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COMPARISON OF STEEL FRAMED AND STEEL DIAGRID STRUCTURAL SYSTEMS FOR TALL BUILDINGS

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Abstract*— Tall buildings are increasing all over the world because of ingenuity of structural engineers, advances in construction equipments and methods, materials and structural systems. Structural design of tall buildings is governed by lateral load mainly the wind load, so structural system selected should be capable of resisting lateral load. The lateral load resisting structural system should provide stiffness, ductility and resistance to the structure. Lateral load resistance of structure is provided by interior and exterior structural systems like shear wall core system, braced tube system, outrigger system and tubular system. Nowadays people want to build unique structure and conventional method of designing have failed to give the desired result. Diagrid structural system is new trending concept in field of Structural Engineering taking into account, the factors of structural stability, aesthetic appearance and economic consideration. Compared to closely space vertical columns in framed structure, diagrid structural systems have special inclined columns on the periphery of the building. Diagrid structural system for tall buildings produces axial force along the periphery diagrid column direction under horizontal load and vertical load, which has the advantage of resisting horizontal wind load and seismic load. This paper presents a comparison of steel diagrid structural system with conventional steel moment frame structural system using ETABS software.

Keywords— Diagrid Structural System, Conventional system, Tall buildings, Steel Structure, CFT Column

I. INTRODUCTION

Over population, high land cost in urban regions, apartment lifestyle, the need to preserve agricultural lands have all contributed to drive buildings upward. The architectural design trend has produced various complex shaped tall buildings such as twisted, tilted, tapered and freeform towers [8]. As the height of building increases, the lateral load resisting structural system becomes more important than the gravity load resisting structural system. The lateral load resisting systems that are widely used are rigid frame, shear wall, wall-frame, braced tube system, outrigger system and tubular system [4]. Recently, the diagrid (diagonal grids) structural system is widely used for tall steel buildings due to its structural efficiency and aesthetic potential provided by the unique geometric configuration of the system. Diagrid is a particular form of space truss. It consists of perimeter grid made up of a series of triangulated truss system. Efficiencies in strength and stability of truss systems have understood in 19th century with its implementation in bridge construction, early on in wood and eventually in cast and wrought irons. Diagrid and braced structures are both variants of truss structures where the primary modes of load transfer is by axial stress in which materials show their maximum efficiency and economy in resisting forces [1]. Diagrid structure is a system of triangulated beams, straight or curved and horizontal ring that together make up a structural system for tall building. Diagrid is used in the large span and high rise buildings, particularly when they have complex geometries and curved shapes. Diagrid is made up of intersecting diagonal and horizontal components. The configuration and efficiency of a diagrid system reduce the number of structural element required on the facade of the buildings, therefore less obstruction to the outside view which allows natural day lighting and saves the energy consumption [8]. The conventional moment frame structural system has more number of columns but the diagrid system has very less number of interior columns, therefore allowing significant flexibility with free and clear floor plan. In general, a diagrid structure has stronger stiffness, better seismic performance and higher building height compared with conventional moment frame structure.

A. Emergence of Diagrid Structural System

The Shukhov tower in Polibino, Russia is the world's first diagrid hyperboloid structure designed in 1896 by Russian engineer and architect Vladimir Shukhov [1]. Its steel shell experiences minimum wind load. Then it took many years to be implemented in buildings. In 1960, Torroja proposed a sketch for diagrid structure. Then, the 13-storey IBM Pittsburgh building was built in the 1960s, which brought the ideal prototype into an engineering practice. In 1968, the 100-story John Hancock Center became the second tallest building in the world but it is a braced tubular structure, it showed the great potential of the truss structure. But the research on diagrid was not continued further because of high cost of handling the joints in diagrid and less popularity of tall buildings. In 21st century due to need of tall buildings, the research on diagrid structure again started and its structural advantages were explored. The Swiss Re building in London marks the first reappearance of the diagrid structure [2]. After 2007 many scholars focused on new type of structure especially diagrid system and many research of diagrid system have enriched. The other popular diagrid structures emerged were West Tower in Guangzhou and China Central Television Headquarters.

