APPLICATIONS OF
MODELLING AND SIMULATION
http://arqiipubl.com/ams eISSN 2600-8084 VOL 4, 2020, 110-124

Reliable Drift of Diagrid Tall Buildings due to Seismic Load

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Submitted 14 February 2020, Revised 11 March 2020, Accepted 18 March 2020.

Abstract: Diagrid structures have become a favorable structural system because of their efficiency in resisting lateral and gravity loads. In addition, they save huge amounts of steel material in the design and construction of tall buildings. This research is concerned about the reliable drift for regular diagrid used in tall buildings and their sustainability in existence of seismic load. The main objective for lateral load resisting system is to satisfy constrained displacement and inter-story drift for tall buildings. The controlled sections process is based on the minimum amount of steel for diagrid elements to conserve specific lateral displacement and inter-story drift. Five groups of tall buildings are considered. Two groups have five models for each with various uniform angles of diagrid with the same height with a view to obtain the reliable angle for diagrid elements. The remaining three groups have six models in each group with various height-to-width aspect ratios, and uniform various diagrid inclination angles with a view to obtaining the reliable cross sections for diagrid elements based on deformation control. An empirical formula is suggested, and verified for the computation of the ratio between bending and shear deformations in existence of seismic load. The results concluded that diagrid buildings may govern by seismic load, sustainability is affected by the diagrid angle and Stiffness based design is a reliable method to control building drift based on an optimum *S*-Parameter.

Keywords: Regular diagrid; Reliable angle; Reliable drift; Seismic load; Sustainability.

1. INTRODUCTION

For urban development, the aesthetic appearance and sustainability for tall buildings are substantial to cope with the remarkable developments in building constructions. The diagrid structure is one of the systems that are attractive to humankind. Previously, tall buildings resistance of gravity loads and lateral loads were evaluated separately using such systems as the braced frames. Recently, most of systems, of which diagrid is a well-known one, are developed to resist gravity and lateral loads simultaneously. This paper has employed the diagrid system as diagrid structures rank among the most efficient systems structurally and architecturally. The first diagrid building is The United Steelworkers Building; it has been constructed in 1963 at Pittsburgh and, designed by Curtis and Davis. The diagrid system had not been used again for many years until Sir Norman Foster has used it in the construction and completion of the Swiss Re Building in London in 2003. There are some well-known examples of the diagrid system buildings such as Hearst Tower in New York and Tour D2 Tower in Paris. Figure 1 shows tall buildings in which diagrid system has been successfully used as a lateral load resisting system [1]–[4].

The reliable configuration process for diagrid tall buildings is governed by the amount of steel material for construction, deformation limits, and efficiency. Many researchers examined the development for different methods of analysis and design of diagrid system. The resisting mechanism of diagrid buildings due to gravity and wind loads and the effect of geometry on the behavior of the structure are studied by [5]–[7]. Modules of diagrid are classified into four different groups including small-rise modules (2-4 stories), mid-rise modules (6-8 stories), high-rise modules more than 10 stories and irregular modules[1]. Comparison between diagrid and conventional structure building lateral stability under various existing seismic shakes is examined by [8]. The results showed that lateral displacement at top for diagrid is less than conventional building by about 30-35%. Diagrid buildings generally be able to resist lateral load without core. So, internal columns designed due to vertical load only [9]. A new high performance steel with tensile stress 800 MPa to solve the problems of stress concentration at nodes of diagrid is suggested by [10]. Giulia Milana *et al.* [11] focused on the sustainability, safety, serviceability of diagrid tall building, also compared to a typical outrigger building.

Performance index is defined to calibrate the sustainability aspect. The performance of twisted, tilted and freeform diagrid towers are studied by [12].The results showed that the twisted tower generally performs better than the straight one for across

(a) (b) (c) (d)

Figure 1. (a)) United Steelworkers Building, Pittsburgh [1], (b) Swiss Re, London [2], (c) Hearst Tower, New York [3], (d) Tour D2, Paris [4]

wind response due to vortex shedding. Jinkoo Kim [13] examined a 36-story diagrid and tubular steel system with inner steel frame. The results showed that the slope of braces affected the shear lag and the lateral strength. The circular plan diagrid structure showed higher strength than the square plan diagrid structure. The diagrid structures displayed higher strength than the tubular structure. Chengqing Liu *et al.* [14] studied Guangzhou West Tower high rise diagrid tube in tube structure which is subjected to the shaking table test and time-history analysis. The results revealed that, Diagrid tube in tube structure appropriate a good seismic performance. The significant modes are the first and second translational modes. Whiplash effect is not significant. William Baker *et al.* [15] presented a new method for determining seismic performance factors of steel diagrid framed systems. The proposed method reduced the efforts to compute response modification factor based on nonlinear static analysis rather than the iterative nonlinear dynamic time history analysis.

In this paper, wind and seismic effect on 80-story diagrid tall building are examined. The analyses are conducted to control the lateral displacement and inter-story drift. The ASCE/SEI 7-10 [16] is used to generate wind and seismic loads. The stiffness-based design proposed by [5] is used. Then, five groups of diagrid buildings are analyzed in existence of seismic load to enhance the reliable amount of steel material for diagrid elements and inter-story drift. The ratio between bending and shear deformation at top is used to satisfy allowable lateral displacement for the buildings ($H/500$) and constrained maximum inter-story drift around almost 0.003 to confirm that the building behavior is in the elastic zone

2. STIFFNESS-BASED DESIGN

2.1 General Assumptions

This paper has employed stiffness-based design [5]. Simplified formulae are derived for the computation of diagrid element cross sections. The basic assumption for the approach defines the building as a simple cantilever with neglecting shear-lag to simplify the distribution of loads. The diagrid elements are assumed to resist moment and shear by axial effect only using pin connections. The approach is based on a lot of parameters which are modulus of elasticity of steel material, the cross sectional area of the element, the length of the element, and the angle of the diagrid elements. Every building is divided into modules according to its height. The module is defined as a number of stories connected to a single level of diagrids. Figure 2 shows the case of an eight-story module and plan description. The diagrid elements are subdivided in two categories: flange and web. The cross sections areas of diagrid elements on the flange A_{df} and web A_{dw} in the *m*-th module of diagrid are obtained by [5].

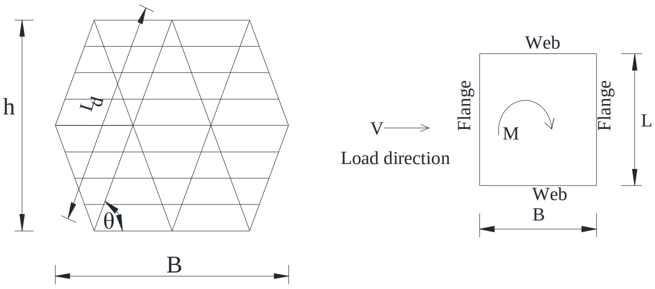
$$A_{df} = \frac{ML_d(1+S)\alpha H}{(N_F+\delta)EB^2 hS \sin\theta^2} \tag{1}$$

$$A_{dw} = \frac{VL_d(1+S)\alpha}{2N_w EH \cos\theta^2} \tag{2}$$

2.2 The Ratio between Bending and Shear Deformation (S-Parameter)

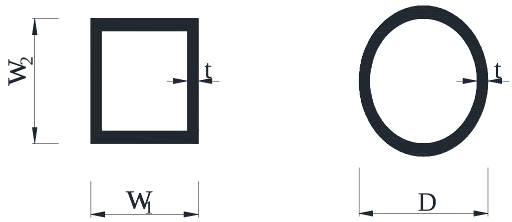
The ratio between bending and shear deformation at top of the building is an important parameter for optimal stiffness-based design method. An empirical formula was suggested by [17]:

$$S = \frac{H}{Bf \tan\theta} \tag{3}$$



(a) (b)

Figure 2. (a) Side view of eight story module for diagrid structure, (b) Plan description



(a) (b)

Figure 3. (a) Vertical columns and beams cross section, (b) Diagrid cross section

