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ANALYTICAL STUDY ON SEISMIC PERFORMANCE OF DIAGRID STRUCTURAL SYSTEM

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Abstract : The current trends of construction industry demand tall and lighter structures. These tall structures are very sensitive to Lateral loads induced by wind or earthquake along with gravitational loading. With the increase in height of the building, the lateral load resisting system becomes more vital than the structural system that resists the gravitational loads. Diagrid system is an innovative technology which promises better lateral load efficiency and is widely used now a days in the design of tall buildings because of its inherent structural efficiency as well as aesthetic potential provided by the unique geometric configuration of the system. Diagrid is an exterior structural system in which all perimeter vertical columns are eliminated and consists of diagonal grids in the periphery at a particular angle and in modules across the height of the building. Although diagrid systems are increasingly used as an efficient lateral load resisting system for tall buildings in modern construction, current literature lacks detailed information regarding their structural performance and appropriate seismic design parameters to ensure their reliability under earthquake events. To bridge this knowledge gap, this research aimed to assess the seismic performance of diagrid structural systems. In this study, analysis of 16 storied RCC conventional building and RCC diagrid building with similar geometric parameters and loading specifications is presented using response spectrum method and the results are compared. ETABS 2018 v18.1.0 software is used for modelling and analysis of structures. Subsequently, comprehensive analysis is done on various factors such as Time Period, Storey Displacement, Storey Shear, Storey Drifts in order to assess the seismic performance of the selected structures.

***Index Terms* - Diagrid structures, G+15 storey, High rise buildings, Response spectrum analysis, ETABS.**

I. Introduction

1.1 General Background

The increasing number of population and activities within the cities leading towards limitation of available land thus resulting to scarcity and high cost of available land, thus to overcome this, taller structures are preferable now a days. Thus, multi-storied structures need proper evaluation of loads for safe and economical design [1]. The consideration of lateral load is very much important in case of tall structures in addition to gravitational loads. 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 efficiency and aesthetic potential [1].

1.2 Diagrid Structural System

The word "diagrid" is combination of two words "diagonal" and "grid". Diagrid is an exterior structural system which resists the lateral forces by axial actions of diagonals provided in periphery [2]. This type of lateral load resisting system (diagrid) has generated a good interest from architects on aesthetic aspect and structural Engineers by their structural efficiency. Diagrid consists of perimeter inclined columns intersecting with horizontal components (ring beams) forming up a series of triangulated truss system, as shown in Figure 2. The diagonal members in diagrid structural systems carry gravity loads as well as lateral forces without any additional structural support.

Diagrid systems can be planar, crystalline or take on multiple curvatures, they often use crystalline forms or curvature to increase their stiffness [4]. The concept of a diagrid system is to convert the resulting building moment, shear and torsion into "axial force" in the diagonalized members. Hence, eliminating the vertical columns which mainly are built to carry gravity loads and might not be able of providing lateral stability [5].

Figure 1. Diagrid buildings
(a) Swiss Re in London (b) Hearst Tower in New York

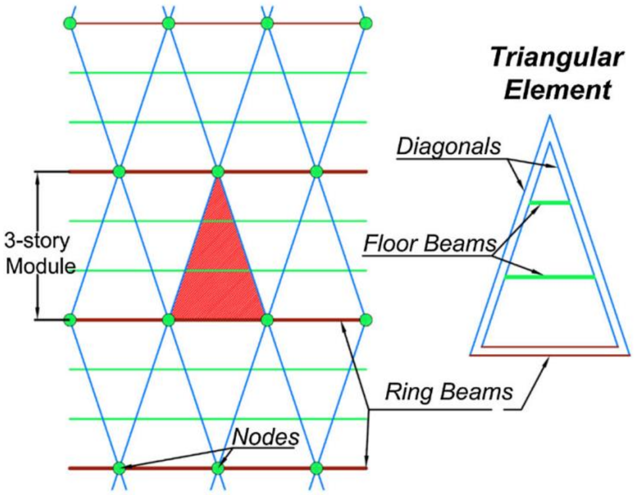


Figure 2. Diagrid elements [3]

1.3 Objectives of Study

- The main objective of this paper is to study the concept of diagrid structural system.
- To execute analysis of diagrid and conventional structure by using response spectrum method in ETABS 2018 v18.1.0. software.
- To study the performance of diagrid structure with respect to different parameters such as storey displacement, storey drift, storey shear and time period.
- To compare the performance of diagrid structural system with conventional structural system.

1.4 Problem Statement

The present study includes the study of the behaviour of high-rise buildings with diagrid systems. In this study, analysis of 16 storey conventional frame structure and diagrid structure is presented. Analysis results of 16 storey conventional frame structure as well as diagrid structure is compared for parameters like storey shear, storey displacement, storey drift and time period. Lateral forces due to earthquake & wind effect are considered as per Indian Standard. IS 1893:2016 and IS 875:2015 were used for the analysis of the structure. Modelling and analysis of structures are carried out using ETABS 2018 v18.1.0 software. Response spectrum analysis is done for earthquake and wind loads. For linear static and dynamic analysis, the beams and columns are modelled as flexural elements and diagonals are modelled as truss elements. Temperature variation is not considered. The analysis is carried out by considering the optimum angle of diagrid on the periphery.

