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Optimum Angle of Diagrid Structural System

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***Abstract*— The evolution of tall building structural systems based on new structural concepts with newly adopted high strength materials and construction methods have been towards "stiffness" and "lightness". Recently diagrid structural system is adopted in tall buildings due to its structural efficiency and flexibility in architectural planning. The use of diagrid structural systems for tall building design has continued to increase. The design methodology is applied to a set of diagrid structures which consist of 24, 36, 48 and 60 stories. 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 and to investigate the structural potential of diagrids with changing angles. Based on these design studies, design guidelines are provided for the optimum configuration of the diagrid structure grid geometry within a certain height range. In this paper, the comparison study of 24-storey, 36-storey, 48-storey and 60-storey of diagrid structural system with a diagrid angle 50.2°, 67.4°, 74.5° and 82.1° is presented here. The comparison of analysis of results in terms of top storey displacement, storey drift, time period, angle of diagrid and steel and concrete consumption is presented here.**

***Index Terms*—Angle of diagrid, Diagrid structural system, Displacement, Storey Drift, Time period**

I. INTRODUCTION

The rapid growth of urban population and limitation of available land, the taller structures are preferable now a day. So when the height of structure increases then the consideration of lateral load is very much important. For that the lateral load resisting system becomes more important than the structural system that resists the gravitational loads. The lateral load resisting systems that are widely used are rigid frame, 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. Hence the diagrid, for structural effectiveness and aesthetics has generated renewed interest from architectural and structural designers of tall buildings.

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So, when the diagrid structural system is provided in tall building, there is a very much important of angle of diagrid. , the questions are arises in our mind that, (1) what should be the optimum angle of diagrid? , (2) what is the economic angle of diagrid? , (3) what should be economy when the no. of storey is increased? So, to evaluate these problems, the present work is carried out.

In the present work, four different models are considered which consist of 24 storey, 36 storey, 48 storey and 60 storey with the provision of different angle of diagrid that is 50.2° (2-storey module), 67.4° (4-storey module), 74.5° (6-storey module) and 82.1° (12-storey module) for each models. So, total 16 (sixteen) models are analysed and design to overcome the problems.

II. BUILDING CONFIGURATION

A. Types of Models

Here, mathematical models are modelled which consist of different storey that is 24 storey, 36 storey, 48 storey and 60 storey with the provision of different angle of diagrid that is 50.2° (2-storey module), 67.4° (4-storey module), 74.5° (6-storey module) and 82.1° (12-storey module). The notations of models are as: (1) A-1, (2) A-2, (3) A-3, (4) A-4; (5) B-1, (6) B-2, (7) B-3, (8) B-4; (9) C-1, (10) C-2, (11) C-3, (12) C-4; (13) D-1, (14) D-2, (15) D-3, (16) D-4;
Where, A = 24-storey (height = 86.4m), 1 = 50.2°; B = 36-storey (height = 129.6m), 2 = 67.4°; C = 48-storey (height = 172.8m), 3 = 74.5°; D = 60-storey (height = 216m), 4 = 82.1°.
The plan view of all the models is as shown in Figure 1.

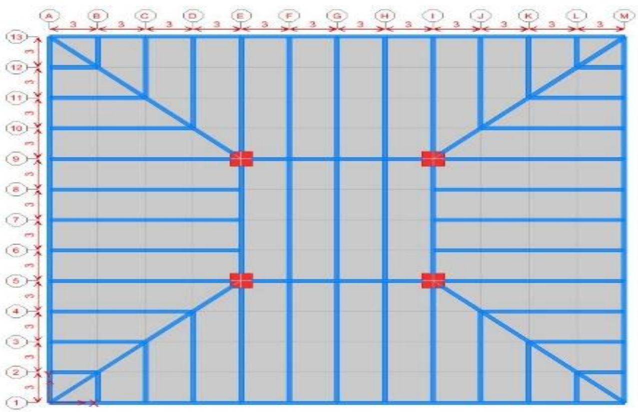


Figure 1 plan view for all models

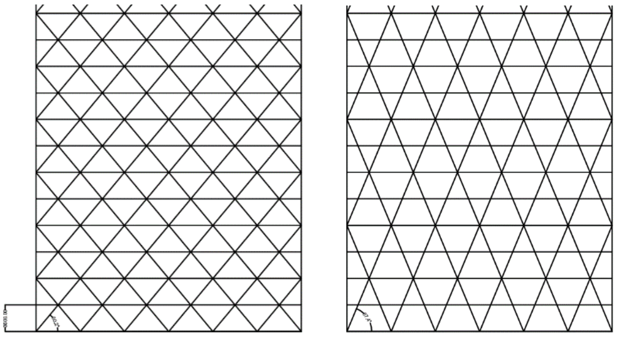
B. Geometry Data

Here, the general geometry data for all the models are as follows.

