SEISMIC RESPONSE OF DIAGRID FRAMED STEEL BUILDINGS

Amit Pratap Singh

PG student of Structural Engineering, Dept. of Civil Engineering and Applied Mechanics,
Shri Govindram Seksaria Institute of technology and Science, Indore, India.

Abstract : Recent advancements and innovations in construction engineering, framed systems, building materials, and analysis and design methods promoted the increment of high rise structures. High-rise structures are more vulnerable to lateral loads and generally lateral load due to earthquake or wind governs the design of high-rise buildings. Hence, it is necessary to develop the structural system which can resist the lateral loads effectively with minimum cost. The diagrid framed system provides the best aesthetical solution to control excessive drift and displacement in high rise buildings. In this study, the diagrid framed building model and the conventional building model are modeled for the 20, 42 and 60 storey building heights in ETABS 2017 software. Analysis results of diagrid buildings and conventional buildings in form of storey drift, displacement, storey shear, time period and steel consumption are compared to get the main objective of the study that is to assess the seismic performance of diagrid framed steel models over conventional models.

***IndexTerms* - Diagrid building, Conventional building, Optimal Angle, ESM, RSM, Non-Linear Time History Analysis.**

I. INTRODUCTION

A diagrid structure is a kind of exterior structural system that consists of perimeter grids formed by a series of triangulate trusses connected through horizontal rings, providing an elegant and redundant structure which is particularly effective for high-rise buildings. Diagrid is a specific form of space truss, which is generated by the diagonal and horizontal component's intersections. A diagrid system's column-free structure provides numerous benefits such as high architectural versatility and beauty, and significant daylight due to its broad free façade surface.

A diagrid framed system is different from braced frame structural system, because diagonals as the main structural components are involved in resisting vertical loads as well as carrying horizontal loads because of its triangular pattern that minimize the requirements for vertical columns while, in braced frame diagonals only carrying lateral load and for gravity loading there are vertical columns. By using the diagrid framed system, shear deformation and overturning moments can be more effectively minimized than conventional framed tubular structures because diagonals in diagrid carry shear force and moment axially due to triangular arrangements in diagrid structure.

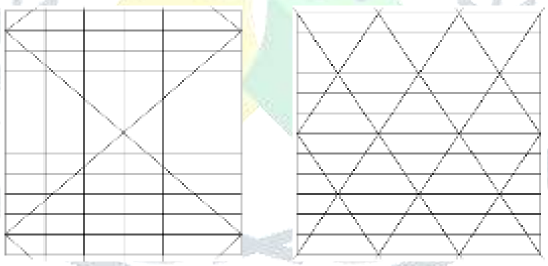


Figure 1 Braced tube system and diagrid system

II. RELATED WORK

Researches on stiffening the structures to control drift started decades ago. Few of the researches on this topic done earlier are discussed in this literature review.

Moon [1] started the studies on the diagrid framed system and checks the functioning of the diagrid buildings with various diagrid angles to obtain the optimum angle of diagonals for different building storeys. He also studied the performance of diagrid system by varying diagonal angle along the height of building. Moon et al [2] provided a design approach for the preliminary member sizes of steel diagrid high rise structures to be determined that is based on stiffness and suggested that this methodology based on stiffness is more effective than a typical iterative methodology based on strength for relatively light and flexible tall structures. Johan Leonard [3] studied an effect of shear lag on high-rise diagrid buildings. He observed that shear lag effect was very less in diagrid buildings compared to framed tube buildings because of higher lateral stiffness in diagrid-system than framed tube system. William Baker et al [4] suggested an approach for steel diagrid system based structures to determine the seismic performance factors and introducing the ATC. This study proposed a methodology that contained both FEMA-450 and ATC-63 two established and related methods. Jani K. and Patel [5] performed an analysis and design of steel diagrid structures as per Indian standard code by dealing all load combinations. Distribution of loads in diagrid structural system was also studied. Gravity loads were found to be about equally resisted by the inner columns and outer peripheral diagrid diagonal columns, while the peripheral diagrid diagonal columns resisted almost all the lateral load.

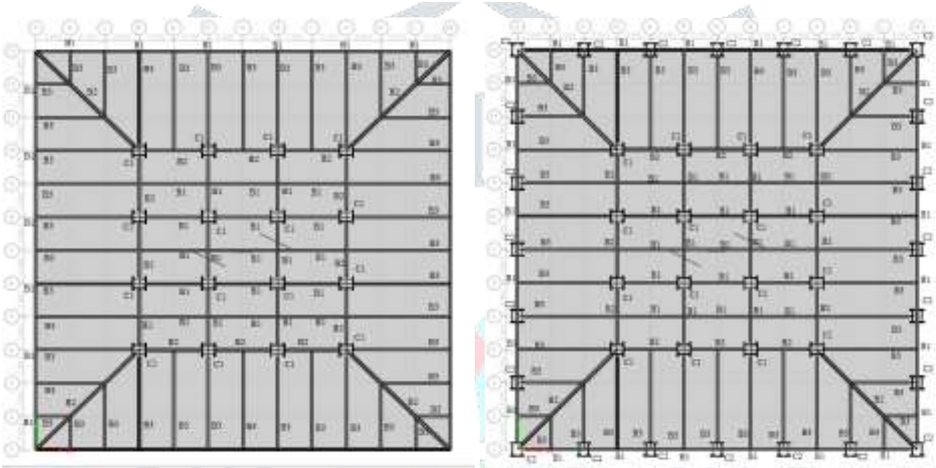
III. METHODOLOGY

For the present study, the structural models of diagrid and conventional system of three different storey heights i.e. 20 storey, 42 storey and 60 storey are prepared for the comparative study based on various parameters. The plan width is kept same in both the directions leading to a symmetrical structural configuration along both the directions for all three storey height. Table 3.1 shows the details of dimensions of the diagrid and conventional framed models. In diagrid model, support condition is kept fixed and end condition is kept as hinged. Figure 3 shows the elevation and 3D of 60 storey diagrid and conventional building. Similarly, 20 and 42 storey models are created. Diagrid models are created with optimal angle.