B. Concrete Filled Steel Tubular (CFT) Column

There are many advantages of concrete filled steel tubular (CFT) column. The concrete confined by a steel tube is under three dimensional compression, so there is an improvement in compressive strength of concrete, thereby the local instability of the steel tube can be prevented by the concrete inside the tube. Therefore bearing capacity of the concrete filled steel tubular column is larger than the sum of the separate bearing capacity of concrete and steel tube. The failure of concrete is changed from brittle to plastic because of the interaction between the steel tube and the concrete. Therefore ductility of the CFT column is improved and the structure has better seismic performance [2]. There is no form work required during the construction period and the steel tube can bear load.

II. ANALYSIS OF FRAMED AND DIAGRID STRUCTURAL SYSTEM

A. Building Configuration

This unit presents the details about dimensions of building, material used and type of analysis for the present study and are as mentioned in TABLE I. 36 storey steel diagrid and steel framed structures having height 129.6 m and lateral dimensions as 36m x 36m is considered for the analysis. The floor plan for diagrid structure is shown in Fig.1 and for framed structure is shown in Fig.2. The inclined columns for diagrid structure are provided at 6m spacing at 74.5 degree inclination. The angle of inclination kept constant throughout the height. The dead load, live load, wind load, seismic load and the default load combinations were considered for the analysis and the structure is modelled and analyzed in ETABS software. The seismic zone taken is zone II as per IS1893 (Part1)-2016 and basic wind speed taken is 33m/s as per IS875 (Part3)-2015. Linear Static analysis and linear dynamic analysis (Response spectrum) are conducted to get the results like displacement, base shear, storey drift and time period.

TABLE I
DETAILS OF DIAGRID AND FRAMED STRUCTURE

S.No.	Building Details		S.No.	Building Details	
1	Plan Dimensions	36m x 36m (1296m^2)	8	Basic Wind Speed	33 m/sec
2	Height of building	129.6 m	9	Slab thickness and concrete used	120 mm & M25
3	No. of stories	36	10	Column details	CFT column – 2mx2m Fe345 grade steel 50mm thickness, M60 grade concrete
4	Storey height	3.6 m	11	Support conditions	Fixed
5	Dead load	2.5 kN/m^2	12	Diagrid Columns	450mm Pipe Section 28mm thick- 1st to 6th storey 24mm thick- 6th to 18th storey 22mm thick-18th to 36th storey
6	Live load	5 kN/m^2	13	Beams	Hot rolled section (Fe250) with different depths as per Indian standards were used
7	Seismic zone	II	14	Type of analysis	Linear Static analysis and Linear Dynamic analysis (Response spectrum)

B. Comparison of Steel Framed and Diagrid structure for Seismic load, Wind load and Response Spectrum function

In this section, the analysis results such as displacement, storey drift and base shear due to wind load, static seismic load and Response spectrum (RS) function are compared. Since it is a square building, the displacement, storey drift and base shear in X-direction and Y-direction are same. Comparison of base shear due to wind load, static seismic load and Response spectrum (RS) are shown in Table II, also graphically represented in Fig.3 and Fig.4. Comparison of displacement due to wind load, static seismic load and Response spectrum (RS) are shown in Table III, also graphically represented in Fig.5 and Fig.6. Comparison of storey drift due to wind load, static seismic load and Response spectrum (RS) are shown in Table IV, also graphically represented in Fig.7 and Fig.8.