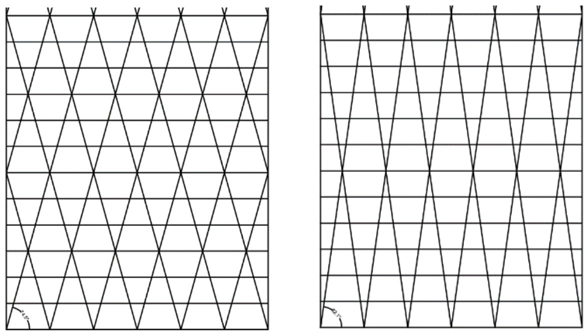
i. Plan dimension : 36m x 36m

ii. Storey height : 3.6m
iii. Slab thickness : 0.120m
iv. Characteristic strength of concrete : 40 N/mm2
v. Characteristic strength of steel : 415 N/mm2

The angle of diagrid is decided on the basis of the storey module. Here, four different storey module is considered, that is 2-storey module, 4-storey module, 6-storey module and 12-storey module as shown in Figure 2.



(a) θ = 50.2° 2-storey module (b) θ = 67.4° 4-storey module



(c) θ = 74.5° 6-storey module (d) θ = 82.1° 12-storey module

Figure 2 Different storey module

The angle is obtained from the height of the storey module to the base width of diagrid, that is,

For example: 2-storey module then,

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

Angle (θ) = tan-1 (7/6)

Angle (θ) = 50.2°

The design dead load and live load on terrace level are 5kN/m2 and 1.5kN/m2 respectively and for typical floor slab is 4kN/m2 and 2kN/m2. 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 Vadodara, Wind speed 44 m/s, Terrain category 2, Structure class B, Risk Coefficient 1, Topography factor 1. Modelling, analysis and design of diagrid structure are carried out using ETABS 9.7.4 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.

C. Structural Plan

Here, Figure 3 is showing the structural plan view of all the models in which the beam notations B1, B2, B3 and column notations C1 are shown.

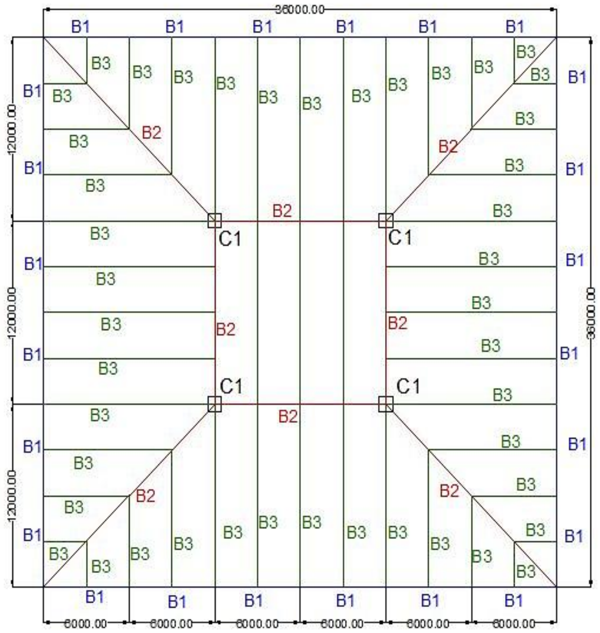


Figure 3 structural plan

The member sizes for all the models are preliminary decided same but after analysis results and designing results, the sizes are modified to prevent the failure and excessive top storey displacement. TABLE 1, TABLE 2, TABLE 3 and TABLE 4 is showing the member sizes for model-A, model-B, model-C and model-D.

TABLE 1 Member sizes for model-A

Member	No	Model-A			
		A-1	A-2	A-3	A-4
Beam	B1	300x600	300x600	300x600	300x600
	B2	300x1050	300x1050	300x1050	300x1050
	B3	300x600	300x600	300x600	300x600
Column	C1	1400x1400	1400x1400	1400x1400	1400x1400
Diagrid	D	500x500	450x450	450x450	500x500

TABLE 2 Member sizes for model-B

Member	No	Model-B			
		B-1	B-2	B-3	B-4
Beam	B1	300x600	300x600	300x600	300x600
	B2	300x1050	300x1050	300x1050	300x1050
	B3	300x600	300x600	300x600	300x600
Column	C1	1700x1700	1700x1700	1700x1700	1700x1700
Diagrid	D	650x650	590x590	600x600	640x640

TABLE 3 Member sizes for model-C

Member	No	Model-C			
		C-1	C-2	C-3	C-4
Beam	B1	300x600	300x600	300x600	300x600
	B2	300x1050	300x1050	300x1050	300x1050
	B3	300x600	300x600	300x600	300x600
Column	C1	2020x2020	2020x2020	2020x2020	2020x2020
Diagrid	D	830x830	740x740	740x740	800x800