1.5 Research Significance

Although diagrid systems are increasingly used as an efficient lateral load resisting system for tall buildings, Diagrid is relatively a newly-developed structural system, current design codes generally do not account them as an independent structural system and therefore, there is not much information regarding its seismic performance in past earthquakes. As a result, there is no agreement on the suitable behaviour factor for these systems to satisfy required performance targets. To address this issue, this study aims to assess the seismic performance of diagrid systems.

1.6 Scope

The research has been limited to, two symmetric five bays by five bays 16-storey reinforced concrete buildings which is regular in plan and regular in elevation. The frames were assumed firmly fixed at the bottom and the soil structure interaction has been neglected. One frame is analysed as conventional framed structure and the second one as a diagrid structure. Module angle of diagrid with fixed spacing has been applied as lateral load bearing system for each of 16-storey multi-story reinforced concrete building which is located in Pune, these a total of two models has been analysed with elastic response spectrum method and verified for their most structural efficiency based on lateral storey displacement, inter-story drift, storey shear and time period excluding node design and cost comparison. The analysis has been performed by using Finite element software (ETABS 2018 v18.1.0). The construction methodology of these structures is also not discussed.

II. LITERATURE REVIEW

This section presents a review of the current literature on Diagrid Structural System. A brief review on diagrid technique of previous studies is presented here.

Aarthi Senthilkumar, R. Umamaheswari (2021)

This paper has shown the structural performance of both conventional and diagrid structure using ETABS v.15. Various parameters like storey drift, storey displacement, storey drift and storey stiffness are obtained and compared in this study. The authors concluded that; diagrid structure emerged as better solution in terms of lateral displacement under seismic loading. It also emerged as better solution in terms of storey drift. It has more stiffness than conventional structure and can resist higher lateral forces, thus vertical columns being eliminated in interior of structure. The diagrid structure is evidently more efficient than the conventional structure [3].

Anshuman R. Prajapati and Ashwin G. Hansora (2021)

Have found that diagrid structural systems are unique and effective compared to other bracing systems. It is the grid of diagonal members which provides lateral and gravity load resistance. In diagrid structural systems vertical columns are removed and replaced by inclined columns called as diagrids. Shear and moments due to lateral loads are resisted by axial action of these diagonals. Diagrid structures have core as partial stability, by providing shear wall at core of diagrid structure maximum displacement reduced by 15–30% and maximum inter storey drift reduces by 15–50%, these shear walls eliminate local stability issue. It has increased base shear around 5 to 6% and material quantity (8-11%) concrete and (3-4%) steel which is considerably small. Thus, it's better to provide shear wall where large inter-storey drift, so that stiffness and stability will increases and displacement are reduced [6].

Neha Thakare, Dr. B. H. Shinde (2021)

The comparative study was executed for different diagrid structures using ETABS software to find the stiffness and flexibility of high-rise structures and also for asymmetrical structure through simple framework. Two structure models one G+40 Building with Conventional system without diagrid and second G+40 Building with 2 storey module Diagrid system is modelled and analysed in ETABS software. It concludes that possibility of failure is much lesser for diagrid structure when compared to conventional system by heavy vibrations during earthquake [7].

Saurabh Babhulkar, et.al. (2021)

In this paper two 15 story structures, one for diagrid and other for customary structures were selected. A square shaped 15 storey building of size 24m x 24m, storey height 3.2m and plan area 576m² is considered for the analysis and design. The three kinds of structures that have been demonstrated are, Diagrid with 2 modules, diagrid with 4 modules, diagrid with 6 module structures. Investigation esteem are thought about as far as Shear, Displacement, Drift and the reaction as far as boundaries such a story uprooting, story float, story shear. It shows that by giving inclining sections at external outskirts of constructions, composite diagrid structure more viably opposes sidelong burden, it opposes gravity burden and sidelong burden from inside as well as outside. Because of vertical segment at external outskirt of structure, there is an enormous decrease of cement in diagrid structure, this makes diagrid structure more effective [8].

Majid Moradi a, Moein Abdolmohammadi (2020)

This article is based on energy approach concepts to achieve better understanding of seismic behaviour and advantages of utilizing energy methods. The performance and fragility of tall building of 50 storey diagrid structure is modelled with finite element method and its behaviour is investigated through the Incremental dynamic analysis (IDA).

It concludes that, plastic strain energy can be considered as an appropriate engineering demand parameter (EDP) in evaluating performance of structure. It measures whole structure not related to specific storey. Fragility of 50 storey diagrid building in all performance levels in both methods plastic energy and maximum drift method in far field earthquakes is higher than near field earthquakes [9].

