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Analysis of Diagrid Structural System for High Rise Steel Buildings

M. Vhanmane*, **M. Bhanuse**

1. Department of Civil Engineering, Annasaheb Dange College of Engineering & Technology Ashta, Dist. Sangli, Maharashtra, India - 416301.

Corresponding author: *mangeshvhanmane92@gmail*

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ABSTRACT

The fast growth of the population and the growing cost of the land leads the construction of buildings to the sky. But as the height of the structure increases, the lateral load resistance mechanism is more important than the response of gravity loading to the structural arrangement. The common systems used to resist lateral loads are braced tube systems, shear walls, rigid frames, wall-frame, outrigger system and tubular systems. The dissertation work goal is to explore the applicability of diagrid structures in high rise steel structures, over the conventional construction systems. This work introduces the analysis of high-rise buildings with a diagrid system. A square plan of size 32 m × 32 m is considered for the study of the behaviour of high-rise buildings with diagrid arrangements. All structural members such as beams, columns are analyzed considering all load combinations as per IS 800:2007. Similarly, analysis is carried out for G+40, G+60 and G+80 storey building models with diagrid arrangements. Comparison of terms such as storey shear, storey displacement and storey drift are also presented in this paper. By using ETABS software the modelling and analysis of structural members are carried out. Diagrid arrangement gives a without column structure which decreases steel required as compared to conventional buildings. Also, they look decent from a beautiful perspective. The diagrid structure performs well in all the parameters such as performance, expression and stability. Diagrid structure is more stiff than other structures.

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1. Introduction

The population, scarcity and high cost of land had a huge impact on the rapidly increasing industry. This has directed to the construction of buildings in an upward direction. Due to developments in Construction technology, materials, structural arrangements, analysis and design software, high rise buildings have been established. As the height of the building increases, lateral resistance for systems are more important than structural resistance due to gravitational loads. The lateral load resisting systems that are mostly used. The diagrid arrangement can be combined to create a triangle shape that is made of very nice artwork or can be seen as a grid shape. The words "diagonal" and "grid" creates "diagrid", which shows the single-thickness in nature and gets its structural integrity through the use of a triangle. The current high-end designers are most favourable in buildings that are called "diagonal grid systems", which are called "Diagrid systems". Less structural steel is required for diagrids as compare to traditional steel frames. The diagrid looks good and it is easily known. The shape of structure and efficiency of the diagrid reduces the number of necessary structural components on the periphery building, so there are fewer obstructions in the outside sight. Structural efficacy of the diagrid arrangement helps excluding internal and external corner columns, resulting in significant flexibility in the floor design. Generally, the work of high- rise buildings has been done as a commercial office building. Other customs such as resident, mixed-use and hotel tower development have increased rapidly. The development of high- rise buildings includes various complex elements like technology, municipal rules, economics, aesthetics and politics. of these, economics is the primary administrative component. For a very high building, its structural design is generally controlled on its lateral stiffness. The Diagrid contains large amounts of assemblies that attach to the form of a triangle or they can appear in grid form. The without column structure of diagrid system suggestions some benefits such as flexibility in architecture, style & huge daylighting due to its small external surface. Diagrid Assembly Building is a type of arrangement with a diagrid that creates a stylish and redundant building structure with a horizontal ring which is especially effective for tall buildings. The construction of the diagrid building has been changed by a braced frame arrangement because in the main structural fundamental elements, the amount required to carry loads of gravity load, in which the triangulated arrangement helps to remove the need for vertical columns. The diagrid reduces the number of structural components required on the external side of the structure and reduced external barriers to the outer side of the configuration. Providing more flexibility in the layout that is beneficial to avoid internal & corner columns.