TABLE 4 Member sizes for model-D

Member	No	Model-D			
		D-1	D-2	D-3	D-4
Beam	B1	300x600	300x600	300x600	300x600
	B2	300x1050	300x1050	300x1050	300x1050
	B3	300x600	300x600	300x600	300x600
Column	C1	2330x2330	2330x2330	2330x2330	2330x2330
Diagrid	D	1020x1020	890x890	890x890	940x940

III. ANALYSIS RESULTS

Here, the dynamic analysis results for all the models are presented here in terms of reaction, Top storey displacement, storey drift storey shear and time period.

A. *Reaction Results*

The summary of reaction of gravity load (DL + LL), lateral loads due to earthquake load and wind load for Model-A, Model-B, Model-C and Model-D is as shown in Figure 4.

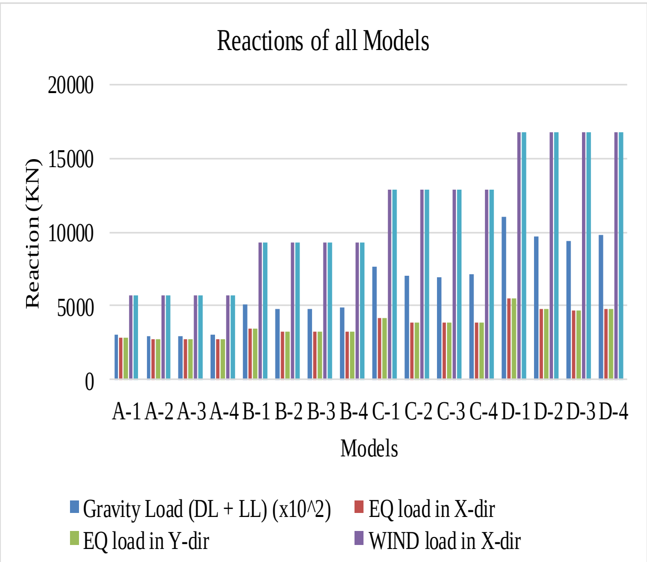


Figure 4 Summary of Reaction

B. *Displacement Results*

Here, the displacement results for Model-A, Model-B, Model-C and Model-D is as shown in Figure 5, Figure 6, Figure 7, and Figure 8. For all the models, wind load is govern the design. So the results are displaced for the wind load cases only.

