Comparative Analysis of Diagrid Structure and Orthogonal Structure with Different Design Parameters

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***Abstract* - Diagrid structural system is a modern way of the construction of the earthquake resistant tall buildings. In a tall structure, the design of the building is governed by lateral loads, instead of gravitational load in the shorter building. Present study includes Analysis and Design of a Diagrid and Orthogonal structural system in using ETABS 2018 and SAP2000. Various parameters like storey shear, maximum displacement, drift, and storey stiffness are analyzed. In this study, the software is used for technical aspect as design of building as well as foundation. For costing, an individual spread sheet has been developed so that with different variables estimated building cost can be calculated. The authors tried to justify their designs for above buildings in regard to estimated cost considering economy a big factor.**

***Index Terms* - Diagrid Structure, Orthogonal Structure, Storey Shear, Maximum Displacement, Drift, Storey Stiffness.**

I.INTRODUCTION

The trends of tall buildings are increasing rapidly, as the population is rising, leading to the conversion of agricultural land to non-agricultural one. Generally, tall structures had been utilised for commercial motives, although they could be altered to residential and multi-purpose systems. As the height of the building increases, the lateral load resisting system becomes more significant than gravitational loads. So, the revolution in design trends of tall buildings presents new obstacles for structural designers, in addition to the standard requirements of strength, stiffness, ductility, and cost-effectiveness. Now to go along with the modern trends in tall buildings, the innovative structural system is being used, known as the diagrid structural system. This system is becoming progressively popular in the design of tall buildings due to its inherent structure, architectural advantages, and aesthetic view. The Diagrid systems are the evolution of braced tube structures since the perimeter configuration still holds for preserving the maximum bending resistance and rigidity, concerning the braced tube, the mega-diagonal members are diffusely spread over the facade, giving rise to closely spaced diagonal elements and allowing for the complete elimination of the conventional vertical columns. Therefore, the diagonal members in diagrid structures act both as inclined columns and as bracing elements, and due to their triangular configuration, they carry both gravity and lateral loads. This system around the perimeter saves approximately 20% of structural steel weight as compared to that of the orthogonal frame structure.

A. Diagrid System

A supporting member of the building is a framework, formed with diagonally intersecting ribs of metal or concrete with the help of nodes. It required less steel compared to any other ordinary steel structure. The use of diagrid banishes the requirement of columns, which reduces the weight of supports from the building. The diagrid system is efficient and advised in achieving stiffness against lateral loads and as a better option in designing a tall building.

B. Design Methodology

For the parametric comparison, symmetrical tall buildings are sorted out: three RCC (Reinforced Cement Concrete), with varying storey heights, which are modeled, analysed, and designed by utilising ETABS software for two different structural systems; diagrid and orthogonal. Considering different types of loads as stated in codal provision of IS (Indian Standards), such as dead load, live load, wind load, and earthquake load, acting on the models are analyzed and designed. For wind load, according to the IS 875 (Part-3)-2015 factors affecting the behavior of the tall buildings, such as wind speed, terrain category, topographical factor, risk coefficient, and location, are taken into account; whereas, for earthquake load, considering IS 1893-2016 moderate conditions of lateral loads, and seismic zones are determined, and response spectrum analysis is taken into account considering those conditions.

Maximum storey displacement, base shear, stiffness, and maximum storey drift are the fundamental parameters chosen for the comparison of tall buildings. After preparing the complete model, all the gravity loads and lateral loads are applied to the tall building. Furthermore, different combinations of dead load and live load are appealed before running an analysis of the structure. Nodes are used for connection when there is the intersection of 4 diagrid members and a ring beam. They are formed typically by bolting or welding the ends of the members to the gusset plate. They assist with the structure in terms of stability as well as flexibility. The ring beam plays a pivotal role in maintaining the stability of the structural system, and they are propped at the periphery of the building, connected to the nodes and diagrid columns. It binds Nodes and diagrid columns together and acts as one member providing better stiffness and stability to the structure.