Table 1. Element types and material properties

Element	Type	Node degree of freedom	Material type	E (kN/m^2)	γ (kN/m^3)
Slab	3 or 4 node shell	6	Concrete	248×10^5	25.56
Diagrid	Line element	6	Steel HSS circular	200×10^6	76.97
Vertical columns	Line element	6	Steel HSS square	200×10^6	76.97
Beams	Line element	6	Steel HSS rectangular	200×10^6	76.97

The optimum value for f factor is proposed by [5] between 0.5 and 1 for diagrid structures then, they suggested an empirical equation between the optimal S value and the aspect ratio for diagrid structures for wind load:

$$S = \frac{H}{B} - 3 \text{ for } \frac{H}{B} \geq 5 \text{ and } 60^{\circ} \leq \theta \leq 70^{\circ} \tag{4}$$

3. THREE DIMENSIONAL MODELLING

3.1 Finite Element Method

The finite element method is used to examine the behavior of building models. Both SAP2000 [18] and ANSYS [19] programs have been used to verify the input data strategy. Then, SAP2000 has been used for analyzing all models. The used finite elements in all models using SAP2000 are frame elements and shell elements. The beams and columns are modelled as frame elements (line elements). The slabs are modelled as thin-shell elements including the flexibility of slabs. Restraints are used to restrain displacement at joints with a specified value which is almost zero at the base level of buildings. The building's main finite elements in ANSYS are BEAM188 and SHELL181. All beams, vertical columns, and diagrid elements are simulated using BEAM188. The BEAM188 is a linear (two-node) line element which has a cross section unrestrained for warping. The slabs are simulated using SHELL181 which is a four-node element.

3.2 Definition of Models

The diagrid system is used to resist lateral and gravity loads. The location of diagrid is exterior along the perimeter for the plane area of building. It is empirically suggested that the diagrid resists mainly the lateral load and part of gravity load. The frame system's main objective is to resist gravity load and part of the lateral load. Some requirements are needed for modelling the structures. Element types and material properties are indicated in Table 1. Two grades of standard steel ASTM A500 [20]: grade B, $F_x = 317158.9$ kN/m^2 for HSS rectangular sections, and grade B, $F_y = 289579.83$ kN/m^2 for HSS circular sections are used. Definitions of the cross sections for all elements are needed for the analysis. For vertical columns and beams, the cross section used is rectangle hollow structural sections (HSS rectangular) as shown in Figure 3(a). For diagrid element, the cross section used is circular hollow structural sections (HSS circular) as shown in Figure 3(b). All cross sections are coated with thin film intumescent for fire resistance. A FORTRAN program is constructed to generate required data $2K file for SAP2000. The mass source used is dead load plus 25% of live load for all models. All shell elements are meshed with maximum size 1 m. All slabs are concrete sections which have $F_{cu} = 27579$ kN/m^2 and 20 cm thickness.

Table 2. Various intensity parameters for seismic load

	S_{DS}	S_{D1}	$T_L(S)$
Zone 1	0.3627	0.2059	8
Zone 2	0.256	0.1344	12
Zone 3	0.2242	0.0816	6

The diagrid elements cross sections are generated by stiffness-based design for flange and web by (1) and (2) with an assumption that motion control the design. The ratio between bending and shear deformations at top of the building is used to satisfy allowable lateral displacement. The lateral displacement is limited by $(H/500)$. The effect of changing cross section of diagrid along the height for each module with the maximum of web and flange area is considered.

The reliable configuration model is generated by trial-and-error processes. The design cycle has been illustrated later in section 4. For all models, the ring beams cross section used is HSS rectangle (30 × 60 cm) with wall thicknesses (0.8 × 1.3 cm), and the inner beams cross section used is HSS rectangle (20 × 45 cm) with wall thicknesses (0.9 × 1.4 cm). The main parameters to be defined for the models are story height, building height, plan widths, number of modules, number of floors in one module, number of diagonals of flange side, and number of diagonals of web side.

Hereafter is an analysis of an 80-story diagrid building and five groups of diagrid buildings classified as follows: groups one and two have five models for each with various uniform inclination of diagrid with the same height, while other groups have six models each with various aspect ratios, and various diagrid inclinations. For the 80-story diagrid building, the equivalent lateral force is computed for three zones of different seismic intensity with $C_t = 0.0488, x = 0.75, R = 1.0, I_e = 1$, and site class C. Parameters for seismic intensities are shown in Table 2. The wind load is generated based on main parameters: wind speed of 100 mph, exposure type B, $K_{zt} = 1, G = 0.921$ and $K_D = 0.85$ as per [16].

For the five groups, the equivalent lateral seismic force is generated using ASCE7-10[16]. The design seismic parameters are $S_{DS} = 0.2242, S_{D1} = 0.0816, C_t = 0.0488, x = 0.75, R = 1.0$, site class is C, $I_e = 1.0$, and $T_L = 6$ s. The load from cover, finishing, and walls are assumed to be 4.5 kN/m^2 for all groups except the second group which is assumed to be 2.5 kN/m^2. All buildings are subjected live load equal to 4.0 kN/m^2 except second group models which are subjected to 3.0 kN/m^2. Plan dimensions for buildings are 40 m × 40 m with four openings 6.0 m × 6.0 m, and 16 core columns except buildings for group two which are 32 m × 32 m with an opening 8.0 m × 8.0 m, and 4 core columns.

4. METHODOLOGY

The cyclic process for stiffness-based design due to equivalent lateral seismic force is summarized as following:

a) Define the main parameters for diagrid model which are building dimensions, height, inclination angle of diagrid from horizontal, story height, number of diagrid elements on web and flange sides, dead and live loads, and number of inner columns.
b) Generate $2k file for SAP2000 for auto-select diagrid and inner column cross sections, then design vertical inner column due to gravity loads and generate the starting equivalent lateral seismic force.
c) Distribute the lateral force between diagrid and inner frame systems with percentage which will be examined later in section 8.
d) A FORTRAN program is constructed for stiffness-based design of diagrid elements which varies the value of *S*-Parameter from 0.5 to 10 with equally step 0.1(total steps number = 95) to satisfy the best *S*-Parameter which can give the minimum steel weight required for diagrid elements.
e) Generate $2k file using FORTRAN program with the new properties of diagrid and inner vertical columns, then apply the meshing process and analyze the model.
f) Extract the base shear, top lateral displacement, and maximum inter-story drift
g) Check the base shear to satisfy the used base shear in stiffness-based design and if not go to step 4 to redesign and reanalyze the model with the extracted new lateral force distribution.
h) Check the target lateral displacement and inter-story drift, if not satisfied change the distribution of lateral force between diagrid and inner frame, then go to step 3.

5. VERIFICATION MODEL

The verification is presented by analyzing an 80-story diagrid building using SAP2000 and ANSYS v18.1 software to emphasis the mathematical model for the buildings. Modal and seismic analyses using equivalent lateral force are proposed. The building has total height of 320.0 m with typical story height of 4.0 m. The diagrid elements have an inclination angle of 71.56° having ten stories in one module. All diagrid and inner vertical columns cross sections are shown in Table 3. Various views of building are shown in Figure 4. The model lateral seismic force in *x*-direction is shown in Figure 5. Figures 6 and 7 show the first forty modal periods, and the lateral displacement in *x*-direction due to equivalent seismic lateral force. The results show that the closer results in both SAP2000 and ANSYS with a negligible error.