Table 3.1 Dimensions of the diagrid and conventional framed models

Parameter	**20 Storey**	**42 Storey**	**60 Storey**
Plan Dimension	36m x 36m	36m x 36m	36m x 36m
Diagrid Spacing	12m	12m	12m
Module Size	4 Storey	6 Storey	6 Storey
Column Spacing	6m	6m	6m
Storey Height	3.8m	3.8m	3.8m
Height of structure	76m	159.6m	228m
Aspect Ratio	2.11	4.43	6.33

A total of 6 models (3 diagrid models and 3 conventional models) are prepared and analysed in ETABS 2017 software. All models have been analysed by three methods i.e. Equivalent Static Method, Response Spectrum Method and Non-linear Time History Analysis. Further, for finding optimal angle of diagonal several models of 20, 42 and 60 storey diagrid building having different diagonal angles i.e. 32^0, 51^0, 62^0, 68^0, 75^0, 82^0 and 90^0 are created and analyzed by equivalent static method and results are compared in terms of maximum lateral displacement.



(a) (b)

Figure 2 (a) Plan of diagrid models, (b) Plan of conventional models

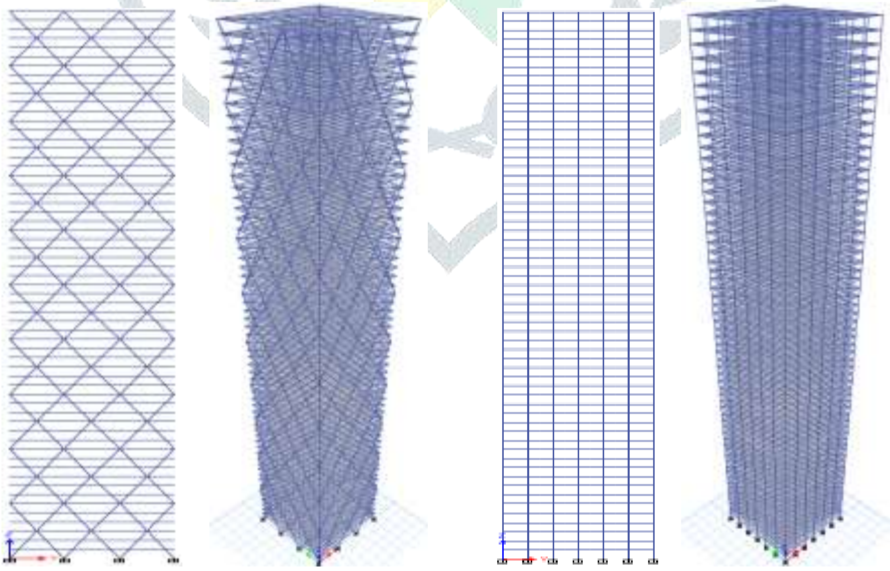


Figure 3 Elevation and 3D of 60 storey diagrid and conventional building

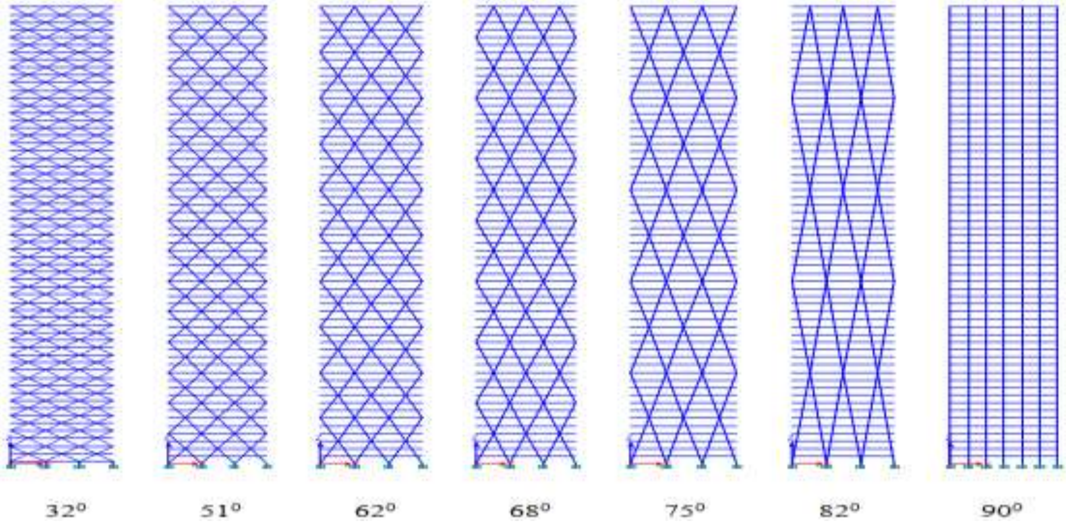
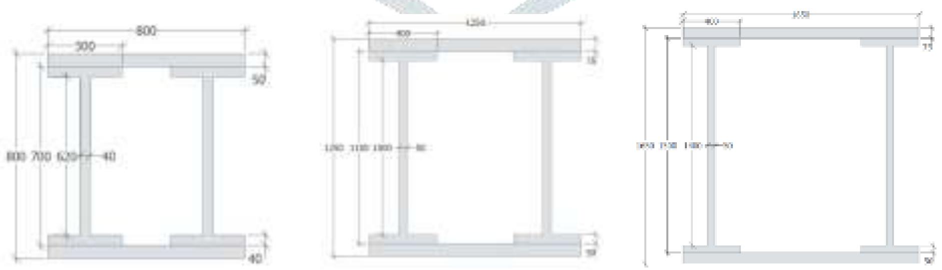


