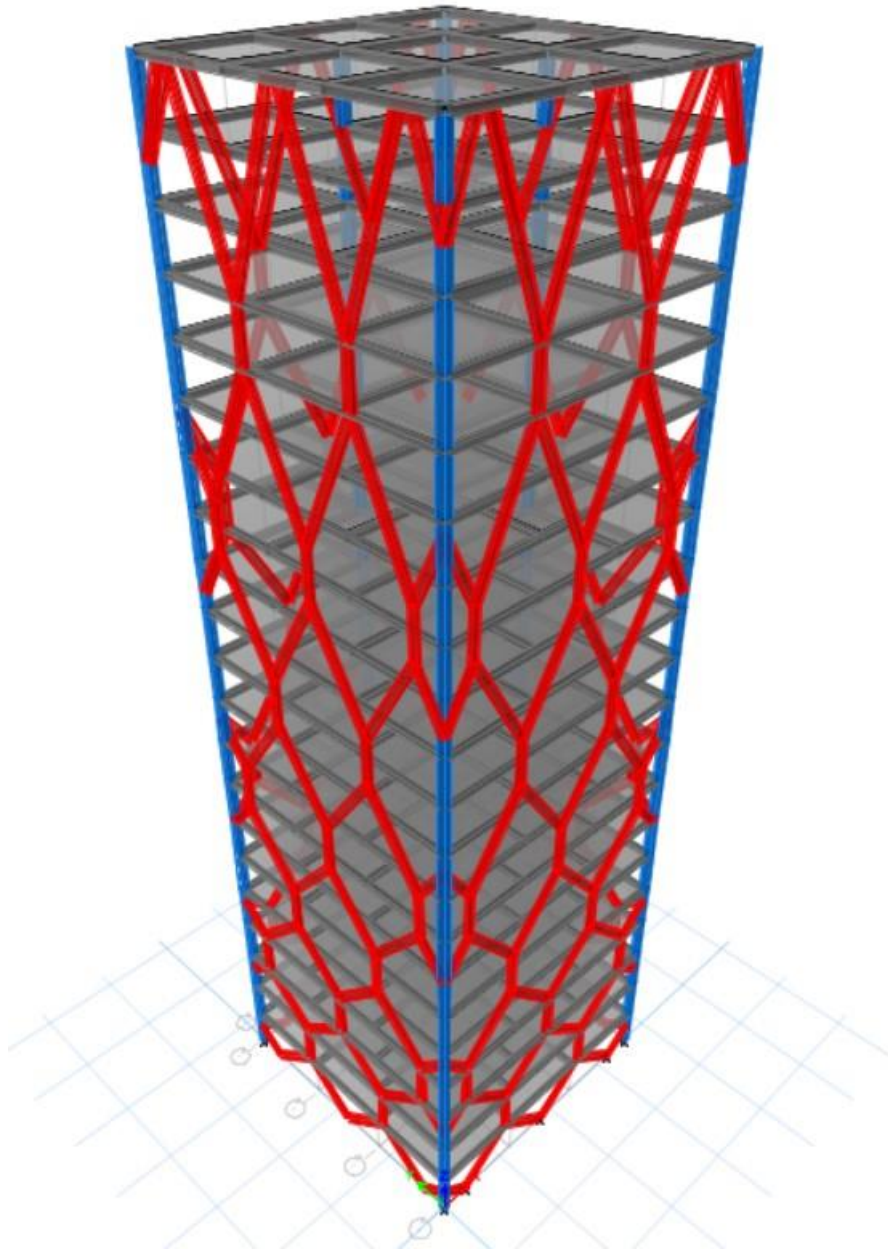


Figure.4.22 Extruded shell and frame overview of VAH model

CHAPTER 5

ANALYSIS

The analysis of the models is performed in ETABS structural design and analysis software. This helps us to perform the conventional static analysis and the more recent analysis methods such as the Response Spectrum analysis. This software supports updated Indian Codes and also supports both user-defined spectra and IS code spectra for Response spectrum analysis.

In terms of analysis, it begins with performing a static analysis and follow it with a dynamic analysis; Response spectrum analysis.

5.1 STATIC ANALYSIS

The static analysis includes the wind and seismic loading conditions, as per IS 875:2015 Part III & IS 1893: 2016 respectively.

For analysis, dead load of 3.75 kN/m^2 , live load of 4.5 kN/m^2 for the floor slabs of 150mm RCC, which is considered along with the rigid diaphragm of the floors.

A basic wind speed of 50m/s is used for wind loading conditions and seismic zone factor of 0.24 for the earthquake loads.

The load assignment along with the various parameters considered for the structure is provided in Table.9

For reinforced concrete, prestressed concrete structures are generally designed as per the Limit state method, the following load combinations are taken into consideration:

1. **1.2(DL+LL+EQX)**

2. **1.2(DL+LL+EQZ)**

3. **1.2(DL+LL+WLX)**

4. **1.2(DL+LL+WLZ)**

DL; Dead load

LL; Live load

EQX; Earthquake load in X-direction

EQZ; Earthquake load in Z-direction

WLX; Wind load in X-direction

WLZ; Wind load in Z-direction

Table.5.1 Structure parameters for design and analysis

S. No	Particulars	Conventional system - RF	Hexagonal system - VH	Variable angle system - VAH
1.	Plan dimension	18m * 18m	18m * 18m	18m * 18m
2.	Total height	63m	63m	63m
3.	Story height	3m	3m	3m
4.	Beam section	RCC; 0.35m*0.3m	RCC; 0.35m*0.3m	RCC; 0.35m*0.3m
5.	Column section	RCC; 0.45m*0.45m Steel; ISWB500	RCC; 0.45m*0.45m Steel; ISWB500	RCC; 0.45m*0.45m Steel; ISWB500
6.	Inclined column section	-	Steel; ISWB500	Steel; ISWB500
7.	Angle of inclined columns	-	45°	40°, 45°, 50°, 55°, 60°, 65°, 70°
9.	Slab section	RCC; 150mm	RCC; 150mm	RCC; 150mm
10.	Grade of concrete	M30	M30	M30
11.	Grade of steel	FE500	FE500	FE500

The three models are structural modelled and analysed using ETABS, a structural design and analysis software. This also produces graphical representations of structure outputs such as shear force, moment and axial force diagrams which helps in better understanding of each model's performance.

Along with response output it also gives 2D & 3D rendered views of the three models. The structure outputs of the models are the response of the structure to the load and stress acting upon it. The structure outputs of the static analysis are story displacement, base shear, story drift, lateral load distribution, and other force/stress tables along with diagrams. Apart from structure responses, it also shows inherent information of the designed models such as the gravity load distribution, quantity of steel and concrete sections used in the entire structure, and steel reinforcement details recommended according to IS codes.