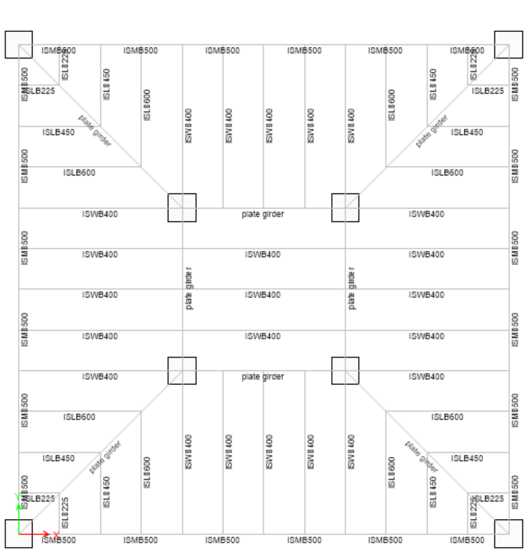

Fig.1 Floor Plan for Diagrid Structure

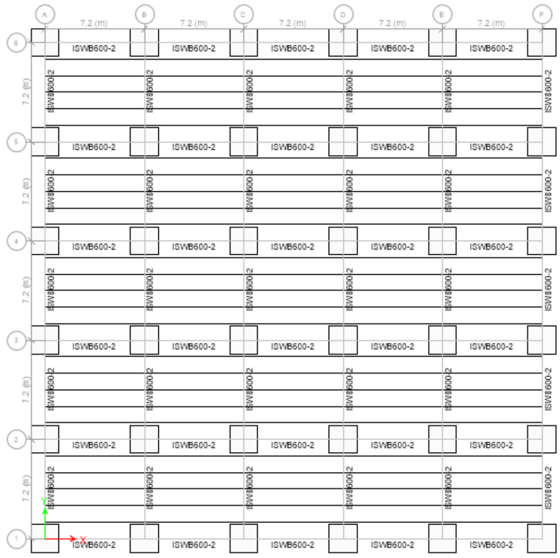

Fig.2 Floor Plan for Framed Structure

TABLE II
COMPARISON OF BASE SHEAR FOR WIND LOAD, SEISMIC LOAD AND RESPONSE SPECTRUM

TYPE OF STRUCTURE	Wind load (kN)	Seismic load-Static (kN)	Response Spectrum (kN)
FRAMED STRUCTURE	5446.26	3287.82	2951.56
DIAGRID STRUCTURE	5446.26	2382.61	1995.69

TABLE III
COMPARISON OF DISPLACEMENT FOR WIND LOAD, SEISMIC LOAD AND RESPONSE SPECTRUM

TYPE OF STRUCTURE	Wind load (mm)	Seismic load-Static (mm)	Response Spectrum (mm)
FRAMED STRUCTURE	87.68	80.82	51.55
DIAGRID STRUCTURE	32.35	21.05	13.18

TABLE IV
COMPARISON OF STOREY DRIFT FOR WIND LOAD, SEISMIC LOAD AND RESPONSE SPECTRUM

TYPE OF STRUCTURE	Wind load (mm)	Seismic load-Static (mm)	Response Spectrum (mm)
FRAMED STRUCTURE	3.273	2.894	1.882
DIAGRID STRUCTURE	1.336	0.749	0.514

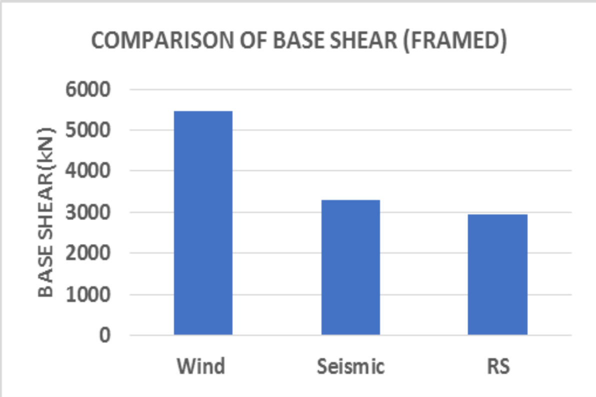

Fig.3 Comparison of base shear due to seismic load, wind load and RS function for framed structure

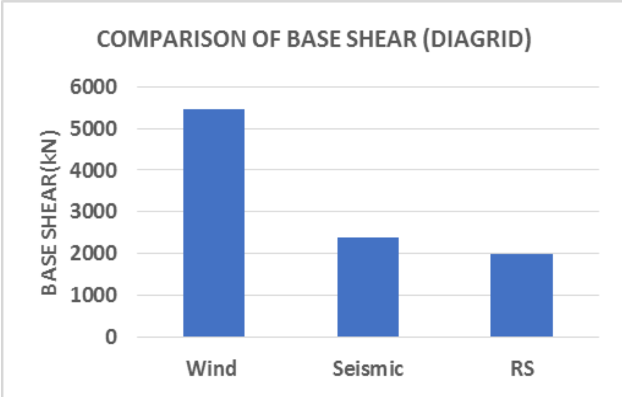

Fig.4 Comparison of base shear due to seismic load, wind load and RS function for diagrid structure