A review of the literature pertaining to the background of the work and methodology of the work is presented

Shah and Patel [1] attempted to parametric study the tall structures with diagrid structural arrangement. Diagrid is an external structural arrangement which resists the lateral forces by axial actions of diagonals provided in periphery. The key objective is to fix the optimum module size of diagrid. The studies five steel buildings having representative plan area, and loadings of 12, 24, 36, 48 and 60 storeys were investigated for the 4, 6 and 8 storey diagrid component size. The investigation was carried out in ETABS 2017 software. Different parameters like fundamental time period, maximum storey displacement, maximum storey drift, maximum base shear was measured. Heshmati [2] studied the seismic performance of 36-story diagrid structures with varying angles are assessed using pushover and nonlinear time history investigation. Additionally, in order to assess the outcome of diagrid core on behavior of structures, internal gravity settings are replaced with diagrid settings. The results of pushover evaluate demonstrate that diagrid core can improve the hardening performance of structures when the angles of perimeter panels are lower or equal than those of the core equated to the conventional diagrids. Nonlinear time history studies are then completed to calculate inter story drift ratio, residual drift, energy dissipation and hinges distribution of buildings. It is experiential that most of the models accomplish well under rare ground motions and hinges are well spread during the height among different elements and diagrid buildings are capable of undergoing large bends under rare earthquakes. Sadeghi and Rofooei [3] The seismic performance of diagrids equipped with buckling restrained braces (BRBs) is investigated. therein regard, the consequences of BRBs on the seismic performance characteristics of diagrids like response modification factor, R, overstrength factor, Ω0, ductility ratio, μ, and median collapse capacity, SCT, are evaluated. to the present end, 6 three-dimensional diagrid structures with various heights and diagonal angles are modeled using Open Sees program and are equipped with BRBs during a novel arrangement. Utilizing nonlinear static analysis, the seismic performance factors of models are evaluated. Subsequently, the median collapse capacity (SCT) of the models are determined by performing nonlinear dynamic analyses. The results indicate that using BRBs improve the seismic performance of the considered models thanks to accumulation of plastic damages in BRBs and a far better distribution of plastic hinges over those models. The nonlinear static analyses indicate that for the first diagrid models, the response modification factor, R, ranges from 1.7–2.5, while the ductility ratio, μ, varies between 1.2 and 2.5, counting on the diagonal angles. Also, the results show that the Ω0 remains fairly constant. However, in BRB equipped diagrids, the range of R increases to 2.4–3.3, while the ductility ratio μ varies within the range 2.1–3.1. almost like regular diagrids, Ω0 remains constant for BRB equipped models. Furthermore, the output of the dynamic analyses indicates that the ^SCT, which may be a function of diagonal angles and usually increases by growing the diagonal angles, could get up to 60% for diagrids equipped with BRB. Rujhan and Ravande [4] studied a arrangement that consists of diagonal columns and horizontal members to mitigate and perform against lateral forces by making up a triangular model on the periphery of the building. Diagrid structural arrangement provided by diagonals on the periphery is adopted in tall buildings because of its structural efficiency as results of its triangular configuration against both lateral loads and vertical loads. Analysis and style of Diagrid module is managed by three manners suggestion Manual Calculation using stiffness method, ANSYS V12.1 software, and ETABS V9.6.0 software. A plan of 36 m by 36 m having six spans of 6 m, and 48 stories with representative storey height of 3.6 m is taken into account.