6. SEISMIC VERSUS WIND ANALYSIS

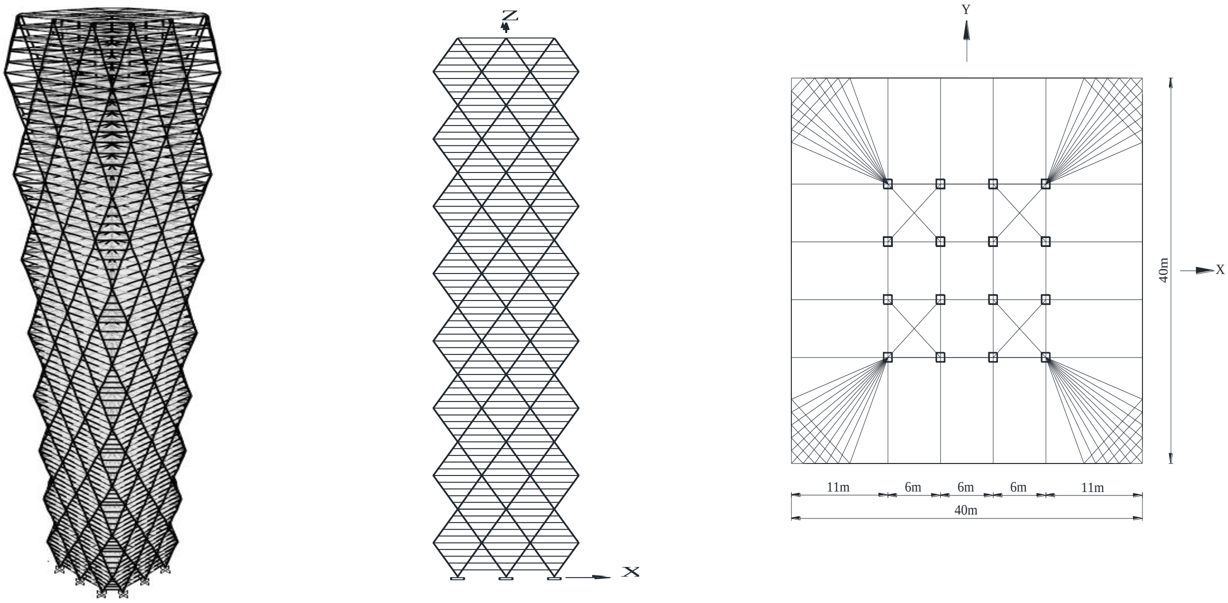
Modal, wind and equivalent lateral seismic analyses are proposed for the verification 80-story model. Diagrid cross section area for different cases of seismic and wind are designed using stiffness-based design. Area of diagrid element in each floor is shown in Figure 8. The model lateral forces in *x*-direction are shown in Figure 9.

Referring from Figures 10 to 12 and Table 4, it can be concluded that:

Table 3. Sections for columns, and diagrid

Story no.	Dimensions[a] (cm)	Dimensions[b] (cm)
1-5	135×135×4.6	174.3×5.8
6-10	135×135×4.6	174.3×5.8
11-15	125×125×4.4	159.1×5.3
16-20	125×125×4.4	159.1×5.3
21-25	115×115×4.2	142.3×4.7
26-30	110×110×4.0	142.3×4.7
31-35	105×105×4.0	123.9×4.1
36-40	095×095×3.8	123.9×4.1
41-45	095×095×3.8	104.2×3.5
46-50	090×090×3.6	104.2×3.5
51-55	085×085×3.4	96.5×3.2
56-60	080×080×3.2	96.5×3.2
61-65	075×075×3.0	84.0×2.8
66-70	065×065×2.6	84.0×2.8
71-75	060×060×2.4	63.1×2.1
76-80	055×055×2.2	63.1×2.1

[a]Dimensions are referred to inner vertical column ($W_1 \times W_2 \times t$)
[b]Dimensions are referred to outer diagrid ($D \times t$)



(a) (b) (c)

Figure 4. Verification model views: (a) 3D view, (b) *XZ* view, (c) Cumulative plan view