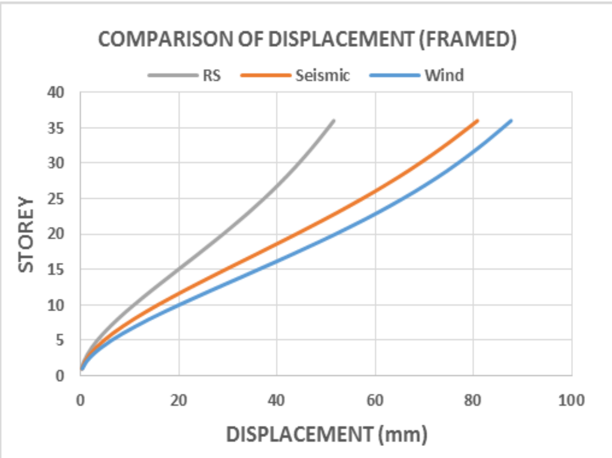

Fig.5 Comparison of displacement due to seismic load, wind load and RS function for framed structure

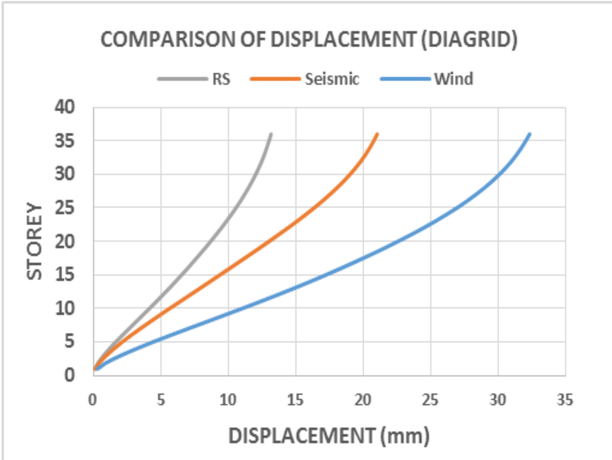

Fig.6 Comparison of displacement due to seismic load, wind load and RS function for diagrid structure

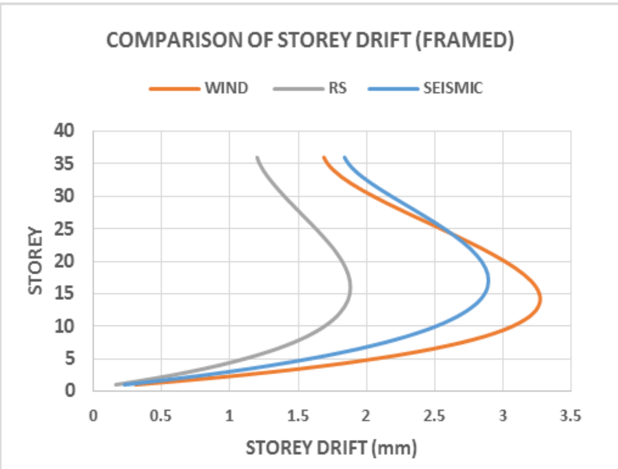

Fig.7 Comparison of storey drift due to seismic load, wind load and RS function for framed structure

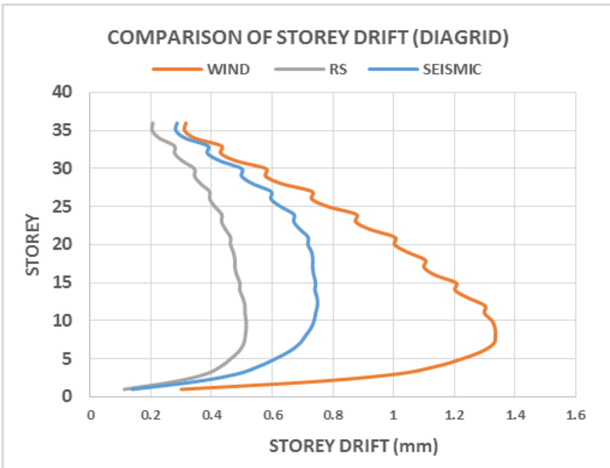

Fig.8 Comparison of storey drift due to seismic load, wind load and RS function for diagrid structure

C. Comparison of Steel Framed and Diagrid structure for Critical load combination

The analysis results such as time period, displacement, storey drift for critical load combination are compared between framed and diagrid structure in this section. The comparison of first mode time period for 36 storey framed and diagrid structure are shown in Fig.9. The first mode time period for framed structure is 6.528 seconds and for diagrid structure is 3.067 seconds. Since it is a square building, the displacement and storey drift in X-direction and Y-direction are same. The comparison of displacement for framed and diagrid structures are shown in Fig.10. It is observed that maximum displacement at top storey for framed structure is 131.52 mm and for diagrid structure is 48.52 mm. The comparison of storey drift for framed and diagrid structures are shown in Fig.11. It is observed that maximum storey drift for framed structure is 4.909 mm and for diagrid structure is 2.003 mm.