Rahul Birla, H.O.D. Sourabh Dashore (2020)

The authors states that in this world development of tall buildings have been increasing day by day. For efficient design initiative, diagrid system is innovative technology. Hexagrid structure is extension of diagrid structure but there is lack of skill and experience to create hexagrid structures, they are too heavy. In this study analysis of 48 storied Steel building with diagrid system and hexagrid system is presented. Modelling and analysis of structural member is done using finite element software ETABS. Loads, load combinations and seismic data are provided according to IS 875:1987and IS 1893:2002 respectively. This study has shown that diagrid structure decreases bending moment, which results in decrease in reinforcement requirement and gives maximum 98.3% durability accuracy. Although volume of concrete used is more but it becomes economical in steel use. The diagonal column periphery shows better resistance to lateral loads whereas the maximum shear force and bending moment at perimeter of beams decreased by diagrid structures [4].

Mahdi Heshmati, et. al. (2020)

In this study, seismic performance of 36-story diagrid structures with varying angles are evaluated using pushover and nonlinear time history analysis. Furthermore, in order to evaluate the effect of diagrid core on behavior of structures, interior gravity frames are replaced with diagrid frames. The results of pushover analyses demonstrate that diagrid core can enhance the hardening behavior of structures when the angles of perimeter panels are lower or equal than those of the core compared to the conventional diagrids. In addition, core diagrids provide safe margins between the damage states under lateral loading. Nonlinear time history analyses are then performed to assess inter story drift ratio, residual drift, energy dissipation and hinges distribution of structures.

It is observed that most of the models perform well under rare ground motions and hinges are well spread throughout the height among different elements and diagrid structures are capable of undergoing large deformations under rare earthquakes Large portion of input energy are dissipated by diagonal members and as the slope of exterior diagonals exceed that of perimeter tube, diagrid core efficiently participates in dissipating energy [10].

Giuseppe Lacidogna, et.al (2020)

In this article they have presented desirability function approach for optimization of diagrid geometry by varying diagonal variation in inclined angles and floor shape. Its methodology presented here is simple, fast and easily implementable for analysis for large structures. A 168-meter-tall building, with four different floor shapes is analysed, and the inclination of the external diagonals is varied between 35° and 84°. The desirability function approach is applied to find the most desirable geometry to limit both the lateral and torsional deformability, the amount of employed material as well as the construction complexity of the building. A sensitivity analysis is also carried out to investigate the influence of the individual desirability weight on the obtained optimal geometry. The effect of the building height is finally evaluated, through the investigation of sets of 124, 210 and 252-meter tall diagrid structures.

The results have shown that optimal solution remains some large majority of weight combinations, with a minority of cases where the optimal diagrid is one with octagonal shape and three intra-module floors. The application of desirability function approach for the optimization of diagrid geometry in preliminary design stages is highly recommended when designer needs to have individual matrics [11].

Neha Tirkey, G.B. Ramesh Kumar (2019)

In this article the diagrid structure is designed, analysed and is compared with the conventional building using ETABS software mainly focusing on seismic and wind analysis parameters. The propose work presented in this paper of a structural dimension of the G+30 storey building of 25 m X 25 m and the floor height is kept as 3 m. The Diaphragm walls are created on all four sides of the building and the mass source of the building is taken as 0.25%. The angle of the diagrid structure taken is 60°. The space between the columns is 4 m. The Chennai region is considered for this proposed data. The load combination taken for wind and seismic parameters are referred from the IS 456:2000 and IS 1893 (PART-1): 2002. Since the structure is G+30, therefore, the Response Spectrum method is analysed.

This paper concludes that the lateral load resisting system is better in resisting the gravity loads than the structural system when the structure height gets increased. The configuration and efficiency of the diagrid system has reduced the number of structural elements. The possibility of failure is much lesser for diagrid structure when compared to the conventional structure by heavy vibrations during an earthquake [12].

Trupti A. Kinjawadekar, Amit C. Kinjawadekar (2018)

This paper presents a comparative study of seismic characteristics of diagrid structural systems for multi-storey structures. The results based on numerical models indicate that these structures can address most of the present-day design requirements. The study aims to explore the applicability of diagrid structures in high rise structures, over the traditional construction systems.

In the present study, two different set of models were considered. One for 18 storeys and other for 36 storeys structure with three different angles of diagrid viz., - 45°, 64°, 72°, and 90° (simple frame). In all, eight different models were analysed. The analysis is done as two-dimensional plane frames. The mathematical models based on above configurations were analysed using software SAP-2016. Dynamic analysis of the models is performed based on following criteria as Storey Displacements, Storey drifts, Time period and Base shear.

The authors conclude that, in 18 storey structures use of Diagrid angle in the region of 45° to 64° provides more stiffness which reflects in lesser top storey displacement. For 36 storey Diagrid structures angles in the range of 64º to 72º display lesser top storey displacement. The optimum angle of diagrid is observed around 64°. At this angle, top storey displacement being lesser, the storey drift is also much lesser. So, it is more economical regarding consumption of steel because though it has similar weight as in the case of diagrid angle 45º, but it has lesser number of joints [13].