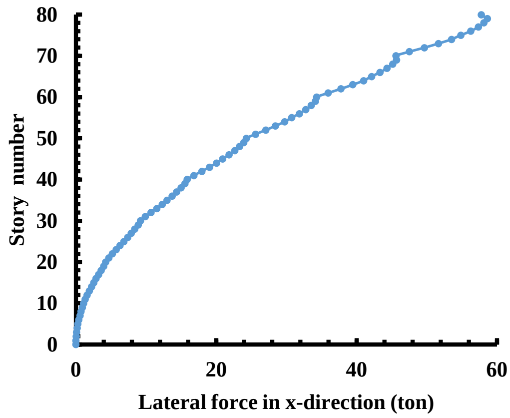


Figure 5. Equivalent lateral seismic force for 80 story diagrid building

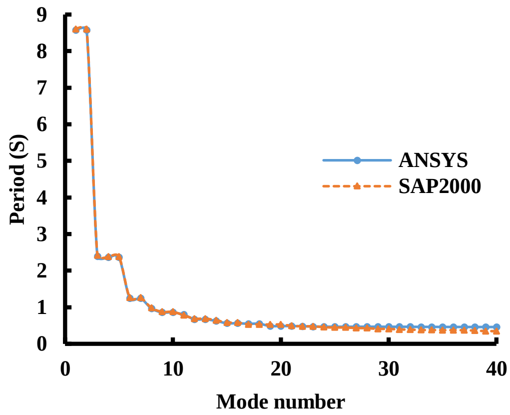


Figure 6. First 40 modal periods for 80 story diagrid building

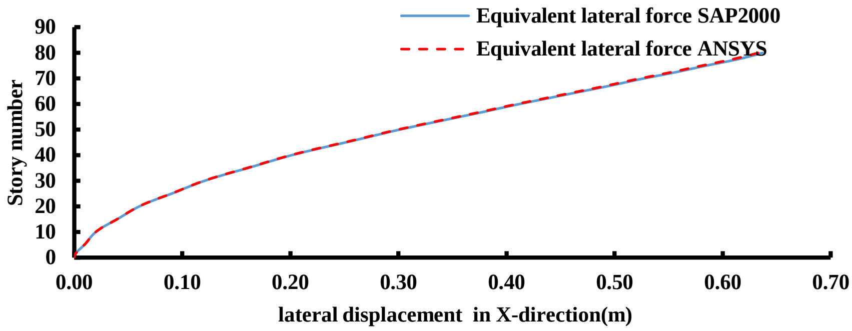


Figure 7. Lateral displacement for 80-story diagrid building

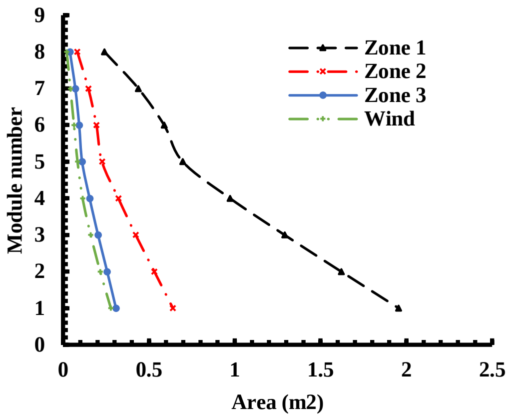


Figure 8. Area of diagrid element each module due to seismic and wind design

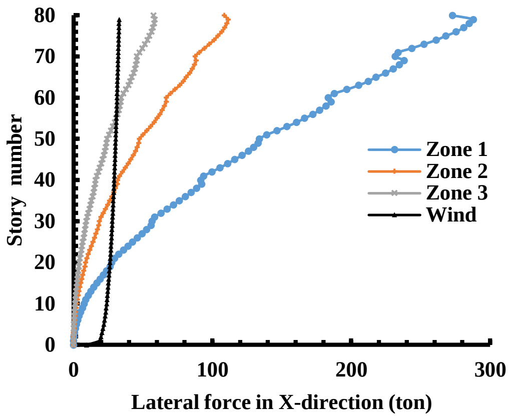


Figure 9. Equivalent lateral force for wind and various seismic zones

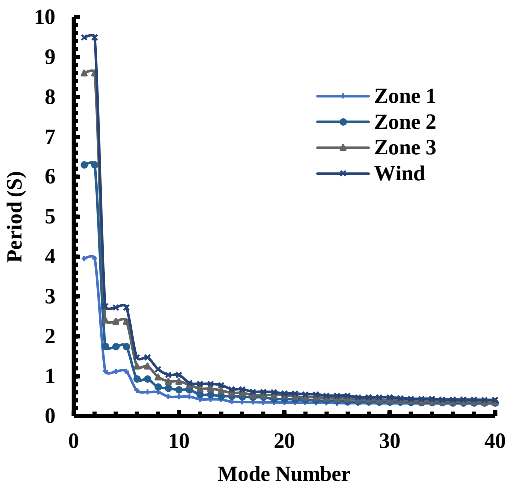


Figure 10. First 40 modal periods for 80-story due to wind and seismic design

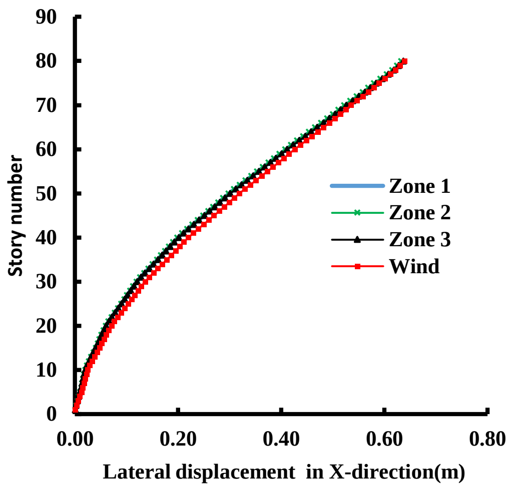


Figure 11. Lateral displacement for 80-story due to wind and seismic design

Table 4. 80-story diagrid building

	Diagrid total weight (ton)	First mode period (s)	Disp. at top (m)	Max inter-story drift	Base shear (ton)
Zone 1	62002	3.952	0.638	0.0031	9876
Zone 2	20421	6.299	0.633	0.0031	3317
Zone 3	9823	8.604	0.637	0.0030	1718
Wind	7792	9.495	0.639	0.0029	2267

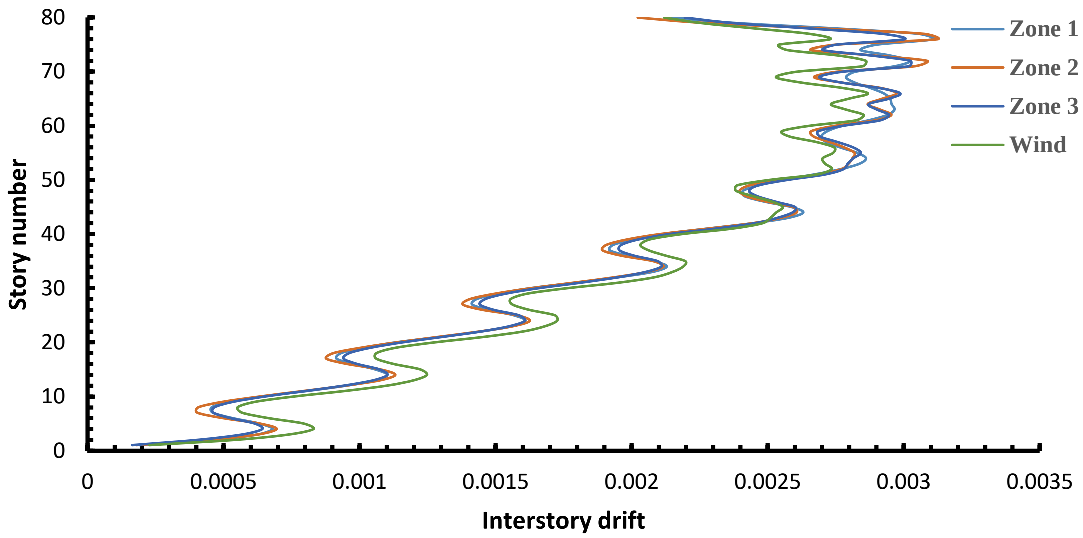


Figure 12. Inter-story drift for 80-story due to seismic and wind design

- High seismic zones give stiff model in design and large base shear.
- Low seismic zones give more flexible building with high period of vibration.
- Period of vibration is affected by wind and seismic design zones.
- The maximum lateral displacement in x-direction at top and maximum inter-story drift are controlled to near about 64 cm and 0.003 respectively.
- Diagrid building need more steel material for high seismic zone to control the lateral displacement and inter-story drift much more than wind so, it may be governed by seismic rather than wind.

7. OPTIMIZATION PROCESS FOR DIAGRID ANGLE

The study is conducted to predict the optimum uniform angle for diagrid elements. The first two groups of tall buildings (with five models for each with various uniform diagrid angles with the same height) are targeted here with a view to obtaining the optimum angle for diagrid elements. The first consists of five models which have heights 320 m with different inclination angles from horizontal. These angles are 50.19° for the four-story module, 60.94° for the six-story module, 67.38° for the eight-story, 71.56° for the ten-story module, and 80.53° for the twenty-story module. The buildings have typical story height of 4.0 m. The HSS square steel sections having outer dimensions of 135 cm × 135 cm and 50 cm × 50 cm with variation between them and wall thickness ranges between 4.6 cm and 2.0 cm are used for the 16 core columns. Diagrid HSS circular steel sections of outer diameter varying between 284.0 cm and 25.3 cm with wall thickness ranges between 9.5 cm, and 0.8 cm are used. The second group consists of five models which have heights 180m with different inclination angles. These angles are 48.36° for the four-story module ,59.34° for the six-story module, 66.03° for the eight-story module, 70.42° for the ten-story module, and 79.919° for the twenty-story module. The buildings have typical story height 3 m. Various *X*-*Z* and cumulative plan views for the two groups are shown from Figure 13 to 16. The HSS square steel sections having outer dimensions of 135 cm × 135 cm and 40 cm × 40 cm with variation between them and wall thickness ranges between 4.6 cm and 1.6 cm are used for the 4 core columns. The HSS circular steel sections of outer diameter varying 153.1 cm and 22.9 cm with wall thickness ranges between 5.1 cm and 0.8 cm are used for diagrid elements. Distribution of cross section area of diagrid element for each module along height for the two groups is shown in Figures 17 and 18.

Figures 19 and 20 and Tables 5 and 7 show the minimum weight of steel diagrid elements with different inclination angles to satisfy the allowable lateral displacement of $(H/500)$, constrained maximum inter-story drift of 0.003. The results have indicated that the best angle for buildings with heights 320m is close to 71.56° and 66.03° for buildings having height 180 m. Tables 5 to 8 indicate the best *S*-Parameter, the lateral displacement at top, the maximum inter-story drift, the first modal period of vibration, and the values for the contribution of diagrid and inner frame to resist lateral and gravity loads for different inclination of diagrid. The results showed that best *S*-Parameter is decreased with increasing angle of diagrid in most cases. The best *S*-Parameter has satisfied lateral displacement near to 64 cm and 36 cm for buildings with 320 m and 180 m heights respectively and constrained maximum inter-story drift near to 0.003. The buildings with best configuration have not a significant effect on the period of vibration for the first mode. The contributions of inner frame system to resist lateral load may be increased with increasing the diagrid angle. Diagrid elements can resist more than 50% of gravity loads for different diagrid angles.

