

Analysis of Proposed Diagrid Geometry Using Golden Ratio in Non-Linear Regime of Material

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Abstract

Lateral loads are critical in the design of high-rise structures. The buildings need to have high stiffness and must be able to resist lateral deformations and torsional rotations without having discomfort to the user. Diagrid structural system is one of the systems used in resisting lateral forces. In this study, diagrid geometry is generated using the 'Golden Ratio' concept and used to model 40, 50, and 60 story structures. Two more diagrid schemes are modeled to compare the results. The diagrid members are designed, and optimized sections are provided by performing iterations with different values of 's' which is the ratio of lateral displacement at the top due to bending and due to shear, and a constant 'α'. The structural performance of the proposed diagrid system is represented in terms of the time period, lateral stiffness, and drift ratio. The non-linear behavior of diagrids is studied by performing pushover analysis up to the point when one or more members reach a collapsed state. Proposed diagrid geometry shows better results than the other two diagrid schemes. Concluding remarks have been made regarding diagrid geometry, the design of diagrid members, the effectiveness of the golden ratio in diagrid geometry, and the non-linear behavior of diagrids.

Keywords: Golden ratio, Diagrid structures, Drift ratio, Lateral stiffness, Non-linear analysis, Material non-linearity

INTRODUCTION

Nowadays, considering the increasing population growth rate and lack of available space, it is necessary to make maximum use of available resources. Available space and financial stability are governing resources when structural work is considered. Because of development in construction technology, materials being used, structural systems, and methods for analysis and design, there is rapid growth in High Rise buildings, and it also can be a pinnacle of a city. High-rise buildings can be visualized as a vertical cantilever beam supported at the ground, in which lateral displacement at the

free end and its fundamental time period are governing criteria. Tall buildings are primarily designed for lateral forces, i.e., wind loads and earthquake loads. To resist these lateral forces without having significant deformation, Diagrid Structures are incorporated into the design.

The diagrid structures were first used by Russian engineer Vladimir Shukhov in 1896 to design the world's first 37 m tall diagrid hyperboloid structure. Diagrid system is consisting of diagonally intersecting elements and horizontal rings and can be visualized as a Lattice structure. The diagonal elements can be made up of rolled steel sections, RCC, or wood, depending upon structural

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Received Date: July 25, 2021

Accepted Date: August 21, 2021

Published Date: August 30, 2021

Citation: N.M. Potdar, S.S. Jamkar. Analysis of Proposed Diagrid Geometry Using Golden Ratio in Non-Linear Regime of Material. Journal of Construction Engineering, Technology & Management. 2021; 11(2): 1–11p.

requirements. The diagrid structure between two main rings is defined as a Module [1]. A high-rise building constructed with a diagrid system makes an efficient structure and adds a unique architectural aesthetic. Diagrids resist 98% of lateral loads [2] by truss action, and they are located at the periphery of the building. The diagrids also support gravity load by nearly 50% [2], reducing the total deadweight coming on the central core of the building, hence making its use for not only standing out architecturally but structurally efficient as well. Diagrids completely eliminate the use of interior columns, hence making more working space inside the building [2-4]. Unlike any other structural systems like tube structures, Hexa-grids structures, or outrigger structures, the diagrid structures have more lateral stiffness [5], and it provides both shear and bending resistance [4].

LITERATURE REVIEW

An extensive literature study has been done on diagrid structures to find out the parameters that must be considered when designing a diagrid system and their influence on the characteristics of the resulting structure. The following literature review mentioned is being done as the initial phase of Non-linear analysis diagrid structures in non-linear regime of material.