Giulia Angelucci, Fabrizio Mollaioli (2017)

The authors examine stiffness based methodology effectiveness proposed by literature review by applying it to 90 storey diagrids with optimal 69° and non-optimal 82°. The authors test the contribution of a hybrid structure combining diagrid and outrigger systems to appraise whether a local increase in the pattern might be advantageous and preferable to a gradual stiffening from the top of the building toward the base. The outcomes clearly demonstrated that 82° model section sized in preliminary phase exceeds strength and stiffness demands under gravity and imposed lateral loads, therefore design needs to be integrated and refined. It also demonstrates that a local density increment is not an appropriate strategy. Despite considerable weight reduction, it is not efficient in restraining top displacement within targets. More efficient solutions involve a varying pattern density, varying diagonal members from base towards top of building [14].

III. RESEARCH METHODOLOGY

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

Among various methods of conducting researches, the research has been conducted based on quantitative nature (analytic study), aimed to verify the structural efficiency of a diagrid structure in Finite element software (ETABS 2018 v18.1.0). There were two phases of the project investigation. The primary data was collected by a literature review that included online searches as well as a review of eBooks, guides and journal articles. Following the evaluation, the issue statement is established, and the model is prepared for detailed research and examination. This research will be carried out according to the flow map below:

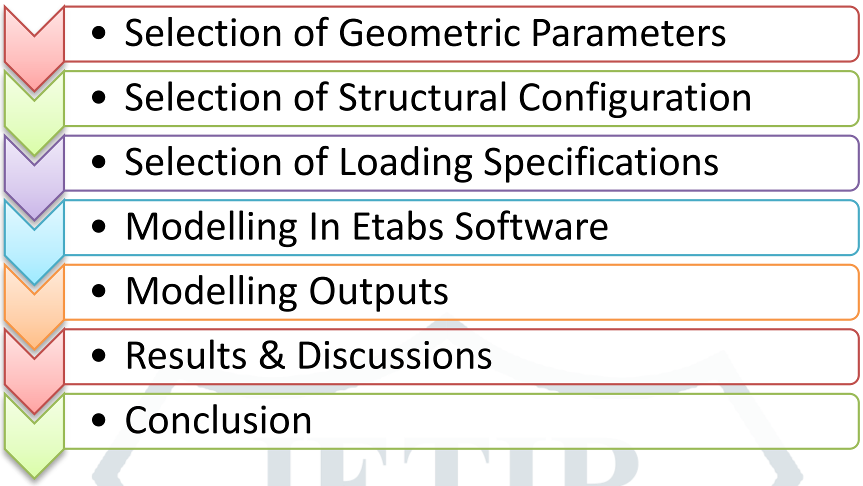


Figure 3. Research approach

3.1 Modelling of Structural Systems

3.1.1 Modelling Description

For the analysis work, the models of high rise reinforced concrete frame building of 16-storey has been made to know the realistic behaviour of the building during earthquake for diagrid structures. Three-dimensional space frame analysis will be carried out for conventional structure and diagrid structure under seismic loading. Two different models as follows will be prepared in ETABS software.

Model 1: Conventional Structure
Model 2: Diagrid Structure

a. Geometric parameters

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 storeys per module.

Table 1. Geometric parameters of the building models

Structure type	RCC structure (OMRF)
Number of stories	16 Stories
Size of plan	20 m X 20 m
Number of bays along X & Y	5
Spacing between bays	4 m
Height of each storey	3 m
Diagrid Angle	72°
Storeys per module	4

b. Structural configuration:

Table 2. Structural configuration of the building models

Structure type	RCC
Grade of structural steel (Fy)	HYSD 500
Grade of concrete (Fck)	M45
Slab thickness	150 mm
Column dimensions	900 X 900 mm
Beam dimensions	300 X 600 mm
Diagrid dimensions	600 X 600 mm

c. Loading specification:

Table 3. Loading specification of the building models

Load details:	
Floor Finish -	1 kN/m²
Live Finish -	2 kN/m²

Seismic parameter details: (as per is 1893-2016)	
Seismic zone -	III
Zone factor -	0.16
Soil type -	II (Medium)
Importance factor -	1
Response reduction factor -	5
Wind parameter details: (as per is 875-2015)	
Location -	Pune
Wind speed -	39 m/sec
Terrain category -	2
Structure class -	B
Risk coefficient -	1
Topography factor -	1

d. Load Combination

The load combination for response spectrum analysis as per Indian standards

1.2(DL +LL ± RSX)
1.2(DL +LL ± RSY)
1.5(DL ±RSX)
1.5(DL ±RSY)
0.9(DL ±RSX)
0.9(DL ±RSY)
0.9DL ± 1.5RSX
0.9DL ± 1.5RSY

3.1.2 Modelling In Etabs

A Conventional structure and a Diagrid structure were modelled using ETABS 2018 v18.1.0 software. The plan and 3-D views of both the structures are given in figures below.

a. Conventional structure system modelling

In the conventional structural system, all the frame members are of special moment resisting frame with no additional lateral force resisting system is considered, considering the conventional system as a reference for comparing to other lateral force resisting system to find out the objectives of this study.