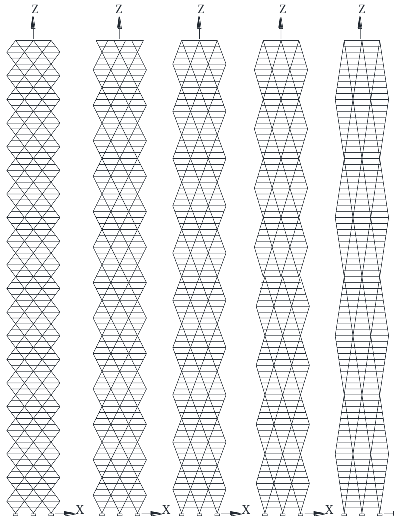


Figure 13. *X-Z* view of group 1 with heights 320 m

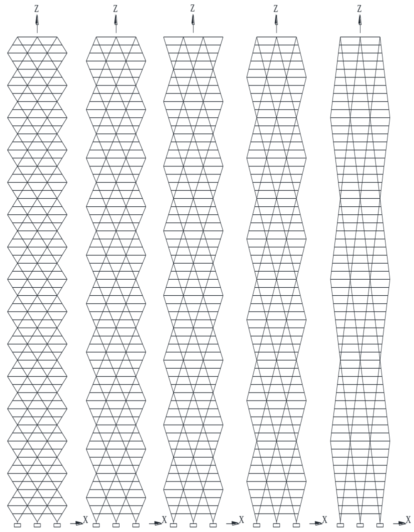
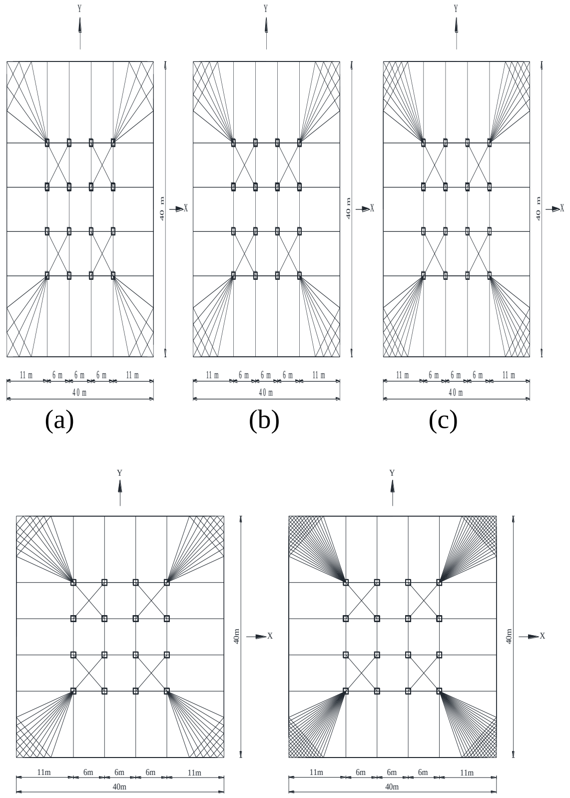


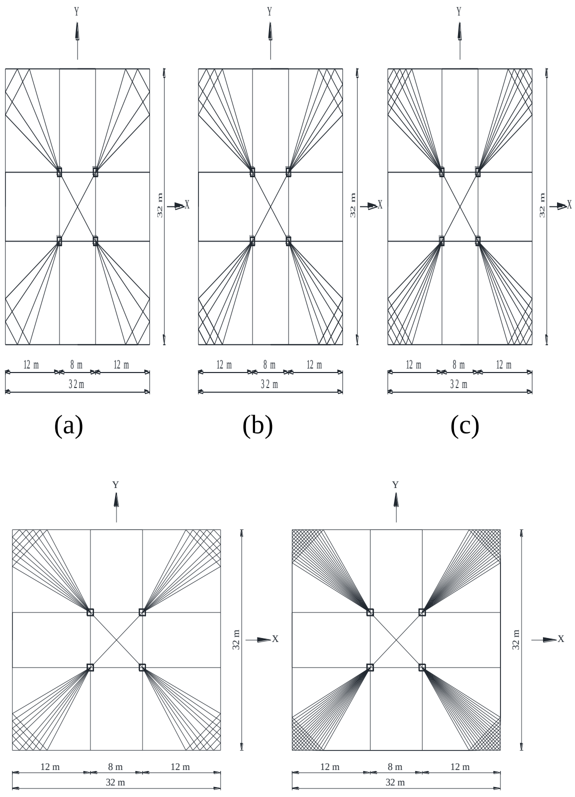
Figure 14. *X-Z* view of group 2 with heights 180 m



(a) (b) (c)

(d) (e)

Figure 15. Cumulative plan view of group 1: (a) Diagrid angle 50.19°, (b) Diagrid angle 60.94°, (c) Diagrid angle 67.38°, (d) Diagrid angle 71.56°, (e) Diagrid angle 80.5°



(a) (b) (c)

(d) (e)

Figure 16. Cumulative plan view of group 2: (a) Diagrid angle 48.36°; (b) Diagrid angle 59.34°; (c) Diagrid angle 66.03°; (d) Diagrid angle 70.42°; (e) Diagrid angle 79.9°

8. OPTIMIZED S-PARAMETER

Optimization of *S*-Parameter to satisfy the allowable lateral displacement and maximum inter-story drift is conducted based on the minimum amount of steel for diagrid elements. The study has been conducted for the range of best inclination of diagrid elements ranging from 60° to 75°. A parametric study is carried out for 90 models with different angles and aspect ratio to compute the optimum *S*-Parameter. A nonlinear regression model is done by SPSS v16 [21] for the 90 model to propose an empirical equation for the optimum *S*-Parameter. The empirical proposed formula is:

$$S = \left(\frac{H}{1.152B\tan\theta}\right)^{1.439}, \frac{H}{B} \geq 3, 60° \leq \theta \leq 75° \quad (5)$$

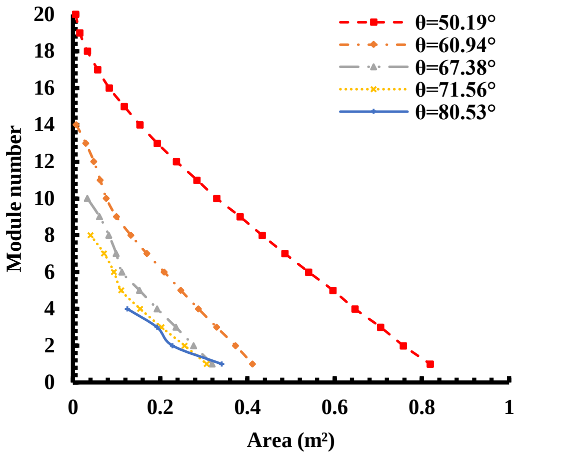


Figure 17. Area of diagrid element for each module (Group 1)

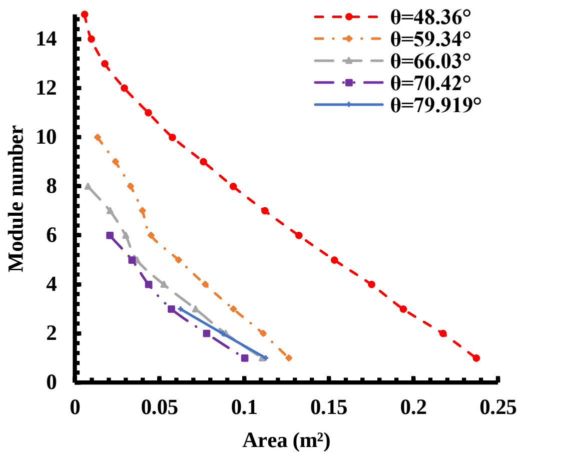


Figure 18. Area of diagrid element for each module (Group 2)

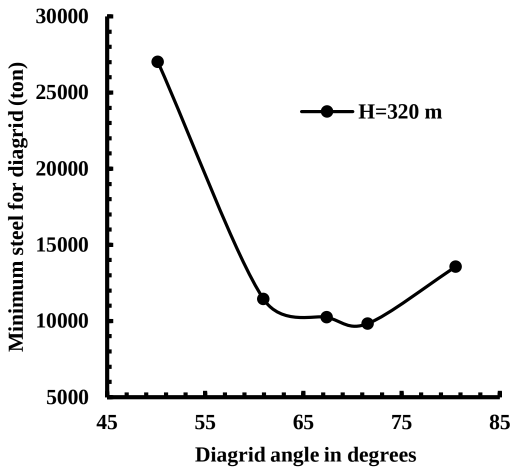


Figure 19. Group 1 (best inclination angle for diagrid)