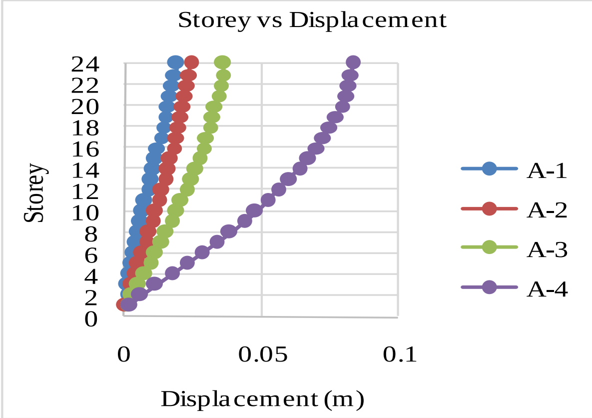


Figure 5 Displacement results for model-A

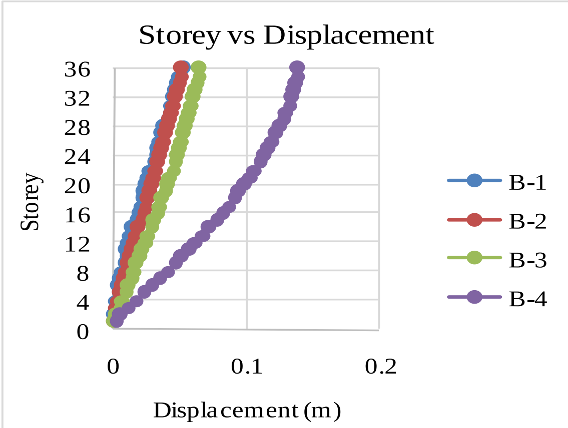


Figure 6 Displacement results for model-B

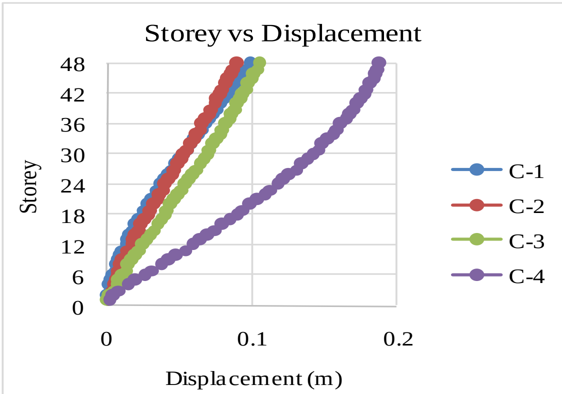


Figure 7 Displacement results for model-C

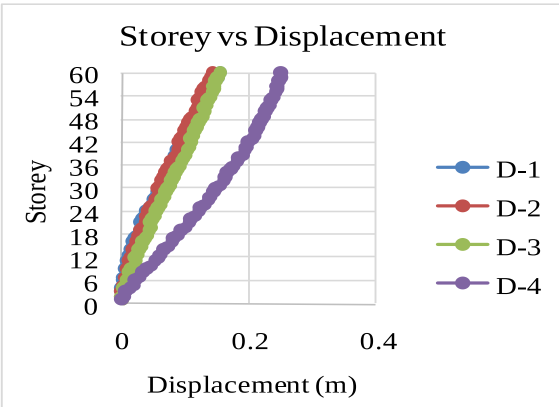


Figure 8 Displacement results for model-D

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 = 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 Model-A, displacement value is smaller for model A-2 and A-3. This effect is similar for the case of Model-B, Model-C and Model-D as shown in Figure 9.

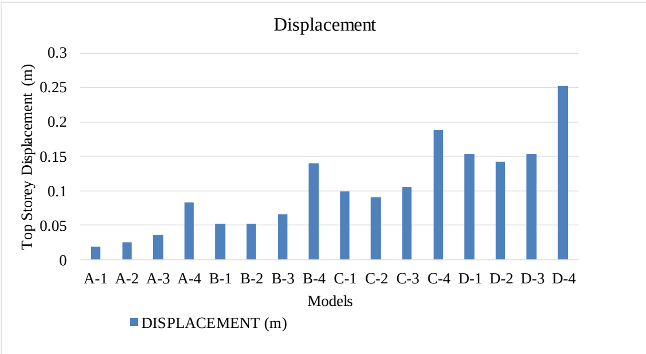


Figure 9 Top Storey displacement for all models

C. *Storey Drift Results*

Here, the storey drift results for Model-A, Model-B, Model-C and Model-D is as shown in Figure 10, Figure 11, Figure 12 and Figure 13. Results are shown for the earthquake load in both the direction here.

