

# Comparative Study of Performance of High Rise Buildings with Diagrid, Hexagrid and Octagrid Systems under Dynamic Loading

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**Abstract** - The developments in construction techniques, materials, structural systems and the analytical methods for analysis and design opened the door for the growth of high rise buildings. The structural design of tall buildings is governed by the action of lateral loads due to wind or earthquake. Lateral load resistance of a structure is offered by interior structural systems or exterior structural systems. Exterior structural system constitutes Diagrid, Hexagrid, Pentagrid and Octagrid Systems. Recently, Diagrid structural system is adopted in tall buildings due to its structural efficiency, superiority in aesthetic appeal and flexibility in architectural planning. Diagrids, Hexagrids and Octagrids contain triangular or diamond shaped modules, hexagons and octagons respectively, throughout exterior of structure and they don't have any external vertical columns. Due to inclined columns, lateral loads are resisted by axial action of the diagonal. A regular floor plan of 36 m x 36 m size is considered. ETABS V15 software is used for modelling and analysis of structural members. Twelve models are created collectively of Exterior Braced steel frame structure, Diagrid, Octagrid and Hexagrid buildings with regard to variation in their diagonal angles and module density. Equivalent static and Response spectrum analysis of these models have been carried out to examine their performance. A comparison of parameters Storey Shear, Storey drift, Storey displacement, Time period and Structural weight is done to determine the efficient and cost effective structure.

**Key Words:** High Rise Structure, Diagrid, Hexagrid, Octagrid, Equivalent Static and Response Spectrum Analysis

## 1. INTRODUCTION

High rise buildings are booming right now especially in major cities of world, due to the progression of efficient structural systems, advances in the construction technology and shortage of urban land available for construction. Lateral loading due to wind or earthquake are the governing factors in the design of high rise buildings along with the action of gravitational loading. In order to resist the lateral loads, either interior or exterior structural systems are employed. The widely used internal lateral load resisting structural systems include rigid frame, braced frame, shear wall and outrigger structure whereas the exterior systems constitute tubular, diagrid, pentagrid, hexagrid and octagrid structures. Lately, diagrid structural systems are adopted in

tall buildings, owing to its structural competency, elegance in appearance and resilience in the aspect of architectural planning.

In the diagrid structures, the vertical columns from the periphery of the structure are eliminated and it consists of diamond shaped modules. A triangulated configuration is formed in the diagrid structural systems because of the modules and due to this, diagrids are able to carry gravity and lateral loads and distribute them in a very uniform and regular pattern. In addition, by the usage of diagonals, lesser amount of material is used. Also, due to the elimination of columns, much space is available to make the structure more flexible. Module size or diagrid module height is the number of stories in the Diagrid module. Moreover, diagrid's diagonal angle is the angle between the diagonal members and the horizontal beams in the exterior of the structure. Diagrid module size and Diagonal angles both play a key role in structural, architectural and aesthetic concepts of these structures.

The hexagrid consists of multiple hexagonal grids at the exterior perimeter surfaces of building. The hexagrid system is a particular form of belt trusses mixed tubular system and resists lateral loads acting in tension or compression. Similarly, Octagrid contain several octagons arranged at the exterior of the structure. Module density of a hexagrid or octagrid denotes the number of hexagon or octagon modules around the periphery. If more number of modules can be incorporated around the periphery, the building is said to be of high module density and vice-versa.

## 2. RESEARCH SIGNIFICANCE

Construction of multi-storey building is rapidly increasing throughout the world due to the rapid growth of urban population and limitation of available land. As the height of structure increases, the influence of lateral loads increases and requires lateral load resisting structures to resist them. The diagrid structural system is widely used for recent tall buildings due to the structural efficiency and aesthetic potential. Hexagrid structural system can be used to challenge the limit to building height in diagrid. The employment of Diagrid, Hexagrid or Octagrid structural systems in a building give rise to numerous advantages like reduction of interior columns giving large column free spaces that can be used as indoor sports auditoriums, exhibition halls etc. The inclined columns take up gravity as well as lateral loads unlike the conventional vertical columns. Also,

these systems lead to huge savings in terms of material cost. Hence, it is necessary to compare the three systems of Diagrid, Octagrid, and Hexagrid with an exterior braced steel structure to find out the efficient structural system.