ETABS software is working for Dynamic Analysis of total Diagrid building, and ANSYS software and Manual calculation are used for Static Analysis of Diagrid's Diagonal Periphery. Analysis is achieved as per IS:800-2007 and IS:1893-2002. Design wind speed is calculated as per IS:875-1987 Part-3, and description of steel is taken as per IS:2062-2011. Assessment of study leads to terms of Static and Dynamic control of Diagrid building; therefore Static Analysis is managed to define Lateral Stiffness/Displacement of Diagrid's Diagonal Periphery, and Dynamic Analysis is managed to define Time History, period of time, Storey Displacement, Storey Drift, Storey Shear, and cargo Distribution in Diagrid. Mele [5] described diagrid structures have emerged in recent decades as an innovative solution for tube tall buildings, capable of merging structural efficiency and aesthetic quality. The author studies the effect of the building slenderness (grossly calculated by means of the ratio, i.e., the ratio between the peak and consequently the plan dimension) on the structural behavior and on the optimal design parameters of diagrid tall buildings. building models with changed slenderness values are designed by adopting preliminary criterion, supported strength or stiffness demands; as well, a design method supported a sizing optimization process that employs genetic algorithms is additionally projected, with the aim to match and/or refine the results attained with simplified approaches. James and Nair [6] studied a massive number of vertically irregular buildings exist in modern urban structures, then the world of vertically irregular kind of building is now having lots of attention. When such buildings are situated during a high seismic zone, the structural engineer's role turn out to be tougher and attention of lateral load is extremely significant. Recently the diagrid structural arrangement is widely used as lateral load resisting arrangement appreciations to its structural efficiency and aesthetic potential provided by the unique geometric configuration of the system. a quick study about diagrids on a geometrically irregular structure. study a building with base dimension 36 m × 36 m and 129.6 m height is taken and vertical geometric irregularity is given to the bottom construction. Each storey height is 3.6 m. Diagrid with uniform angle throughout the peak is provided as lateral load resisting arrangement. Time history analysis is completed using ETABS 2016. Seismic concert of geometrically irregular building given diagrids is calculated by varying diagrid angles. The leads to terms of maximum storey displacement, maximum storey drift, period of time, structural weights and base shear are equated Mascarenhas et al. [7] work carried out for diagrid structures arrangement with various aspect ratios such as 1:1, 1:2, 1:3 and 1:4. G + 60 storey diagrid building the structure with diagrid angles of 33.69°, 53.13°, 63.43°, and 69.44° were considered. The study was done for the behaviour of the diagrid building structure under the wind load action. Also, the optimum angle of diagrid for G + 60 storey model was studied. The modelling, analysis, and design of model were done using ETABS software. Nawale et al. [8] analyzed the building structure of unsymmetrical dimensions of 32-storey with a height of 95 meters. The diagrid system is used for a structure without a vertical column on the periphery of the building. The ETABS software was used for modelling, analysis & design the model. IS code IS 800:2007 [9] and IS 1893:2002 [10] are also considered for loads. storey displacement & storey drift are compared to analysis results. Shah et al. [11] studied seven steel structures of the defined plan area and various loads on various heights were analysed & designed for optimum sections for the conventional and diagrid structure frame in ETABS. For comparing results parameters such as maximum base shear, maximum top storey displacement, the difference in the percentage of steel, maximum storey drift, and fundamental time period were considered. Diagrid arrangement performs more than conventional frame system and increases in the percentage of steel with an increase in height of the building was a smaller amount in diagrid arrangements. Bhuiyan et al. [12] studied 03 buildings with 38, 64, 82 storey with height 133 m, 224 m & 287 m and with plan size 33 m x 33 m, 52 m x 35.5 m and 48 m x 48 m respectively. Some iterations were done to determine the optimal member sizes and shape for diagrid assemblies. Both the earthquake and wind actions were taken into account for checking the member sizes sustainability. Several design assumptions were used such as the constant inclination of braces along with the height of the structure, uniform bending and shear strain distribution along the height of structure and wind drift of H/500 should be achieved. Nimisha et al. [13] studied the tubular and diagrid building structures were equated on the basis of study the structural efficiency. The models were prepared of tubular type structure and diagrid building structure for comparison. Both tubular and diagrid building structures of 24, 30, 36, 42, 48, 54, 60, 66 storeys were modelled in ETABS software and analysis was done. For the loads IS 875-1987 [14–16] used & for earthquake load IS 1893-2002 [10] used. The analysis results, parameters like storey displacement, storey drift, time period & storey shear were compared. For the same loading conditions, the result values for tubular building structures were greater than the diagrid building structures. From that comparison, it was found that diagrid building structure was more efficient structurally than tubular building structure. Thomas et al. [17] described the objectives aimed to find out the optimal angle for diagrid structure. ETABS software was used for modelling, analysis, design etc. different building configurations like, square, circular, rectangular in the plan were taken for analysis. Dissimilar diagrid modules are used such as 2, 4, 6, 8, 12 storey modules. 36 storey building was analyzed for inner storey drift, storey displacement . Panchal et al. [18] studied twenty storey building structure of height 72 m with plan 18 x 18 meters was designed for a storey height of 3.6 m. The diagonal member sizes were already taken and the diagonal angle was taken as 78.2^0. The dead load and live loads with floor load were also considered for design. ETABS software was used for modelling, analysis and design purpose. The conclusion was made that, the lateral loads resisted by the simple frame were less than the diagonal component. Also, diagrid makes the structure more effective in load resistance property. Jani and Patel [19] studied the tall structure of G+36, G+50, G+60 & G+70 storey and plan size 36 x 36 m. The building structures were modelled and analyzed in ETABS software. IS 800:2007 [9] was used for the design of the diagrid members. The conclusion was made that lateral load was taken by diagrid columns on the periphery of structure, while the gravity load was resisted by both inner & diagonal columns on the periphery. So, the inside columns have to design individual for vertical gravity loads. Increment in lever arm of diagonal columns on the periphery leads the diagrid system to becomes further effective in resistance of lateral loads. Diagrid arrangement offers extra flexibility in planning inner space & in front of the building. Moon et al. [20] studied the behaviour of the diagrid structure of square size 36 m x 36 m in the plan. The structure also includes a braced core. Diagrid and tubular structures are correspondingly compared for shear effect. The conclusion taken from the work is that the best diagrid angle is in between 65° to 75°. The author also gives a recommendation for the sizing of member methods for early design of diagrid structure which is useful to take structural and architectural choices at an early stage.

