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Behavior and Design of Plus (+) Shape of Diagrid Structure

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***Abstract*: Rapid population expansion and high land costs have a significant influence on the construction sector, which leads to an upward trend in building construction. However, when building heights rise, lateral load resisting systems become more critical than gravity load resisting structural systems. Some common systems for resisting lateral loads include rigid frame, shear wall, wall-frame, braced tube system, outrigger system, and tubular system. Because of the structural efficiency and aesthetic possibilities given by the system's distinctive geometric design, the diagonal grid structural system has recently become popular for tall structures. Because of the layout and efficiency of a diagrid system, the number of structural elements required on the outside side of buildings is reduced, resulting in fewer blockages to the outside view. The structural efficiency of the diagrid system also aids in the avoidance of interior and corner columns, allowing for great floor plan flexibility. The "Diagonal Grid System," also known as the "Diagrid method," is the most recent high-rise building system that has gained popularity among today's designers. The Diagrid system is made up of multiple diagonal components that join to produce a triangulated or grid-shaped design. The name "diagrid" is derived from the phrase's "diagonal" and "grid." A diagrid structure is a sort of structural system that consists of diagonal grids connected by horizontal rings to provide a beautiful and redundant structure that is particularly useful for high-rise structures. Due to its triangulated configuration, diagrid structures differ from braced frame systems in that diagonal as key structural components contribute in supporting gravity load as well as lateral load, obviating the requirement for vertical columns. A diagrid system's column-free structure has various advantages, including great architectural freedom, elegance, and huge day illumination due to its small outside surface.**

***Keywords*: Diagrid structure, ETABS, Spectrum analysis, Seismic analysis, Wind load analysis.**

1. Introduction

Diagrid is a type of space truss in which there are no traditional columns on the structure's external perimeter. Diagrid is made up of the series 2 of triangulated truss system, which is produced by intersecting diagonal columns and horizontal beams. When compared to bending of vertical columns in a framed tube construction, shear and over-turning moments are resisted by axial action of these diagonals. The core's vertical columns are solely meant to sustain gravity loads, but the diagrid can handle both gravity and lateral stresses. Structural steel members are used in diagonalized applications to provide effective solutions. Both in terms of strength and stiffness are not new, but there is a revived interest in them, as well as a widespread use of diagrid, in long span and high rise structures, particularly when they have complicated geometries and curved shapes. The advancement of braced tube constructions led to the diagrid systems. The main difference between a braced tube building and a diagrid building is that the diagrid building has no vertical columns around its perimeter. The diagonal members of diagrid constructions serve as both inclined columns and bracing components, and their triangulated design causes the members to experience mostly internal axial forces because shear can be carried by the diagrid on the perimeter, diagrid structures do not require high shear rigidity cores.

2. Objectives

- To evaluate the response of high rise building with diagrid system
- To understand the behaviour of plus (+) shape of diagrid structure by locating same height of building in seismic zone III.
- To carry out static analysis & response spectrum analysis.
- To find optimum diagrid angle of diagrid system in seismic zone III.

3. Methodology

The study of a 48-story diagrid structure with a plus (+) form is described in this work. As per Indian Standard, lateral forces owing to earthquakes and wind effects are taken into account. The structure was analyzed using IS 1893:2016 and IS 800:2007. The ETABS program is used for modeling and analysis of diagrid systems. Earthquake loads are subjected to response spectrum analysis. Beams and columns are treated as flexural elements for linear static and dynamic analysis, whereas diagonals are modeled as truss elements. The main focus of this study is on the behavior of high-rise buildings using Diagrid systems of various angles for structures with a plus (+) form and find optimum diagrid angle in seismic zone III by using static, dynamic and wind analysis.

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Phase-I
ETABS software was used to model 48-story high-rise structures using Diagrid systems by defining material and section attributes and having the same height with varying diagrid angles.
Phase-II
Define several forms of loads and their combinations on the structure's plus (+) shape initially. Define the functions necessary for the response spectrum in dynamic analysis. Finally, using the findings of the study, examine the behavior of the plus (+) form structure using Diagrid systems of the same height and different angle in seismic zone III.
Phase-III
The collecting of data for plus (+) shape of structures in the form of distinct metrics like Storey shear and Story Drift and evaluate all seismic zone III criteria to determine the best angle of plus (+) form of structures with each and every combination of 2-storey, 4-storey, 6-storey, and 8-storey modules.