The objective of this paper is to study and compare the performance of Diagrid, Octagrid and Hexagrid buildings with varied diagonal angles and varied module density under dynamic loading and also to find the structural system that exhibits least top storey displacement and drift, the optimal range of diagonal angle possessing better stiffness and relationship of time period to lateral stiffness. Compare the structural weight and material cost of all building models to determine the most economical option among the models.

### 3. BUILDING DESCRIPTION AND MODELING

A square shaped 36 storey building of size 36m x 36m, storey height 3.6m and plan area 1296m<sup>2</sup> is considered for the analysis and design. The four types of buildings that have been modelled include Exterior Braced steel frame structure, Diagrid, Octagrid and Hexagrid buildings. Diagrid buildings are modelled with regard to variation in their diagonal angles represented by their storey module size. Diagrid's diagonal angle is the angle between the diagonal members and the horizontal beams in the exterior of the structure. Diagonal Angle =  $\tan^{-1}(\text{module height} / \text{base width})$ . Hexagrid and Octagrid buildings are modelled to cater variation in the module density. Module density is a function of the number of modules in the buildings. If there are more number of modules, then the module density is high and vice-versa. The models are a) Diagrid with 2 storey modules [2DIA] with diagonal angle = 50.19°, b) Diagrid with 4 storey modules [4DIA] with diagonal angle = 67.38°, c) Diagrid with 6 storey modules [6DIA] with diagonal angle = 74.475°, d) Diagrid with 8 storey modules [8DIA] with diagonal angle = 78.23°, e) Diagrid with 10 storey modules [10DIA] with diagonal angle = 80.54°, f) Diagrid with 12 storey modules [12DIA] with diagonal angle = 82.09° g) Hexagrid with 3m modules [3mHEX], h) Hexagrid with 6m modules [6mHEX], i) Hexagrid with 12m modules [12mHEX], j) Octagrid with 9m modules [9mOCT], k) Octagrid with 12m modules [12mOCT] and l) Exterior Braced Steel Structure [EBSS].

The floor plan of Diagrid, Hexagrid and Octagrid Structural systems are shown in Fig 1. For these three structural systems, there are no vertical columns in the exterior of the structure and also, only 8 internal columns are there. For linear static and dynamic analysis, the beams and columns are modeled by flexural elements and braces are modeled by truss elements. The support conditions are assumed as fixed. All structural members are designed using IS 800:2007. Secondary effect like temperature variation is not considered in the design, assuming small variation in inside and outside temperature. Exterior Braced Tubular Steel Building contains vertical columns throughout the exterior of the structure unlike Diagrid, Hexagrid and Octagrid Structural systems. X-Bracings are also provided at the exterior within a height of 6 stories. The base floor plan of exterior braced tubular steel

structure is shown in Fig 2. The interior frame of the diagrid, hexagrid and octagrid structures is designed only for gravity load. Diagonals carry both lateral as well as gravity loads. The design live load on floor slab is 2.5 kN/m<sup>2</sup>. The wind loading is computed based on the basic wind speed of 30 m/sec and terrain category III as per IS: 875 (III)-1987. The design earthquake load is calculated considering medium soil, zone factor of 0.16, response reduction factor of 5 and importance factor of 1 (IS: 1893 (Part-I), 2002).The elevation of all models are given below.