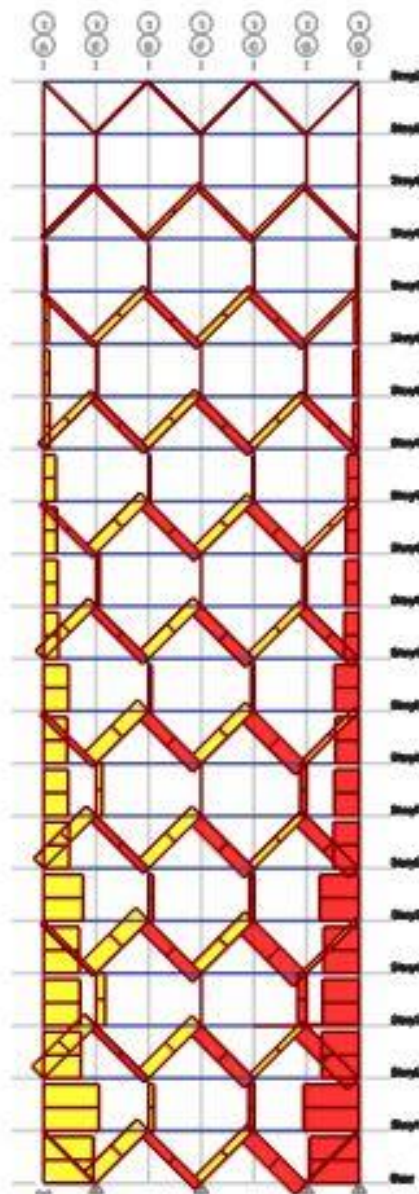


Figure.5.1 Axial force diagrams from VH model

Table.5.2 Loading and analysis parameters

S. No	Particulars	Conventional system - RF	Hexagonal system - VH	Variable angle system - VAH
1.	Dead load	3.75 kN/m ²	3.75 kN/m ²	3.75 kN/m ²
2.	Live load	4.5 kN/m ²	4.5 kN/m ²	4.5 kN/m ²
3.	Seismic load - IS Code Seismic Zone Importance factor Zone factor Damping Ratio Response reduction factor	IS1893: 2002 (Part 1) IV 1 0.24 5% 5	IS1893-2002 (Part 1) IV 1 0.24 5% 5	IS1893-2002 (Part 1) IV 1 0.24 5% 5
4.	Wind load – IS Code Basic wind speed Terrain Category Structure Class Risk Coefficient (k1 factor) Topography (k3 factor) Windward coefficient Leeward coefficient	IS 875: 1987 (Part 3) 50 m/sec 3 B 1 1 0.8 0.5	IS 875: 1987 (Part 3) 50 m/sec 3 B 1 1 0.8 0.5	IS 875: 1987 (Part 3) 50 m/sec 3 B 1 1 0.8 0.5
5.	Soil condition	Medium soil (Type II)	Medium soil (Type II)	Medium soil (Type II)

5.2 Response spectrum analysis

It is one of the dynamic analysis methods which utilizes the natural frequency and the function of it to find the peak response of the structure under short dynamic events. The concept behind this analysis is that, every object or a structure possess a specific natural frequency or period. This natural frequency of a structure is influenced by the mass source of it and the stiffness of the structure that may vary along the height in case of multi-storeyed structures. This is shown in **Figure. 5.2**.

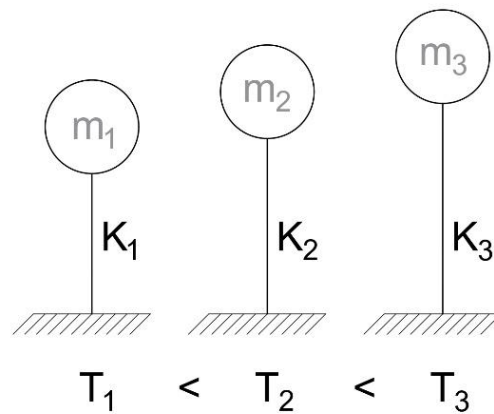


Figure.5.2 Natural frequencies of different structures with varying mass source and stiffness

Considering this case for a mass system with linear single degree of freedom, and a fixed damping value. As the stiffness of the structure increases, the natural frequency of the system increases. As the mass of the structure increases the natural frequency of the system decreases. For mass source m_1 , m_2 , and m_3 of three different structures with stiffness K_1 , K_2 and K_3 where each stiffness value is greater than the one behind it respectively. This varying stiffness and mass source results in increasing natural frequencies of the structures; T_1 , T_2 & T_3 .

The response spectrum analysis involves taking this natural frequency of the structure, considering a ground acceleration for a short time or certain oscillators for the maximum response of the structure.

By modifying the mass of structures of different stiffness, or varying the stiffness when structures are of different mass, the natural period of all the structures with different stiffness or mass can be matched respectively.

In order for the natural frequencies of the structures to be identical, then for the given ground acceleration, the maximum response is the same for all the structures. Considering a linear single degree of freedom system for a given ground acceleration, it is completely dependent upon the natural frequency and the damping.

In regards to the ground acceleration, it is usually taken from ground acceleration and the time data of earthquakes that have occurred in the past. But in the case of the Response spectrum, this study is not concerned with the time variation of the responses but only on the maximum response of the structure. These maximum responses such as displacement, maximum forces show the maximum limit of the responses the structure must withstand for it to be safe and serviceable.

So, the response spectrum can be defined as a plot of the maximum responses of linear single degree of freedom system oscillators as a function of natural period for a given value of damping.

This response can be displacement, acceleration, or velocity

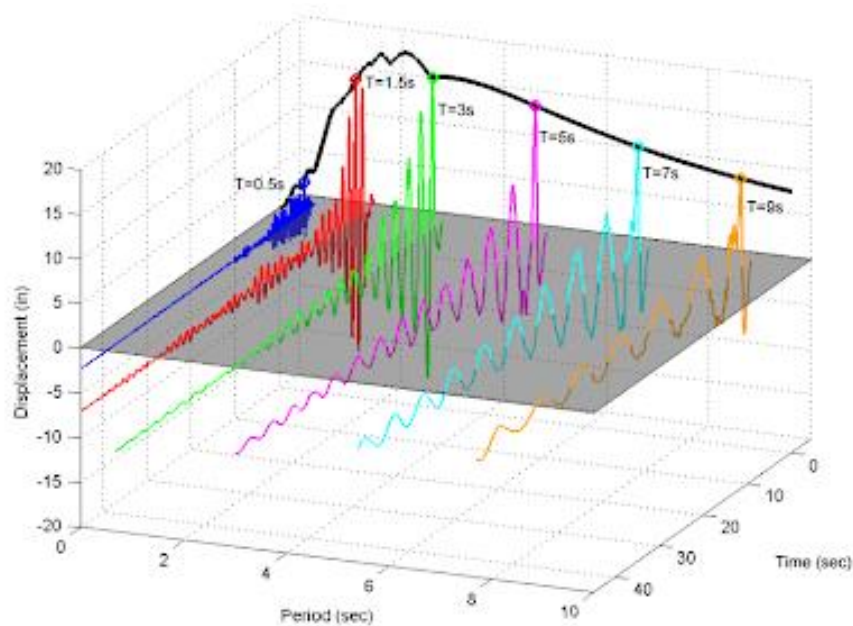


Figure.5.3 Linear displacement spectra of 1986 North Palm Springs earthquake

The linear spectra plot the maximum response such as acceleration, displacement or velocity forming the respective spectra against the period and time.