Diagonal arrangements and design

A module consists of a bracing system, as shown in Figure 1, having inclined members who carry the lateral loads and gravity loads axially [6]. The diagonal members are straight or curved sections made up of steel or RC structures with uniform or varied spacing along the elevation [7]. There is an optimum combination for top and bottom diagrid angle with respect to the aspect ratio of the structure, which results in an efficient structure [7]. The nodes are structural junctions at which diagonals and ring beams are connected and hence making its design and assembly very complicated. These junctions can be steel connections, CFST (Concrete Filled Steel Tubular) connections, or RC connections [8]. At any particular locations where the amount of load to be distributed across the diagrid frame is large, additional diagonal members can be provided with closer spacing [8]. The diagrid module can be supported with additional secondary bracings [9, 10] for having increased stiffness if necessary. For the buildings with twisted floor plans, the angle of twist per floor should be limited to 3° as it alters the optimal diagonal angle and reduces the overall stiffness [11]. Had the non-structural requirements been satisfied by the diagrid structures, it can be feasible to use tilted structures for architectural aesthetics [11]. The top portion and bottom portion of the high-rise structures are subjected to different actions. Because of the high lateral forces due to wind near the top portion, the diagrids are designed for shear and torsional stiffness [12], and the bottom portion is subjected to bending and vertical loads; more steep diagonal members are provided and are designed for bending [12].

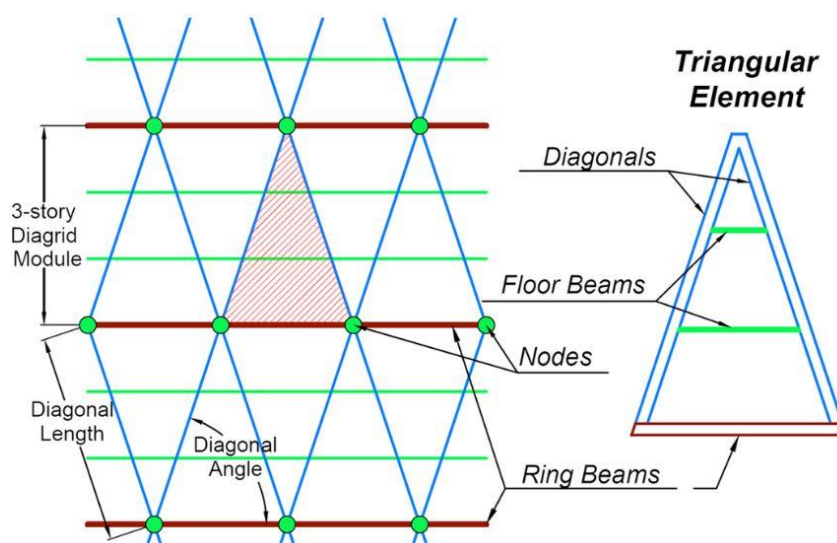


Figure 1. Typical Diagrid Module (Source: ASCE library).

The geometry of diagonal members can be established using a graphical approach with varying diagonal angles [13]. The diagrid member sizes for preliminary design are calculated based on strength requirements or stiffness requirements or based on both [14, 15]. For buildings with steep diagonal members where top lateral displacement is limited to five-hundredths of the total height are primarily designed based on stiffness requirements, and for diagonal members, with low angle (64°), the members are designed based on strength requirements [15]. Hence, for slender buildings, stiffness governs the design criteria, and for shorter buildings, strength governs the design criteria. The diagrid structures also show less time period than the conventional steel tubular frame [16]. This study aims at using Golden Ratio in the generation of a unique diagrid pattern [17].

SYSTEM DEVELOPMENT

Golden Ratio

In this study, the golden ratio is used to decide the dimensions of a module and to generate a unique diagrid pattern. The diagrid pattern so generated is as shown in Figure 2. The proposed building dimensions in the plan are 30×30 m. Given a base width of 30 m, the module height becomes 18.55 m. Here, a typical diagrid module is considered as a set of floors between three vertically consecutive nodal points. Each module consists of 5 stories at the vertical spacing between the floors of 3.71 m. Three models of 40 stories, 50 stories, and 60 stories have been prepared using this geometry consisting of eight modules, ten modules, and twelve modules, respectively. The aspect ratio of the structures ranges from 4.9 to 7.4. The diagonal members are spaced at 6 m c/c horizontally and at an angle of 72° with the ground level. The floor plan for different floors of diagrid structures is shown in Figure 3.