4. Data Collection and Analysis

The primary data will be collected through analysis buildings with diagrid structure by using ETABS software. The secondary data will be collected from previous literature papers, IS codes and books. The result will come through analysis of high-rise buildings i.e. primary data will be compared with secondary data and experimental results will be carried out. A parametric study will be carried out after the validation of result. Validation will be made to show up the conclusion of study.

5. Diagrid Configuration

A diagrid (diagonal grids) structure is a set of triangulated beams, straight or curved, and a horizontal ring that together form a skyscraper's structural system (Tall Building). In a nutshell, it's made up of diagonal and horizontal components that intersect. In comparison to a traditional steel frame, it uses less structural steel. Diagrid has a pleasing look and is easily identifiable. A diagrid system's layout and efficiency minimize the amount of structural elements necessary on a building's facade, resulting in fewer blockages to the outside view. The diagrid system's structural efficiency also aids in the avoidance of interior and corner columns, allowing for great floor design freedom. When compared to a standard perimeter "diagrid" system, the perimeter "diagrid" system saves around 20% structural steel weight than conventional moment-frame structure.

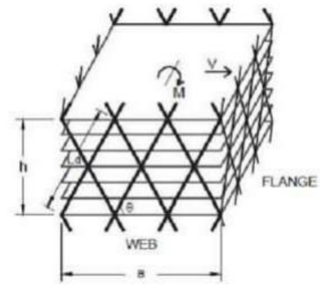

Fig. 1. Diagrid configuration

A diagrid structure is modeled on the ground as a vertical cantilever beam that is segmented longitudinally into modules following the repeated diagrid pattern. A single level of diagrid that span numerous levels defines each module. The instance of a 6-story module is depicted in the diagram. To more correctly estimate the lateral stiffness provided by diagrid, the needed lateral stiffness is distributed to the perimeter diagrid and core structures, as shown in Figure 1. Depending on the loading direction, the faces serve as web planes (planes parallel to the wind) or flange planes (i.e. planes perpendicular to wind). Because the diagonal elements are considered to be pinned, the transverse shear and moment are solely resisted by axial action. The design challenge is reduced to estimating the cross-sectional area of typical web and flange members for each module with this idealization. Member sizes for the modules may be calculated using Equations (1) and (2) adjusted for each design instance, using the design process described by Moon et al (2007). d, w.

$$A_{d,w} = \frac{VLd}{2NdwE\ hJ\ cos2\theta\ T} \quad (1)$$

$$A_{d,f} = \frac{2MLd}{(Nd,f+G)B2Ed\ Fhsin2\theta\ T} \quad (2)$$

The area of each diagonal on the web is referred to as ad,w. The area of each diagonal on the flange is given by Ad,f. Shear force is denoted by the letter V. The letter M stands for moment. Ld is the diagonal length. Steel's modulus of elasticity is called Ed. is the diagonal members' angle. x is a Shear strain in the transverse direction. Curvature is represented by the letter y. The number of diagonals on each web plane is Nd,w. The number of diagonals on each flange plane is Nd,f. The contribution of web diagonals to bending rigidity is denoted by G. In the direction of applied force, B is the building breadth. Under the design loading, optimal stiffness-based design corresponds to a condition of homogenous shear and bending deformation. Only statically determined structures can have uniform deformation states. On the ground, tall building structures may be treated as vertical cantilever beams, and homogeneous deformation can be accomplished for the deflection at the top u. (H).

$$(H) = y * H + x{*}H2\ 2 \quad (3)$$

H is the building height; y* is the desired uniform transverse shear strain; x*is the desired uniform curvature.

6. Geometric Parameters of the Building Models

Structure type: Steel structure
Shapes of building used: plus (+) shape
Number of stories: 48
Size of plan for plus shape: 48m x 48m
Spacing between bays: 4m
Spacing between diagrid along perimeter: 8m
Height of each storey: 3.5m
Number storeys per module: 2, 4, 6 & 8 storey
Grade of structural steel (Fy): Fe 500
Grade of concrete (Fck): M40