Figure 4 Sixty storey diagrid models with different diagonal angles

Figure 4 shows the models of 60 storey diagrid buildings having different diagonal angles. Similarly, 20 and 42 storey diagrid buildings with various angles are modeled for investigating the optimal angle of diagrid. The structural members of the various models under consideration are designed as per IS 456:2000 and IS 800:2007 using the ETABS 2017 software. Table 3.2 shows the dimensions of elements used in models and Fig.5 shows the detailing of columns used in models.

Table 3.2 Size of elements of 20, 42 and 60 storey buildings

Storey	Diagonals	Interior/Exterior Columns	Beams
20 Storey	400 mm pipe sections with 50 mm thick (form 5th to 20th storey), 450 mm pipe sections with 50 mm thick (from 1st to 4th storey)	800 mm X 800 mm	B1 and B3 = ISMB 550 with 180 X 25 mm plate at top and bottom, B2 = ISWB 550 with 200 X 50 mm plate at top and bottom
42 Storey	450 mm pipe sections with 50 mm thick (form 22th to 42th storey), 625 mm pipe sections with 50 mm thick (from 1st to 21th storey)	1250 mm X 1250 mm	B1 and B3 = ISMB 600 with 200 X 25 mm plate at top and bottom, B2 = ISWB 600 with 220 X 50 mm plate at top and bottom
60 Storey	575 mm pipe sections with 50 mm thick (form 31st to 60th storey), 875 mm pipe sections with 50 mm thick (from 1st to 30th storey)	1250 mm X 1250 mm (from 31th to 60th storey), 1650 mm X 1650 mm (from 1st to 30th storey)	B1 and B3 = ISMB 600 with 200 X 25 mm cover plate at top and bottom, B2 = ISWB 600 with 220 X 50 mm plate at top and bottom



(a) 800mm x 800mm (b) 1250mm x 1250mm (c) 1650mm x 1650mm

Figure 5 Detailing of interior and exterior columns used in all models

IV. LOADINGS

The loads are applied to the structural models as per the standard guidelines mentioned in relevant IS codes. Table 4.1 shows the gravity loadings that have been applied on models. Earthquake load has been applied as per the guidelines of IS 1893 (Part 1) – 2016 considering the seismic zone IV. Seismic zone factor of 0.24, importance factor of 1.2 and R-factor of 5 is taken considering the building to be SMRF. The soil type is type II medium soil. Damping of 5% is considered. The load combinations are formed as per the Indian standard codes.

Table 4.1 Gravity loads and values

S.No.	Loads	Value
1.	Floor Finish @ Floor Level as per IS 875 (Part 1)-1987	1.5 KN/m^2
2.	Floor Finish @ Roof Level as per IS 875 (Part 1)-1987	3.3 KN/m^2
3.	Partition Load	1 KN/m^2
4.	Live Load @ Floor Level as per IS 875 (Part 2)-1987	2.5 KN/m^2
5.	Live Load @ Roof Level as per IS 875 (Part 2)-1987	1.5 KN/m^2
6.	Wall Load (for light weight bricks)	6.5 KN/m
7.	Parapet Load	3 KN/m

For time history analysis ground acceleration data of 1940 Imperial Valley (El Centro) earthquake having the PGA of 341.69 cm/s^2 and PGV of 33.45 cm/s is used, which is obtained from peer ground motion database.

V. ANALYSIS AND DESIGN

The approach based on stiffness is used for an approximate analysis of 20, 42 and 60 storey diagrid buildings. Table 5.1 shows the maximum allowable lateral displacement of buildings.

Table 5.1 Maximum allowable lateral displacement

Storey	Height (m)	Allowable Lateral Displacement {H/500} (m)
20 Storey	76.00	0.152
42 Storey	159.6	0.320
60 Storey	228.0	0.456

5.1 Design Methodology of Diagrid Based on Stiffness

The design methodology based on stiffness is applied to 20, 42 and 60 storey diagrid buildings. For the calculation of preliminary member sizes of each module in diagrid structural system Moon 2005 derived a procedure and formulae in their study which are used in this study. In this method of design first step is to divide the building appropriately into number of structural modules then for each module bending moments and shear forces are calculated using the applied loadings. Apiece module is represented by a single diagrid level, which expends over 'n' number of stories. For 20 storey building, a four storey structural module with 51 degree diagonal angle is used and for 42 and 60 storey building, a six storey structural module with 62 degree diagonal angle is used. Fig.6 shows the typical 6 storey diagrid module. Size of members for the modules can be determined using Eq. 1 and 2, given by Moon 2005.