C. Structural Benefits

A diagrid structure is a type of system consisting of diagonal networks connected through horizontal rings, which create potent and essential buildings that are principally efficient for high-rise buildings. Diagonalized application of structural steel members provides efficient solutions both in terms of strength and stiffness. In the diagrid system, structures are free from peripheral columns, which give some advantages such as high architectural flexibility and a substantial amount of daylight due to its immense free surface. Along with the resistance toward lateral and gravity load, it provides an adequate amount of aesthetic appearance.

Some other benefits of diagrid system are as given below:

- Safer and taller structure.
- Increased stability due to triangulation.
- It provides more efficiency.
- Enhance the stiffness and strength.
- Material saving property.
- It provides maximum natural light.

II.LITERATURE REVIEW

In light of the review by T. R. Somvanshi, P. K. Kolase, V. R. Rathi [12], 8, 16, and 24 storey building module of both simple framed structure and diagrid structure has prepared using ETAB software, by comparing the different parameters that affect the tall building, a detailed study of the simple framed structure and diagrid structure has executed. Detailed analysis and design of the building have been done [12].

Different diagrid modules have been placed here in different storey interval that is 2,4,6,8 and 12 storey to find out the optimum angle, which offers the maximum stiffness to the building. They notice that the diagrid angle between 65° to 75° gives maximum stiffness. Paper by Harshita Tripathi, Dr. Sarita Singla [3] prepared a graph showing outcomes of the different parameters that act on the building [3].

Contemplating both lateral and gravity loads act on the property an elaborative report had prepared, including all the parameters that work on the building. Khushbu Jani, Paresh V. Patel [1], showed a model of 36 stories, and a time history analysis report has composed, also the aspect regarding how much lateral load act on different levels of the building has been noted [1].

Structural modeling of Conventional Rigid Framed Building- Rectangular Plan, Diagrid Structural System Building- Rectangular Plan, and Diagrid Structural System Building- Circular Plan has done using ETAB software. Pattan Venkatesh, Sujay Deshpande, Shweta Patil [8] have carried out a comparison of storey stiffness, storey displacement, and storey drift with a detailed report has been prepared [8].

Here the Optimization for Diagrid High-Rise Buildings has been done by Kyoung Sun Moon, Simos Gerasimidis, Panagiotis Pantidis, Brendan Knickle [4], design studies for different storey building, and their application considered. Also, the effect of intermediate loading steps mentioned here, and apart from this, the member grouping based on the thickness and internal core is included here [4].

The materials used in the construction of diagrid structures like sand, cement, aggregate, steel, and many more are mentioned here by Terri Meyer Boake [5] with the plan size and dimension of the building. Details about 60 storey tall diagrid buildings and their diagrid stiffness due to the triangular shape represented here. The overall cost of both simple structure and diagrid structure are also included [5].

Pwint Wai Wai Aung, Nyan Phone, Kyaw Lin Htat [9] in his paper focus on the settlement of piled raft foundation of a high-rise building resting on sandy soil in the Yangon area. The critical column load of the superstructure is obtained by utilizing ETABs software and loading consideration for the superstructure based on UBC -97 [9].

A comparative study was performed by Kwa Sally Fahmi, Mohammed Y. Fattah, and Andrey Pustovgar [6] in results of 3- dimensional finite element (3D FEM) analysis in SCAD software. The results showed that the plate foundation of the building does not satisfy to carry the total load without some meaning of improvement. The 3D FEM by PLAXIS 3D depicted that the used stone columns decreased the settlement because about 70-80% of the total building loads were carried by columns when the raft was placed in the stiff clay layer [6].

The relationship of the superstructure of a building and a foundation has been reviewed by Yang T. S, Yoo N.J, Hong S.H, and Kim T.H [13] while admitting the tendency of design from a capacity-driven design to a performance design. A database for deciding the measured-to-predicted geotechnical parameters of foundation types in several soil deposit conditions is examined, such as laboratory to in-situ tests [13].

A three-stage process of foundation design and verification described by Harry G. Poulos [2], and the importance of proper ground characterization and assessment of geotechnical parameters had emphasized. The application of the foundation design principles meets the challenges, which have been illustrated via three high-rise projects [2].