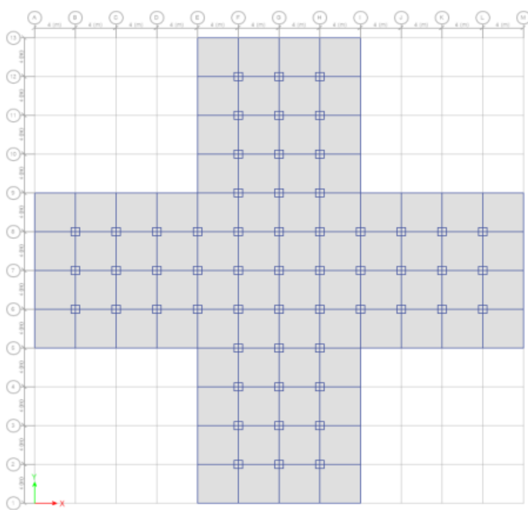

Fig. 2. Plan of Plus (+) shape building model

A. Basic design consideration

The building is subjected to following Loads as per IS 875 (part 1 and 2)-2015:

Dead load: 2 kN/m^2
Live Load: 3 kN/m^2

The following table shows that basic design consideration in seismic zone III.

Zone	Zone factor	Location of building	Basic wind speed of city in m/s	Soil type
III	0.16	Pune	39	Hard(site type 1)

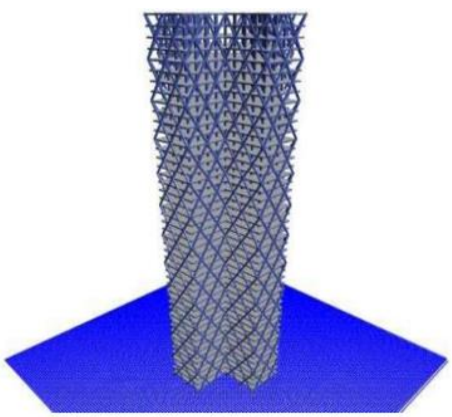

Fig. 3. 3D rendered view of plus (+) shape structure

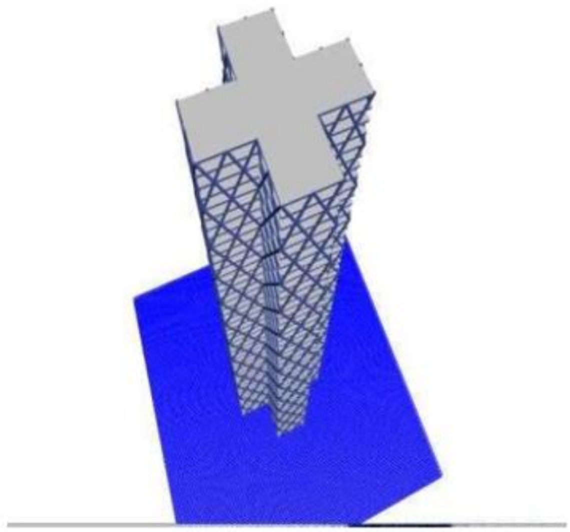

Fig. 4. Top view of plus (+) shape structure

B. Section properties for plus (+)

In zone III, all section attributes were the same in any building shape. Steel tubes are utilized for columns and Indian standard wide flange beam sections are used for beams. Steel pipes are utilized for diagrid members. The section properties for all storey modules of the building model with diagrid systems are shown in Table (Table 1).

Table 1
Section properties for Plus (+) structure

Story	Beam	Column [tube section]	Diagrid [pipe section]
1-16	ISMB 550	750 X 750 X 50	750 X 25
17-32	ISMB 500	700 X 700 X 45	750X 25
33-48	ISMB 500	600 X 600 X 35	750 X25

The values of diagrid angles for the corresponding story modules of the plus (+) form of construction are shown in the table below (Table 2). The angle of diagrid rises as the storey module increases. The study's diagrid angles range from 41 to 74 degrees.

Table 2
Diagrid angle for plus (+) shape of building

Number storeys per module	Angle
2	41.18^0
4	60.25^0
6	69.14^0
8	74.05^0

7. Result Analysis

The zone factor value for the Plus (+) shape of building in Seismic Zone III is 0.16. Because our structure is included in the importance service, the importance factor was set to 1.5. The structure is located in Pune city for wind load consideration, and the fundamental wind speed is 39 m/s.

Because the aim of the diagrid structure is to serve as a hospital, the structure's average likely design life is 100 years, and the risk coefficient of 1.06 is used. Our structure belongs to the 3rd category. The structural class is C because the structure's greatest dimension, or height, exceeds 50 meters. The k4 factor is 1.30, which is determined by the kind of structure. The coefficients for windward and leeward are 0.8 and 0.6, respectively. Dynamic analysis is used to do response spectrum analysis. In this case, the SSRS and CQC methods are taken into account. The damping ratio is assumed to be 5%. The extent of diaphragms approach is utilized in ETABS for wind analysis. First, all scale factors are taken into account, and because dynamic base shear is less than 80% of static base shear, it was altered.