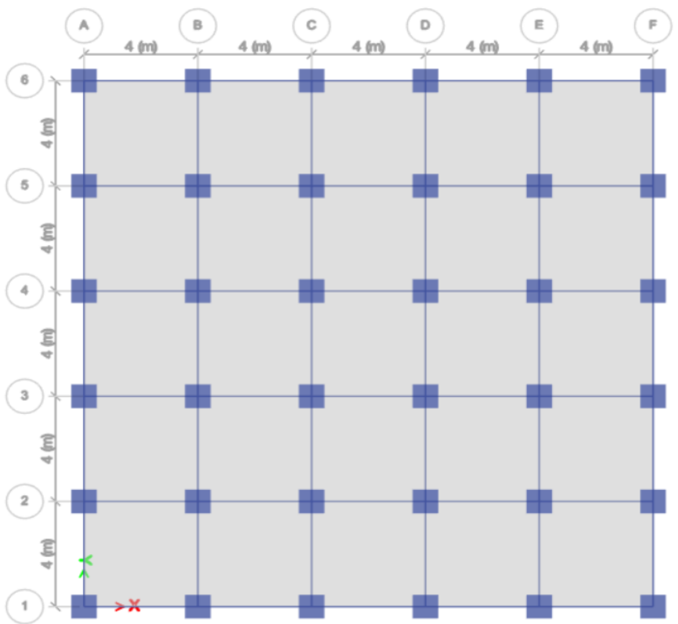


Figure 4. Typical Floor plan for conventional frame building model

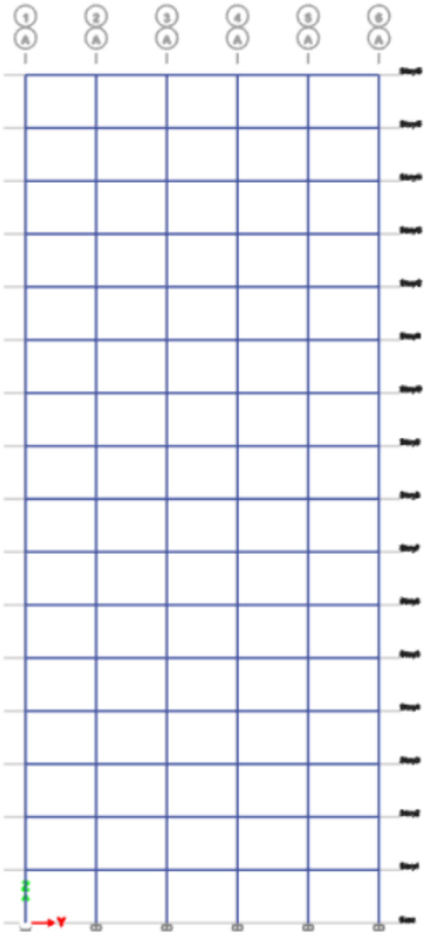


Figure 5. Elevation view of 16-storey conventional frame structure

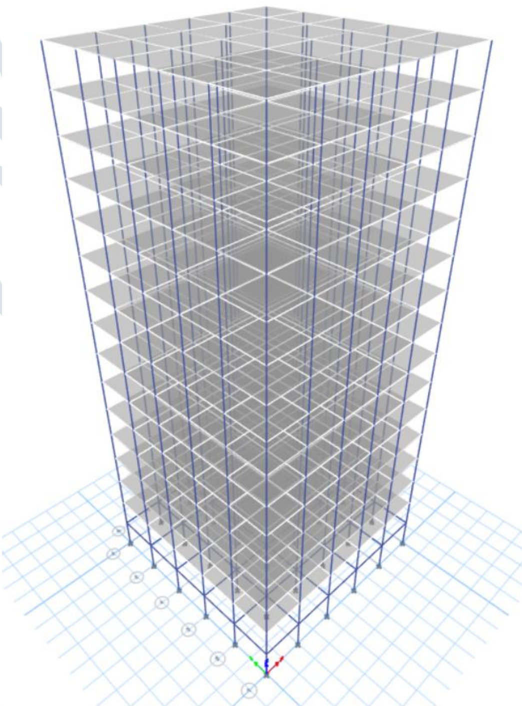


Figure 6. 3D model of frame structure for G+15 Building.

b. Diagrid structural system modelling

For the Diagrid structural system, the diagrids are provided at the exterior to resist lateral loads and the interior column to take up gravity loads, the optimum angle is considered as a 60-75 degree from previous literature studies to obtain the best result.

