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Comparative Study of Diagrid Structures with Conventional Frame Structures

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ABSTRACT
In modern age, the decrease of available free land and increase of land prices along with the wide spread of urban area has made architects and engineers to develop the cities vertically. For vertical growth, the only option is to construct the buildings as high as possible. It is a task of a structural designer to make the desired building stand and stable throughout its life. There are various structural systems for tall buildings, among them diagrid system is selected for this work. Diagrid is an exterior structural system which resists the lateral forces by axial actions of diagonals provided in periphery. Statistical analysis of tall buildings in India is carried out and presented for buildings having height more than 150 m or 40 storeys. Parametric study and detailed comparison of diagrid structural system with respect to conventional frame is carried out for symmetrical buildings. In this study seven steel buildings of identical base area and loadings with different heights are designed for optimum sections for both structural systems diagrid and conventional frame in ETABS. Various parameters like fundamental time period, maximum top storey lateral displacement, maximum base shear, steel weight, percentage differences in change of steel weight, maximum storey displacement and maximum storey drift are considered in this study. A Diagrid structure performs well than conventional frame structures and increase in steel weight with increase in height of building is considerably less in diagrid structures.

***Keywords* -** Tall buildings, Diagrid system, Tall buildings in India, Conventional frame system, lateral loads, Optimum design, Parametric Study, ETABS

I. INTRODUCTION

Early tall building systems started with steel/iron frame structure which minimized the dimensions of the structural members at building perimeters. In this system, large openings were filled with transparent glasses and steel/iron members were clad with solid materials. Later on, new cladding concept of curtain walls was developed with the emergence of new structural systems. Most of tall buildings employed steel rigid frame with wind bracings as a structural system, and were quite over-designed as the advanced structural analysis techniques and computer software were not available at that time. Innovative structural systems like composite structures, mega-frames, tubes, core-and-outrigger structures and artificially damped structures are some of the new developments since the 1960s. The diagrid system, however used at few places in past but utilised for buildings with unique shapes and form, developed in the beginning of twenty-first century; so diagrid can be considered as one of the latest structural systems for tall buildings.

Fazlur Khan proposed the concept of "premium of height"; that as buildings became taller, there is a "premium for height" due to lateral loads and the demand on the structural system dramatically increased, and as a result, the total structural material consumption increases drastically (Mir and Moon 2007). If a rigid frame is used for a very tall building, the column sizes increases progressively towards the base due to accumulation of gravity load at the base and material quantity required to resist lateral farces also increases drastically with height.

Khan also recognized that the stiffness based design concept controls the design rather than the strength based approach when the building height increases beyond 10 storeys. (Mir and Moon 2007). Diagrid structures are emerging as a new aesthetic trend for tall buildings in the modern age of architecture as a most versatile structural system and it is a special form of the space truss. Diagrid system gives unique façade and it can be identified at a first glance. Diagrid structures, which represent the latest mutation of tubular structures, play a major role due to their inherent aesthetic quality, structural efficiency and geometrical versatility (Elena, Toreno, et al. 2014). Diagrid structural system differs from conventional braced systems in a way that, almost all the vertical columns are eliminated, as shown in the Figure 1. In diagrid, the diagrids are considered as pin jointed truss elements. Due to the triangular configuration of diagonals, diagrid can carry gravity loads as well as the lateral loads efficiently. To transfer end moments, universal connection can be used which are developed by K. Moon as shown in Figures 2 and 3.

the ratio of approximately 50-50% in interior frame and peripheral diagrid and about 98% of lateral loads are taken by the peripheral diagrid system (Jani and Patel 2012, 2013). Diagrid structures are found to be safe against progressive collapse and progressive collapse potential decreases as the twisting angle increases (Kwon and Kim 2014).

Based on the literature review carried out herein, it is some researchers have worked on the effectiveness of diagrid system. However, there is a need for detailed parametric study for diagrid system.