2. Problem statement for study

The present study includes the study of the behaviour of high-rise buildings with diagrid systems. Analysis results of G+40, G+60 and G+80 storey diagrid structure is compared for parameters like Storey shear, storey displacement & storey drift. Also, the optimum diagrid angle is found out for a particular height.

In this study, analysis of G+40, G+60 and G+80 storey diagrid structure is presented. Lateral forces due to earthquake & wind effect are considered as per Indian Standard. IS 1893:2016 and IS 800:2015 were used for the analysis of the structure. Modelling and analysis of diagrid structures are carried out using ETABS software. Response spectrum analysis is done for earthquake loads. For linear static and dynamic analysis, the beams and columns are modelled as flexural elements and diagonals are modelled as truss elements. Several iterations are carried out to determine preliminary member sizes and configuration of the diagrid structure so that it can resist both earthquake and wind action efficiently. The support conditions of diagonals are assumed as hinged. Temperature variation is not considered. In order to obtain the optimum angle for diagrid structural system, G+40, G+60 and G+80 storey steel buildings are considered. To find out optimum angle four different cases having the angle of diagonal 56.18^0, 66.2^0, 71.33^0 and 75.4^0 with 4, 6, 8 & 10 storey modules respectively are considered for each diagrid building. The analysis is carried out by considering the optimum angle of diagrid on the periphery.

3. Geometric parameters of the building models

The table shows the geometric parameters of the building models used for the present study. It includes the various data such as Structure type, number of storeys, size of the plan, spacings, the height of each storey and number of storey per module. Also includes the grade of steel and concrete.

Fig 1 shows the typical plan of the building models which are considered for the study. All the building models of G+40, G+60 and G+80 storey is having same plan. Number of bays in X and Y directions are 8 as shown in figure and spacing between each bay is 4 meters. Table No 2 shows the values of diagrid angles for the respective storey modules. As the storey module increases the angle of diagrid increases. Diagrid angles taken for the study are varies from 56^0 to 76^0.