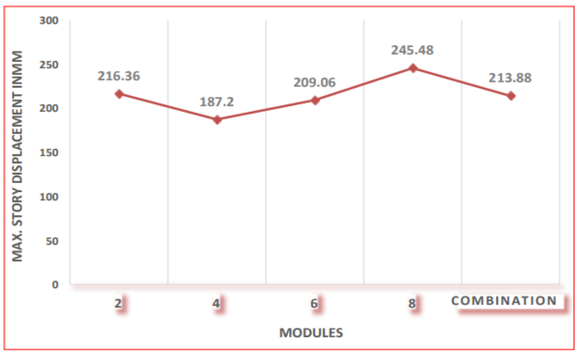

Fig. 5. Maximum storey displacement for all modules in zone III

The graphical depiction of maximum storey displacement of 48 story building modules in zone III is shown in the graph above. This is the graphical representation for wind load analysis because, in contrast to seismic and response spectrum analysis, wind load analysis offers maximum values of narrative displacement in zone III. Modules vs. maximum storey displacement are presented on a graph. In the 8-module diagrid, the maximum storey displacement is 245.48 mm. The greatest storey displacement with the least value is 187.2 mm, which is found for the four-story module. The minimum value of maximum story displacement is found to be between 60 and 70 degrees. The highest allowable storey displacement is 336 mm, and all modules in zone III have maximum story displacements that are within the allowable limit. When eight module diagrid is compared to four and six module diagrid, the maximum story displacement for four and six module diagrid is lowered by 23.74 % and 14.83 % respectively.

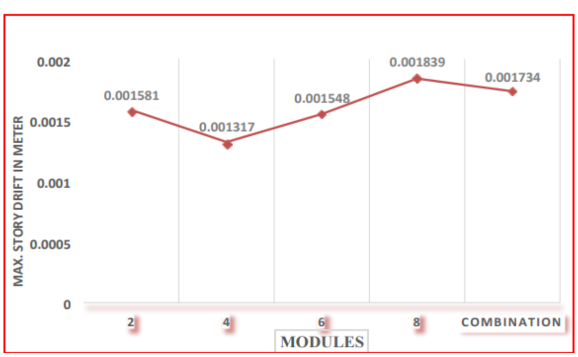

Fig. 6. Maximum storey drift for all modules in zone III

The previous graph (Fig. 6) depicts the maximum storey drift of 48 story building modules in zone III graphically. Modules vs. maximum storey drift are presented on a graph. Eight modules have a greater maximum storey drift of 0.001839 m. The smallest maximum storey drift value is 0.001317 m, which may be found in the four-story module diagrid. The maximum allowable storey drift is 0.014 m, and maximum story drift for all modules in zone III is observed to be within this limit. When eight module diagrid is compared to four and six module diagrid, the maximum narrative drift for four and six module diagrid is lowered by 28.38 % and 15.82 % respectively.

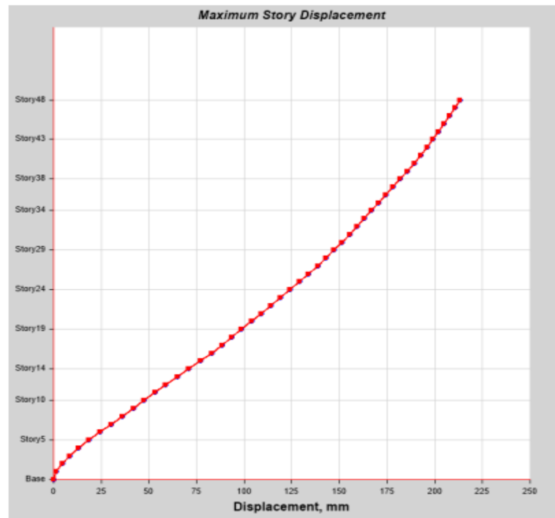

Fig. 7. Maximum storey displacement by wind load analysis

The maximum story displacement by wind load analysis for combination modules made up of two, four, six, and eight in zone III is shown in the graph above (Fig. 7). For wind load analysis, many load combinations are examined, as shown below. 5.8 in the table The combination of 1.5(D.L+ WL-X), 1.5(D.L+ WL-Y), and (0.9 D.L+ 1.5 WL-Y) yielded the highest story displacement of 223.27 mm.