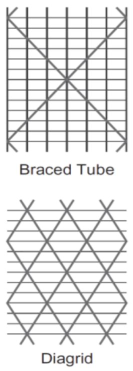


Fig. 1: Braced Tube and Diagrid Structure (Kyoung, Jerome and John2007)

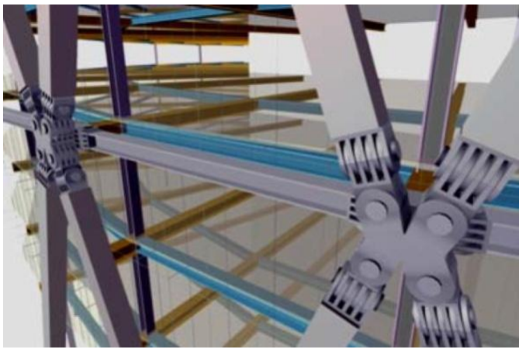


Fig. 2: Node details of universal connection (K. Moon 2009)

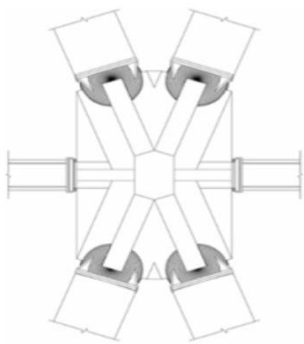


Fig. 3: Typical Universal Connection

For exterior structural systems the significance of diagrid system is identified for about 100 storey buildings where frames, tubes or braced tubes are less efficient or uneconomical (Ali and Kyoung 2007). Optimal angle range for diagrids is found to be between 60° to 70°. Preliminary design procedure and formulae for area of diagonals are derived according to the stiffness based design Moon et al. (2007). Though the outrigger system is most commonly used structural system for tall buildings, the diagrid system is the most efficient; because diagrid forms an exterior tube that can maximise the moment arm to resist overturning. Kim (2008) Diagrid structures showed considerably less lateral displacement than in tubular structure in non-linear static and dynamic analysis. Shear leg in diagrid building is considerably less compared to the framed tube (Kim et al. 2010). In case of twisted diagrid building, as the angle of twisting increases the top storey lateral displacement also increases. Diagrid structural system is found to be one of the most appropriate structural solutions for free-form towers (Moon 2011, 2013). Gravity load is shared in

Following are the main objectives of the present study:

- To review the tall buildings in India.
- To compare the performance of the building with diagrid structural system and conventional frame system.
- To study the critical effects of lateral forces such as wind and earthquake forces on diagrid structural system.
- To obtain the response in terms of parameters such as time period, displacement, drift, base shear and steel consumption.

II. TALL BUILDINGS IN INDIA

In this section, the review of tall buildings in India has been presented. Total data for 270 buildings was obtained from Indian website of Council on Tall Buildings and Urban Habitat (CTBUH). From this largely spread data, buildings with height greater than 150 m or storeys greater than 40 were separated for further study. After separation, total 168 of buildings were obtained. For detailed study these buildings were further classified based on construction stage, building usage, location of building and construction materials. The classification based on construction stage, type of building use, location of building and construction material is presented in Figures 4 to 7.