Table 1
Geometric parameters of the building models.

Structure type	Steel structure
Number of stories	G+40, G+60, G+80
Size of plan	32m x 32m
Number of bays along X & Y	8
Spacing between bays	4m
Spacing between diagrid along perimeter	8m
Height of each storey	3m
Number storey per module	4, 6, 8, 10
Grade of structural steel (Fy)	Fe 345
Grade of concrete (Fck)	M30
Loads:	
Dead Load[18] -	6.5 kN/m^2 (Public building)
Live Load[19] -	2.5 kN/m^2 (Public building)
Seismic parameter details: (as per is 1893-2016)[16]	
Seismic zone -	Zone III
Zone factor -	0.16
Soil type -	Medium
Importance factor -	1.2
Response reduction factor -	5
Wind parameter details: (as per is 875-2015)[20]	
Place -	Pune
Wind speed -	39 m/s
Terrain category -	2
Structure class -	B
Risk coefficient -	1
Topography factor -	1

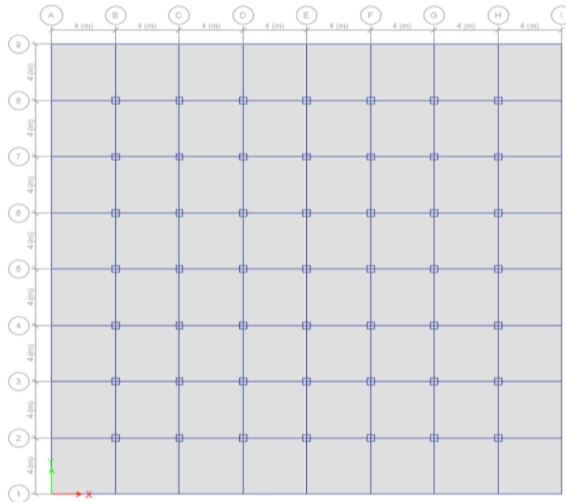

Fig 1. Plan of the building models.

Table 2
Diagrid angles.

Number storeys per module	Angle
0	0^0
4	56.18^0
6	66.2^0
8	71.33^0
10	75.4^0

Following fig 2 shows the Elevation and 3D of four storey module of building model. The four storey module represents that the diagrid member is placed from ground storey to the storey number four which create angle of 56.18^0. All the diagrid members are placed as mentioned above by keeping angle of diagrid constant throughout the building model.

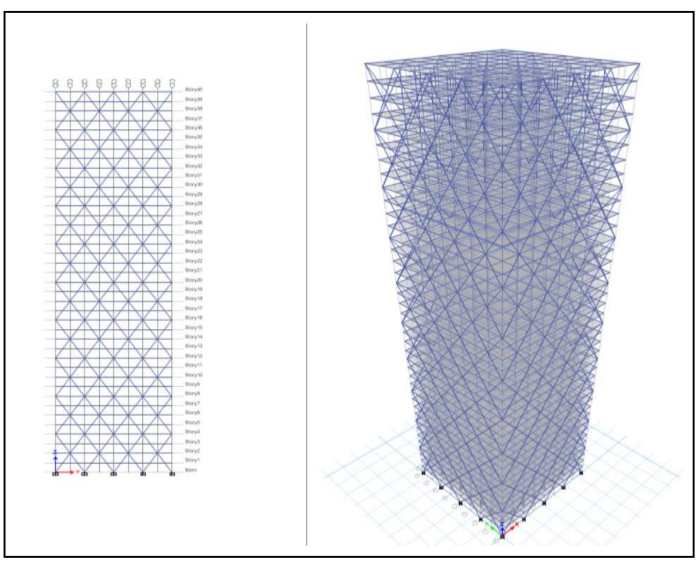

Fig. 2. Elevation and 3D of four storey module.