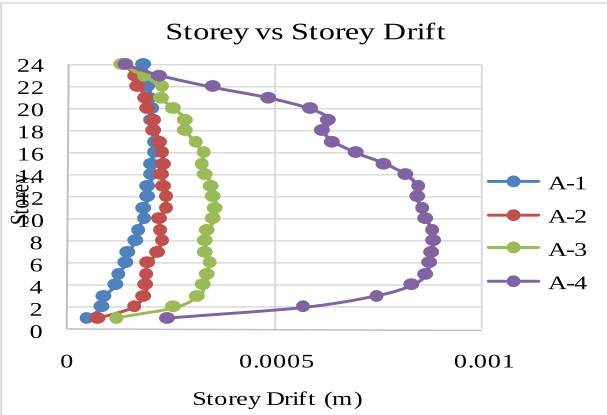


Figure 10 Storey drift results for model-A

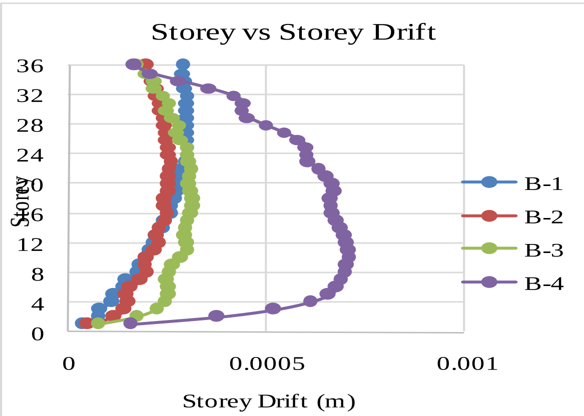


Figure 11 Storey drift results for model-B

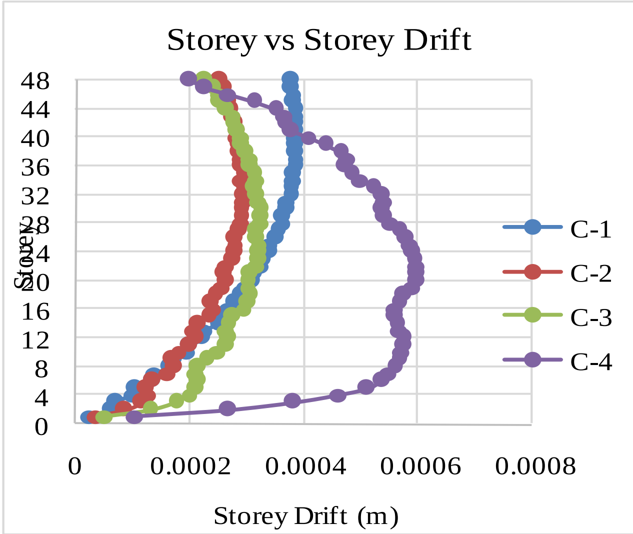


Figure 12 Storey drift results for Model-C

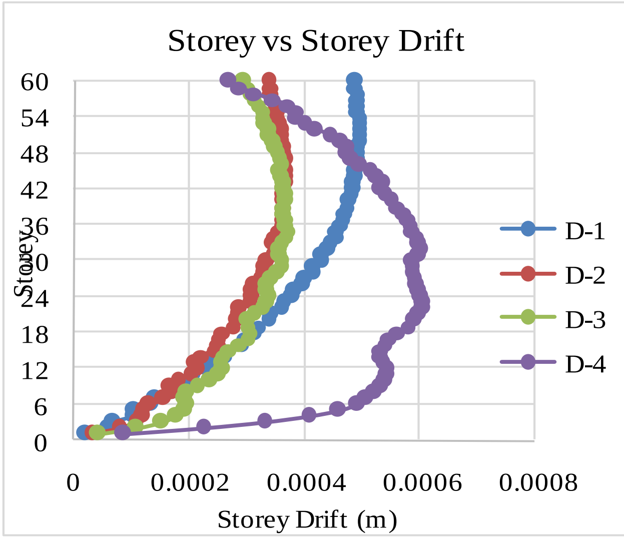


Figure 13 Storey drift results for model-D

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 A-4, B-4, C-4 and D-4. Model A-2, B-2, C-2 and D-2 is giving the better results as compared to other models as shown in Figure 10, Figure 11, Figure 12 and Figure 13.

D. *Storey Shear Results*

Here, the storey shear results are presented in Figure 14, Figure 15, Figure 16 and Figure 17 for all the models respectively for the lateral load earthquake EQX/EQY and wind load WLX/WLY.