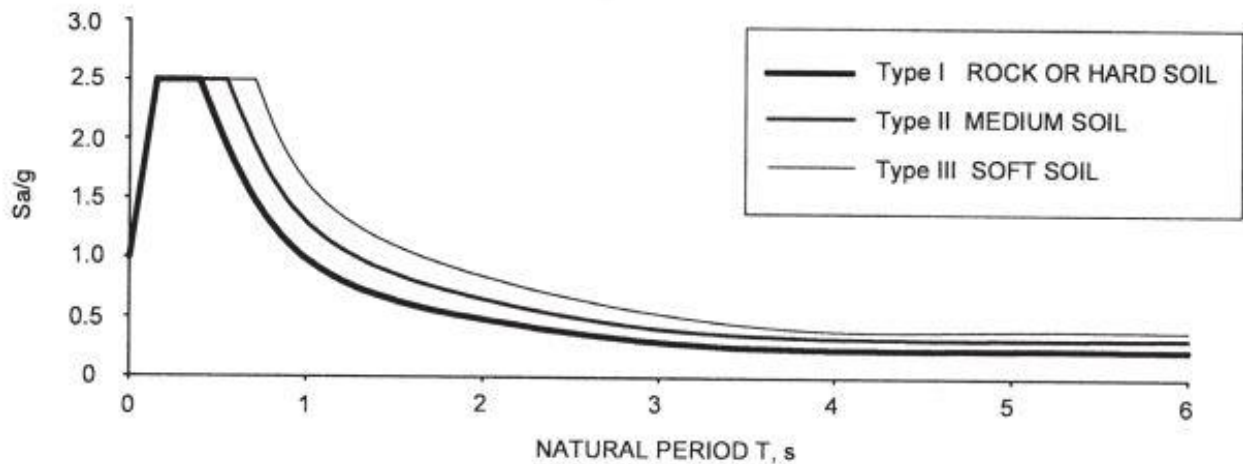


Figure.5.4 Response spectra providing design acceleration coefficient (S_a/g) corresponding to 5% damping

For performing the response spectrum analysis, the mass source is considered, with lumping the lateral mass at story levels and also including the mass multipliers for each loading case; Dead load: 1 & live load: 0.5. The modal case with Eigen Modal type is considered with horizontal acceleration in two directions; U1 & U2. The Eigen mode is used to determine the response from horizontal ground acceleration.

The number of modes for a building is considered as number of stories multiplied by the degrees of freedom as a rule of thumb. In this case, the degree of freedom is 3, two translational and one rotational.

Response spectrum function for horizontal acceleration is added as per IS 1893. In this the damping ratio is taken as 5% as per clause 7.2.4 in IS 1893 (Part 1): 2016. Seismic zone: IV, Seismic zone factor (Z): 0.24, Importance factor (I): 1, Soil type: II, Response reduction factor (R): 5. With the user provided factors, the natural period and the respective acceleration is defined and plotted.

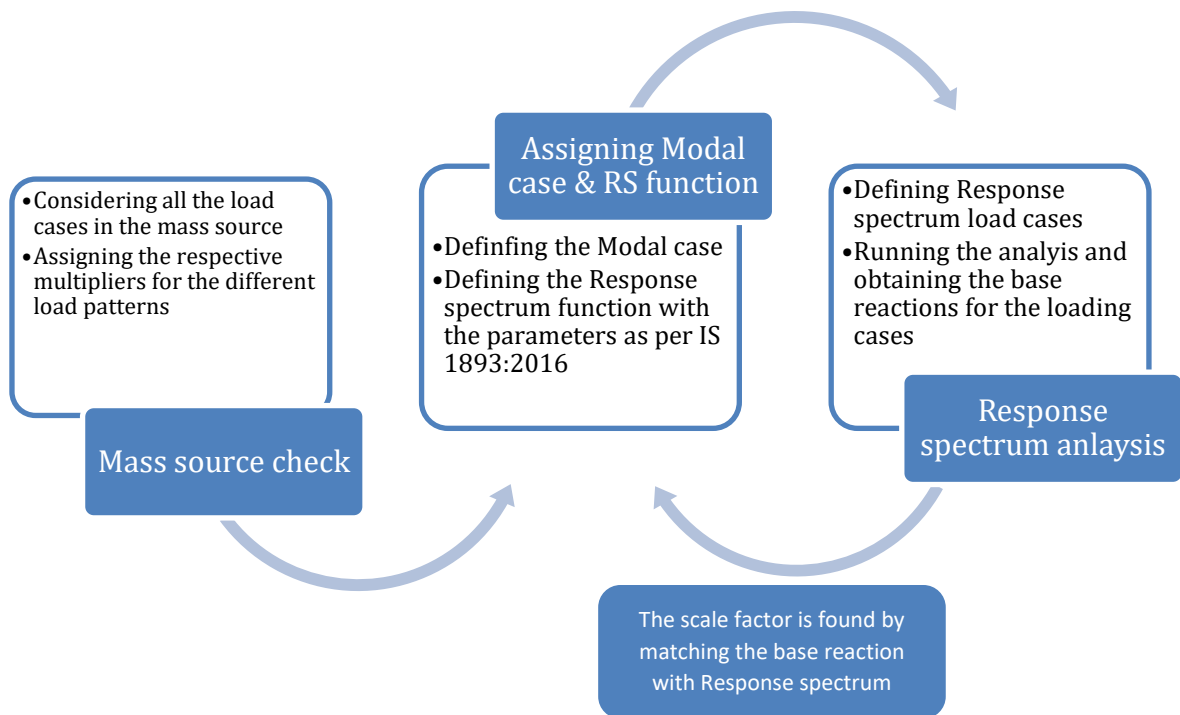


Figure.5.5 Flowchart of the Response spectrum analysis in ETABS

Load cases for the response spectrum function is defined with mass source, in two horizontal directions, named as RSx & RSy. Before providing the scale factor, manual calculation for the design horizontal acceleration seismic coefficient (A_h) is determined as per clause 6.4.2 IS 1893-2016.

$$A_h = \frac{\left[\frac{Z}{L} \right] \left[\frac{S_a}{g} \right]}{\left[\frac{R}{I} \right]}$$

Z, Seismic zone factor = 0.24

R, Response reduction factor = 5

I, Importance factor = 1

S_a/g , Design acceleration coefficient for different soil types

In our case, Soil type II – Medium or stiff soils.