4. Analysis results

The results of the analysis are in terms of storey shear, storey displacement and storey drift are presented here. Following graphs show the maximum values of storey shear, storey displacement and storey drift for G+40, G+60, G+80 storey high rise buildings:

4.1. Comparison of storey shears

Fig 3 shows the graph of comparison of maximum storey shear for G+40, G+60, G+80 storey building models. Graph is plotted for modules vs maximum storey shear.

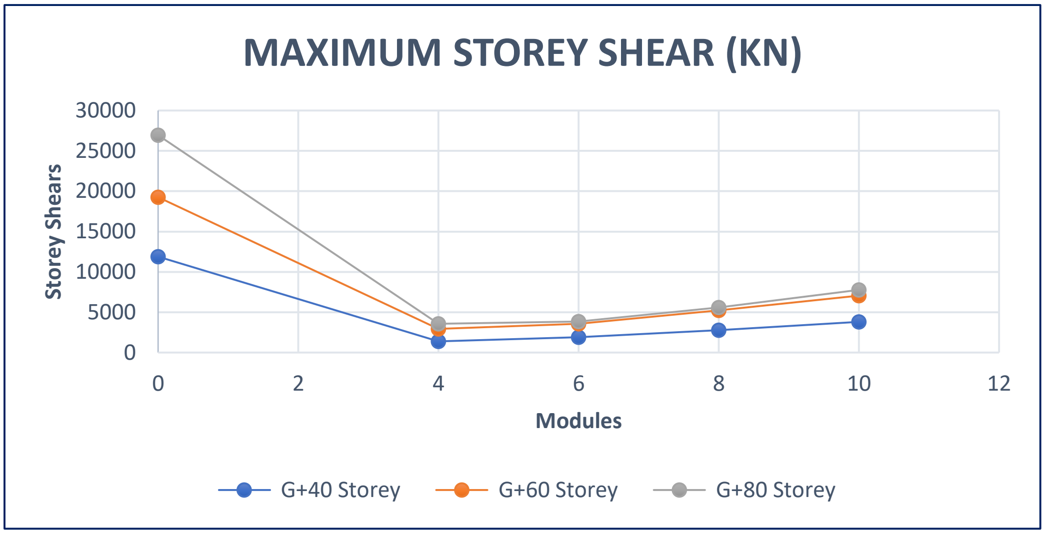

Fig. 3 Maximum Storey Shear In Kn.

4.2. Comparison of storey displacements

Fig 4 shows the graph of comparison of maximum storey displacement for G+40, G+60, G+80 storey building models. Graph is plotted for modules vs maximum storey displacement.

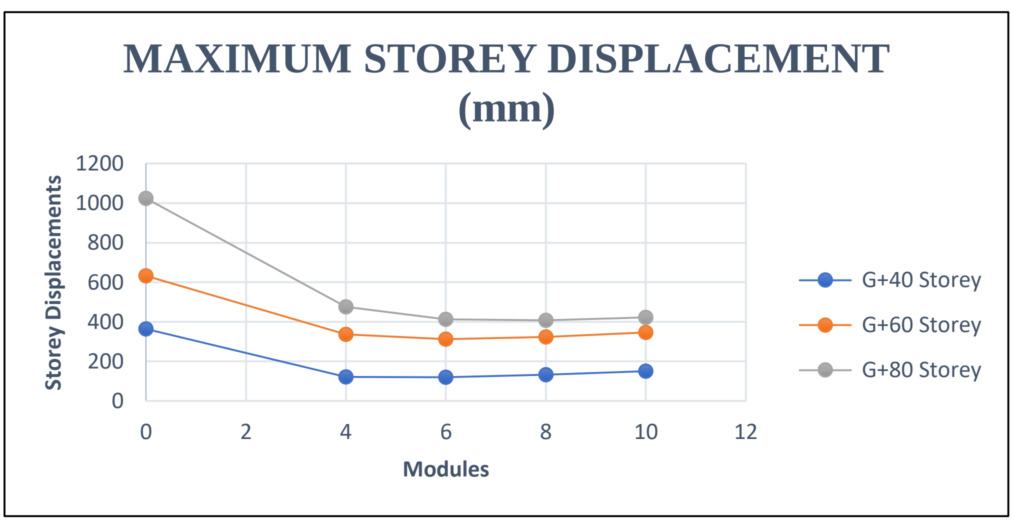

Fig. 4. Maximum Storey Displacement in mm.