It set out an ultimate limit state approach for the computer-based design of pile foundation for high rise building and provide an example of 151 storey building of South Korea. The overall stability analysis given by Harry G. Poulos [14], a serviceability analysis, and structural design of pile and raft foundation has been done here [14].

A G+20 Storey building is analysed and designed in ETABS software by Reshma T.V, Bhavya B.S, Rashmi Mishra, Sankalpasri S.S [10]. The modeling and analysis of piles with raft foundations are completed in SAFE software by importing the building loads. The storey drift and story displacement of the structure had scrutinized for the superstructure loads using response spectrum analysis and time history analysis in both X and Y axes. Then the behavior of piles with Raft foundation is studied in this work by considering different parameters [10].

In a comparison of the behavior of building, when applied with the seismic load as per the code, IS 1893 (Part 1) 2002 and IS 1893 (part 1)2016 and seismic analysis of high rise building that is G+12 storey in ETABS. The loads are applied separately based on code IS 1893 (part 1) 2002 and IS 1893 (part 1) 2016, and analysis of superstructure carried out in ETABS software then results are compared as per the paper given by Vikas Siddesh, Praveen J V, Dr. T V Mallesh, S.R Ramesh [11]. With the help of superstructure axial load, the sub-structure of the building is analyzed in SAFE software by considering the load from the superstructure [11].

The article taken from Svetlana Kolobova's [7] research paper outlines methods of assessing the consumer quality of high-rise residential buildings and the formation of prices based on consumer characteristics of a tall residential building. It put forwarded to evaluate the premises under their quality characteristics, and the study conducted to establish the influence of individual, comprehensive, and integral indicators of comparable and effective quality living spaces [7].

III.OBJECTIVES

Objectives pertaining this research work are described as follows:

- This study is focused on the correlation between diagrid structure and RC framed structure based on the result obtained from ETAB software.
- Analysis and design of the diagrid structure for high rise building with varying geometry.
- Comparison of the structures based on the stiffness, relative displacement and resistance toward lateral loads.
- To propose an optimum angle of the diagonal braces for better stability.
- To study the response of buildings in terms of storey shear, storey drifts, storey stiffness and storey overturning moment.

IV.BUILDING CONFIGURATION

A detailed model discussion along with their geometry data and structural layout is given below:

A. Types of Models

In this study, nine mathematical models were prepared using ETABs v.18 software. So, Table-1 describes the nomenclature of different models used in the study.

Table 1

Storey Module	Angle of Diagrid		No. of Storeys		
		Module Name	12	24	36
Orthogonal	__	M3	A3	B3	C3
4 Storey	66°48"	M1	A1	B1	C1
6 Storey	74°03"	M2	A2	B2	C2

B. Geometry Data

Plan dimension : 36 × 36 m
Storey height : 3.5 m
Slab thickness : 130 mm
Location : Ahmedabad
Earthquake load : Zone: III
: Zone factor: 0.16
: Soil type: II
: Importance factor: 1
: Response reduction: 5
Wind load : Wind speed: 39 m/s
: Terrain category: 3
: Risk coefficient: 1
: Topography factor: 1
Shear wall thickness (For elevator) : 230 mm
Characteristic Strength of concrete : M40
Characteristic Strength of steel : Fe500

As the building is assumed as a commercial one, loads considered such as dead load 2 kN/m², while live load between 2-4 kN/m², and floor load as 1 kN/m², as per IS 875. These loads are applied on all the slabs of each floor, and also wind load is applied on the peripheral surface of the tall building. Columns and diagrids are deemed as hinged at the free end, but the support conditions are assumed as fixed, and IS 456-2000 is used for design consideration.