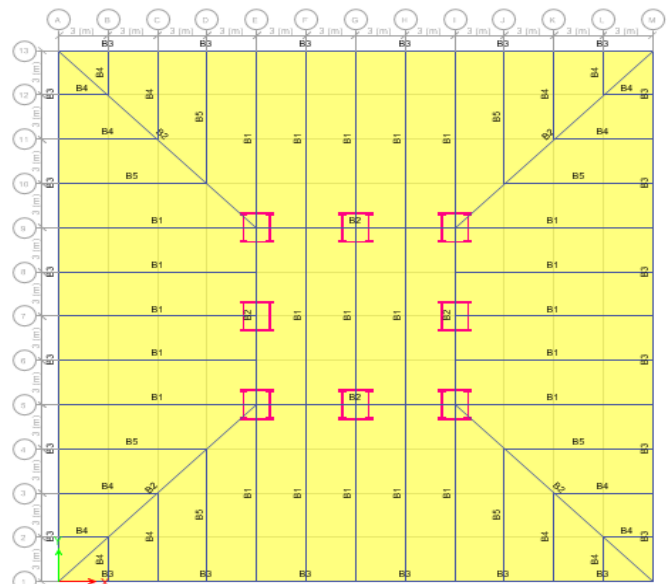


Fig -1: Floor Plan of Diagrid, Hexagrid & Octagrid Building

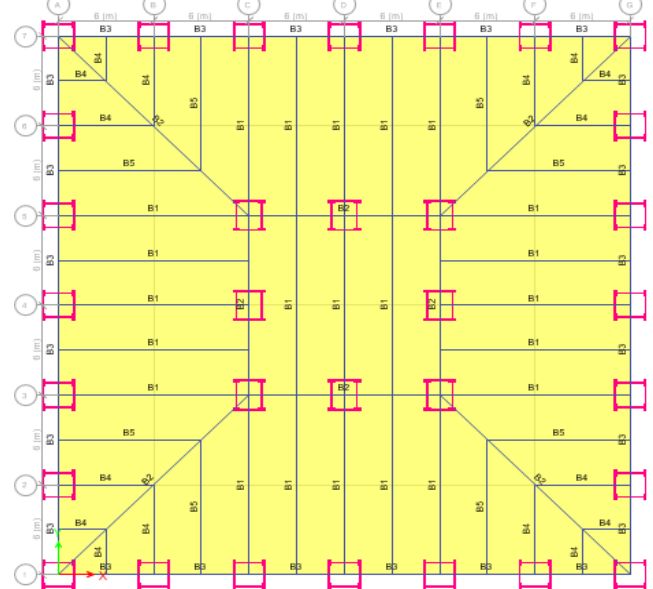
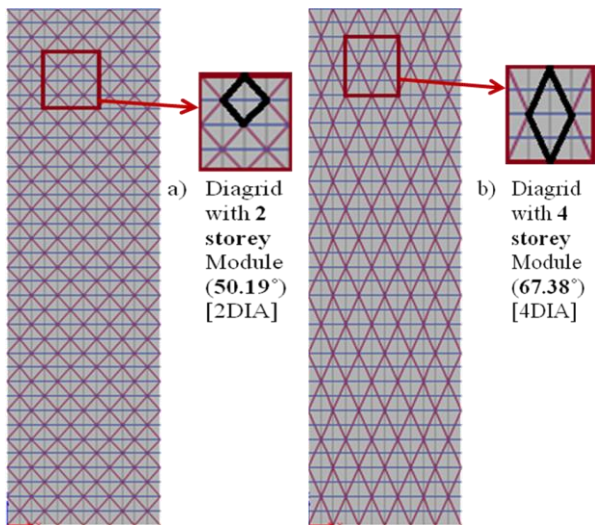
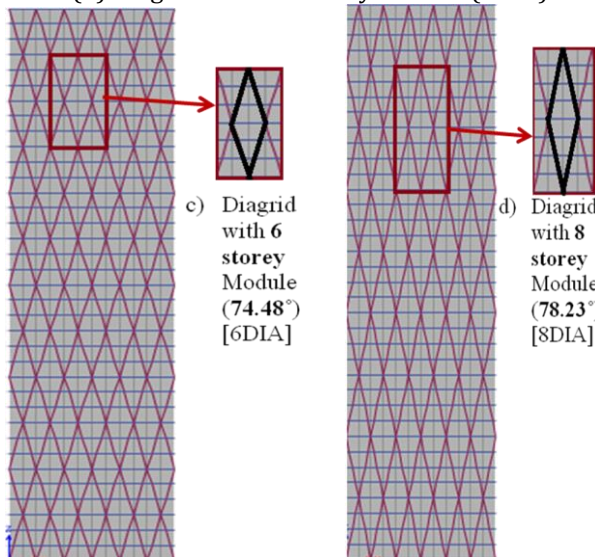