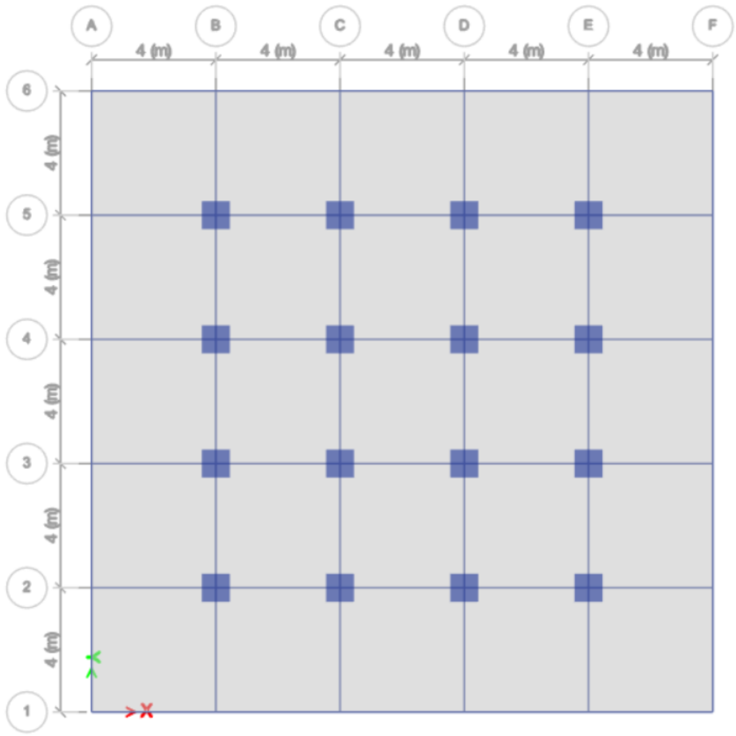


Figure 7. Typical Floor plan for diagrid building model

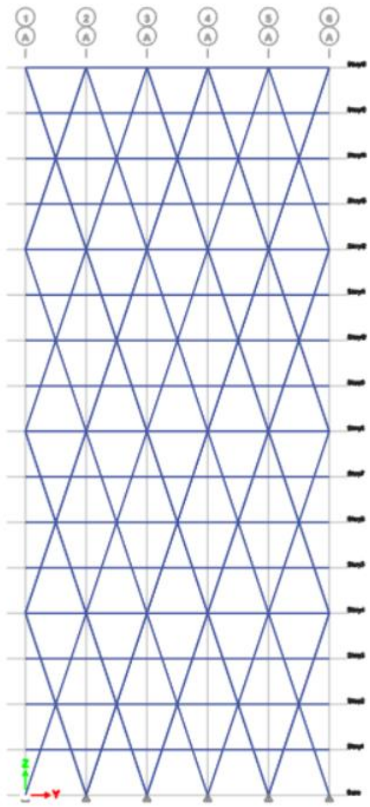


Figure 8. Elevation view of 16-Storey four module diagrid structure

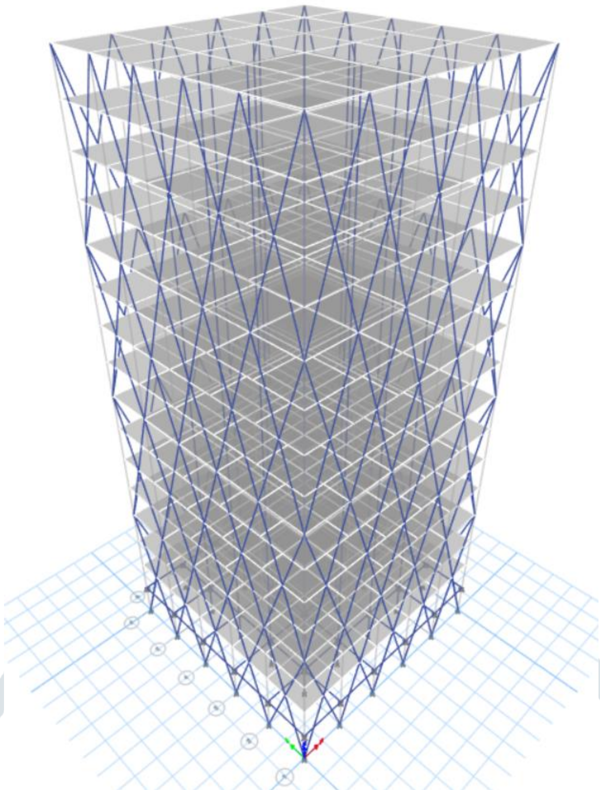


Figure 9. 3D model of diagrid structure for G+15 Building.