4.3. Comparison of storey drifts

Fig 5 shows the graph of comparison of maximum storey shear for G+40, G+60, G+80 storey building models. Graph is plotted for modules vs maximum storey shear.

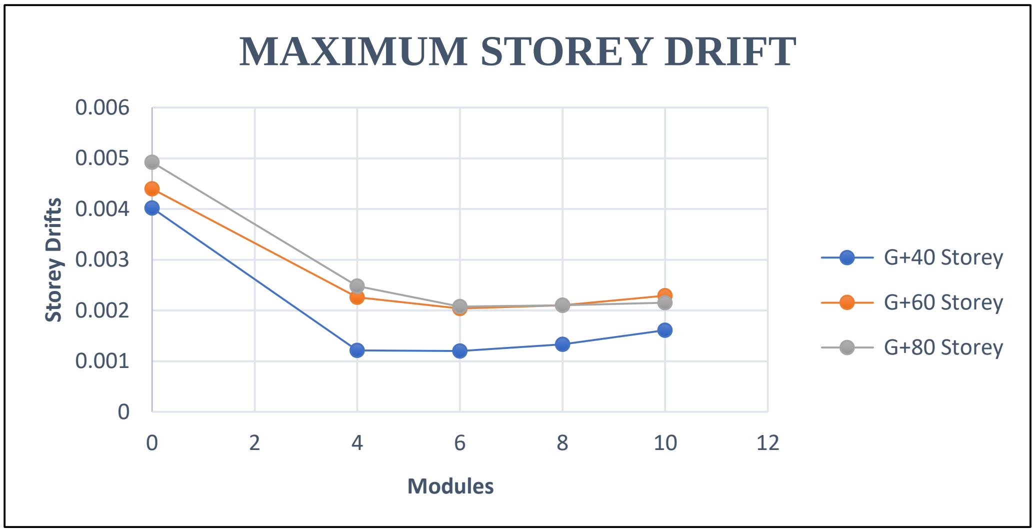

Fig. 5. Maximum Storey Drift.

The models of diagrid buildings and conventional buildings have been generated in ETABS software. The analysis has been carried out based on Indian Standards. For the comparison member sections and loading conditions are kept the same for both the conventional and diagrid type of building models. Result tables show the analysis results of G+40, G+60 & G+80 storey diagrid structures. The comparison of analysis results reveals that the storey shear, displacement and drift of conventional building models are greater than that of diagrid building models under the same member sections and loading conditions. Many of the members of conventional building models have been failed while analyzing under the same loading conditions as that of diagrid building models. On the other hand, diagrid building models are found to resist these loads effectively. It implies that the member sections of conventional building models have to be increased or it has to be strengthened by some other means to carry the same number of loads.

5. Optimum diagrid angle calculations

To obtain the optimum angle for diagrid structural system, G+40, G+60 and G+80 storey steel buildings are considered. Four different cases having an angle of diagonal 56.18^0, 66.2^0, 71.33^0 and 75.4^0 with 4, 6, 8 & 10 storey modules respectively are considered for each diagrid building to find an optimum angle. By considering the optimum angle of diagrid on periphery analysis is carried out. Table 4.2 shows the structural steel quantities for diagrids of G+40, G+60 and G+80 storey building structures having four different angles of diagrids.