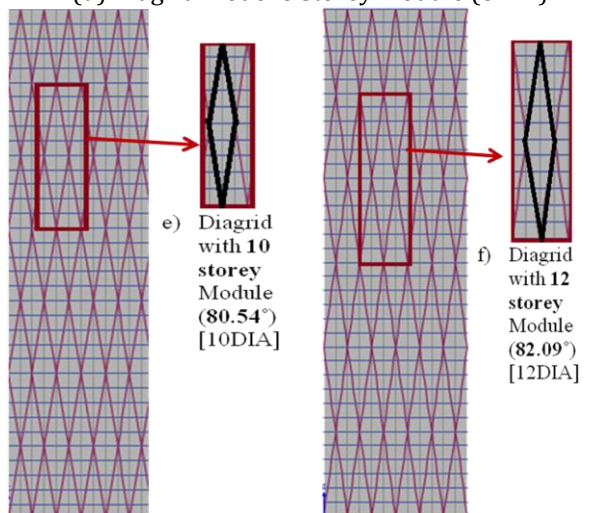
Fig -2: Base Floor Plan of Exterior Braced Tubular steel structures (EBSS)



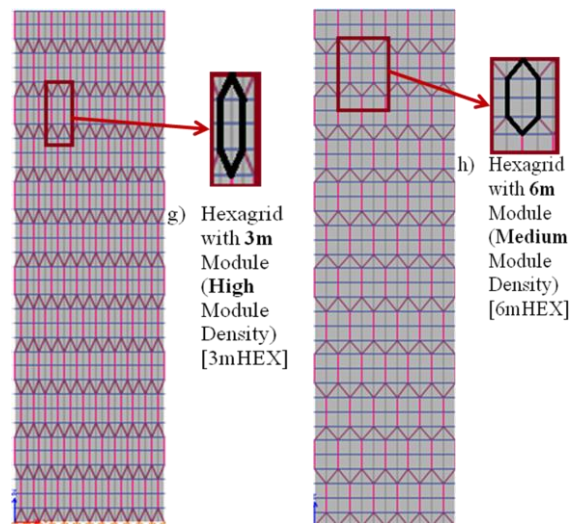
**Fig -3:** (a) Diagrid model with 2 storey module (2DIA), (b) Diagrid model 4 storey module (4DIA)



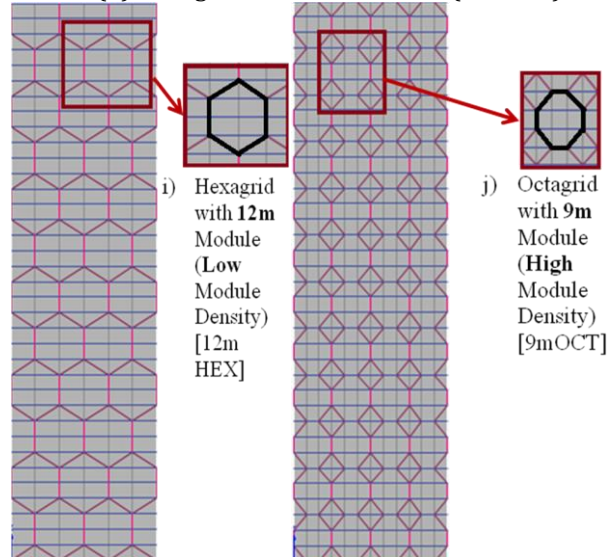
**Fig -4:** (c) Diagrid model with 6 storey module (6DIA), (d) Diagrid model 8 storey module (8DIA)



