Optimal Diagrid Angle of High-Rise Buildings Subjected to Lateral Loads

Jayesh Venkolath[1], Rahul Krishnan K[2]

[1] *P.G. Student, Department of Civil Engineering, Vedavyasa Institute of Technology, Malappuram, Kerala, India*
[2] *Associate Professor, Department of Civil Engineering, Vedavyasa Institute of Technology, Malappuram, Kerala, India*

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Abstract - *Construction of multi-storey building is rapidly increasing throughout the world. Recently diagrid structural system is adopted in tall buildings due to its structural efficiency and flexibility in architectural planning. The diagrid structure of each storey height is designed with diagonals placed at various uniform angles as well as gradually changing angles along the building height in order to determine the optimal uniform angle for each structure with a different height. As the height of building increase, the lateral load resisting system becomes more important than the structural system that resists the gravitational loads. The lateral loads are resisted by axial action of diagonal members. The aim of this study is to find the optimal diagrid angle to minimize the lateral drift and displacement in high-rise building. Five different diagrid angle configurations (36.8°, 56.3°, 66°,77.5° and 83.6°) have been considered for 24-storey circular buildings. The results were tabulated by performing finite element analysis using ETABS software. The comparison of analysis of results in terms of lateral displacement, storey drift, storey shear and time period.*

***Key Words*: Angle of diagrids, Diagrid structural system, Lateral displacement, Storey drift, Storey shear.**

1. INTRODUCTION

The rapid growth of urban population, scarcity and high cost of available land greatly influenced the construction industry. So that the taller structures are preferable now a days. So when the height of the structure increases then the consideration of lateral load is very much important. For that lateral load resisting system become more important than the structural system that resist the gravitational loads. The lateral load resisting systems are widely used in rigid frames, shear wall, wall frame, braced tube system, outrigger system and tubular system. Recently the diagrid – diagonal grid structural system is widely used for tall buildings due to its structural efficiency and aesthetic potential provided by the unique geometric configuration of the system. Structural efficiency of diagrid system makes the number of interior column decrease, therefore much flexibility on the plan design. The primary idea behind the development of the diagrid system was the recognition of the savings possible in the removal of the vertical columns. The vertical columns were only engineered to carry gravity loads and were incapable of providing lateral stability. The diagonal grid, if properly spaced, was capable of assuming all of the gravity loads as well as providing lateral stability due to its triangular configuration. Hence the diagrid, for structural effectiveness and the aesthetic has generated renewed interest from architectural and structural designers of tall building. So when the diagrid structural system is provided in tall buildings, there is very much important the angle of diagrid. The questions are arises in our mind that, (1) what should be the optimum angle of diagrid? , (2) Is that angle is economical for tall structures? , (3) why we are selecting such an angle instead of vertical structure? So, to evaluate these problems, the present work is carried out using different angles by considering different storey module. ETABS software is used for modelling and analysis for structural members. The results are discussed in terms of lateral displacement, storey drift, storey shear and time period by considering static and dynamic properties.

In present work, five different models of a 24 storey circular building is considered with provision of different angle of diagrid, that is 31°(1-storey module), 50.2°(2-storey module), 61°(3-storey module), 74.5°(6-storey module) and 82.1°(12-storey module). This five models are labelled as model-A, model-B, model-C, model-D and model-E. The modelling and analysis of this five models were done by using ETABS software to find the optimum angle of diagrid for high-rise buildings.

2. BUILDING CONFIGURATION

2.1 Types of Models

In this work, five different models of 24 storey buildings are considered which are having different angle of inclination i.e. 36.8°(1-storey module), 56.3°(2-storey module), 66°(3-storey module) ,77.5°(6-storey module) and 83.6°(12-storey module) which are represented by letter A, B, C, D and E respectively. The building is circular symmetrical in shape and the diameter used is 30.7m and total height of the building is 86.4m. The same sections were considered for the diagrid members and other members in each model type. The plan view of all the models is shown in fig -1.