C. Structural Layout

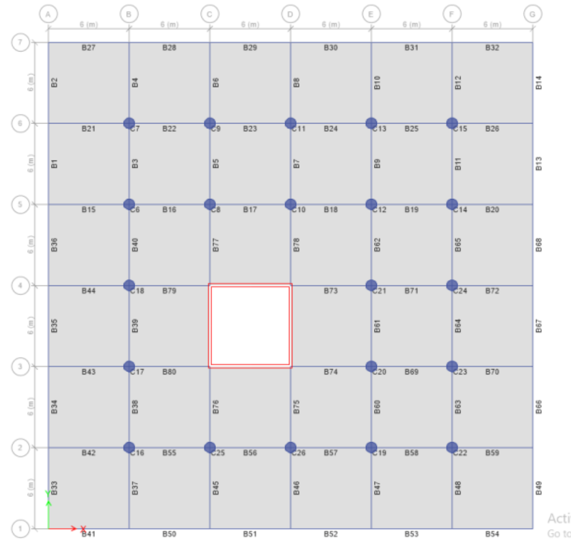

Fig. 1: Structural Plan

Fig. 1 depicts the typical plan of the diagrid structure without columns at its periphery; whereas, figs. 2&3 illustrate the elevation of 4 and 6 storey diagrid modules respectively of 24 storey structures. Size specifications of different structural members for 12, 24, and 36 storey buildings are given in Tables 2, 3, and 4 respectively.

Table 2

Member	12 Storey Building		
		4 Storey Module	6 Storey Module
Beam	B	400mmx200mm (Rectangular)	400mmx200mm (Rectangular)
Column	C1	600mm (Circular)	600mm (Circular)
	C2	230mmx230mm (Rectangular)	230mmx230mm (Rectangular)
Diagrid	D	d=400mm & t=25mm	d=450mm & t=25mm
Shear Wall	SW	t=230mm	t=230mm

Table 3

Member	24 Storey Building		
		4 Storey Module	6 Storey Module
Beam	B	700mmx300mm (Rectangular)	700mmx300mm (Rectangular)
Column	C1	900mm (Circular)	900mm (Circular)
	C2	230mmx230mm (Rectangular)	230mmx230mm (Rectangular)

Diagrid	D	d=450mm & t=25mm	d=600mm & t=25mm
Shear Wall	SW	t=230mm	t=230mm

Table 4

Member	36 Storey Building		
		4 Storey Module	6 Storey Module
Beam	B	900mmx650mm (Rectangular)	900mmx650mm (Rectangular)
Column	C1	1500mm (Circular)	1500mm (Circular)
	C2	230mmx230mm (Rectangular)	230mmx230mm (Rectangular)
Diagrid	D	d=500mm & t=25mm	d=650mm & t=25mm
Shear Wall	SW	t=230mm	t=230mm