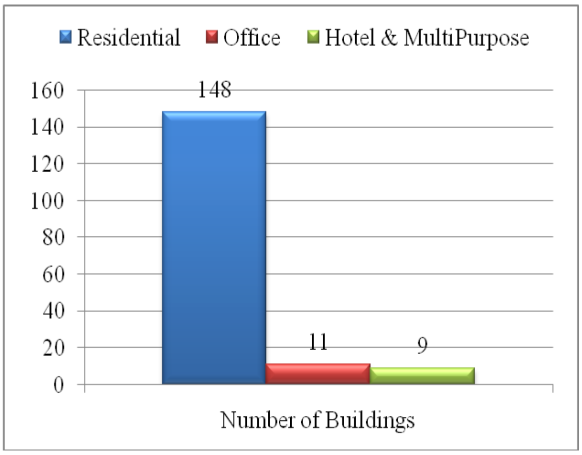


Fig. 4: Classification Based on Building Use

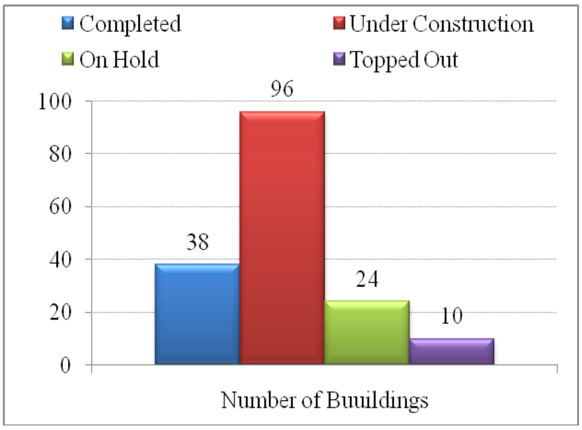


Fig. 5: Classification Based on Construction Stage Type

It is observed that out of total 168 buildings selected, 38 (23%) tall buildings are constructed, 96 (57%) building are under construction at the time and 24 (20%) buildings are in controversy. Out of 168 buildings, about 148 (88%) buildings are residential, 11 (6.5%) buildings are office buildings and 9 (5.5%) buildings are hotels of multipurpose buildings. It is observed that in India, the trend of tall buildings is for residential buildings. It is interesting to note that, 82% of the Indian tall buildings (138 Buildings) are located in Mumbai only. 6% of buildings are in Kolkata, 6% of buildings in Bangalore and Hyderabad while 6% in Gurgaon, Noida and Greater Noida. Further, remarkable obsession is that 93% of Indian tall buildings (156 Buildings) are made with concrete only and 3% of buildings (5 Buildings) are made with composite materials. But data of material use of 4% buildings (7 Buildings) is not available. But, form this scenario it is seen that in India, no tall buildings are constructed with steel as only structural material.