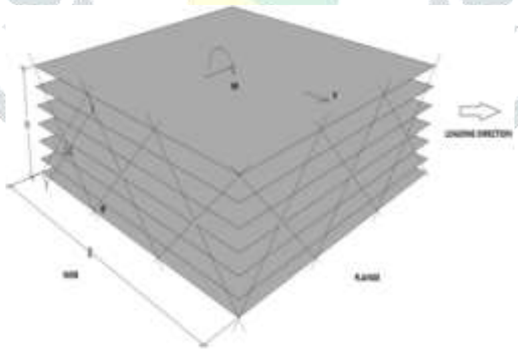


Figure 6 Six storey diagrid module

$$A_{dw} = \frac{V L_d}{2 N_{dw} E_d\, h\, \gamma \cos^2\theta} \quad (1)$$

$$A_{df} = \frac{2 M L_d}{(N_{df} + \delta) B^2 E_d\, \mathcal{X}\, h \sin^2\theta} \quad (2)$$

Where,

A_{dw} and A_{df} : Area of each diagonal on the web and flange of module
M and V: Moment and shear force on module
B and L_d: Width of building and diagonal length
$\mathcal{X}$ and ϒ: Curvature and transverse shear strain
N_{dw} and N_{df}: Total diagonals on each web and flange plane
θ and h: Angle and height of module
δ: Web diagonals contribution to the bending rigidity in this case it is 2

The design commences with assigning the coveted shear deformation and bending deformation of the building. For assigning the comparative contributions of bending versus shear deformation a factor 'S' is incorporated, which is a dimensionless quantity. 'S' value is calculated by Eq. 3

$$S = (\frac{X^* H^2}{2})/(\gamma^* H) = \frac{HX^*}{2\gamma^*} \quad (3)$$

The choice of 'S' value depends not only on the height to width ratio of buildings but also the least amount of material usage. Optimal 'S' value for 20, 42 and 60 storey building is determined by using different 'S' values to get the minimum area for diagonals. 'S' value at which area needed for limiting the shear and bending deformation both take part into design is selected as optimal value. Figure 7 shows the preliminary sizing of diagonal members for the 60 storey diagrid building for different 'S' values in which S = 6 gives the optimal design.

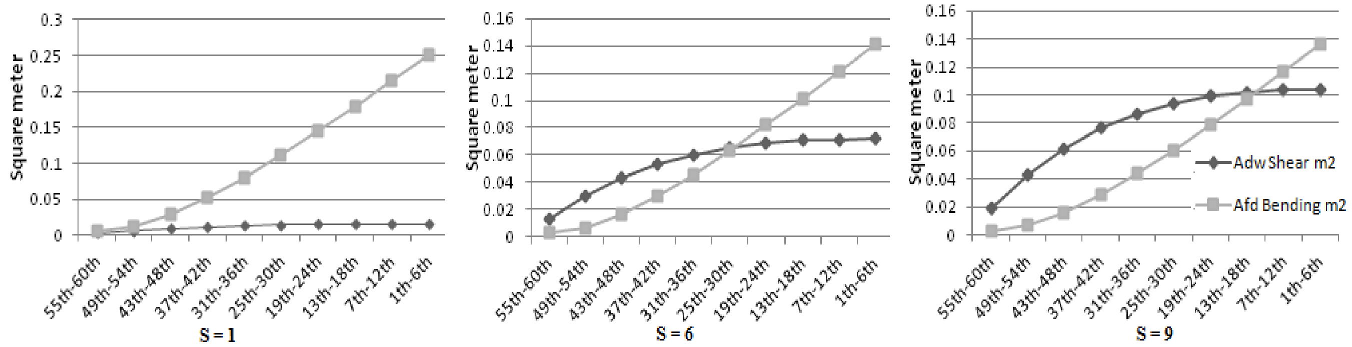


Figure 7 Primary member sizes for the 60 storey diagrid building for different 'S' values

Similarly, 'S' value for 42 and 20 storey diagrid building is calculated. For 42 and 20 storey optimal 'S' value is 4 and 2 respectively. The design has been checked for strength using IS 800: 2007. For 20 storey building, very less sectional area is obtained from this method, which not satisfies the strength check. Hence, for 20 storey building design is done by strength based iterative method.

VI. RESULTS AND DISCUSSION

6.1 Optimal Angle Range

Optimal angle of 60, 42 and 20 storey diagrid building is shown in Fig.8. The optimal angle range for 60 and 42 storey diagrid building is from 62^0 to 75^0. 68 degree and 62 degree model experiences least displacement for 60 storey and 42 storey diagrid building respectively. The optimal angle range for 20 storey diagrid building is from 51^0 to 68^0 and 51 degree model experience the least displacement. Table 6.1 shows the 1^{st} mode period and lateral displacement of diagrid models with various angles.