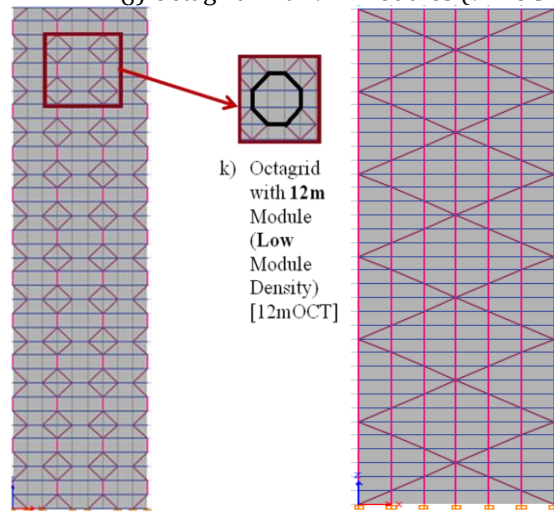
**Fig -5:** (e) Diagrid model with 10 storey module (10DIA), (f) Diagrid model with 12 storey module (12DIA)



**Fig -6:** (g) Hexagrid with 3m module (3m HEX), (h) Hexagrid with 6m modules (6m HEX)



**Fig -7:** (i) Hexagrid with 12m module (12m HEX), (j) Octagrid with 9m modules (9m OCT)



**Fig -8:** (k) Octagrid with 12m module (12m OCT), (l) Exterior Braced Steel Structure (EBSS)

#### 4. ANALYSIS, DESIGN AND RESULTS

Equivalent Static Analysis and Response Spectrum Analysis are conducted for all the models. The sectional properties adopted after the analysis and design of these models to meet the safety criteria and lateral displacement limit thereby giving optimized sections are given in Table 1. The values of Lateral Displacement, Storey Drift, Storey Shear, Time period and Structural weight are compared for all models to determine the most cost effective and optimal structure. The results of the analysis are explained below.

#### 4.1 Storey Displacement

As per IS 1893 (Part 1): 2002, Permissible Maximum Storey Displacement =  $H/500 = 129.6/500 = 0.2592m$ , where H is height of the building. The values of Storey Displacement of all the models for load cases of Earthquake and Wind load in X and Y direction are found to be within the limit.

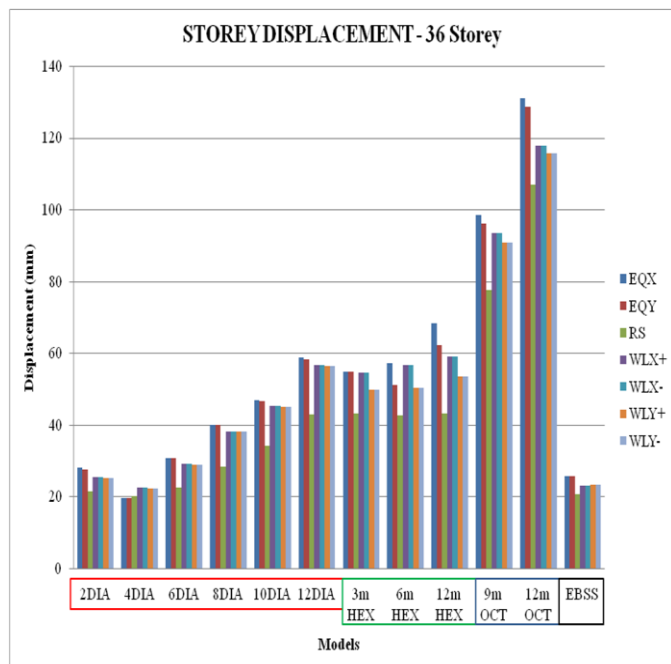


Chart -1: Storey Displacement

The storey displacement of Diagrid with 4 storey module has the least displacement of all the models and the model with highest displacement is Octagrid with 12m module. In the case of Diagrids, it can be seen that the displacement reduced from 28.04mm of Diagrid with 2 storey module to 19.69mm of Diagrid with 4 storey module and then there is an increasing trend in the displacement value to 58.69mm of Diagrid with 12 storey module. Whereas in the case of Hexagrids, displacement value is increasing with a decrease in the hexagrid density, i.e, displacement is highest for Hexagrid with 12m module and lowest for Hexagrid with 3m module. A similar pattern is found in Octagrid as in Hexagrid.