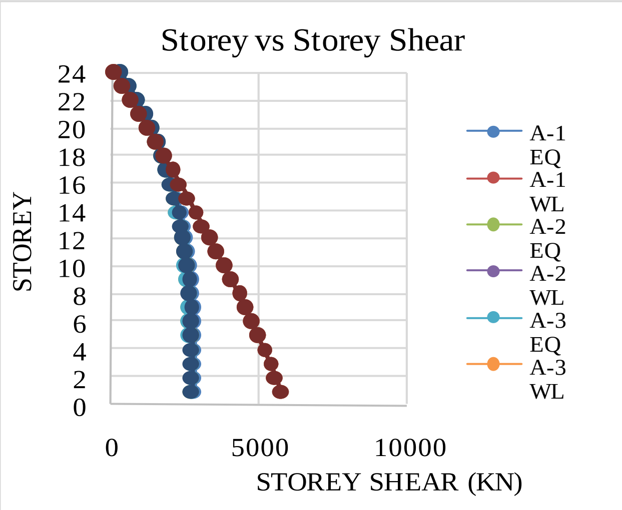


Figure 14 Storey shear results for Model-A

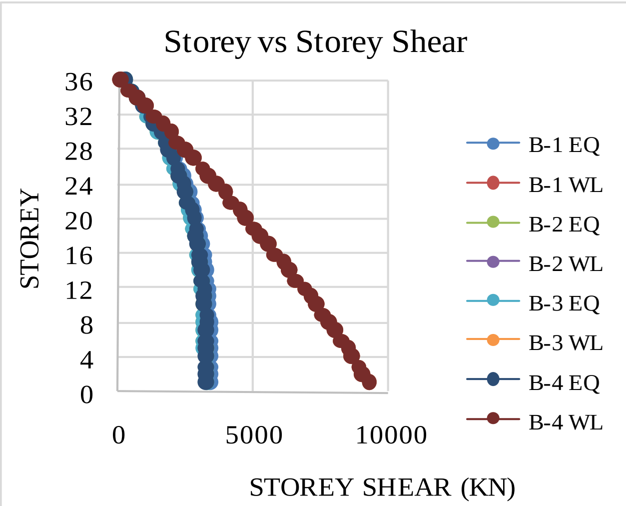


Figure 15 Storey shear results for Model-B

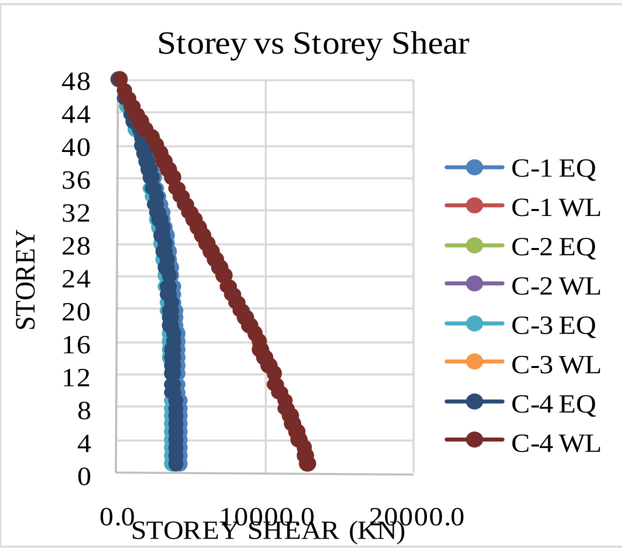


Figure 16 Storey shear results for Model-C

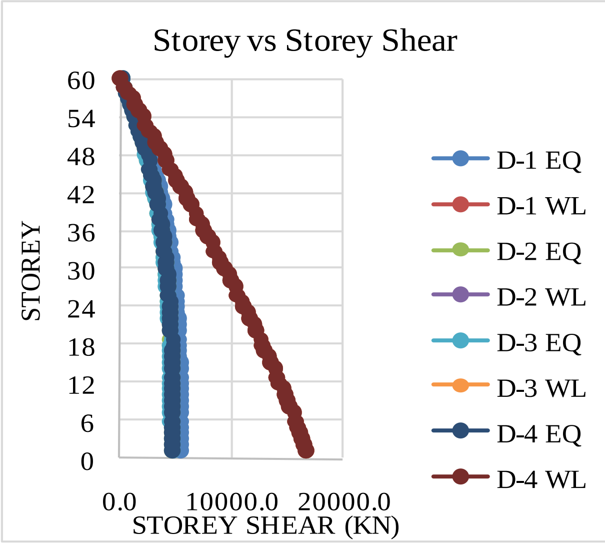


Figure 17 Storey shear results for Model-D

Form the analysis results, it can been seen that the storey shear for model A-4, B-4, C-4 and D-4 is more as compared to the others. From the Figure 14, Figure 15, Figure 16 and Figure 17, the gradual variation is noticed for the model A-2, B-2, C-2 and D-2.

E. Time Period Results

By performing the dynamic analysis, time period is found out by considering 12 mode shape for all models, is presented here. Figure 18, Figure 19, Figure 20 and Figure 21 shows the results of modal analysis for Model-A, Model-B, Model-C and Model-D respectively.