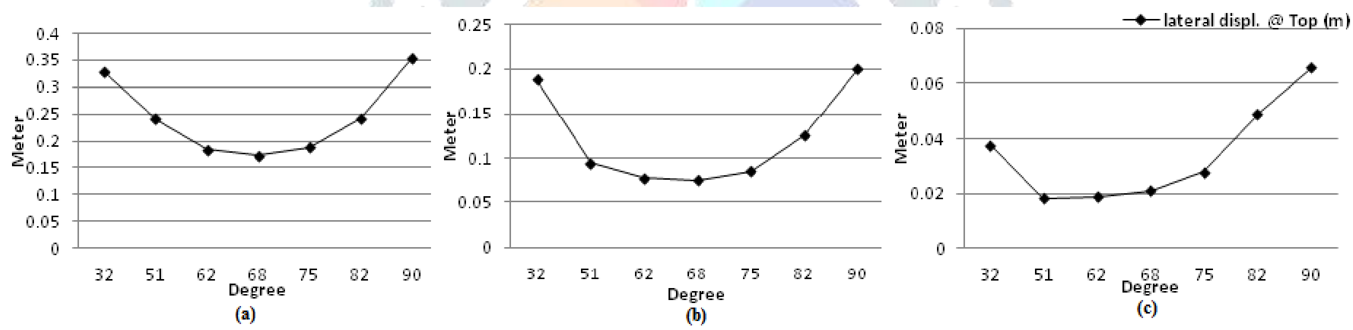


Figure 8 Optimal angle of diagrid buildings (a) 60 storey (b) 42 storey (c) 20 storey

Table 6.1 1^{st} mode period and lateral displacement of 60, 42 and 20 storey diagrid buildings with different angle

Angle	60 storey		42 storey		20 storey	
	1st mode period (sec)	Lat. Displ. @ Top (m)	1st mode period (sec)	Lat. Displ. @ Top (m)	1st mode period (sec)	Lat. Displ. @ Top (m)
32	7.712	0.328	5.332	0.188	1.877	0.0378
51	6.198	0.241	3.757	0.095	**1.293**	**0.0182**
62	**5.447**	**0.184**	**3.387**	**0.078**	**1.286**	**0.0189**
68	**5.331**	**0.173**	**3.435**	**0.076**	**1.398**	**0.0211**
75	**5.538**	**0.188**	**3.736**	**0.086**	1.683	0.0278
82	6.652	0.243	4.652	0.125	2.273	0.0488
90	7.62	0.354	5.247	0.199	2.821	0.0656

6.2 Displacement

The lateral displacements of 20, 42 and 60 storey models are shown in Fig.9, Fig.10 and Fig.11 respectively by different analysis approaches and the top storey displacement is shown in Table 6.2. A reduction in lateral displacement of approximately 72%, 50% and 41% for 20, 42 and 60 storey models respectively have been found by equivalent static method for diagrid models compared to conventional models. Response spectrum method shows a reduction of 69%, 54% and 54% for 20, 42 and 60 storey respectively and time history analysis shows a reduction in lateral displacements of 77%, 66% and 57% for 20, 42 and 60 storey models respectively.