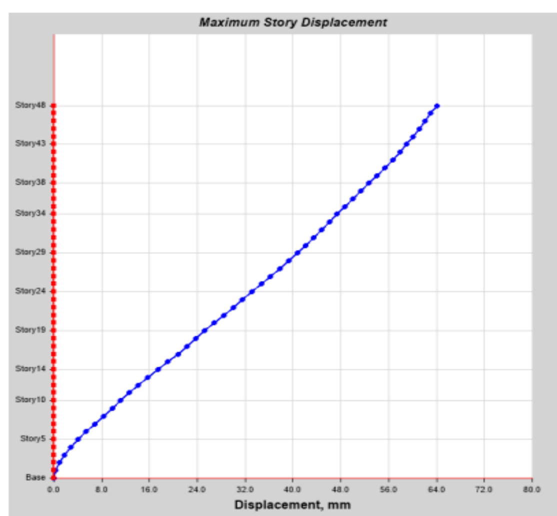

Fig. 8. Maximum storey displacement by seismic analysis

The maximum storey displacement by seismic load analysis for combination modules made up of two, four, six, and eight in zone III is shown in the graph above (Fig. 8). For seismic load analysis, many types of load combinations are examined, as shown in table 5.8. Combinations of 1.5(D.L+ EQ-X), 1.5(D.L+ EQ-Y), and (0.9 D.L+ 1.5 EQ-Y), (0.9 D.L+ 1.5 EQ-X), (0.9 D.L- 1.5 EQ-Y), and (0.9 D.L- 1.5 EQ-X) have resulted in a maximum story displacement of 64 mm.

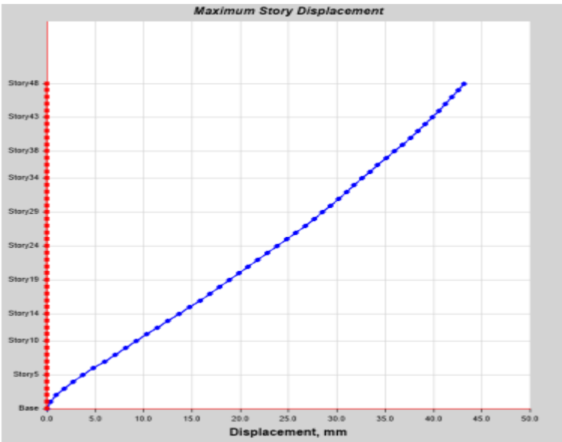

Fig. 9. Maximum storey displacement by response spectrum analysis

The previous graph (Fig. 9) depicts the maximum narrative displacement calculated using reaction spectrum analysis for a combination module made up of two, four, six, and eight in zone III. For response spectrum analysis, many types of load combinations are investigated, as shown in table 5.8. It was discovered that the combination of 1.5 (D.L+ RS-X), 1.5(D.L+ RS-Y), (0.9 D.L+ 1.5 EQ-Y), (0.9 D.L+ 1.5 RS-X), and (0.9 D.L- 1.5 RS-Y) resulted in the highest story displacement of 43.16 mm.

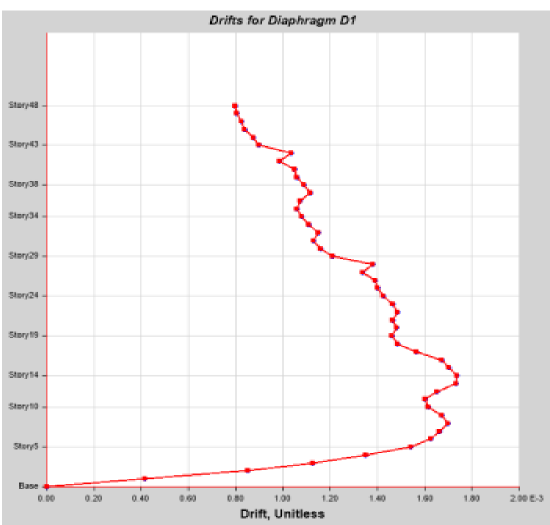

Fig. 10. Maximum storey drift by wind load analysis

Maximum story drift by wind load analysis for combination module made up of two, four, six, and eight in zone III is shown in the graph above (Fig. 10). For wind load analysis, many types of load combinations are examined, as shown in table. The greatest value of drift for all combinations was evaluated, and it was discovered that the combinations 1.5(D.L+ WL-X), 1.5(D.L+ WL-Y), and (0.9 D.L+ 1.5 WL-Y) gave the largest story displacement of 0.001734 m.