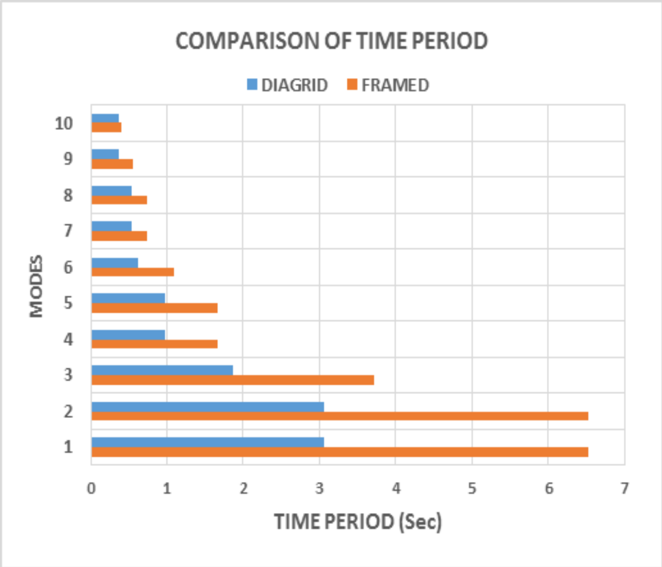

Fig.9 Comparison of time period for framed and diagrid structures in zone II with wind speed of 33m/s

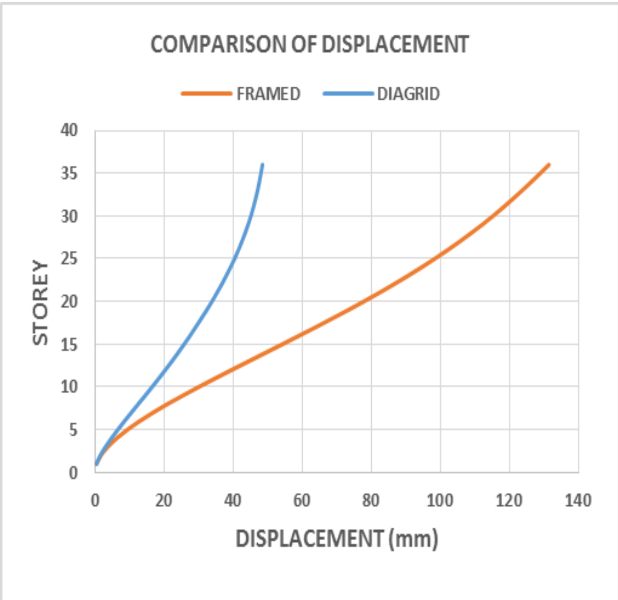

Fig.10 Comparison of displacement for framed and diagrid structures in zone II with wind speed of 33m/s

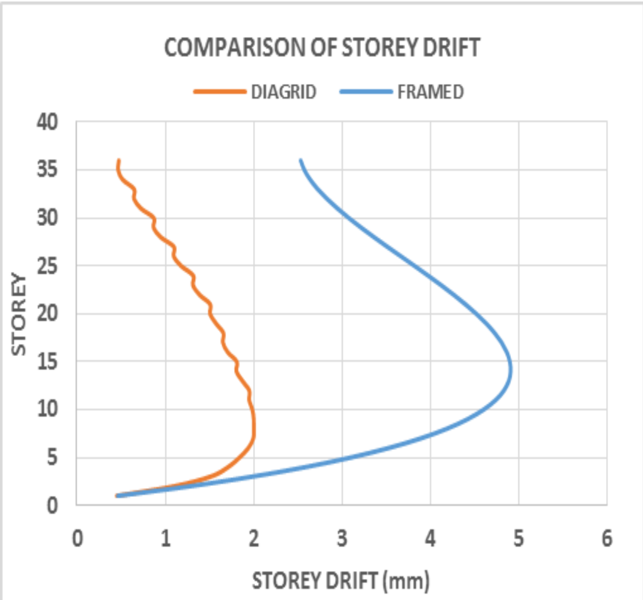

Fig.11 Comparison of storey drift for framed and diagrid structures in zone II with wind speed of 33m/s