Design of Diagrid Members

A diagrid structure is assumed as a vertical cantilever beam supported at the ground. It is divided into modules, and each module consists of stories according to a particular diagrid pattern that extends over

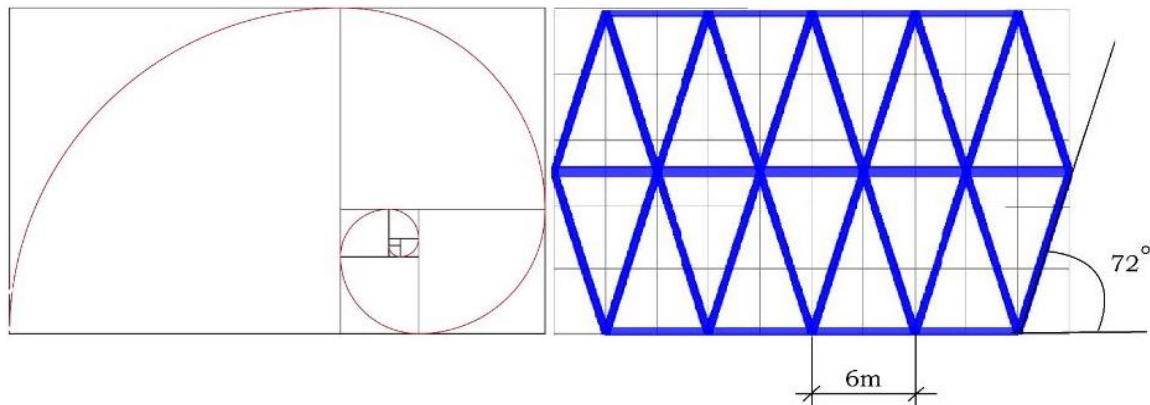


Figure 2. Proposed Diagrid Geometry.

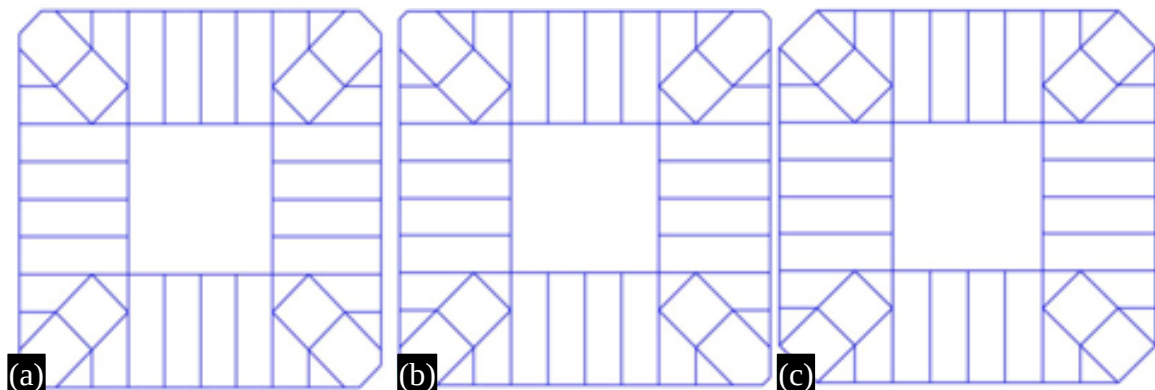


Figure 3. Floor Plan of (a) Floor 1 And 4; (b) Floor 2 And 3; (c) Floor 5.