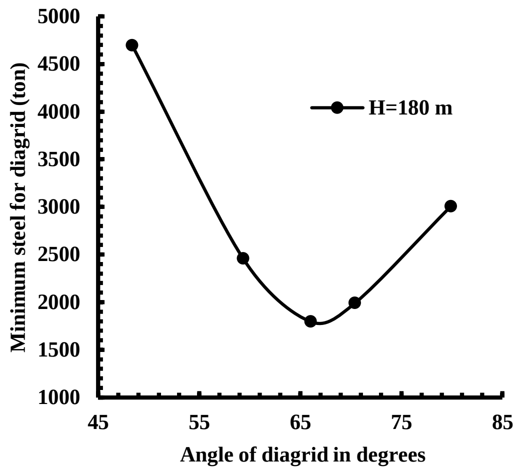


Figure 20. Group 2 (best inclination angle for diagrid)

Table 5. Group 1 (Controlling of buildings with height 320 m)

Diagrid inclination angle	Best *S*-Parameter	Diagrid weight (ton)	Lateral displacement at top (m)	Maximum inter-story drift	Mode 1 period (s)
50.19	3.0	26996.5	0.6414	0.0035	8.022
60.94	6.4	11439.7	0.6374	0.0031	8.345
67.38	5.0	10238.9	0.6429	0.0031	8.568
71.56	3.3	9823.61	0.6368	0.003	8.603
80.53	1.3	13559.5	0.6378	0.0027	9.118

Table 6. Group 1 (Distribution of loads for buildings with height 320 m)

Diagrid inclination angle (degree)	% Gravity load		% Equivalent lateral load	
	Diagrid	Inner frame	Diagrid	Inner frame
50.19	55.52	44.48	100	0.0
60.94	52.19	47.81	89	11
67.38	51.81	48.19	83.5	16.5
71.56	52.33	47.67	80	20
80.53	55.76	44.24	72	28

Table 7. Group 2 (Controlling of buildings with height 180 m)

Diagrid inclination angle	Best *S*-Parameter	Diagrid weight (ton)	Lateral displacement at top (m)	Maximum inter-story drift	Mode 1 period (s)
48.36	3.5	4695.31	0.3564	0.0035	4.906
59.34	5	2459.00	0.3583	0.0031	5.109
66.03	3	1795.98	0.589	0.0031	5.157
70.42	2.2	1991.76	0.361	0.003	5.270
79.919	0.9	3007.69	0.355	0.0028	5.570

Table 8. Group 2 (Distribution of loads for buildings with height 180 m)

Diagrid inclination angle (degree)	% Gravity load		% Equivalent lateral load	
	Diagrid	Inner frame	Diagrid	Inner frame
48.36	63.41	36.59	100	0
59.34	62.81	37.19	91	9
66.03	63.03	36.97	79.5	20.5
70.42	63.88	36.12	78.5	21.5
79.919	66.97	33.02	68	32

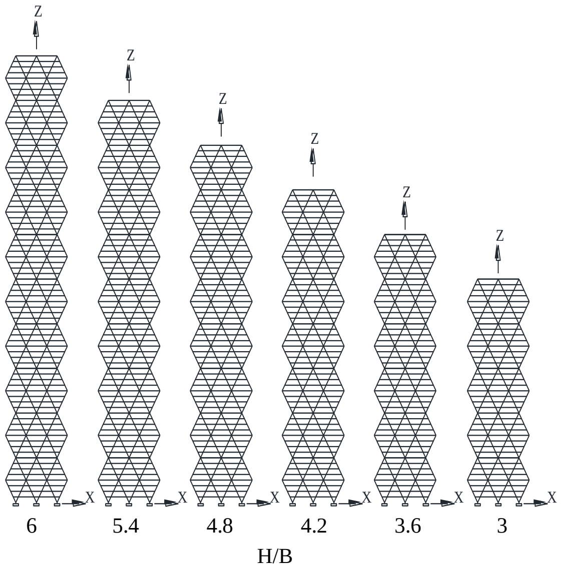


Figure 21. *X*-*Z* view for the third group models (Diagrid angle 60.94°)

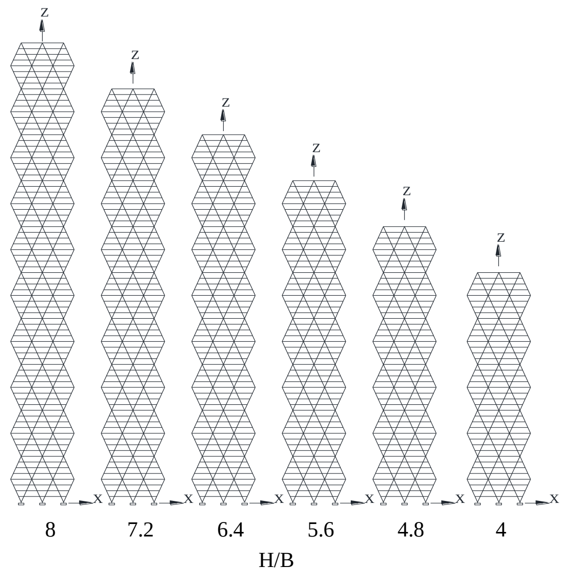


Figure 22. *X*-*Z* view for the fourth group models (Diagrid angle 67.38°)

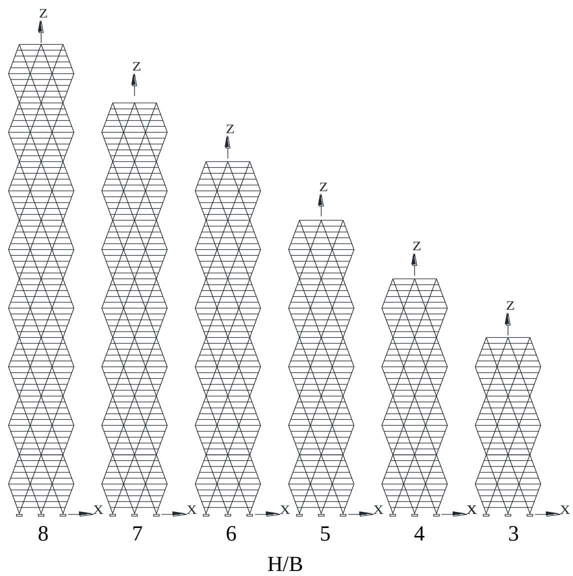


Figure 23. *X*-*Z* view for the fifth group models (Diagrid angle 71.56°)

The remaining three groups which have various heights and diagrid inclinations are studied to check the validity of the proposed formula for *S*-Parameter. The HSS square steel sections having outer dimensions of 135 cm × 135 cm and 50 cm × 50 cm with variation between them and wall thickness ranges between 4.6 cm and 2.0 cm are used for the 16 core columns. Diagrid HSS circular steel sections of outer diameter varying between 178.6 cm and 39.7 cm with wall thickness ranges between 6.0 cm, and 1.3 cm are used. The third group consists of six models which have different aspect ratios from 6.0 to 3.0 with story height 3m as shown in Figure 21. The diagrid angle is 60.94°. The fourth group consists of six models which have aspect ratios from 8.0 to 4.0 with story height 4m as shown in Figure 22. The diagrid angle is 67.38°. The fifth group also consists of six models which have different aspect ratios from 8.0 to 3.0 with story height 4.0 m as shown in Figure 23. The diagrid angle is 71.56°. Distribution of cross section area of diagrid element for each module along height is shown in Figures 24 to 26.

Figures 27 to 29 show the amount of steel for diagrid elements to satisfy the *S*-Parameter with various aspect ratios. Figure 30 shows the actual and predicted best *S*-Parameter for different aspect ratios with various best inclinations. Table 9 shows the computed error for best S-Parameter using the proposed formula. The results showed that the best *S*-Parameter is increased with the increase of aspect ratio then, bending deformations exceeds shear deformations with increasing aspect ratio. The suggested empirical formula for best *S*-Parameter is acceptable for a range of diagrid angles between 60° and 75°**.** Figure 31 shows the contributions of inner frame for different groups to resist lateral load. The results showed that the inner frame contributions increased with decreasing in aspect ratio.