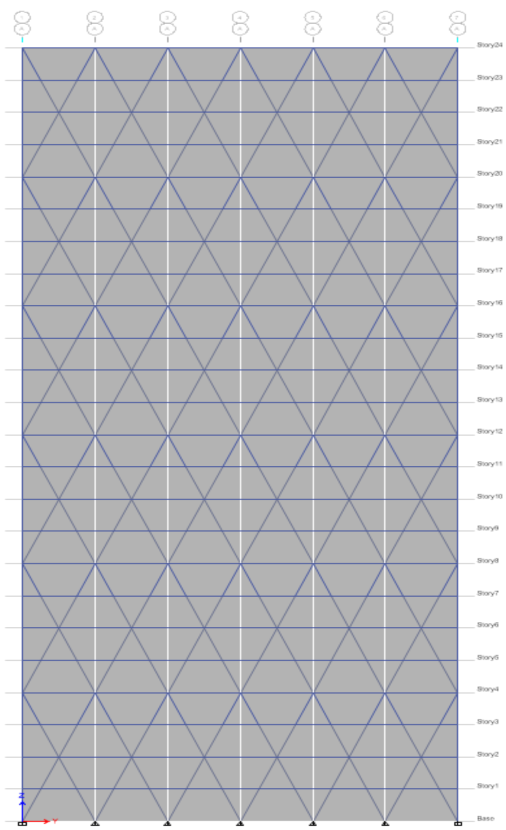

Fig. 2: 4 Storey Module

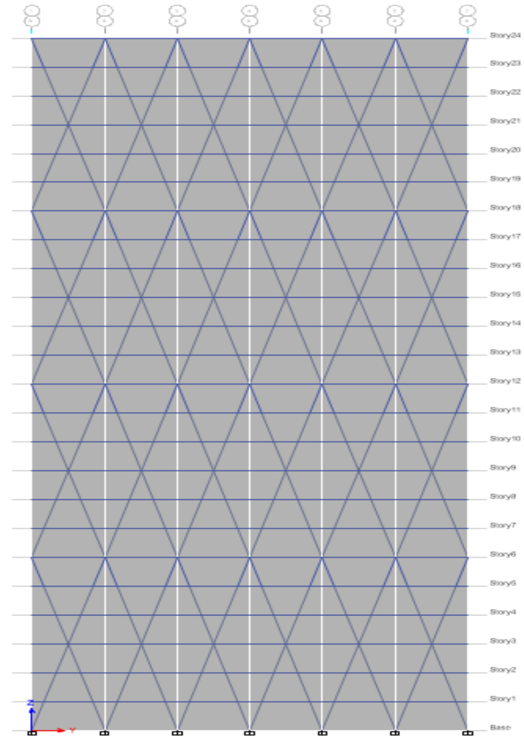

Fig. 2: 6 Storey Module

V.RESULTS AND DISCUSSION

After analysis, comparison of different parameters between Orthogonal RC and Diagrid Structures are discussed below:

A. Base Shear

Fig. 4 represents the comparison of maximum storey shear for both the building systems using both equivalent static analysis and response spectrum analysis.

Table 5

Orthogonal RC Structure		Diagrid Structure		
No. of Storey	Base Shear (kN)	No. of Storey	Base Shear (kN)	
			4 Storey Module	6 Storey Module
12	1067.4	12	202.71	334.99
24	3207.04	24	1281.81	1084.05
36	5292.25	36	2983.92	3383.47

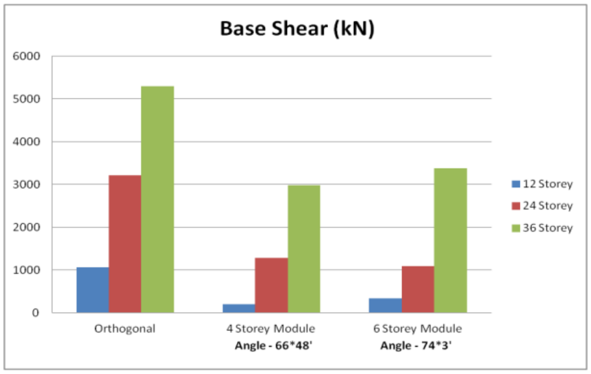

Fig. 3

B. Displacement

Fig. 5 and 6 represent a comparison of the maximum storey displacements for both the systems i.e. Orthogonal & Diagrid Structure. The lateral displacement is observed to be similar in both directions, as the building selected is symmetrical.

Table 6

Orthogonal RC Structure		Diagrid Structure		
No. of Storey	Base Shear (kN)	No. of Storey	Base Shear (kN)	
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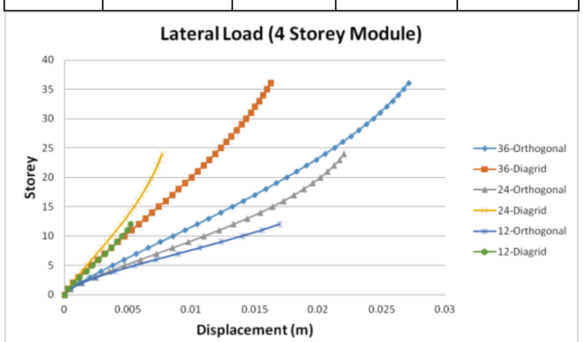

Fig. 4

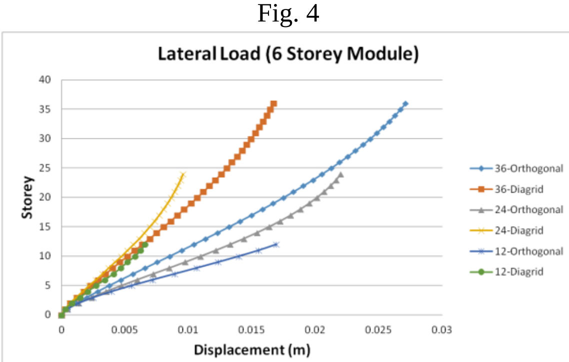

Fig. 5

C. Storey Stiffness

It is observed that storey stiffness for diagrid structure due to lateral load is higher compared to the orthogonal one. Due to an increase in stiffness, the diagrid structures show less displacement as shown in Fig. 7 and 8.