D. Comparison of material used in model for analysis

Comparison in terms of number of columns, weight of steel and volume of concrete are presented in this section. The comparison of number of columns for 36 storey framed and diagrid structure are shown in Fig.12. On comparing the number of CFT columns, framed structure has 1296 columns and diagrid structure has 288 columns. Comparison of weight of steel for framed and diagrid structures are shown in Fig.13. Weight of steel used in framed structure for beams alone is 4766 tons whereas in diagrid structure for both beams and periphery diagrid columns, the weight of steel used is 4269 tons. Comparison of volume of concrete for framed and diagrid structures are shown in Fig.14. The volume of concrete used for slabs and CFT columns in framed structure is 21820m^3 and for diagrid structure it is 9204m^3.

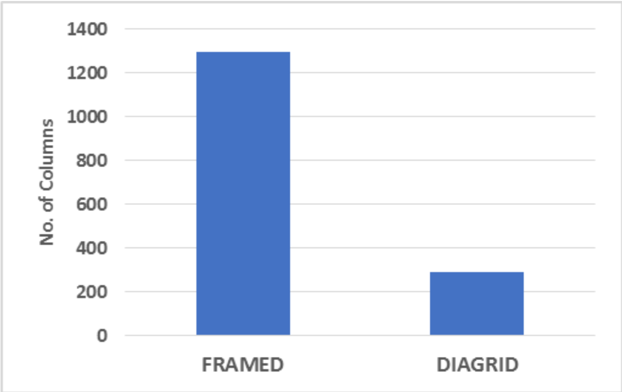

Fig.12 Comparison of number of columns for framed and diagrid structures

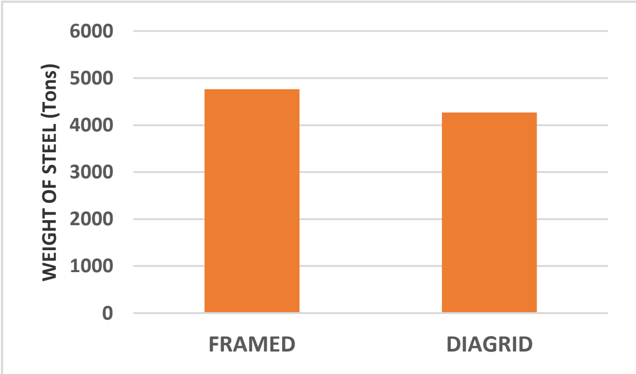

Fig.13 Comparison of weight of steel for framed and diagrid structures

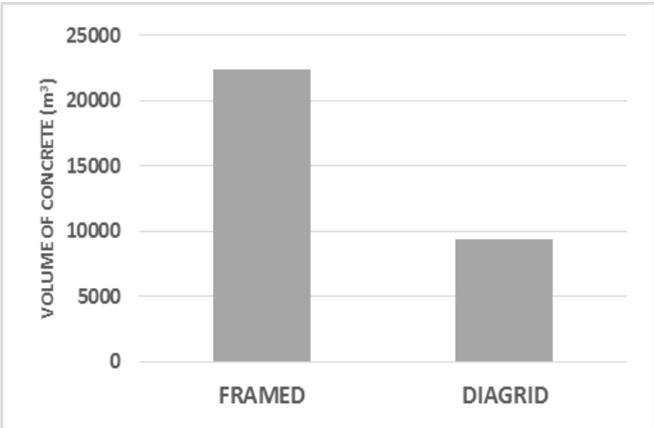

Fig.14 Comparison of volume of concrete for framed and diagrid structures

E. Comparison of displacement by varying the wind speed

A comparison of displacement is made with the same model of framed and diagrid structure by varying the basic wind speed specified in IS875 (Part 3)-2015. The maximum displacement at top storey for framed and diagrid structure with different wind speed are shown in Table V. The comparison of displacement for 36 storey framed structure with different wind speed are shown in Fig.15. The comparison of displacement for 36 storey diagrid structure with different wind speed are shown in Fig.16.