For RC-Steel composite buildings:

Natural period of structure, $T_a = 0.080h^{0.75}$

The scale factor for the response spectrum load cases is given by $\left(\frac{I_g}{2R}\right) = 980.67$.

This scale factor is used to match the RSx, RSy with 85% of the static base reactions, EQx, and EQy.

For a particular structure, there might be many modes. Thus, to summarize the base shear for the modes uses the ABS, CQC and SRSS method depending upon the modes and the pattern among them. In case of using SRSS method, the result may not be accurate if the modes lie very close to each other. This study chooses the CQC method, i.e., complete quadratic combination method.

Since, the number of modes taken into consideration for a G+20 structure will result in a complicated understanding of the various frequencies the structure will oscillate along, only take 12 basic modes with respective period and acceleration taken using the Response spectrum graph from IS 1893:2016.

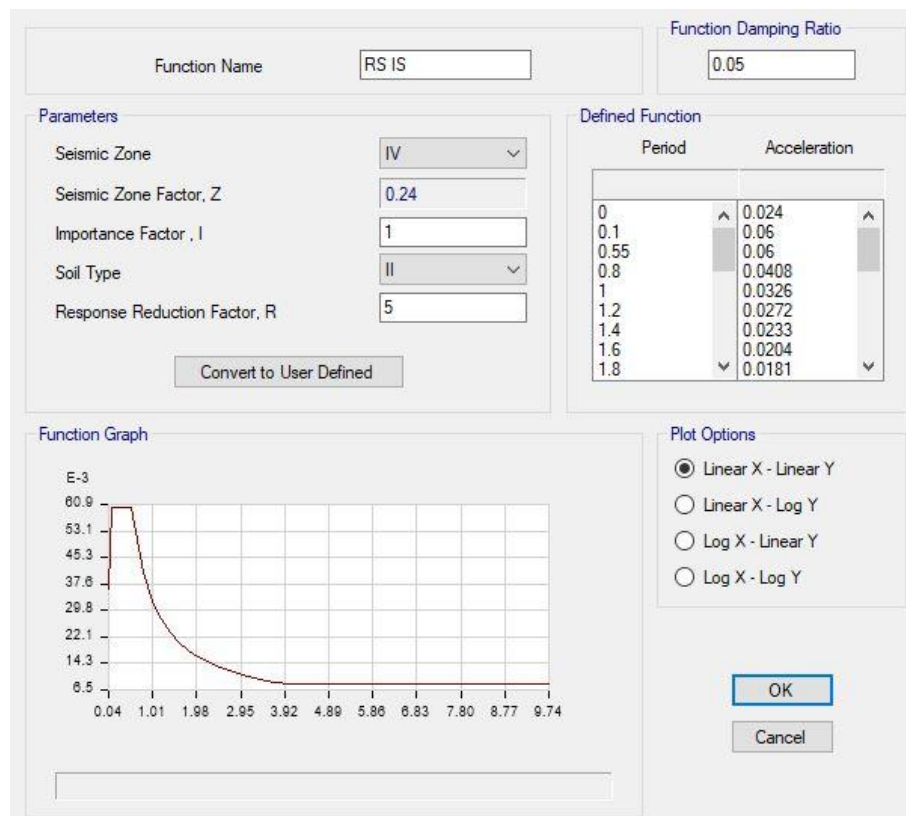


Figure.5.6 Response spectrum function definition as per IS 1893:2016

CHAPTER 6

RESULTS & DISCUSSION

6.1 Static Responses

6.1.1 Story Drift

Story drift is the difference of displacement between the two consecutive stories divided by the height of that story. Minimum story drift is desired, in the case of the conventional frame building.

From **Figure.6.1** of the conventional frame model, it can be seen that there is a significant spike in the story drift for the 1st story. This is called the soft story effect, which can be identified by the comparatively high story drift. This occurs in a structure when a level of the building has lower resistance to lateral loads compared to the levels above it.

The story drift of the VH & VAH structure lies in an identical range, with the maximum story drift being 0.002.

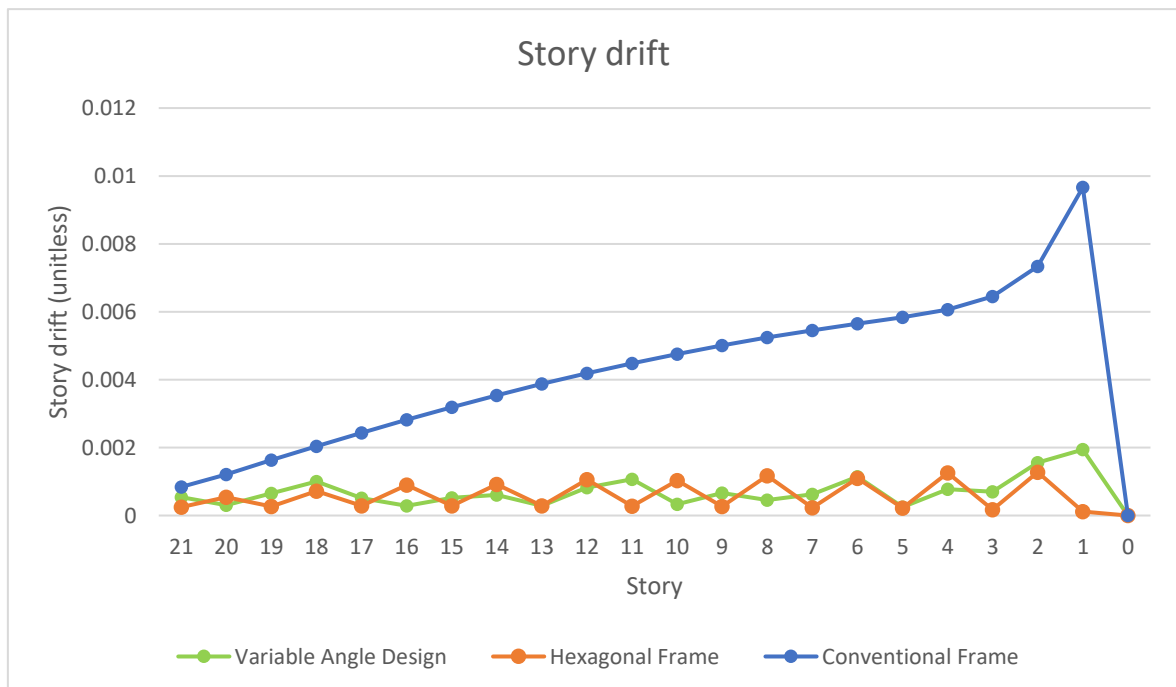


Figure.6.1 Story drift vs Story plot for conventional structure, 45° diagonal Hexagrid structure and varying angle Hexagrid structure

6.1.2 Story displacement

Story displacement is the lateral displacement of the story relative to the base. The lateral force-resisting system can limit the excessive lateral displacement of the building. The acceptance lateral displacement limit for wind load case could be taken as $H/500$ (some may take $H/400$).