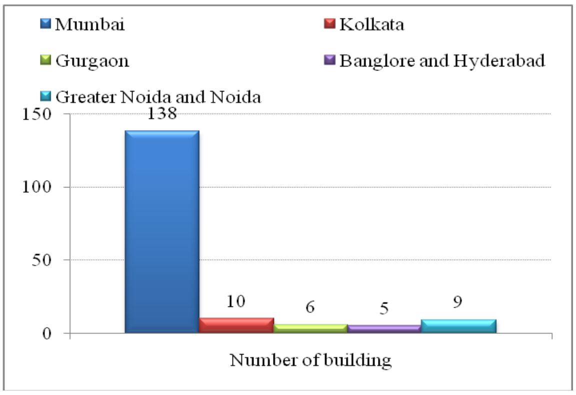


Fig. 6: Classification Based on Location of Building

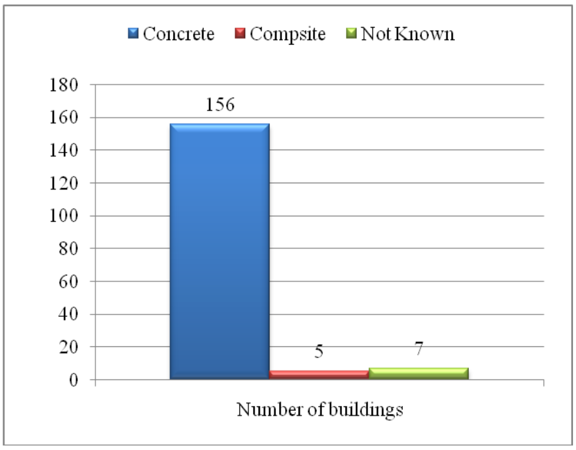


Fig. 7: Classification Based on Construction Material

III. PARAMETRIC STUDY OF DIAGRID AND CONVENTIONAL FRAME

For the parametric comparison, a symmetrical building is selected. Seven steel buildings for different heights are modelled, analysed and designed in ETABS for two structural systems; diagrid and conventional frame. Analysis and design are carried out for dead load, live load, lateral earthquake load and lateral wind load. For earthquake loads, both static and response spectrum analysis are done. To consider extreme conditions of lateral loads, the buildings are considered to be located in Zone V. The parameters selected for the comparison are fundamental time period, maximum top storey lateral displacement, maximum base shear, steel weight and percentage difference of weight, maximum storey displacement and maximum storey drift. Further, governing lateral force is also determined.

A. Building Configuration

Seven buildings are designed with different number of storeys such as 4, 8, 12, 16, 20, 40 and 28 for both diagrid and conventional frame systems. The physical properties and data of the building considered for the present study is as follows:

Plan Area :	**18 m × 18 m**
Location :	**Bhuj**
Typical Storey Height :	**3 m**
Steel Sections :	**Fe 250**
Concrete (Slabs) :	**M 25**
Dead Load :	**3 kN/m^2**
Live Load :	**2.5 kN/m^2**
Wall/Cladding Load :	**4 kN/m**
Slab Thickness :	**120 mm**
Earthquake Load:	**IS 1893 (Part 1) : 2002**
Importance Factor:	**1**
Response Reduction Factor :	**5**
Modal Damping :	**2%**
Wind Load :	**IS: 875 (Part 3) - 1978**
Basic Wind Speed:	**50 m/s**
Steel Design Code:	**IS 800:2007**
Limiting Top Storey Displacements :	**H/500;**
Limiting Inter Storey Drifts :	**0.004h**

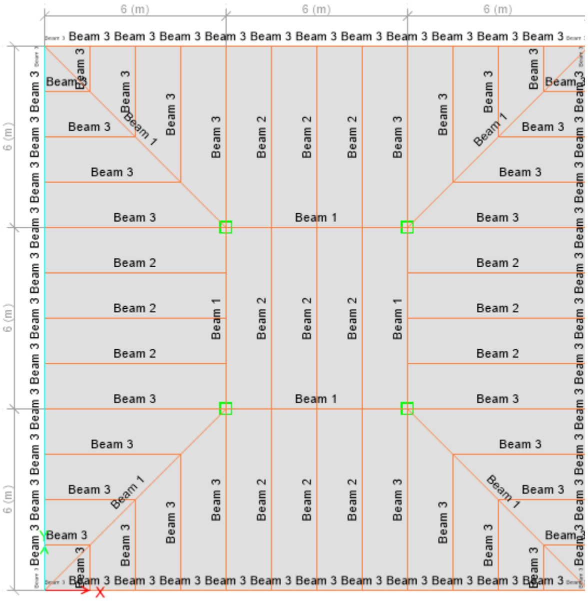
B. Diagrid Buildings

The structural elements like columns, beams and diagrids are assigned structural steel properties while the slabs are considered of RCC. All sections in buildings are optimized for design sections. For that, all buildings having storeys 12 and above are divided into three parts along the height of the buildings. For the design of diagrids and columns, built-up box sections are used and for the design of beams, Indian Standard I-Sections are used. The typical plan, beam arrangements, elevation and 3D views of a 24 storey diagrid building are shown in Figure 8.

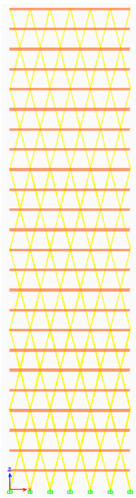
C. Conventional Frame Buildings

In case of conventional frame, as the height increases, stiffness based design criteria becomes predominant and even if the column sections suffice the strength criteria, maximum lateral displacement exceeds 1/500th of building height. To overcome these excessive member sizes are required as height increases.