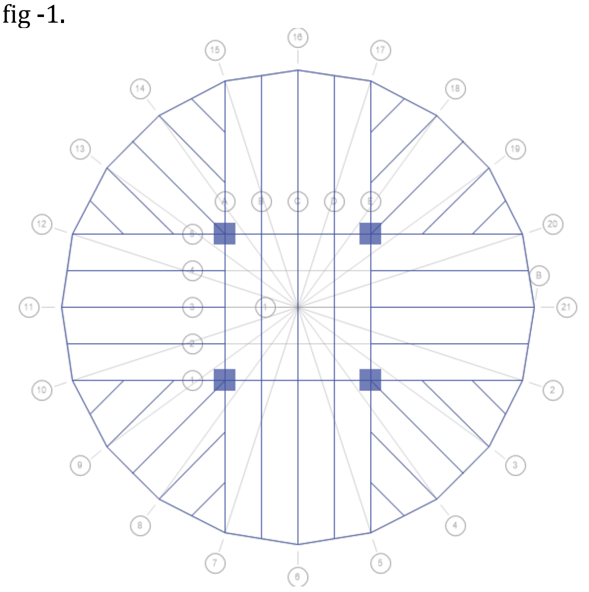

Fig -1: Plan view of all models

2.2 Geometry Data

The general geometry data for all the models are as follows

i. Plan dimension : 30.7 diameter
ii. Number of storeys : 24 storeys
iii. Storey height : 3.6 m
iv. Slab thickness : 0.120 m
v. Characteristic strength of concrete : 40 N/mm^2
vi. Characteristic strength of steel : 500 N/mm^2

The angle of diagrid is decided on the basis of the storey module. The module means that the number of stories stacked per model. In this study, five different storey module is considered, that is 1-storey module, 2-storey module, 3-storey module, 6-storey module and 12-storey module. The angle is obtained from the height of the storey module to the base width of diagrid. The diagrid angles varies with varying of height of storey module.

For example: 2-storey module then,

Angle (θ) = tan-1 (height of module / base width)

Angle (θ) = tan-1 (7.2/4.8)

Angle (θ) = 56.3°

The geometry of the basic triangle model plays a major role in the internal axial force distribution, as well as in conferring global shear and bending rigidity to the building structure. Since the optimal angle of the columns for maximum bending rigidity is 90°, (i.e. vertical columns in traditional buildings) and that of the diagonals for maximum shear rigidity is about 27° (only one storey stacked per basic triangle model), it is expected that the optimal angle of diagonal members for diagrid structures will fall between these angles. So the selected the angles for analysis is in between these angles.

2.3 Structural plan

Here, fig -2 is showing the structural plan view of all the models, in which the beam notations B1, B2 and B3 are shown. There are 3 types of beams namely as B1, B2, B3 and different beams shown with different color. The beam B1 is the larger span beam in the structure. And there are four columns with same dimensions at the center square portion of the building.

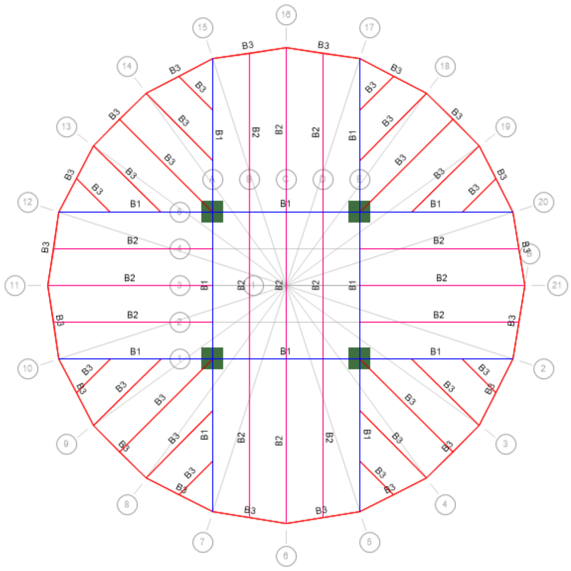

Fig -2: Structural plan

The member sizes for all models are preliminary decided same but after analysis results and designing results, the sizes are modified to prevent failure and excessive top storey displacement. Table 1 showing the member sizes for all the models. There are three types of beams and the size of the columns for all the structure are same. The member D1 indicates the diagonal member which passes through the outer periphery of the structure and it is same in size for throughout the structure. The size of all the members are same for five models namely as A, B, C, D and E.

Table -1: Member sizes for all models

Member	Notation	Dimension
Beam	B1	500 X 1100
	B2	300 X 650
	B3	300 X 450
Column	C1	1400 X 1400
Diagrid	D1	650 X 650

The design dead load and live load is considered as per IS 875 Part I and Part II and are 3.75kN/m^2 and 3kN/m^2 respectively. . Self-weight of the structural members will be calculated by the software ETABS. The design earthquake load is computed based on the zone factor 0.16, soil type II, Importance factor 1, Response Reduction 5 as per IS-1893-2002. The design wind load is computed based on location Calicut, Wind speed 39 m/s, Terrain category 2, Structure class B, Risk Coefficient 1, Topography factor 1. The load combinations are considered according to IS 1893(Part I):2002. Modelling, analysis and design of diagrid structure are carried out using ETABS 15.2.0 software. The end condition for diagrid is assumed as hinged. The support conditions are assumed as fixed. The design of member is carried out on the basis of IS-456-2000.

3. ANAYSIS RESULTS

The analysis results of model-A, model-B, model-C, model-D and model-E in terms of lateral displacement, storey drift, storey shear and time period are presented.