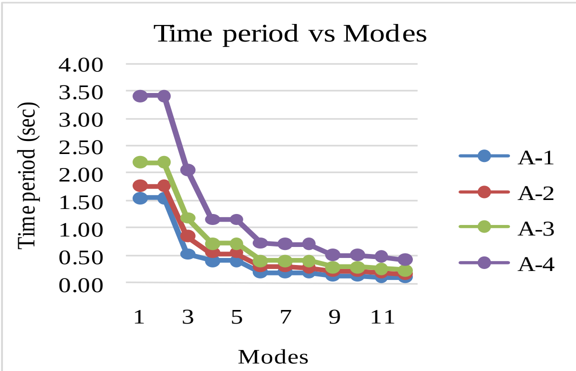


Figure 18 Time period for Model-A

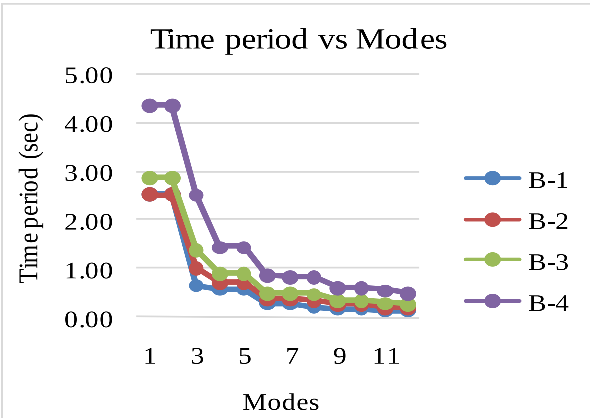


Figure 19 Time period for Model-B

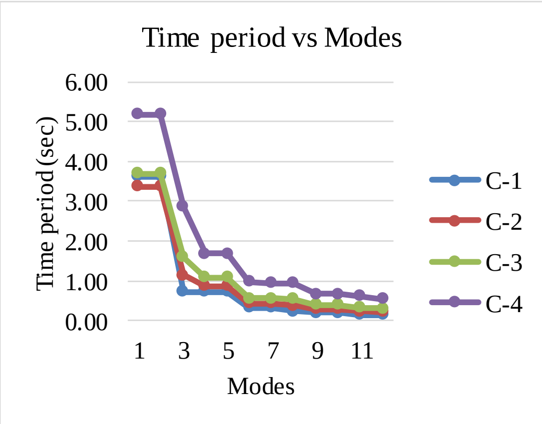


Figure 20 Time period for Model-C

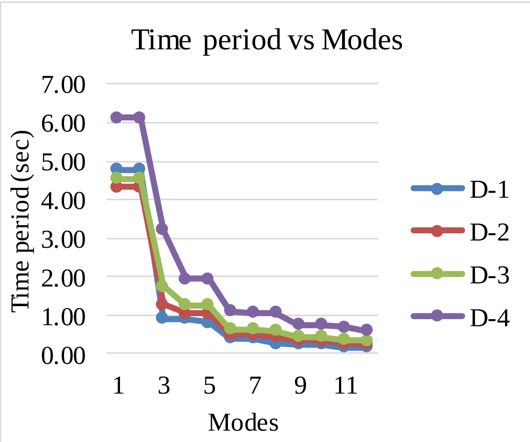


Figure 21 Time period for Model-D

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,

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 A-2, B-2, C-2 and D-2, so the stiffness of that models is more as compare to others. The time period for the models A-4, B-4, C-4 and D-4 is very much more as shown in Figure 18, Figure 19, Figure 20 and Figure 21.

IV. DESIGN RESULTS

The design of all the model is carried out using ETABS v9.7.4 software. All the load combinations of gravity load, earthquake load and wind load are assigned to both the models. From the analysis results, design of beam, column and diagonal members are carried out as per IS: 456-2000. The characteristic strength of concrete is 40 N/mm2 and characteristic strength of steel is 415 N/mm2 is considered. The final optimum sizes of members for all the models are as shown in TABLE 1, TABLE 2, TABLE 3 and TABLE 4 respectively.

A. Material Consumption and Structural Cost

Here, the consumption of material that is concrete and steel is calculated for all the models is presented here. The consumption of material for the beam, column and diagonal members (diagrid) are as shown Figure 21.

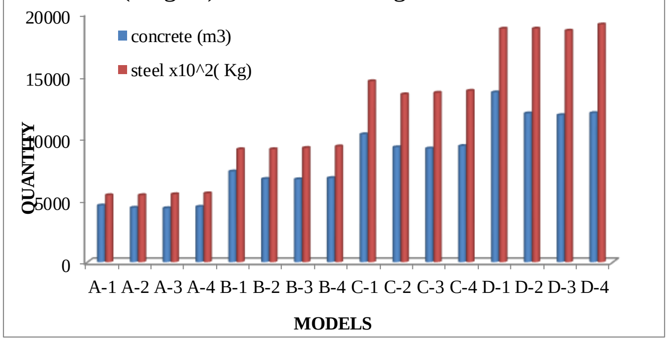


Figure 22 Material quantity for all models

For evaluating the cost of the material consumption, the approximate cost of concrete is taken as 4500 Rs/m3 and cost of steel is taken as 55 Rs/m3. Figure 22 shows the graph of total quantity's cost.

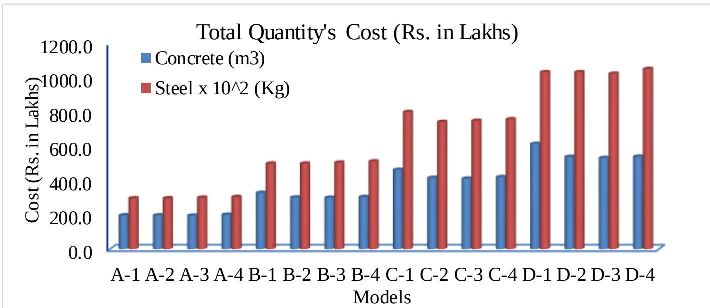


Figure 23 Total quantity's cost

It can been noticed that the material consumption is minimum for the models A-2, A-3, B-2, B-3, C-2, C-3, D-2 and D-3 which is directly affected the structural cost of the building. It can also noticed that there is not so much difference in the steel material for the beam because the sizes of the beam for all the models is similar.

V. DISCUSSION OF RESULTS

For the diagrid structural system, angle of diagrid is the most 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.

A. Top Storey Displacement

As we have consider four angle of diagrid and also for the four types of no. of storey, we can get the results as shown in Figure 24.