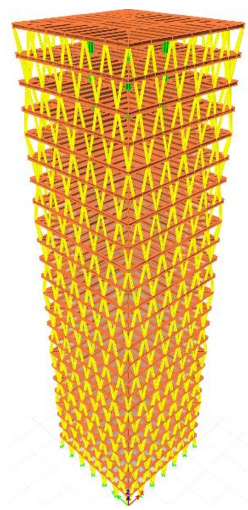
For the design of columns, built-up box sections are used and for the design of beams, Indian Standard I-Sections are used. The typical plan, beam arrangements, elevation and 3D views of a 24 storey conventional frame building are shown in the Figure 9. Optimum design sections for 24 storey building are shown in Table 1 with notations as shown in Figures 8 and 9.



8 (a): Typical Floor and Beam Arrangement of 24-Storey Diagrid Building

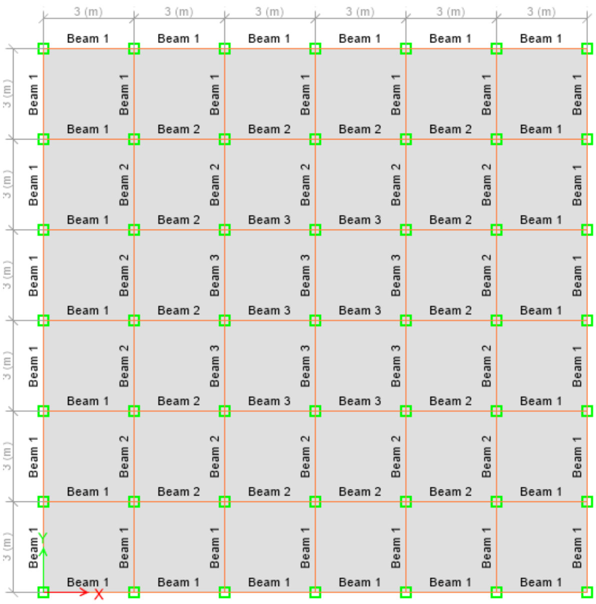


8 (b): Elevation of 24-Storey Diagrid Building

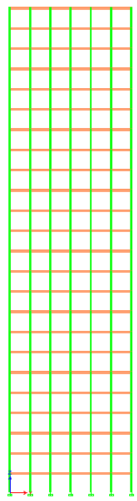


8(c): 3D View of 24-Storey Diagrid Building

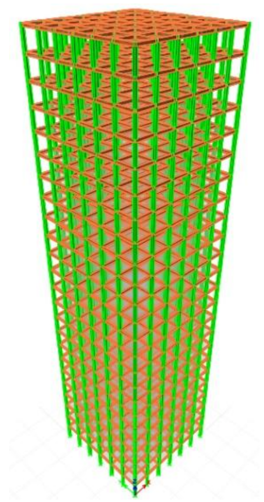
Fig. 8: Typical Diagrid Building



9 (a): Typical Floor and Beam Arrangement of 24-Storey Conventional Frame Building



9 (b): Elevation of 24-Storey Conventional Frame Building



9(c): 3D View of 24-Storey Conventional Frame Building

Fig. 9: Typical Conventional Frame Building

Table 1: Design Sections for 24 Storey Building

Design Sections for 24 Storey Building								
Building	**Type**	**From**	**To**	**Diagrid**	**Column**	**Beam 1**	**Beam 2**	**Beam 3**
24 Storey	Diagrid	0	8	B-200X17	B-400X45	ISMB 450	ISMB 450	ISMB 450
		9	16	B-150X10	B-400X30			
		17	24	B-125X10	B-400X15			
	Simple Frame	0	8	--	B-350X55	ISMB 400	ISMB 350	ISMB 350
		9	16	--	B-350X45			
		17	24	--	B-350X35			

IV. RESULTS COMPARISON AND DISCUSSION

After analysing and designing all the structures, the governing loads for each building for both diagrid and conventional frame systems are tabulated in the Table 2. It is observed that in diagrid system earthquake forces are predominant upto 16 storeys and in conventional frame upto 12 storeys. This means wind forces are predominant after 16 storeys in diagrid system and 12 storeys in conventional frame system. It can be concluded that diagrid system resists wind forces upto higher heights than conventional frame system. Further it is important to note that the section for conventional frame is not possible from feasibility and practicability point of view.