#### 4.2 Inter - Storey Drift

The Permissible Inter - Storey Drift as per IS 1893 (Part 1): 2002, is  $0.004h = 0.004 \times 3.6 = 0.0144$  where h is the storey height of the structure. All models satisfy the Storey Drift condition.

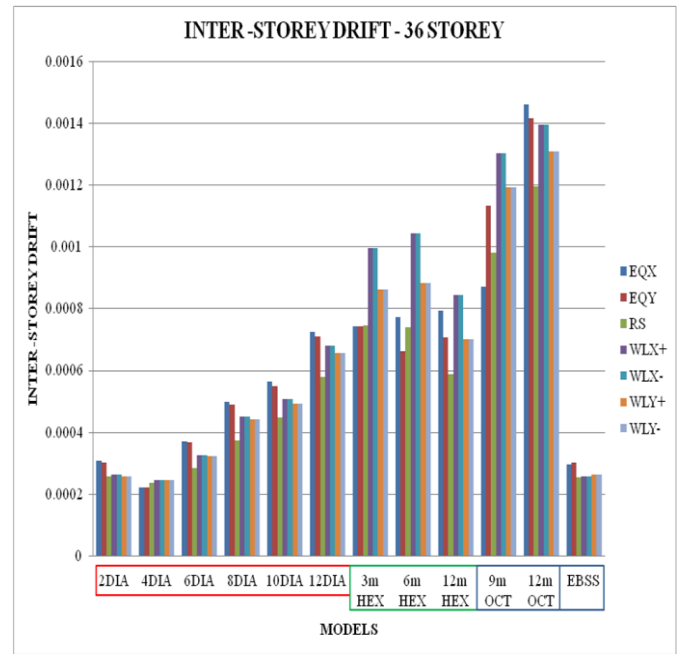


Chart -2: Inter - Storey Drift

The lowest storey drift is that of Diagrid with 4 storey module which has a diagonal angle of  $67.38^\circ$ . For hexagrids, under earthquake load, Storey drift value seems to reduce at first and then increase with a decrease in the hexagrid density; whereas under wind load, Storey Drift values follow an initial increase and then a decrease with decreasing Hexagrid density. Now considering octagrids, value increases with decrease in octagrid density for both earthquake and wind load cases.

#### 4.3 Storey Shear

The highest storey shear value is possessed by the octagrid with 12m module and Diagrid with 4 storey module has minimum storey shear value. For Hexagrids and Octagrids, the value of Storey shear increases with a decrease in their corresponding module densities. For Diagrids, storey shear value decreases initially and then increases with an increase in their storey module size.