From **Figure.6.2**, the displacement in the RF structure is 150% greater than that of the VH & VAH structures.

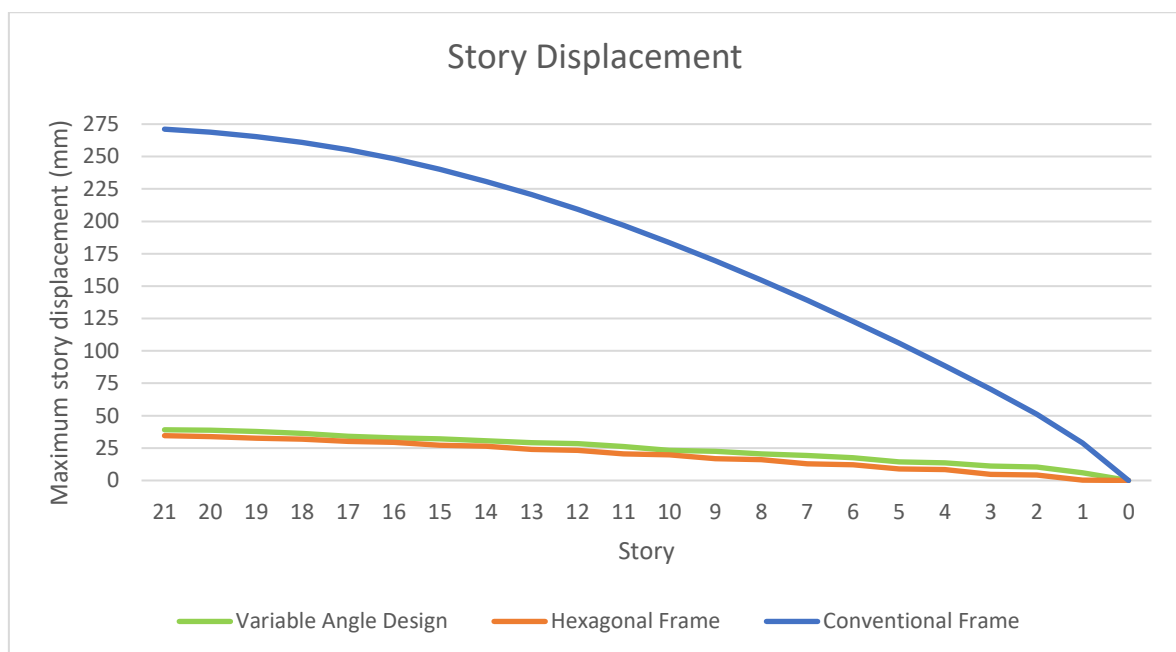


Figure.6.2 Story displacement vs Story plot for conventional structure, 45° diagonal Hexagrid structure and varying angle Hexagrid structure

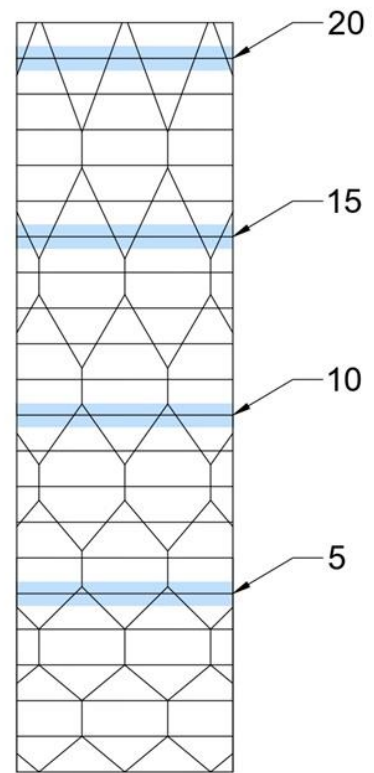
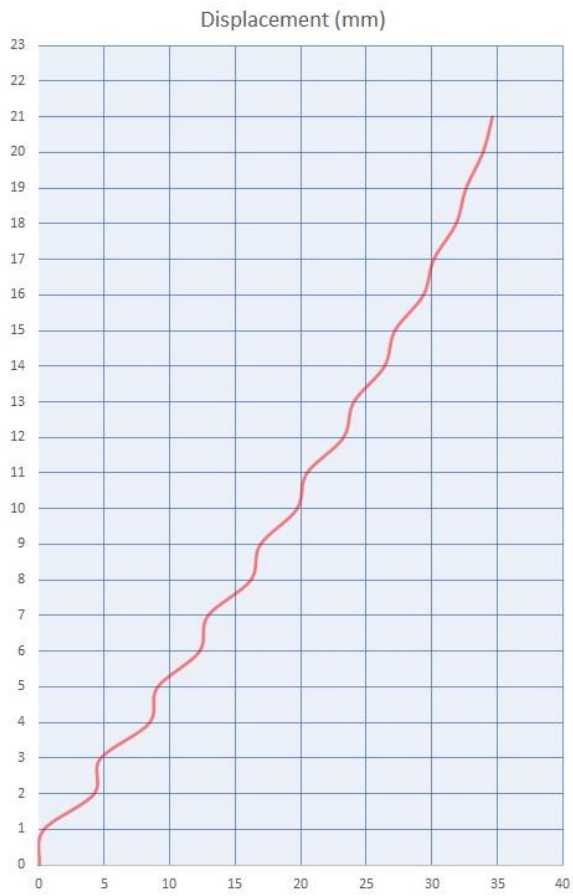


Figure.6.3 Displacement for 5th, 10th, 15th & 20th story of Varying angle Hexagrid

6.1.3 Story overturning moment

The overturning moment of an object is the moment that tends to make the structure overturn, topple or become unstable, when an additional lateral force acts upon it.