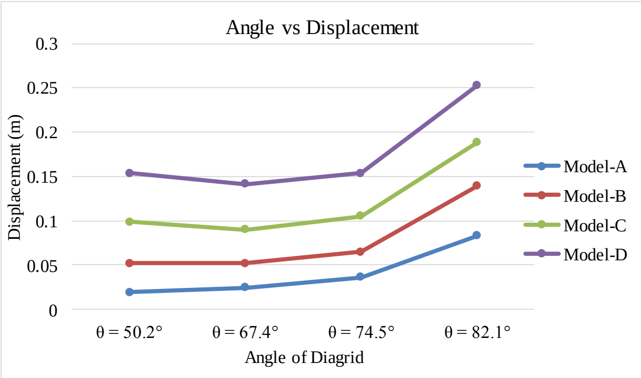


Figure 24 Graph of angle of diagrid vs. displacement

From above graph, it is clearly seen that the displacement is less for the diagrid angle 50.2° for model-A 24 storey building. But from the results of model-B, model-C and Model-D, the displacement results is less for the angle 67.4° and 74.5° as compared to others. So the angle of diagrid is optimum in the region of angle 65° to 75° and also for the more no of storey.

B. *Storey Drift*

From the results of storey drift, it is clearly noticed that the model A-2, B-2, C-2 and D-2 gives better results, which is clearly indicating that the angle region 65° to 75° is optimum.

C. *Storey Shear*

From the results of storey shear, it is clearly noticed that the model A-2, B-2, C-2 and D-2 gives better results, which is clearly indicating that the angle region 65° to 75° is optimum.

D. *Time Period*

By considering the only first mode time period, as shown in Figure 25,

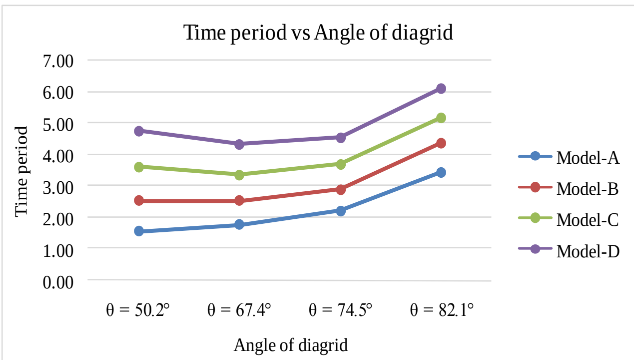


Figure 25 Graph of time period vs. angle of diagrid

It can been observed that the first mode time period is minimum for angle region 65° to 75° 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°.

E. *Material Consumption*

From the results, it is observed that there is not so much difference in the steel quantity but more difference is observed when the angle of diagrid changed and increased the no of storey of the structure in concrete quantity as shown in Figure 26.

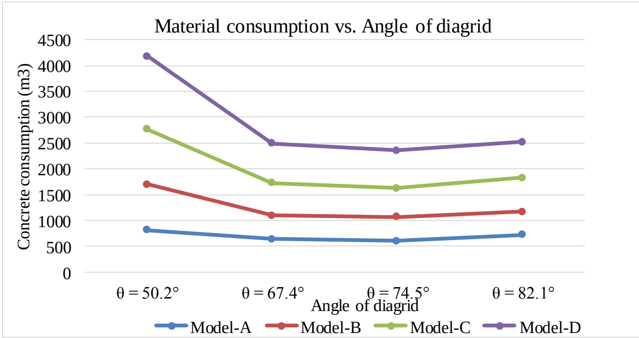


Figure 26 Material consumption vs. angle of diagrid

From above graph, it can been seen that the consumption is in the region 65° to 75° angle of diagrid but when the no of storey increased, there is minimum consumption in concrete is observed. This observation is also directly affected to the structural cost of the building. So the optimum angle is in the region of 65° to 75°.

VI. CONCLUSION

The current study is carried out by considering the different angles of diagrid and also different storeys of the building. The plan of 36m x 36m is considered with four different types of angles of diagrid that is 50.2°, 67.4°, 74.5° and 82.1° and also by considering 24-storey, 36-storey, 48-storey and 60-storey building, a comparative study is carried out.

We conclude 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°.

- As time period is less, lesser is mass of structure and more is the stiffness, 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.

- It should be noticed that the results for the angle of diagrid 82.1° is quite random for the storey drift, storey shear and time period.

- Diagrid angle in the region 65° to 75° provides more economy in terms of consumption of steel and concrete as compared to different angles of diagrid.

- 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 material consumptions.

- Diagrid structural system provides more economy and more benefits when no of storey is more than 40 with the diagrid angle in the region of 65° to 75°.
- Optimum angle of diagrid is observed in the region of 65° to 75°.
- Diagrid structural system provides more flexibility in planning interior space and façade of the building.

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