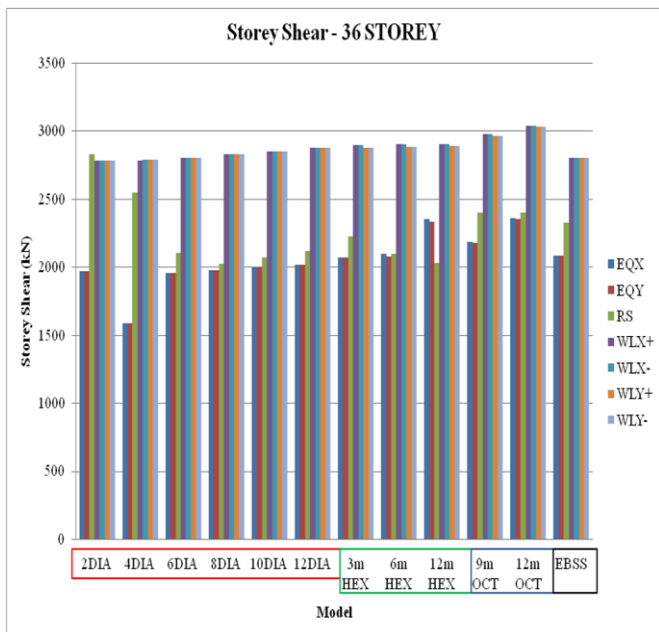


Chart -3: Storey Shear

#### 4.4 Fundamental Time Period

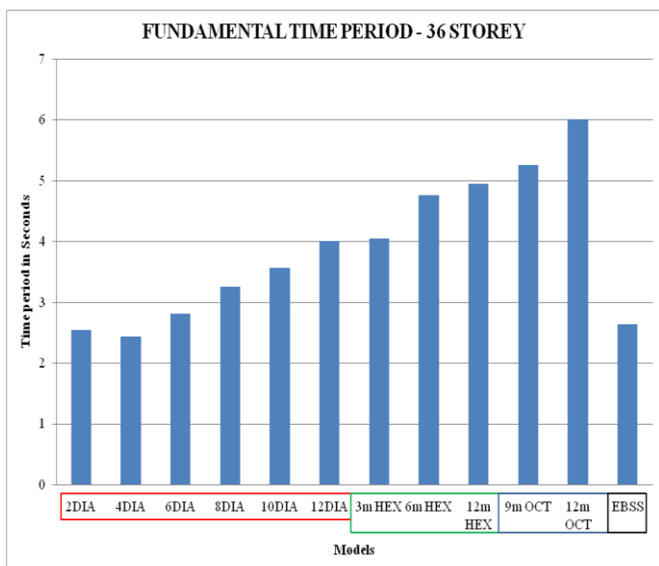


Chart -4: Fundamental Time Period

Least Time period is for Diagrid with 4 storey module and highest time period is for Octagrid with 12m module. Except Diagrid with 4 storey module, all other models show a trend of increasing time period with increase in Diagrid module size and decrease in Hexagrid or Octagrid module density.

#### 4.5 Structural Weight

On comparison of the structural weight of all the models, it was found out that the quantity of concrete is same for all the models and is equal to 17835.68618 tonf. The model with the least amount of steel is Diagrid with 12 storey module with 8285.8484 tonf and Hexagrid with 12m module has the

highest amount of steel equal to 12806.20693 tonf. Exterior Braced Steel structure consumes a quantity of steel equal to 10350.0642 tonf which is greater than all models except Hexagrid with 12m module and Octagrid with 12m module.

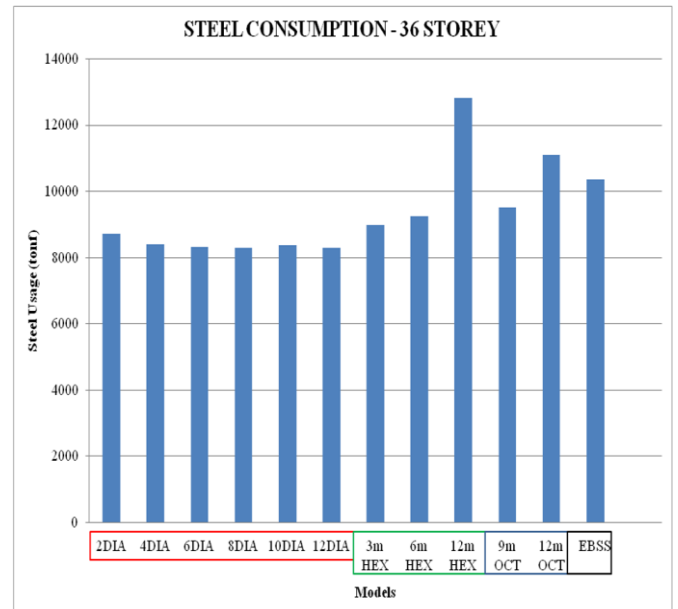


Chart -5: Steel Consumption

#### 4.6 Section Properties

All the models were assigned same section property initially and these were modified after the analysis and design. All structural members except slab are made up of YST 310 grade steel. Slab is made up of M30 grade concrete with 150mm thickness. The Diagonal columns are Tube sections and the Interior columns are Built up columns with I section and top and bottom plates. The section properties of all the models were given in Table 1.