Figures 32 to 37 and Table 10 show the lateral displacement and inter-story drift for various models at each floor. The results have indicated that all models are constrained to satisfy lateral displacement ($H/500$) and maximum inter-story drift is equal to about 0.003.

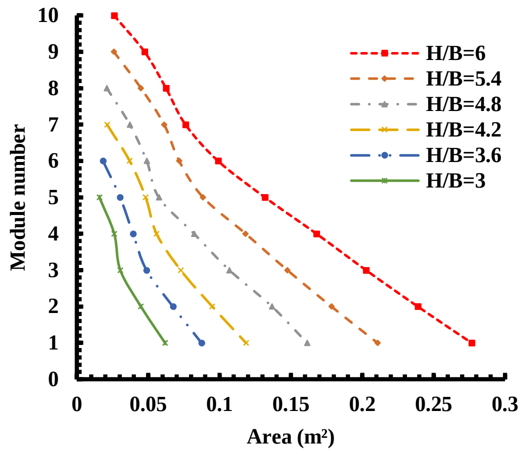


Figure 24. Third group models (Area of diagrid element for each module)

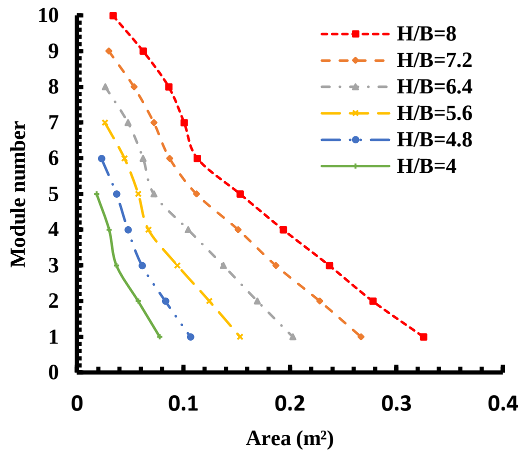


Figure 25. Fourth group models (Area of diagrid element for each module)

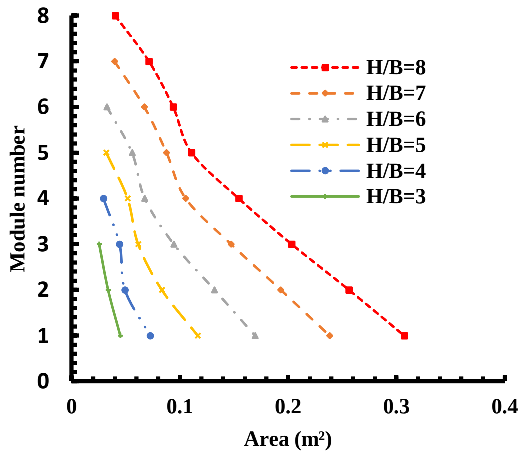


Figure 26. Fifth group models (Area of diagrid element for each module)

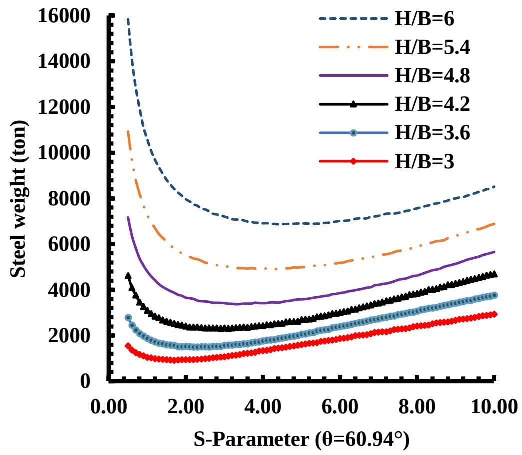


Figure 27. Third group models (amount of steel for various *S*-parameter)

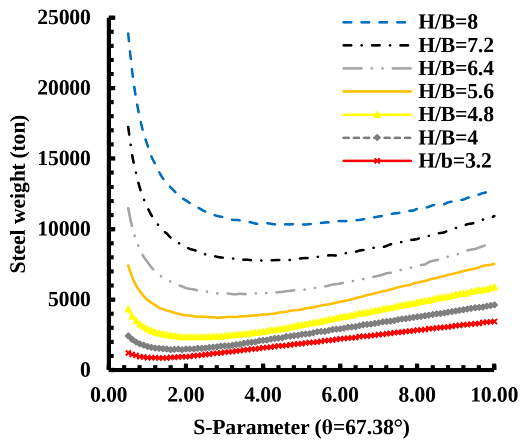


Figure 28. Fourth group models (amount of steel for various *S*-parameter)

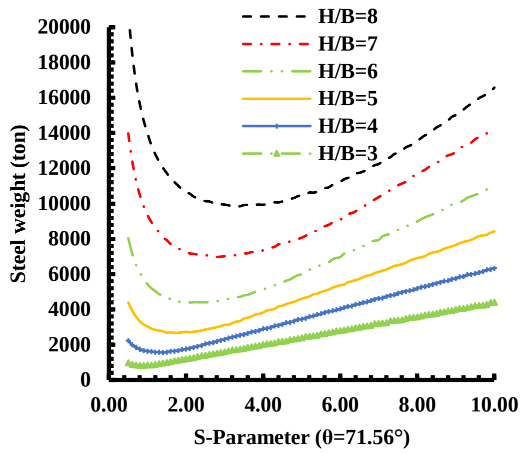


Figure 29. Fifth group models (Amount of steel for various *S*-Parameter)

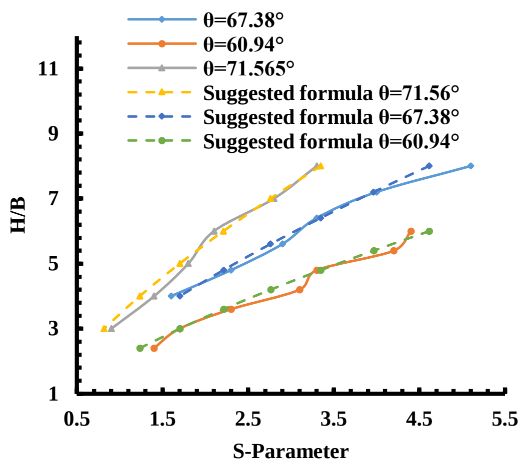


Figure 30. Best *S*-parameter for the last three groups

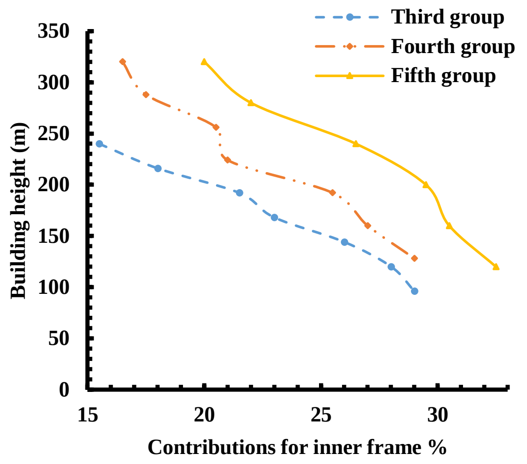


Figure 31. Contributions of inner frame to resist lateral displacement in stiffness-based design