3.1 Lateral displacement Results

The lateral displacement of any building increases with increasing the height of the building due to its lateral load effect. Here, chart -1 shows the lateral displacement corresponding to each storeys for Model-A, model-B, model-C, model-D and model-E. For all the models, wind load govern the design. So the results are shown in terms of wind load cases only.

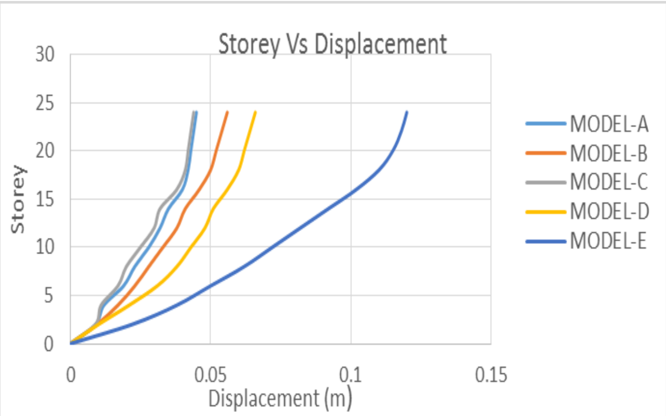

Chart -1: Displacement results for all models

As per code IS: 456-2000, clause: 20.5, page no. 33, the maximum top storey displacement due to wind load should not exceed H/500, where H is the total height of the building. The displacement results for all the models are within the permissible limit. It can been seen that when the height of the building is increasing, the top storey displacement is also increased but for the case of all models, displacement value is smaller for model-C by comparing others.

3.2 Storey Drift Result

Storey drift is the difference of maximum lateral displacements of any two adjacent floors under the factored loads, divided by respective storey height. In terms of elastic deflections, the storey drift, S is given by

$$S = \delta\varepsilon / h$$

$$\delta\varepsilon = d_{n+1} - d_n$$

Where,

d_n = maximum elastic deflections of the n^{th} floor under the factored loads.

$\delta\varepsilon$ = deference of the elastic deflections between two neighboring floors.

h = storey height.

The relative lateral deflection in one storey under the characteristic wind load to a maximum of H/500, where H is the storey height. Higher value of storey drift limitation Sm are permitted to vary between 0.004 and 0.008 when non-structural elements are isolated from and not integrally connected to the main structure. Here chart -2 shows the storey drift results for all models. The results are shown for the earthquake load. Model-E shows large variations in storey drift by comparing with other models.

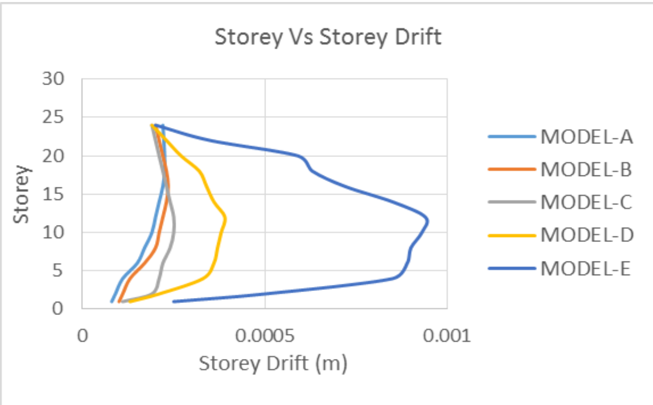

Chart -2: Storey drift results for all model

For earthquake load, as per code IS: 1893-2002, clause: 7.11.1, page no: 27, the storey drift in any storey due to minimum specified lateral force with partial load factor of 1.0 should not exceed 0.004 times storey height that is

H/250, where H = storey height in meter. The storey drift value is within the permissible limit. It can be seen that the excessive drift for the model-E. Model-C and model-D are giving the better results as compared to other models as shown in above figure.

3.3 Storey Shear Result

Here, the Storey shear results for model-A, model-B, model-C, model-D and model-E are shown in chart -3. Results are shown for the earthquake load. The four models A, B, C and D shows small variation in storey shear by comparing with each other but the model-E shows large variation in shear by comparing with other models.

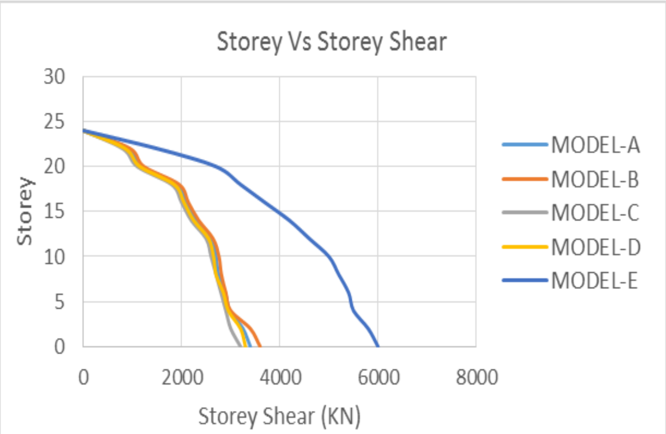

Chart -3: Storey shear results for all model

From the analysis results, it can been seen that the storey shear for model-E is more as compared to the others. From the above figure the gradual variation is noticed for the model-C and it gives better result by comparing with others. From the analysis of above graph it is clear that model-C and model-D gives less storey shear by comparing the five models in that graph.