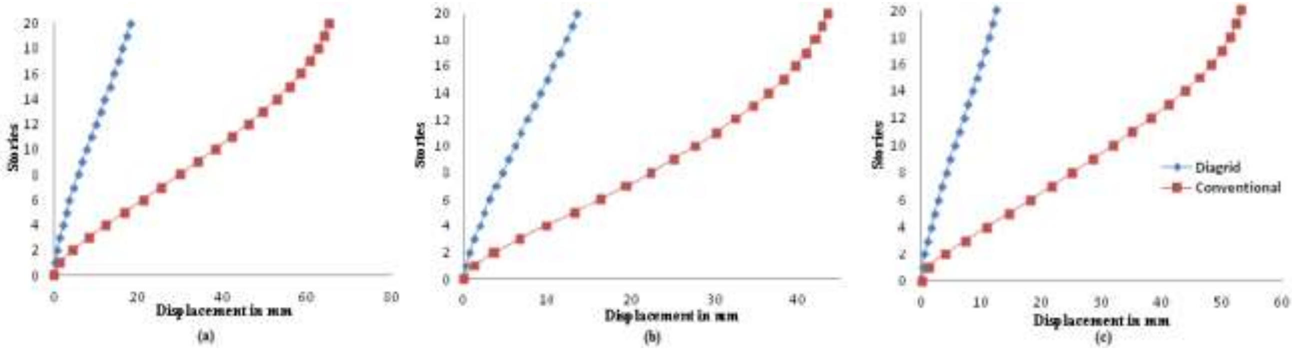


Figure 9 Lateral Displacement for 20 storey models by (a) ESM (b) RSM (c) THA

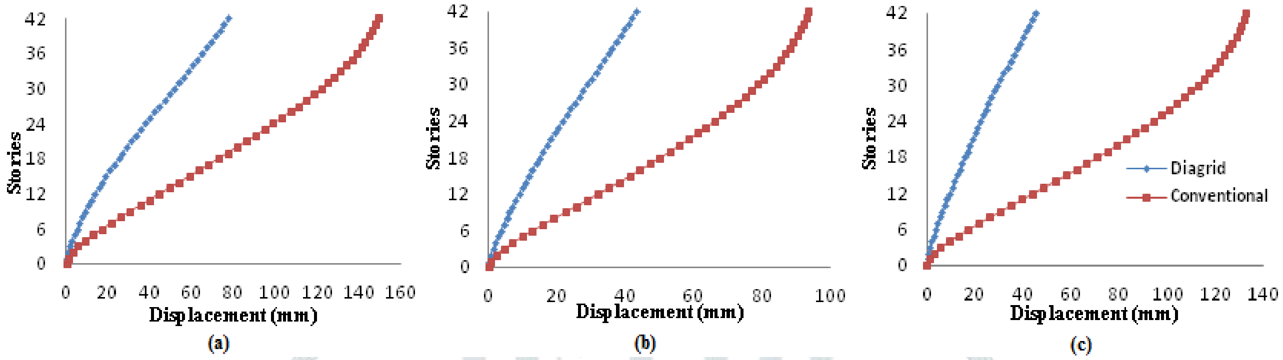


Figure 10 Lateral Displacement for 42 storey models by (a) ESM (b) RSM (c) THA

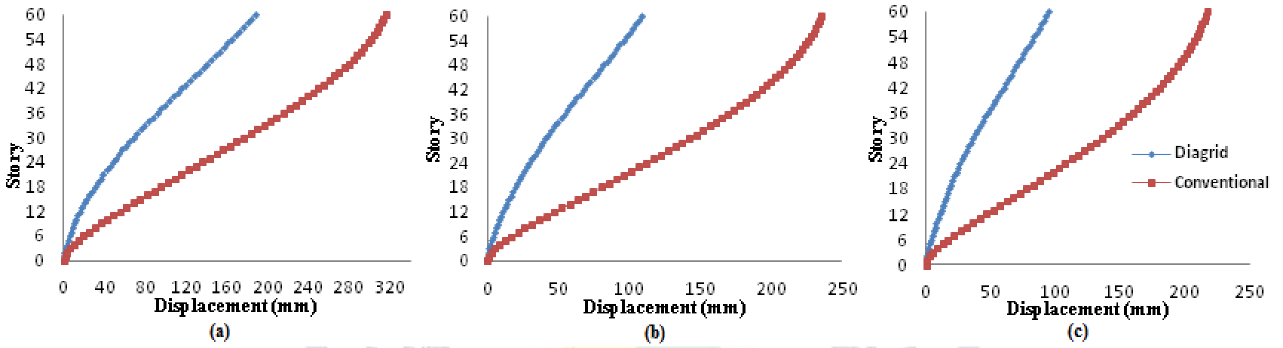


Figure 11 Lateral Displacement for 60 storey models by (a) ESM (b) RSM (c) THA

6.2 Storey Drift

Storey drifts variation of 20, 42 and 60 storey models are shown in Fig.12, Fig.13 and Fig.14 respectively. The minimum drift is found in all diagrid models compared to conventional models by all the analyses. The maximum drift ratio values are given in table 6 for all models by all analysis. As per IS 1893 (part 1): 2016 allowable drift ratio is less than or equal to 0.004.