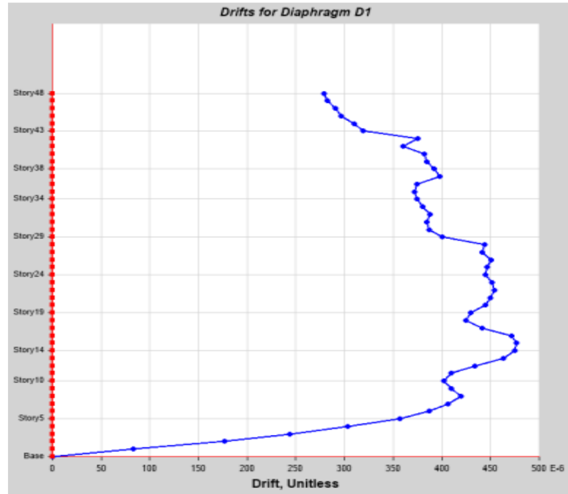

Fig. 11. Maximum storey drift by seismic analysis

The previous graph (Fig. 11) depicts the maximum story drift calculated using seismic load analysis for a combination module made up of two, four, six, and eight in zone III. For seismic load analysis, many types of load combinations are examined, as shown in table. The maximum value of drift was examined for all combinations, and it was discovered that the combinations 1.5(D.L+ EQ-X), 1.5(D.L+ EQ-Y), and (0.9 D.L+ 1.5 EQ- Y) produced the highest story drift of 0.000477 m.

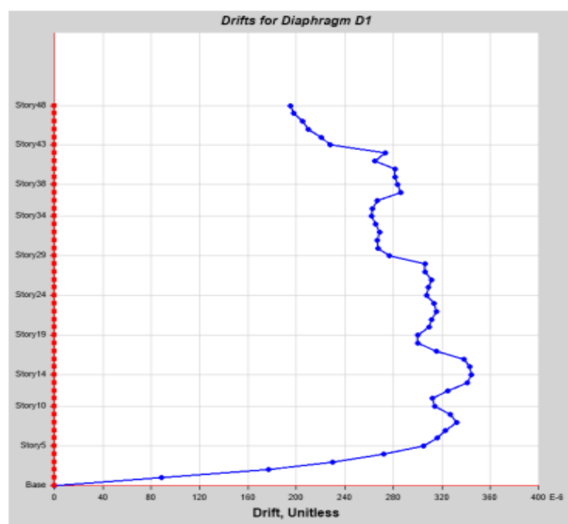

Fig. 12. Maximum storey drift by response spectrum analysis

Maximum narrative drift by response spectrum analysis for combination module consisting of two, four, six, and eight in zone III is shown in the graph above (Fig. 12). For seismic load analysis, many types of load combinations are examined, as shown in table. The maximum value of drift was calculated for all combinations and determined to be 0.000334 m for 1.5(D.L+ RS-X), 1.5(D.L+ RS-Y), and (0.9 D.L+ 1.5 RS-Y), (0.9 D.L+

1.5 RS-X), and (0.9 D.L- 1.5 RS-Y).

Following are the details which shows the tabular representation of story displacement & story drift for plus (+) shape of building in seismic zone III.

Table 3
Story displacement & story drift

Plus(+) shape	III	2	216.93	71.34	39.52	0.001581	0.000522	0.0003
		4	187.20	64.13	40.27	0.001317	0.000465	0.000303
		6	209.06	66.05	42	0.001548	0.000481	0.000361
		8	245.48	70.42	45.93	0.001839	0.000522	0.000354
		Combination	213.65	63.324	43.51	0.001734	0.000477	0.000344

Wind load has the highest value of story displacement and story drift in the plus(+) form of building when compared to earthquake load, and the 8-story diagrid module has the highest value of story displacement and story drift in the plus(+) shape of building. In comparison to 2-storey, 6-storey, and 8-storey modules, the 4-storey module in (+) form of building delivers smaller value of maximum store displacement and maximum storey drift.

8. Conclusion

In this paper the basic design consideration with their geometric parameters of the building models has been discussed. The graphical representation & results of seismic analysis, spectrum analysis, and wind load analysis has been clearly studied.

Diagrid angle in the region of 60° to 70° provides more stiffness to the diagrid structural system which reflects the less top storey displacement.

Static analysis, dynamic analysis and wind load analysis are performed on diagrid structure and it observed that, maximum story displacement and maximum story drift are maximum in case of wind load analysis as compare to earthquake analysis and response spectrum analysis in plus (+) shape of building.

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