IV. RESULTS AND DISCUSSION

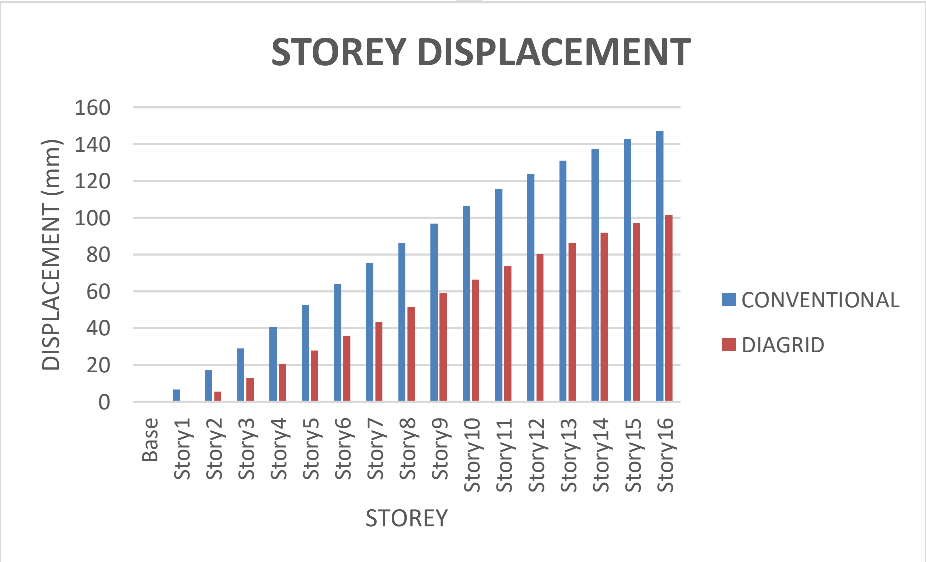
Results of Response Spectrum Analysis have been used to observe and compare floor response of all the models in terms of the following parameters.

1. Storey displacement
2. Storey drift
3. Storey shear
4. Time period

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

1. Storey displacements

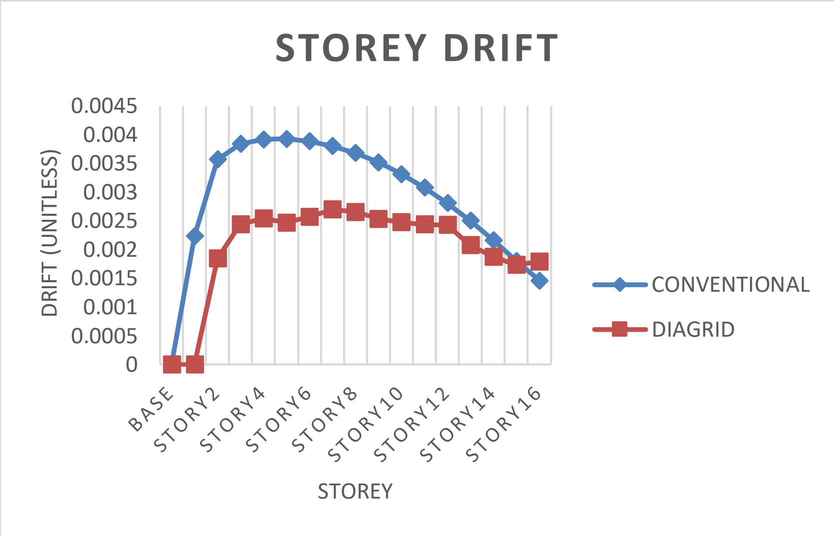
Storey displacement is the absolute value of displacement of the storey under the action of the lateral forces. Storey performance evaluation is directly related to displacement or deformation and thus estimation of seismic deformation demand is a primary or fundamental concern in performance evaluation of reinforced concrete structures under seismic excitation. Considering the lateral load on buildings i.e., Wind load and Earthquake load following results are shown in graphs. Figure below shows the graph of comparison of maximum storey displacement for 16-storey building models. Graph is plotted for building storeys vs storey displacement. The maximum storey displacement in diagrid structure is 101.54mm at the 16th storey whereas in conventional structure it is 147.21mm. Thus, storey displacement in frame structure is quite more as compare to diagrid structure.



Graph 1. Comparison of maximum storey displacement

2. Storey drift

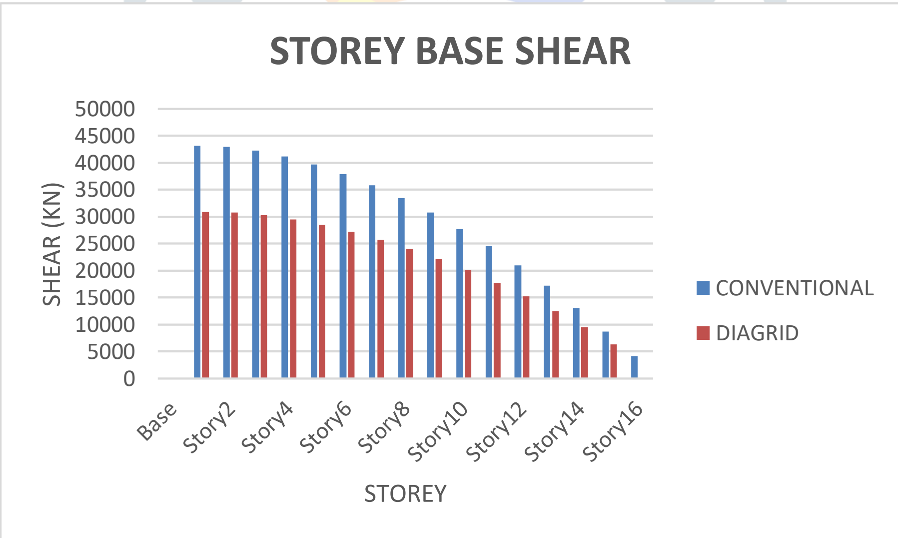
Storey drift is the relative story displacement due to acting of total lateral load. It is defined as a Drift of one level of multi-story relative to level below. Storey drift is the difference of displacements between two consecutive storeys divided by the height of that storey. Figure below shows the graph of comparison of maximum storey drift for 16- storey building models. Graph is plotted for building storeys vs storey drift. It is observed that maximum storey drift in diagrid structure is 0.00269 at 7th storey, whereas, maximum storey drift in conventional structure is 0.00392 at 5th storey. Thus, diagrid structures has less drift ratio compared to conventional framed structures.