It has been seen that, for G+40 and G+60 storey building structures with the storey module 6 gives minimum values off storey displacement and storey drifts and for G+80 storey building structures with the storey module 8 gives minimum values off storey displacement and storey drifts. This means that the module 6 with diagrid angle 66.2° is suitable for G+40 & G+60 storey building structures and module 8 with diagrid angle 71.33° are suitable for G+80 storey building structures.

Table 3
Structural steel quantity of perimeter diagrids.

Building Model	Module	Length of each diagrid (m)	Total number of diagrids	Weight of each diagrid (kg)	The total weight (tons)
G+40 storey	4	14.422	320	3779	1209.28
	6	19.697	288	5161	1513.89
	8	25.298	160	6629	1060.64
	10	31.048	128	8136	1041.40
G+60 storey	4	14.422	480	5780	2774.4
	6	19.697	320	7894	2526.08
	8	25.298	224	10138	2376.992
	10	31.048	192	12443	2989.056
G+80 storey	4	14.422	640	14672	9390.08
	6	19.697	448	20038	9004.54
	8	25.298	320	25736	8235.52
	10	31.048	256	31585	8085.76

The analysis result shows that the storey shear values increase while moving from a lower model to higher models i.e. the storey shear values increases when the height of the building increases. As per code IS 456-2000 the maximum storey displacement due to loads should not exceed H/500, where, H is the total height of the building. All the building models satisfy these criteria. But the lateral displacement of conventional building model is very larger than that of the diagrid building model under the same load. As per code IS: 1893-2016, the storey drift in any storey due to minimum specified lateral force should not exceed 0.004 times storey height that is H/250, where H is the total storey height in meter. The storey drift values are found to be within the permissible limit.

6. Aim of the study

The aim of the present study is to study the behaviour of high-rise buildings with diagrid systems. Analysis results are compared for parameters like Storey shear, storey displacement & storey drift. Also, the optimum diagrid angle is found out for a particular height.

6.1. The objective of the study:

Following are some objectives of the study:

1) Modelling of high-rise buildings with Diagrid systems of different angles.

2) To study the behaviour of high-rise buildings with Diagrid systems under gravity and lateral forces.

3) To study the behaviour of high rise buildings with diagrid systems for different parameters as follows: Storey shear, storey displacement, storey drift.

4) To find the optimum diagrid angle for a particular height.

7. Conclusion

From this study, it is concluded that, for G+40 and G+60 storey building structures with the storey module 6 gives minimum values off storey displacement and storey drifts and for G+80 storey building structures with the storey module 8 gives minimum values off storey displacement and storey drifts. This means that the module 6 with diagrid angle 66.2° is suitable for G+40 & G+60 storey building structures and module 8 with diagrid angle $71.33^{\circ}$are suitable for G+80 storey building structures. The diagrid angle ranges between 65° & 72° is best suitable for height ranges between 120m to 240m Diagrid angles in the region 70° to 76° are more economical regarding consumption of steel as compared to other angles of diagrid.

It has been also concluded that for the high-rise buildings, the diagrid system is used for the better performance of lateral load and gravity load resistance in the recent year. Diagrid columns on the perimeter of the building resist the lateral loads and both the internal columns and columns on periphery resists gravity loads, so the internal columns are designed for vertical loads only. Diagrid arrangement gives a without column structure which decreases steel required. Also, they look decent from a beautiful perspective. The diagrid structure performs well in all the parameters such as performance, expression and stability. Diagrid structure is more stiff than other structures. Comparison with traditional systems, Diagrid configurations have less deflection. The weight of the structure has decreased to a greater extent so that the structure becomes more resistant to the lateral forces. Displacement of each floor, shear and drift compared to conventional structures has been found to be low in diagrid structures. The diagrid gives maximum interior space to the structure and gives a good aesthetic perspective. Due to a smaller number of columns, effective and efficient planning of the facade of the building is possible. Diagrid structural system has emerged as a better solution for lateral load resisting system in terms of lateral displacements, steel weight and stiffness. It is stiff enough to resist wind forces up to higher heights.

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