TABLE V
COMPARISON OF MAXIMUM DISPLACEMENT FOR DIFFERENT WIND SPEED

Wind Speed (m/sec)	**Framed Structure (mm)**	**Diagrid Structure (mm)**
33	131.52	48.52
39	183.69	67.79
44	233.81	86.26
47	266.78	98.42
50	301.93	111.39

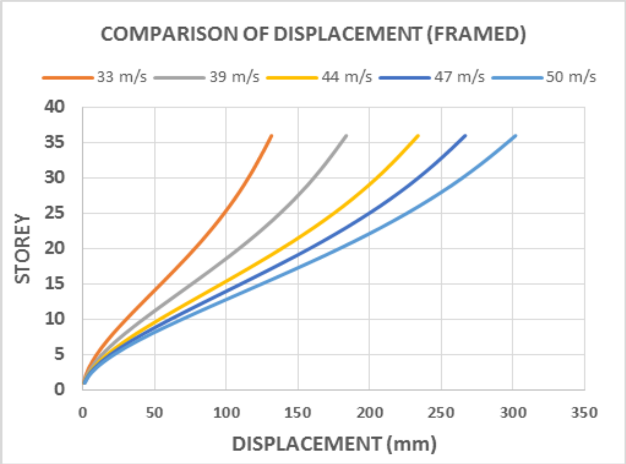

Fig.15 Comparison of displacement for framed structure in zone II with different wind pressures

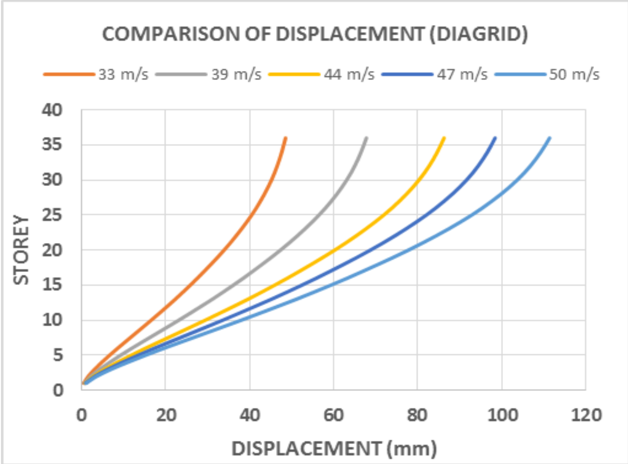

Fig.16 Comparison of displacement for diagrid structure in zone II with different wind pressures

III. RESULTS AND DISCUSSION

(a) The base shear, displacement and storey drift due to wind load is more than seismic load in both framed and diagrid structures. Hence wind load govern the design.
(b) On comparing, the first mode time period for diagrid structure is 50% less than that of framed structure.
(c) On comparing, the displacement for diagrid structure is 63% less than that of framed structure.
(d) On comparing, the storey drift for diagrid structure is 60% less than that of framed structure.
(e) Only 2/9th of the columns is used for diagrid structure when compared with framed structure.
(f) About 10.4% of weight of steel is less for diagrid structure when compared with framed structure.
(g) About 58% of volume of concrete is less for diagrid structure when compared with framed structure.
(h) On comparing the displacement with different wind speeds, diagrid structure shows less displacement than framed structure. Even in maximum wind speed(50m/s) diagrid structure shows less displacement compared with framed structure with minimum wind speed(33m/s).

IV. CONCLUSIONS

Using diagrid structural system, structures with less columns, free and clear floor plans can be constructed. Natural day lighting saves energy consumption. Also aesthetically dominant and expressive structure can be created. The diagonal columns in the periphery of diagrid structural systems can carry gravity load and lateral forces due to their triangulated configuration. Wind load governs the design of tall buildings than seismic load. From the study it is observed that diagrid structural system has less displacement, storey drift, base shear and time period when compared with framed structural system. Also the materials like steel, concrete and number of columns are less for diagrid structure when compared with framed structural system. Thus Diagrid structures are structurally stable and economic when compared to framed structure. Also the use of reinforced concrete columns for diagrid column are not recommended for tall buildings.

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