The story overturning moment is highest for the RF structure, followed by the VH and VAH structure respectively is shown in **Figure.6.4**.

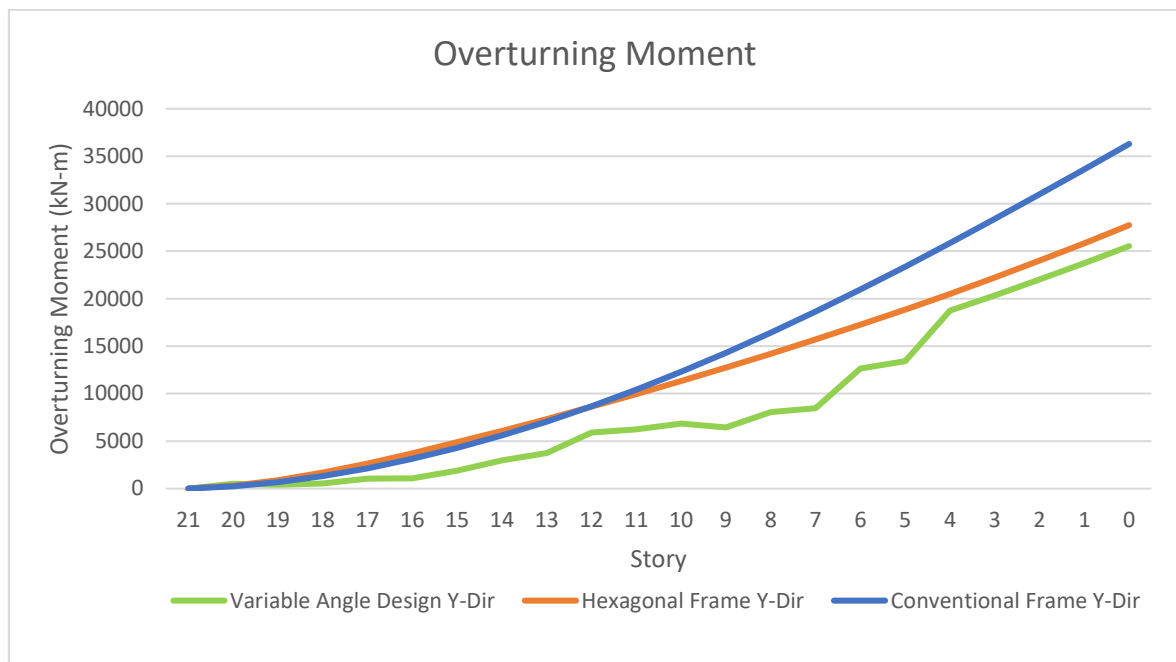


Figure.6.4 Story overturning moment vs Story for conventional structure, 45° diagonal Hexagrid structure and varying angle Hexagrid structure

6.1.4 Story stiffness

Story stiffness can be defined as lateral forces by story displacement, it is basically the ability of a structure or element to resist displacement, deflection due to the applied stress.

From the **Figure.6.5**, VH structure has a higher story stiffness than the RF & VAH structure, this may be due to the symmetrical distribution of gravity and lateral loads through the optimized and symmetrical hexagrid frame in the perimeter of the VH structure.

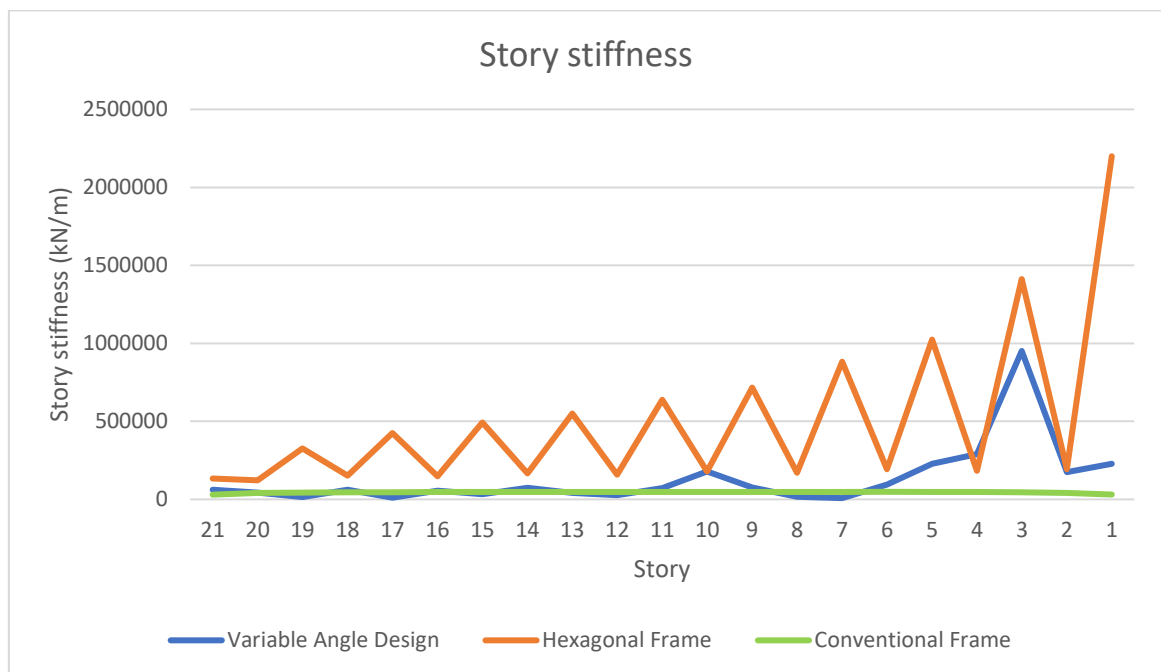


Figure.6.5 Story stiffness vs Story plot for conventional structure, 45° diagonal Hexagrid structure and varying angle Hexagrid structure

6.1.5 Lateral load

Lateral loading is the load applied on a structure in a horizontal direction or parallel to the x-axis. Typical lateral loads would be a wind load, seismic loads or special loads such as impact loads. Lateral loads depend upon the building's terrain, structural system, height and shape.