Table 2: Governing Loads

Storey	**Diagrid**	**Conventional frame**
4	EQ STATIC	EQ STATIC
8	EQ DYNAMIC	EQ DYNAMIC
12	EQ STATIC	EQ STATIC
16	EQ STATIC	WL
20	WL	WL
24	WL	WL
28	WL	--

A. Time Period

Figure 10 represents the comparison of the time period of both the systems. It is observed from the figure that as the building height increases, the time period of diagrid remains lower than that of the conventional frame building. Thus it is observed that the diagrid building is stiffer than the conventional frame.

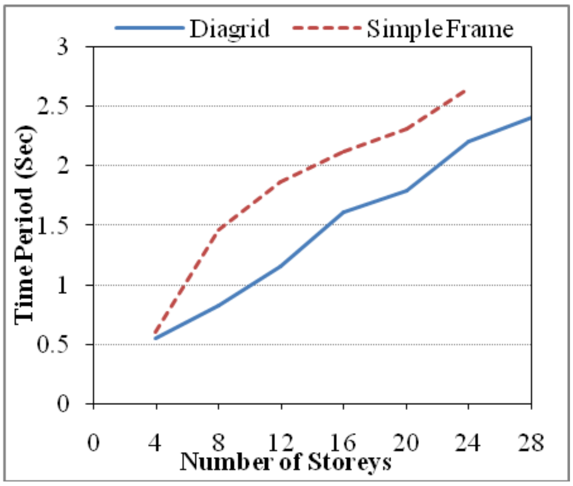


Fig. 10: Time Period Comparison

B. Maximum Top Storey Displacement

Figure 11 represent the comparison of the maximum top storey displacements for both the systems. The trend of lateral displacements is observed to be similar in both the directions because the building selected in study is symmetrical. It is observed that the pattern of the plot is similar for both systems but the overall displacement values are quite higher for conventional frame even if they are designed for excessive column sizes. Thus it proves the effectiveness of diagrid structures.

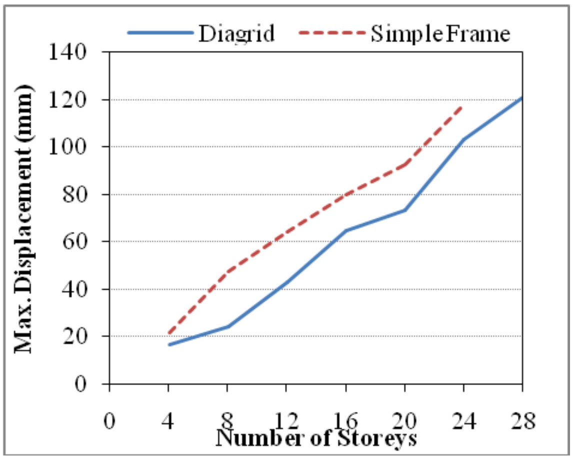


Fig. 11: Maximum Top Storey Displacement

C. Maximum Base Shear

The Figure 12 represents the comparison of the maximum base shear for both the systems:

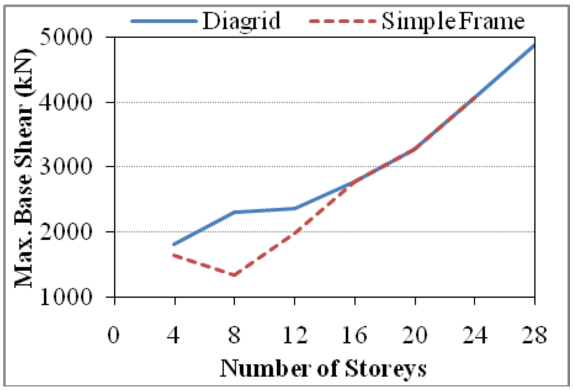


Fig. 12: Maximum Base Shear Comparison

As the building is symmetric, the base shear will be the same in both the directions. As it is known that the diagrid system is stiffer than the conventional frame, it attracts more lateral force and hence it has more base shear upto 12 storey buildings. After 12 storeys, static wind loads takes hold and becomes governing forces and the base shear is governed by static wind loads. Thus after 12 storeys the base shear for both the systems is observed to be similar.

D. Steel Weight

The conventional frame buildings are designed with excessive column sizes. And thus it has in turn increased the steel consumption or steel weight of the buildings. The rate of increment also increases tremendously with the height of building as seen in Figure 13. This presents an example of the concept of “Premium for Height” given by Fazlur Khan (Ali and Kyoung 2007). Due to excessive member size requirements, it is not possible to design 28 storey conventional frame building. In the Figure 14, the maximum steel weight is compared for both the systems:

The overall increase in the steel weight of the conventional frame system as compared to diagrid system is very high. The percentage differences in steel weight of conventional frame with respect to the diagrid system are presented in the Figure 14. It is observed that between 6 to 12 storeys, conventional frame is more economical that diagrid system. After that, the concept of *Premium of Height* becomes significant and makes the conventional frame system uneconomical with respect to diagrid system.

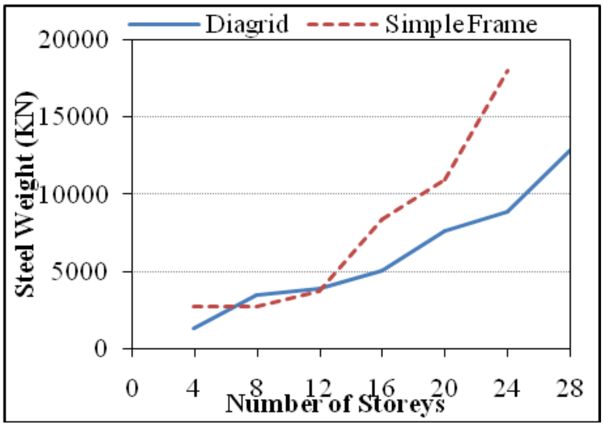


Fig. 13: Steel Weight Comparison

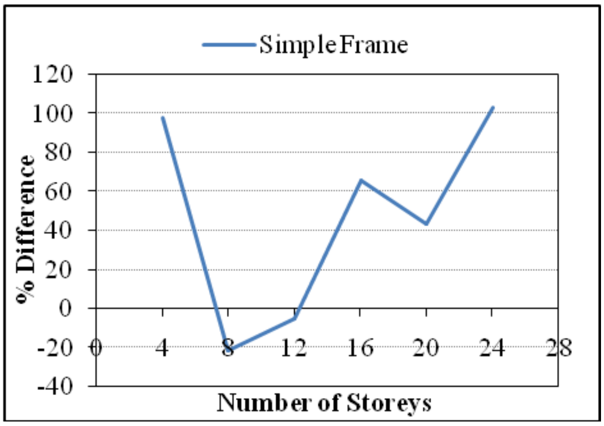


Fig. 14: Percentage Difference of Steel Weight Between Conventional and Diagrid Systems

E. Maximum Storey Displacements

Patterns of storey displacement curves are observed to be uniform in both the cases. Storey displacement patterns of conventional frame buildings are observed more uniform while in case of the diagrid buildings better results are observed. The trend of plots for diagrids is found to be nearly linear while that of conventional frame building is found to be curvilinear. As the building is symmetrical, results in both directions are identical. The results showing typical trend of displacements at each storey level for 20 storey building are presented in Figure 15.