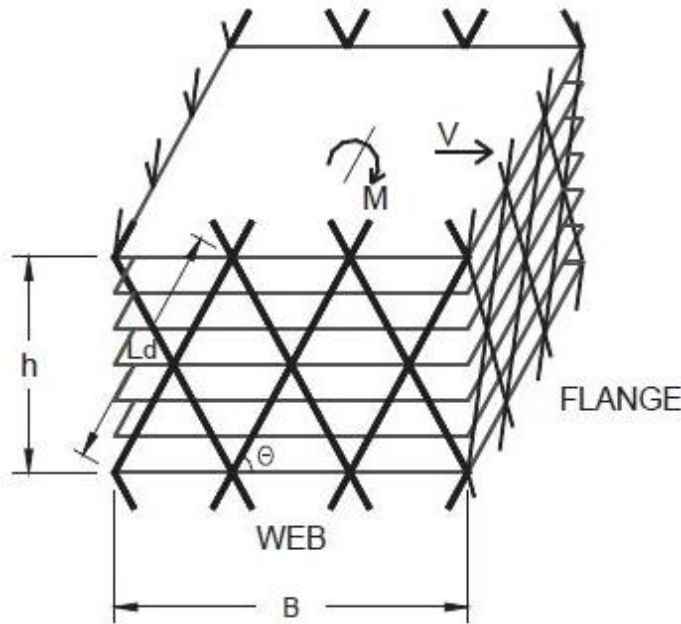


Figure 4. The Web and The Flange Face of The Module.

‘n’ stories vertically. The diagrids are assumed to take all the lateral loads and provide stability to the structure, and the core is designed only to take gravity loads, hence omitted in FEM modeling of the structure. The diagonal members are pinned at all the nodes so that the load transfer occurs only through axial action only. The floor beam sections provided are standard ISMB 550, ISLB 600-1, and ISLB 600-2 sections. The floor plan of all three buildings is 30×30 m with a central core of 12×12 m which is 25% of the floor area. The site is assumed to be located at Amaravati, Andhra Pradesh. The design Dead loads and Live loads are 5.15 KN/m² and 3 KN/m² as per IS 875 1987 part 1 [18], including partition wall load and floor finishes. Lateral forces due to wind are considered as per IS 875 1987 part 3 [19] and earthquake forces as per IS 1893 2002 part 1 [20]. The web face and flange face of the typical module is shown in Figure 4.

The area of diagonals at the web and flange face can be calculated as follows:

$$Ad_w = \frac{VLd}{2Nd_w E h \gamma (\cos \theta)^2}$$

$$Ad_f = \frac{2MLd}{(Ndf + \delta) B^2 E h \chi (\sin \theta)^2}$$

Where,

Ad_w : Area of each diagonal on the web face

Ad_f : Area of each diagonal on flange face

V : Horizontal Shear force

M : Moment

Ld : Length of diagonal member

E : Modulus of elasticity of diagrid steel used

θ : Angle of the diagonal member with horizontal

γ : Desired shear strain

χ : Desired curvature

δ : Contribution of web diagonals for bending rigidity

B : Width of building in the direction of applied load

Ndf : Number of diagonals on each flange plane

Ndw : Number of diagonals on each web plane

H : Height of the building

And

$$\Upsilon = \frac{1}{(1+s)\alpha};$$

$$\chi = \frac{2s}{H(1+s)\alpha}$$

s: Ratio of displacement at the top due to bending to that due to shear

All the lateral forces are required to be resisted by the external diagrid tube. Hence modeling of the central core in FEM software is omitted in this study (Figures 5 and 6). Iterations have been done with different values of 's' from 1 to 8 combined with 'α' ranging from 400 to 600. All three structures were designed with the sizes obtained at each iteration for 's' and 'α' and the most economical sections are selected for analysis. The value of 's' and 'α' for 40, 50, and 60 stories are 4 and 500; 3 and 400; 3 and 400 respectively. The member sizes further increased to reduce lateral displacement and presented for 60 story diagrid structures are represented in Table 1, and for 40, 50, and 60 stories are shown in Figure 7. The provided sections are determined after multiple analysis and design iterations in SAP 2000 v16 [21]. The proposed diagrid pattern and other diagrid schemes studied are as shown in Figure 5. Scheme 1 consists of 4 stories with a diagonal angle of 68°; scheme 2, which is proposed geometry, consists of 5 stories with a diagonal angle of 72°, and scheme 3 consists of 6 stories and a diagonal angle of 75°.