3.4 Time Period Result

By performing the dynamic analysis, time period is found out by considering 12 mode shape for all models, is presented here. Chart -4 shows the results of modal analysis for model-A, model-B, model-C model-D and model-E respectively. It shows the time period results against 12 mode shape.

The building's natural time period is obtained from the equation,

$$T = 2\pi\sqrt{\frac{m}{k}}$$

Where, m = mass of the structure and

k = stiffness of the building

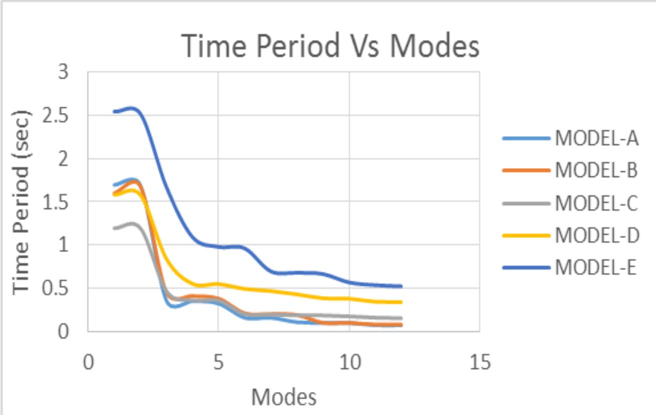

Chart -4: Time period results for all model

From the above equation, it can been observed that, time period depends upon the mass and stiffness of the structure. If the time period is more, the modal mass is more but the stiffness of the building is less vice-versa. It can been noticed that the time period is minimum for the model-C, so the stiffness of that models is more as compare to others. The time period for the model-E is very much more as shown in above chart.

4. RESULTS AND DISCUSSION

The For the diagrid structural system, the angle of diagrid is the most important and considerable point because it is directly affected to the stiffness, displacement, storey drift, storey shear, time period and material consumption of the structure. These factors are directly affected the structural cost if the proper angle is not provided. So, by considering above factors, economical and optimum angle is evaluated.

4.1 Top Storey Displacement

From analysis and design result (Chart -1), it is clearly seen that the displacement is less for the diagrid angle 66° for Model-C. But from considering the results of all models, the displacement results is less for the angle 66° (model-C) and 77.5° (model-D) as compared to others. So the angle of diagrid is optimum in the region of angle 65° to 75°.

4.2 Storey Drift

From the results of storey drift, it is clearly noticed that the model-C and model-D gives better results, which is clearly indicating that the angle region 65° to 75° is optimum.

4.3 Storey Shear

From the results of storey shear, it is clearly noticed that the model-C and model-D gives better results, which is clearly indicating that the angle region 65° to 75° is optimum.

4.4 Time Period

By considering chart -4 ,it can been observed that the time period is minimum for angle region 66° (model-C) and 77.5° (model-D) and also when the no of storey is increased, the time period is decreased. So the optimum angle is in the region of 65° to 75°.

5. CONCLUSION

The current study is carried out by considering the different angles for a 24 storied circular diagrid building. The circular plan of 30.7 diameter is considered with five different types of angles of diagrid that is 36.8°, 56.3°, 66°, 77.5° and 83.6° A comparative study is carried out using the parameters lateral displacement, storey drift, storey shear, time period.

Concluded from the study that,

- ✓ Diagrid angle in the region of 65° to 75° provides more stiffness to the diagrid structural system which reflects the less top storey displacement.
- ✓ The storey drift and storey shear results are very much lesser in the region of diagrid angle 65° to 75°.
- ✓ The time period is observed less in the region of diagrid angle 65° to 75° which reflects more stiffness of the structure and lesser mass of structure.
- ✓ The effect of lateral force to stories is less in the structure with diagrid angle 65° to 75°
- ✓ When number of storey increases means height of building increases, diagrid angle in the region 65° to 75° gives better results in terms of top storey displacement, storey drift, storey shear, time period and effect of lateral force.
- ✓ The optimum angle of diagrid is observed in the region of 65° to 75°

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BIOGRAPHIES

I am **Jayesh Venkolath.** I am pursuing my Master of Engineering study in Structural engineering branch from the University of Calicut. I am doing my dissertation work under the guidance of Mr. Rahul Krishnan K. I have completed my Bachelor of Engineering (civil engineering) study from M.G. University.