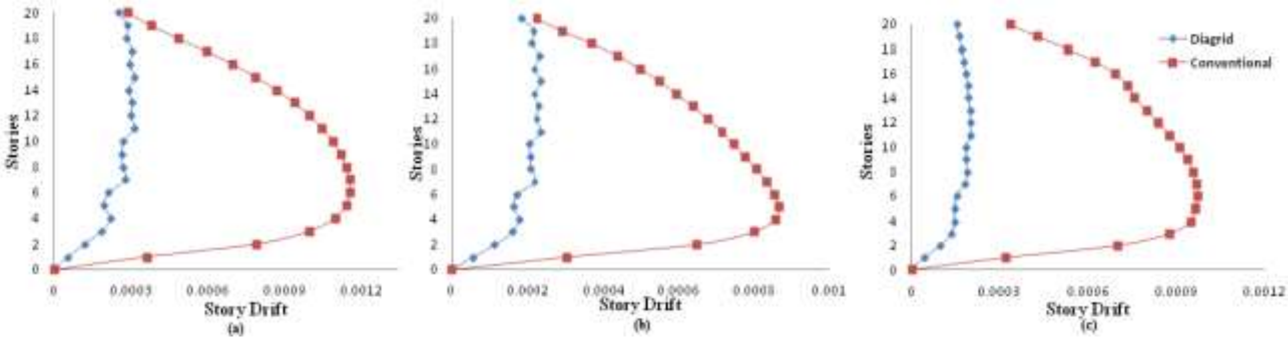


Figure 12 Storey drift for 20 storey models by (a) ESM (b) RSM (c) THA

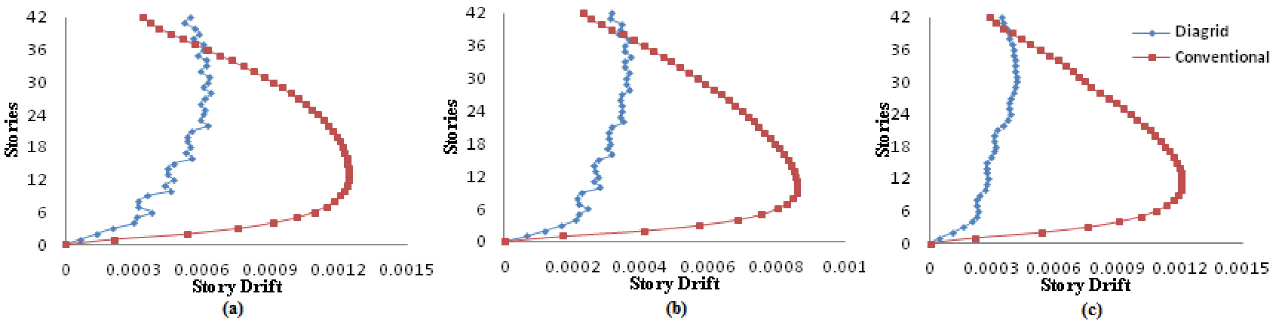


Figure 13 Storey drift for 42 storey models by (a) ESM (b) RSM (c) THA

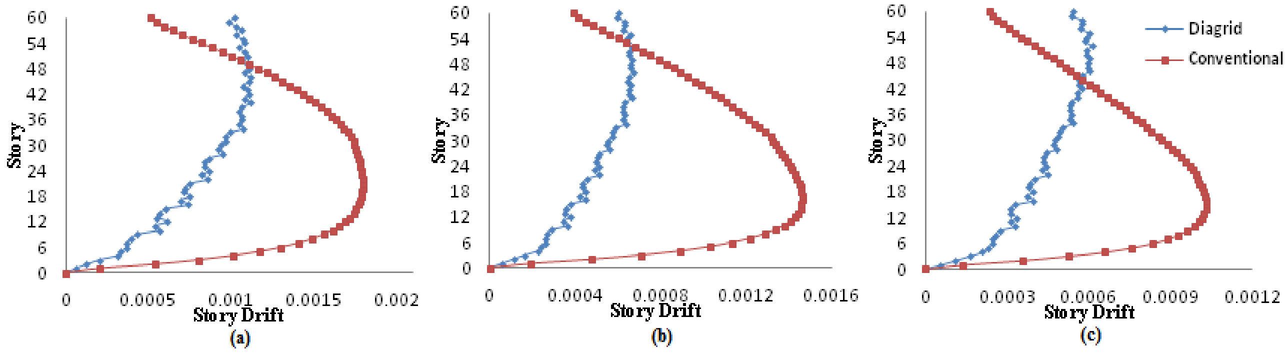


Figure 14 Storey drift for 60 storey models by (a) ESM (b) RSM (c) THA

Table 6.2 Maximum storey displacement, drift ratio and shear values by ESM, RSM and THA.

Equivalent Static Method						
Parameters	**20 Storey**		**42 Storey**		**60 Storey**	
	Diagrid	**Conv.**	**Diagrid**	**Conv.**	**Diagrid**	**Conv.**
Storey Displacement (mm)	18.028	65.076	77.43	149.091	187.621	315.729
Storey Drift	0.000315	0.001156	0.000639	0.001241	0.00112	0.001797
Storey Shear (KN)	4147.942	4395.483	5872.289	6330.0452	7763.011	8961.6635
Response Spectrum Method						
Storey Displacement (mm)	13.458	43.405	43.04	93.5	109.172	235.956
Storey Drift	0.000237	0.000865	0.00037	0.000868	0.000612	0.00146
Storey Shear (KN)	4098.715	4395.437	5449.27	6335.705	7701.538	8994.753
Time History Analysis						
Storey Displacement (mm)	12.37	53.061	44.912	132.904	94.455	216.837
Storey Drift	0.000202	0.000973	0.000412	0.00121	0.000612	0.00141
Storey Shear (KN)	3649.365	4063.007	5315.586	7506.971	7651.724	9199.391

6.3 Storey Shear

Storey shear variation of 60 storey models by equivalent static method is shown in Fig.15. Similar variation is observed for 42 and 20 storey models by all analysis. In diagrid models storey shear is more at the location of nodes. For 42 and 60 storey diagrid models at every 3rd storey there are nodes because of 6 storey diagrid module is used and for 20 storey 4 storey module is used hence, the location of nodes are at every 2nd storey. For all diagrid models storey shear is less compared to diagrid models. Maximum storey shear is given in Table 6.2 for all models by all analysis.