Graph 2. Comparison of maximum storey drift

3. Storey shear

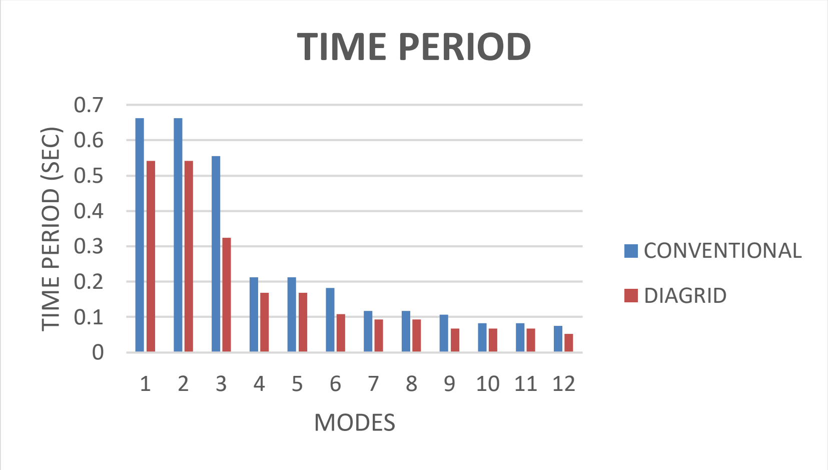
Base shear is the approximate maximum expected reactions that would be generated due to seismic motion of ground at the base of the structure. Maximum shear occurs at base of any structure. Figure below shows the graph of comparison of maximum storey shear for 16- storey building models. Graph is plotted for building storeys vs maximum storey shear. From the results obtained it can be seen that maximum storey shear in diagrid structure is 30889.24 kN occurred at base, whereas maximum storey shear in conventional building occurred at base is 43098.29 kN which is less as compared to diagrid structure.



Graph 3. Comparison of maximum storey shear

4. Time period

Time period is a property of system, when it allows to vibrate freely without any external force and it depends on mass and stiffness of the structure. Time period is defined as time required in seconds to complete one cycle of oscillation for a given system. If the time period for a given structure is more, then the structure is considered to be less stiff. As per result obtained time period for the diagrid structure is 0.542 seconds, whereas for conventional structure is 0.662 seconds, thus it can be stated that time period for diagrid structure is less as compared to conventional frame structure.



Graph 4. Comparison of time period

V. CONCLUSION

This paper presented an analytical investigation on the efficiency of concrete diagrid building against the concrete conventional framed building system. Two models for each system with 16- stories were generated. The dynamic demands (lateral storey displacements, storey drift, storey shear forces and time period) were evaluated. Based on the model building cases considered in this study the following specific conclusions has been made according to the linear (response spectrum) analysis results and comparative study,

1. Under seismic loading conditions maximum storey displacement of diagrid structure is less as compared to conventional framed structure. As the storey performance evaluation is directly related to displacement, thus diagrid structure has more efficiency in terms of lateral displacement under seismic loading.
2. The conventional structure has more storey drift as compared to diagrid structure under seismic loading, which results to be diagrid structure as more stiff than conventional structure which emerged as a better solution in terms of storey drift.
3. The storey shear in diagrid structure is generated less as compared to conventional structure, hence diagrid structure will be subjected to less lateral forces thus can resist higher lateral forces and generally do not need high shear rigidity cores.
4. Under same structural configuration and seismic loading conditions, it is observed that diagrid structure shows low values of time period, which results in stiffer structure hence, can be preferred over conventional structure.
5. The diagrid structure is evidently more efficient than the conventional structure. Hence the diagrid, for structural effectiveness and aesthetics has generated renewed interest from architectural and structural designers of tall buildings.

VI. FUTURE RECOMENDATIONS

- Higher storey buildings with different diagrid materials can be studied in R.C.C symmetrical building for diagrid structure.
- Asymmetrical building with different diagrid angles can be taken into consideration for diagrid structure.
- Further studies can be carried out using push over analysis (static non-linear) and time history analysis (dynamic non-linear) methods.
- Steel buildings can also be studied as diagrid structures.

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