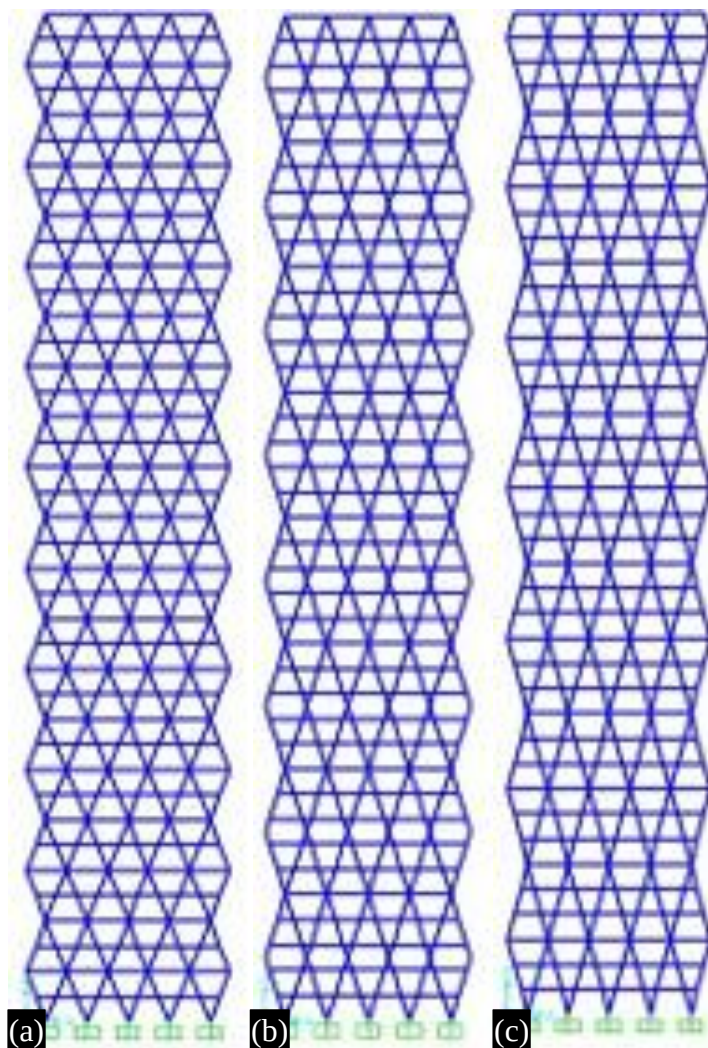
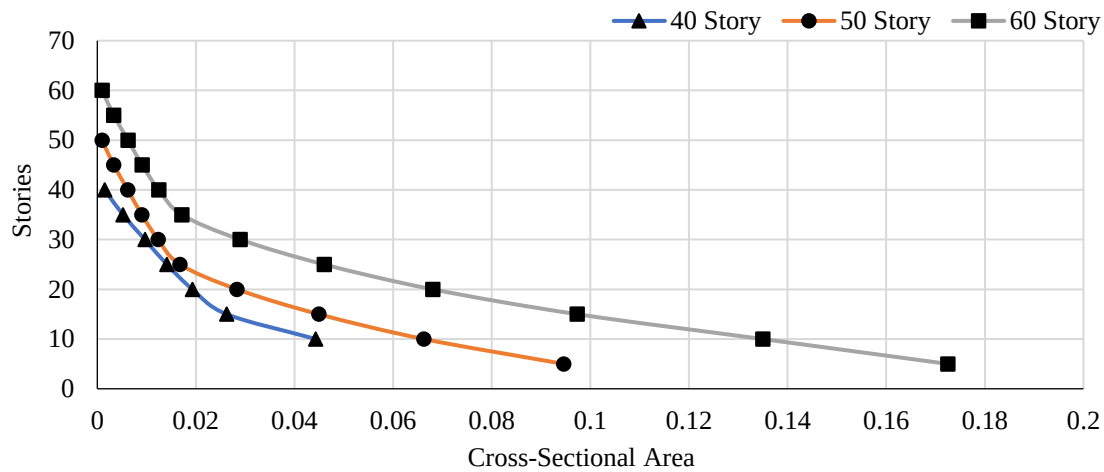


Figure 5. Diagrid Pattern Schemes (a) Scheme 1; (b) Scheme 2; (c) Scheme 3.

Table 1. Member Sizes for Scheme 2 of 60 Story Diagrid Structure.