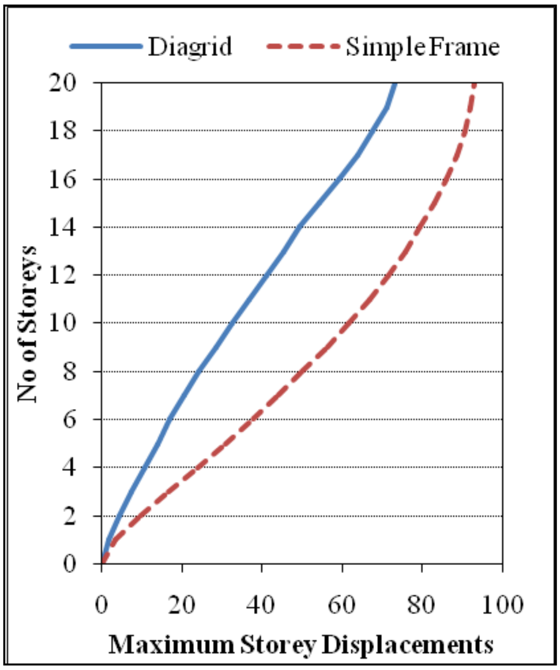


Fig. 15: Maximum Storey Displ. for 20 Storey Symmetrical Building

F. Maximum Storey Drifts

Uniform storey drift curves are observed in both the cases. But storey drift patterns of conventional frame buildings are observed more uniform while in case of the diagrid buildings highly conservative results are observed. Maximum storey drift are observed at the lower portion of the conventional frame building, while in diagrid buildings sudden variations are observed at storeys where the diagrid sections are changed. As the building is symmetrical, results in both directions are identical. The results showing typical trend of drifts at each storey level for 20 storey building are presented in Figure 16. The storey drifts are within permissible limits in both the cases.

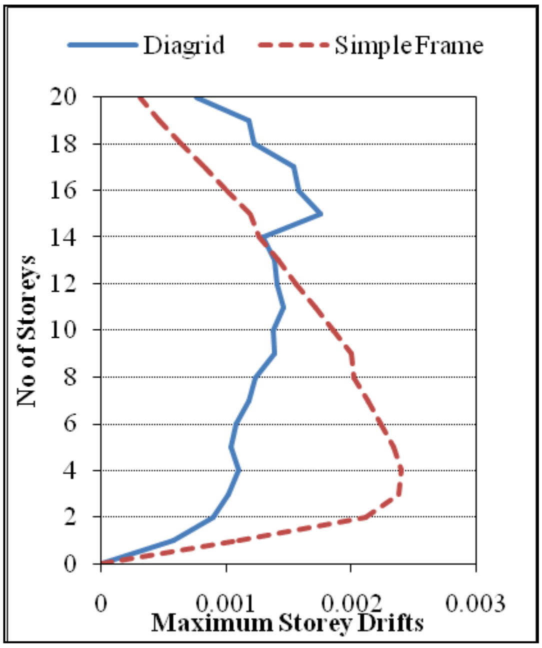


Fig. 16: Maximum Storey Drifts for 20 Storey Symmetrical Building

V. CONCLUSIONS

Based on the numerical study carried out in the present research work, following major conclusions can be drawn:

1) Diagrid structural system has emerged as a better solution for lateral load resisting system in terms of lateral displacements, steel weight and stiffness. It is stiff enough to resist wind forces upto higher heights.
2) The diagrid structure provides high efficiency in terms of steel weight along with the aesthetic appearance. For 24 storey building, weight of conventional frame is 100% more than diagrid building.
3) Displacements on each storey and storey drifts are observed to be less in diagrid systems as compared to conventional frame.

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