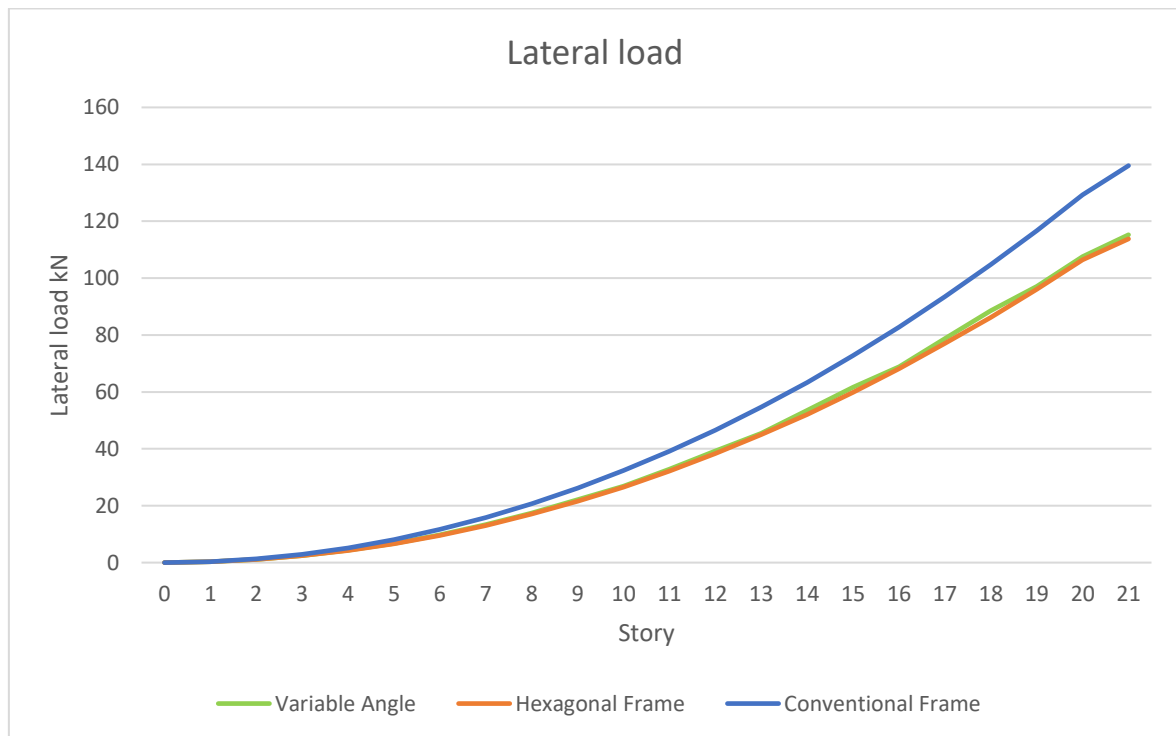


Figure.6.6 Lateral load vs Story for conventional structure, 45° diagonal Hexagrid structure and varying angle Hexagrid structure

6.1.6 Quantity

Quantity of material or section used presents the factor of having an economical design for structures.

The **Figure.6.7**, the quantity of steel used in the structures are depicted.

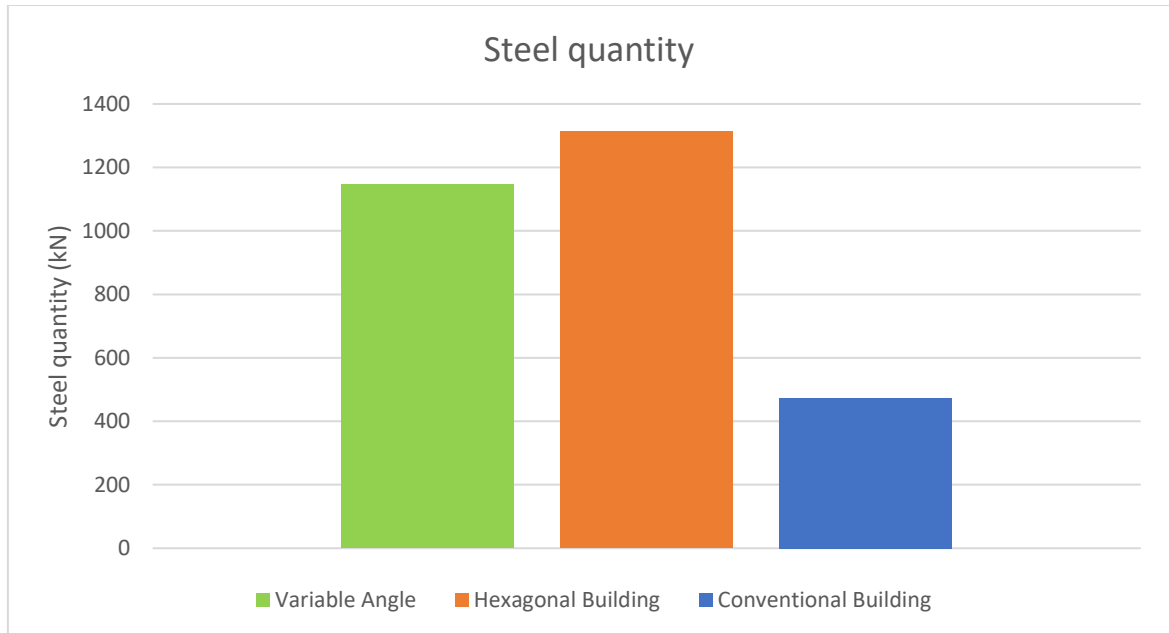


Figure.6.7 Steel quantity for conventional structure, 45° diagonal Hexagrid structure and varying angle Hexagrid structure

6.2 Dynamic Responses

6.2.1 Time period

Simply put, the time period of a building is its natural period of oscillation when subjected to ground shaking in the event of an earthquake. The building is modelled to be under harmonic oscillation and the time period is calculated in a similar way as in harmonic oscillation

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

where k is the total stiffness and m is the total mass.