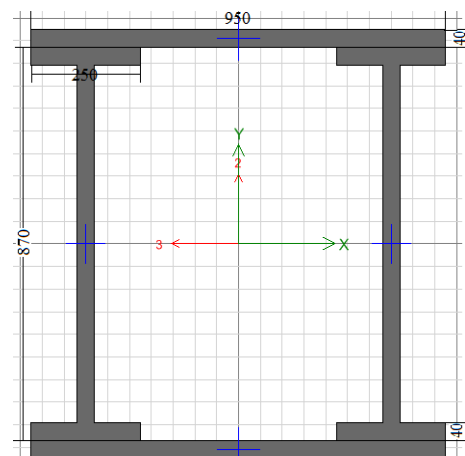


Fig -9: Interior Column C1

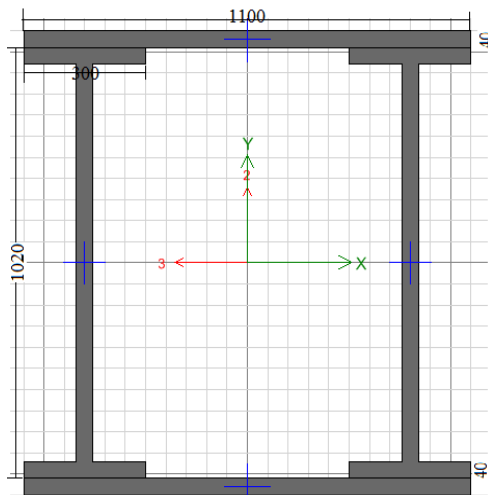


Fig -10: Interior Column C2

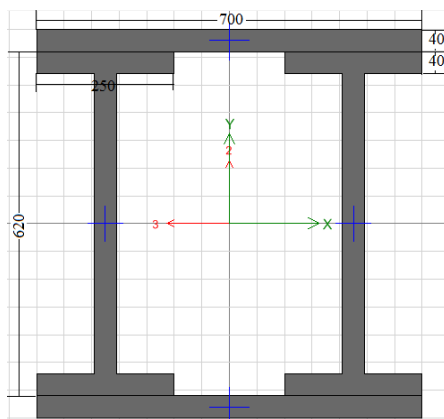


Fig -11: Interior Column C3

Table -1: Section Properties

Models	Diagonal Columns Dimension(mm), Thickness(mm)		Interior Columns	Beam sizes
	From 1st To 18th Storey	From 19th To 36th Storey		
2DIA	450, 25	375, 12	C1	B1 - ISWB600 with 250 x 25 mm top and bottom plates
4DIA	450, 25	375, 12	C1	
6DIA	450, 25	375, 12	C1	
8DIA	450, 25	375, 12	C1	
10DIA	450, 25	375, 12	C1	
12DIA	450, 25	375, 12	C1	B2 - ISWB600 with 250 x 50 mm top and bottom plates
3m HEX	450, 25	400, 15	C1	B3 - ISMB550
6m HEX	450, 55	400, 30	C1	
12m HEX	550, 75	450, 40	C2	B4 - ISLB600
9m OCT	450, 55	400, 25	C1	B5 - ISWB600
12m OCT	450, 55	400, 25	C2	
EBSS	450, 25	375, 12	C3	

## 5. CONCLUSIONS

The Equivalent static and Response spectrum analysis of Diagrid, Hexagrid, Octagrid and Exterior Braced steel building were performed. The performance of Diagrid buildings modeled with different diagonal angle, Hexagrid and Octagrid with different module density and Exterior Braced steel structure under dynamic loading were investigated and the values of parameters Storey Displacement, Storey Drift, Storey Shear, Time Period and Structural weight were compared. The inferences of the study are as follows:

- Every model considered here has satisfied the limits for displacement and storey drift as per IS 1893(II) – 2002.
- Diagrid with 4 storey module exhibits lower displacement, storey drift, storey shear, time period and Structural weight. Parameters show a rising trend below and above this module size. Hence, it can be said that Diagrid building with 4 storey module having a diagonal angle of 67.38° is the optimal diagonal angle and it is the best, structurally efficient and cost effective model.
- The structural performance of Hexagrid and Octagrid structural system deteriorates with decrease in module density.
- All models except Hexagrid 12m module and Octagrid 12m module, which are the low module density models, can be considered as an economical and efficient alternative to the exterior braced steel structures.
- Diagrid structural system provides more flexibility in planning interior space and facade of the building.

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