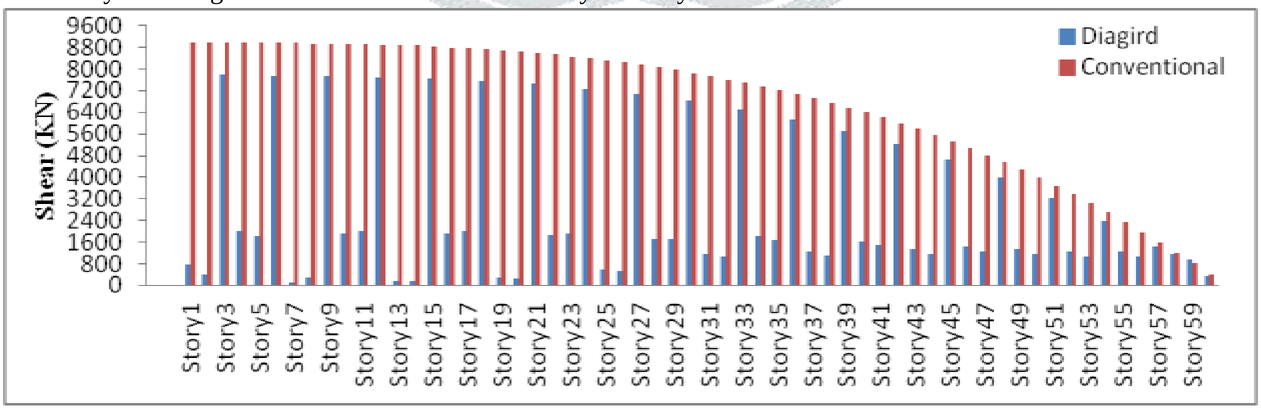


Figure 15 Story shear of 60 story buildings by ESM

6.5 Roof Acceleration, Velocity and Base Force

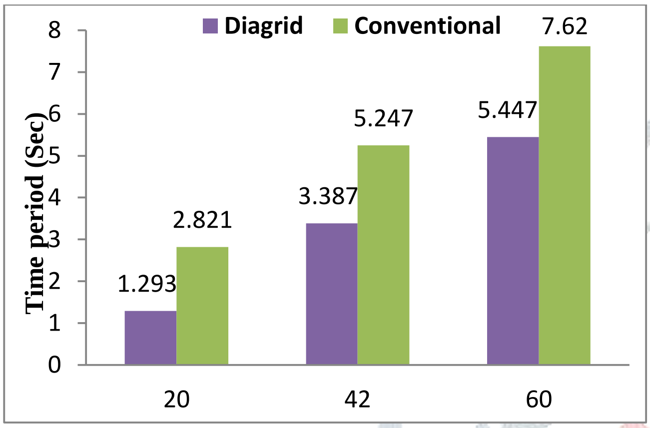
Table 6.3 shows the maximum roof acceleration, maximum roof velocity and base force of all the models under consideration from the time history analysis. It is evident from the results that the minimum roof acceleration and velocity is experienced by the diagrid models.

Table 6.3 Maximum Roof displacement, Acceleration, Velocity and Base force by Time History Analysis.

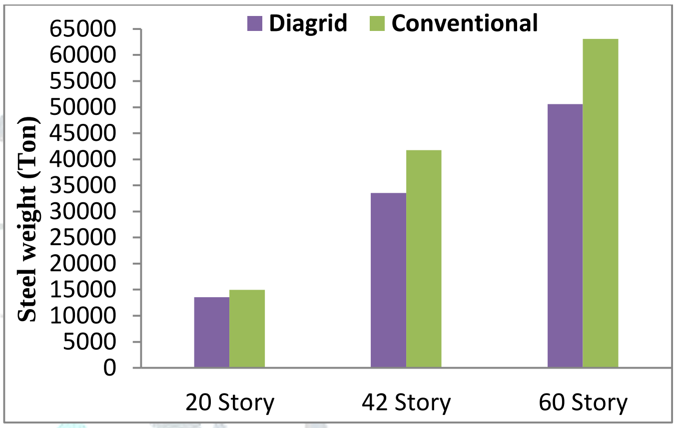
Parameters	20 Storey		42 Storey		60 Storey	
	Diagrid	Conventional	Diagrid	Conventional	Diagrid	Conventional
Roof Acceleration (m/s2)	0.529	0.664	0.40	0.570	0.398	0.548
Roof Velocity (m/s)	69.53	149.88	96.97	152.37	114.86	206.35
Base Force (KN)	4155.46	4396	5849	7522	7769.21	8962.82

6.4 Fundamental Time Period and Steel Consumption

Figure 16 (a) shows the fundamental time period of all the models under consideration. It is evident from the results that all diagrid models have less time period compared to conventional models. This means that diagrid system provides stiff structural configuration and hence the time period reduces. Figure 16 (b) shows the total steel used in tons for diagrid and conventional models, from which it is clear with the use of diagrid system steel consumption is reduced to 10 to 20%.



(a) Fundamental Time Period



(b) Steel Consumption in Tons

Figure 16 Fundamental time period and steel consumption of diagrid and conventional buildings

VII. CONCLUSIONS

From the analysis results by three methods of all models following conclusions are drawn;

1. The optimum angle range for 20 story diagrid building is 51 degree to 68 degree and for 42 storey and 60 storey diagrid building is 62 degree to 75 degree.
2. Significant reduction in lateral displacement, drift and storey shear is seen in all diagrid models compared to conventional models.
3. Roof acceleration and roof velocity is least in the diagrid models and 5 to 10% reduction in base shear is observed in diagrid models compared to conventional models.
4. The time period of diagrid models is very less compared to conventional models due to the increase in stiffness of the structure.
5. Steel usage in diagrid models are found to be 10 to 20% less compared to conventional models. Hence, diagrid buildings are economical than conventional buildings in terms of material consumption.
6. Peripheral diagonals take part in resisting lateral load and gravity loads more efficiently in diagrid models, hence no need of rigid central core in diagrid models.

REFERENCES

[1] Moon K. S. (2005). "Dynamic Interrelationship between Technology and Architecture in Tall Buildings". Thesis (PhD), Massachusetts Institute of Technology, June, 2005.

[2] Moon K. S., Jerome J Connor, John E Fernandez (2007). "Diagrid Structural Systems for tall buildings: characteristics and methodology for preliminary design", Struct. Design Tall Spec. Build. 16(2007), 205–230.

[3] Johan Leonard (2007). "Investigation of shear lag effect in high rise buildings with diagrid system", M.E Thesis, Massachusetts Institute of Technology, Cambridge, United States (2007).

[4] Baker W, Besjak C, Sarkisian M, Lee P, Doo C.S (2010), "Proposed methodology to determine seismic Performance factors for steel diagrid frame structures", Conference proceeding, 13th U.S Japan Workshop (2010).

[5] Khusbu Jani and Paresh V.Patel (2013), "Analysis and Design of Diagrid Structural System for High Rise Steel Buildings, Proceedia Engineering, 51(2013), 92 – 100.

[6] IS 1893(Part I): 2016." Criteria for Earthquake Resistant Design of Structures". Bureau of Indian Standard, New Delhi.