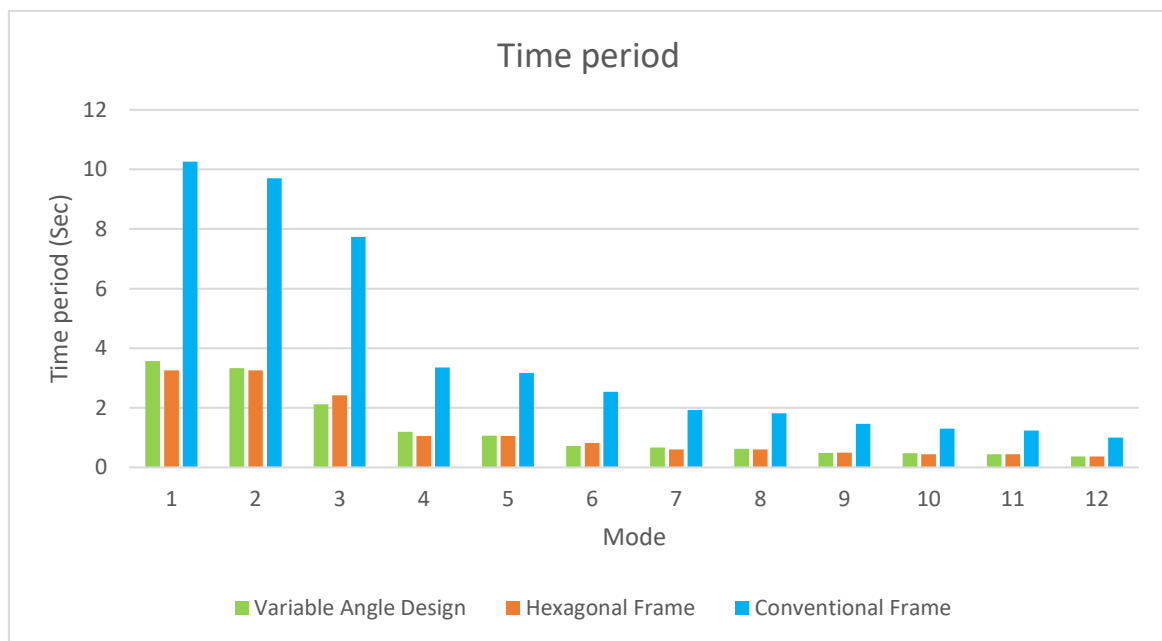


Figure.6.8 Time period vs mode for conventional structure, 45° diagonal Hexagrid structure and varying angle Hexagrid structure

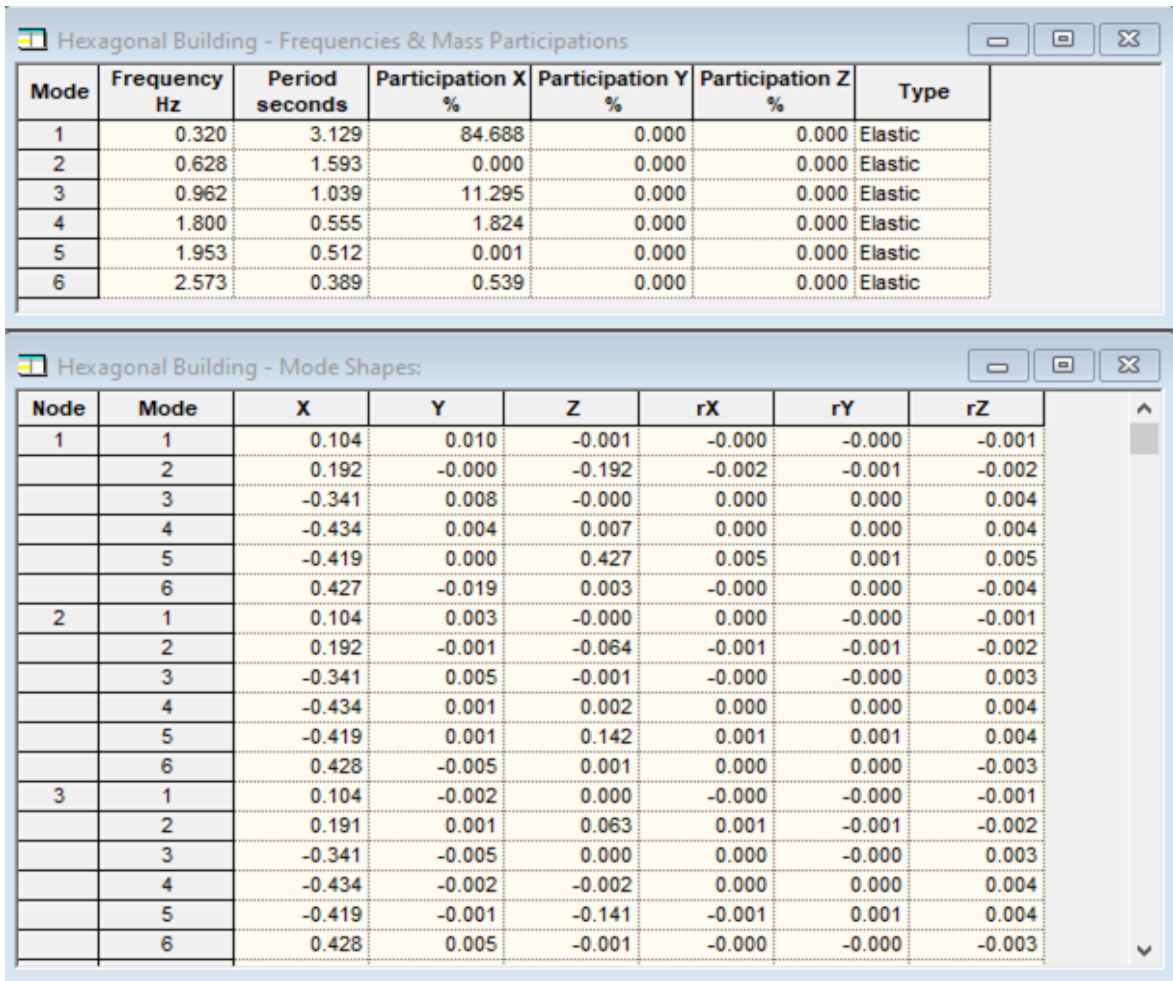


Figure.6.9 Frequency, time period and the participation ratio of modes for 45° diagonal angle Hexagrid structure

CHAPTER 6

CONCLUSION

The objective of the project was to design and analyse a hexagonal frame building and compare its structural performance with a conventional frame building.

1. The story drift of conventional building not only vastly exceeded the story drift of the hexagonal building but also was under the influence of the soft story effect. This can be due to the lack of lateral load resistant members in the conventional model. And about the variable angle design, there's a slight difference with the hexagonal optimal angle design.
2. In terms of the story displacement under the Response Spectrum condition, the hexagonal buildings with 45° optimal angle (VH) and variable angle (VAH), only resulted with 12% of the conventional building, thus making it more efficient in terms of structural performance. The story displacement of the hexagonal two designs is approximately the same as shown in the graph.
3. Initially, the story overturning moment is similar for the top storeys of the three structures but as the storey height decreases, the overturning moment of the RF model is higher than that of the two Hexagrid structures by 28.5%. This is due to lower lateral supports in the conventional frame system used in the RF structure.
4. The VH structure has a higher story stiffness than the RF & VAH structure, this may be due to the symmetrical distribution of gravity and lateral loads through the symmetrical hexagrid frame in the perimeter of the VH structure.
5. As there are more steel sections used in the hexagonal designs, so the steel quantity is higher than RF structure. The quantity of steel is more in the VH structure than the VAH structure because as the angle increases with height the story covered by the sections is also increased.
6. The time period of modes of the conventional structure is significantly higher than that of the Hexagrid structures by an average of 100%. This is due to the less stiffness against the vibrations of the various modes.

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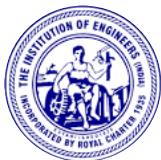
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