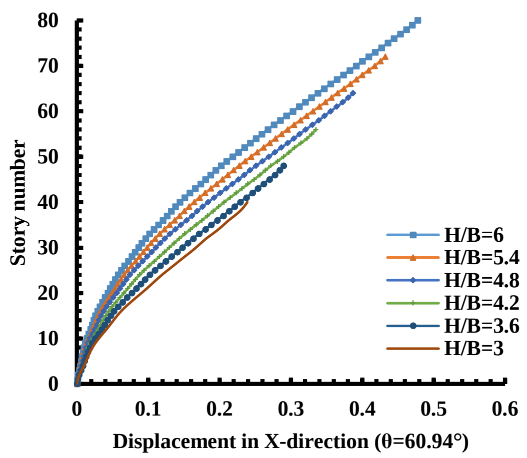


Figure 32. Lateral displacement for the third group models

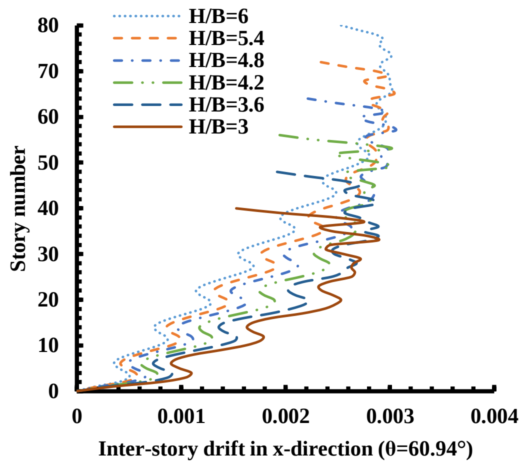


Figure 33. Inter-story drift for the third group models

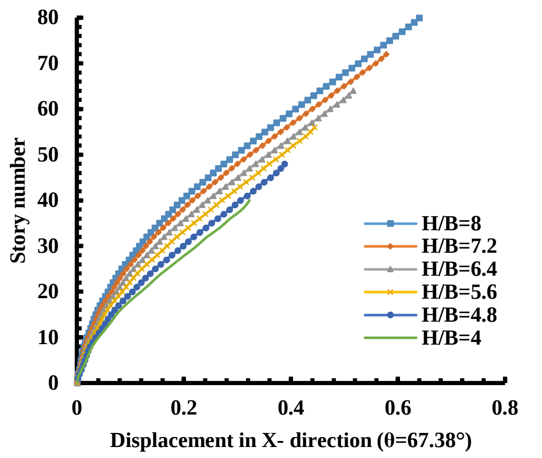


Figure 34. Lateral displacement for the fourth group models

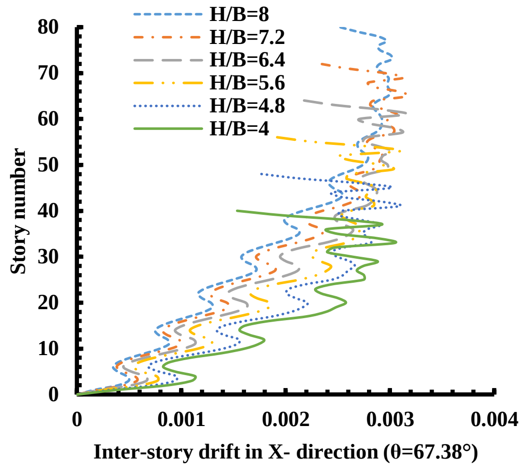


Figure 35. Inter-story drift for the fourth group models

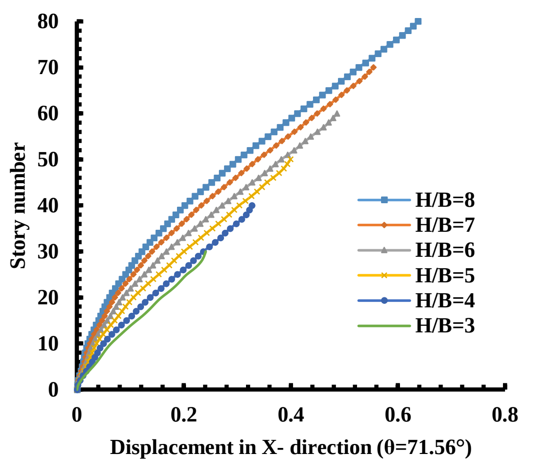


Figure 36. Lateral displacement for the fifth group models

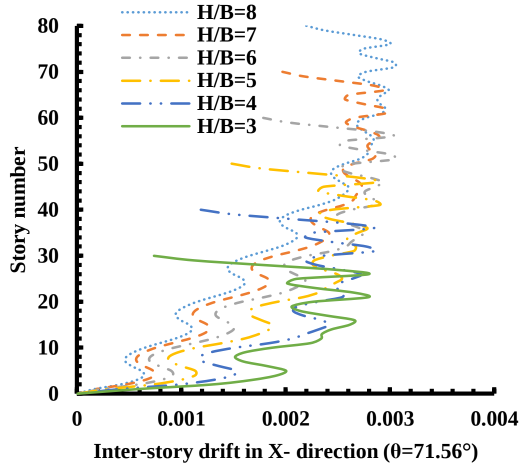


Figure 37. Inter-story drift for the fifth group models

Table 9. Error for best *S*-Parameter using proposed formula

Group 3		Group 4		Group 5	
H/B	%Error	H/B	%Error	H/B	%Error
6	4.77	8	-9.61	8	1.52
5.4	-5.48	7.2	-1.00	7	-1.43
4.8	1.52	6.4	1.52	6	5.24
4.2	-10.97	5.6	-4.83	5	-5.56
3.6	-3.91	4.8	-3.91	4	-12.14
3	0.00	4	6.25	3	-8.89

8. CONCLUSION

From the conducted numerical analyses on the diagrid buildings, it can be concluded that:

- The diagrid buildings may be governed by seismic load rather than wind load.
- The diagrid angle has a significant effect on the sustainability based on material requirements of diagrid buildings.
- Stiffness-based design for diagrid buildings is a simplified acceptable method for preliminary analysis and can be used to control the inter-story drift.
- The amount of steel for diagrid elements is based on the best selection of *S*-Parameter value.
- Bending deformations exceed shear deformations with increasing the height of diagrid buildings.
- Contributions of the inner frame to resist lateral force are increased with the increase in the diagrid angle as well as with the reduction in aspect ratio of building.

The proposed equation simplifies the selection of the empirical value of the best *S*-Parameter for seismic control.

Table 10. The lateral displacement at top and inter-story drift for various models

Group 3			Group 4			Group 5		
H/B	Disp. at top and max. inter-story drift	Constrained top disp. and max. inter-story drift	H/B	Disp. at top and max. inter-story drift	Constrained top disp. and max. inter-story drift	H/B	Disp. at top and max. inter-story drift	Constrained top disp. and max. inter-story drift
6	0.477	0.48	8	0.64	0.64	8	0.637	0.64
	0.0030	0.003		0.003	0.003		0.0030	0.003
5.4	0.432	0.432	7.2	0.58	0.576	7	0.554	0.56
	0.0030	0.003		0.0032	0.003		0.0030	0.003
4.8	0.387	0.384	6.4	0.52	0.512	6	0.486	0.48
	0.0031	0.003		0.0032	0.003		0.0030	0.003
4.2	0.335	0.336	5.6	0.44	0.448	5	0.399	0.4
	0.0030	0.003		0.0031	0.003		0.0029	0.003
3.6	0.290	0.288	4.8	0.39	0.384	4	0.327	0.32
	0.0029	0.003		0.003	0.003		0.0029	0.003
3	0.239	0.24	4	0.32	0.32	3	0.240	0.24
	0.0029	0.003		0.0030	0.003		0.0028	0.003

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NOMENCLATURE

M	The moment at level of consideration
L_d	The diagrid member length
S	The ratio between bending and shear deformations at top of the building
α	A factor used for the allowable lateral displacement at top constrained to 500
H	The building height
N_F	The number of diagonals on flange side
δ	An estimate of the contribution of the diagonals on each web to the bending rigidity is made by adding one extra diagonal on each flange
E	The modulus of elasticity
B	The plan dimension of the building parallel to the considered lateral load direction
h	The module height
θ	The angle of diagrid elements
V	The shear force at level of consideration
N_w	The number of diagonals on web side
f	A factor for diagrid structures ranged between 0.5 and 1.0
S_{DS}	The design earthquake spectral response acceleration parameter at short period
S_{D1}	The design earthquake spectral response acceleration parameter at 1 s
C_t	Building period coefficient
x	Constant depends on structure type
R	Response modification factor
I_e	Important factor
T_L	Long period transition
K_{zt}	The topographical factor
G	The gust factor
K_D	The directionality factor