Table 7

Orthogonal RC Structure		Diagrid Structure		
No. of Storey	Stiffness (kN/m)	No. of Storey	Stiffness (kN/m)	
			4 Storey Module	6 Storey Module
12	205529	12	29101	51737
24	438964.3	24	200652.5	402291.3
36	223128.8	36	206329.9	150727.1

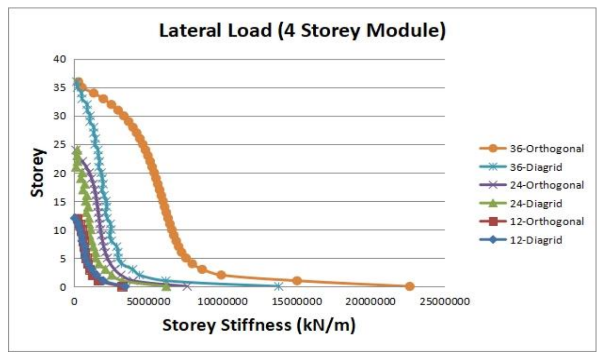

Fig. 6

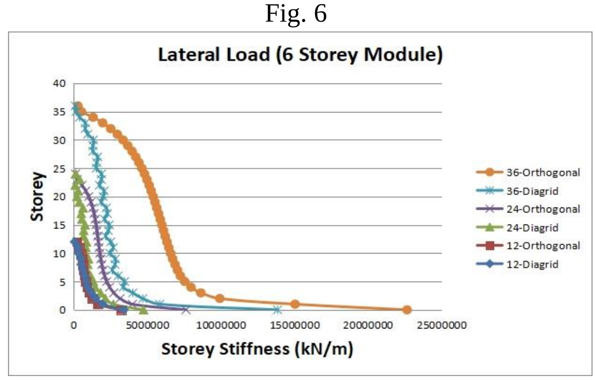

Fig. 8

D. Storey Drift

Storey drift curves are perceived in both cases. Storey drift patterns of the orthogonal structure are observed more uniformly, while highly conservative results are detected in the diagrid structure.

Table 8

Diagrid Structure		
No. of Storey	Storey Drift	
	4 Storey Module	6 Storey Module
12	0.000109	0.000151
24	0.000059	0.000074
36	0.00009	0.000086

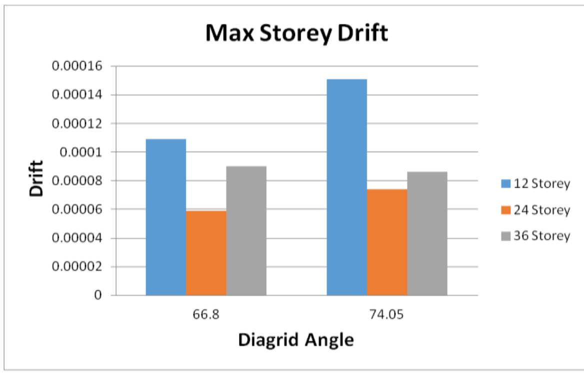

Fig. 9

VI.CONCLUSION

Following are the compared result between orthogonal and diagrid structure considering lateral loads:

- The value of the base shear for the diagrid structures is 4 times lesser than the orthogonal structures.
- The displacement of orthogonal structure is 3.2 times more in 12 storey, 2.8 times more in 24 storey, and 1.6 times more in 36 storey building as compared to diagrid structure.
- For Drift, it is clear that 6 storey module drifts 25-40% more than the 4 storey module in all the structures, but for 36 storey diagrid structure, 6 storey module drifts 5% less than the other one.
- 12, 24, and 36 storey orthogonal buildings are 7, 2.1, and 1.1 times stiffer than the respective diagrid buildings.

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