Stories	Module	Shear Force (KN)	Moment (KNm)	Ad _w in Web (m ²)	Ad _f in Flange (m ²)
56–60	12	108.2176086	1018.297723	0.000962	2.79253E-05
51–55	11	376.5350622	7101.360631	0.003349	0.000389
46–50	10	699.868233	19867.47748	0.006226	0.001634
41–45	9	1023.306761	38897.76265	0.009103	0.004266
36–40	8	1400.685014	66779.19298	0.012460	0.009156
31–35	7	1814.12928	104105.4456	0.016138	0.017129
26–30	6	2248.706475	150998.0033	0.200044	0.028986
21–25	5	2726.279274	209754.5767	0.024252	0.046017
16–20	4	3174.162534	275591.6027	0.028237	0.068019
11–15	3	3668.725813	354853.7227	0.032636	0.097313
6–10	2	4194.944358	447394.3842	0.037318	0.135960
1–5	1	4618.615209	524204.2116	0.041087	0.172506

**Figure 6.** Member Sizes for Preliminary Design of 40, 50, and 60 Stories.

The member sizes of the diagrid members for all three stories are represented in Figure 6.

Non-linear Behavior

In order to investigate the non-linear performance of diagrid members, a non-linear static analysis (Pushover Analysis) is carried out for all three models. The structure is displaced laterally, step by step, to a magnitude of 2% of the total height of the structure, and plastic hinges so formed are studied. All the plastic hinges are modeled according to the provisions of FEMA 356 [22]. The typical force deformation curve for a plastic hinge is as shown in Figure 7. The modeling parameters of the plastic hinge according to FEMA 356 are represented in Table 2.

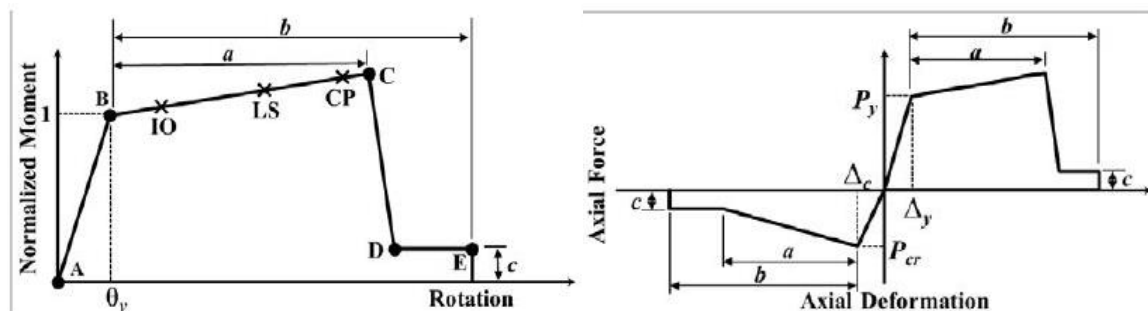
**Figure 7.** Typical Force-Deformation Curve of a Plastic Hinge.

Table 2. Modeling Parameters and Acceptance Criteria for Non-Linear Procedures for Axial Members.

Component		Modeling Parameters			Acceptance Criteria		
		Plastic Deformation		Residual Strength Ratio			
		<i>a</i>	<i>b</i>	<i>C</i>	<i>IO</i>	<i>LS</i>	<i>CP</i>
Tube Section	Compression	$0.5\Delta_c$	$3\Delta_c$	0.2	$0.25\Delta_c$	$1\Delta_c$	$2\Delta_c$
	Tension	$11\Delta_T$	$14\Delta_T$	0.5	$0.25\Delta_T$	$7\Delta_T$	$9\Delta_T$

Here,

Δ_c : Axial deformation at expected buckling load.

Δ_T : Axial deformation at expected tensile yielding load.

RESULTS AND DISCUSSION

The diagrid sections provided at each module of 40, 50, and 60 stories are shown in Table 3. The Fe345 steel tube sections provided are such that the maximum allowed values of displacements and time periods are within the limit for one of the diagrid schemes.

Axial forces

The axial forces generated in diagrid members due to lateral loads in 40, 50, and 60 stories for all three schemes are shown in Table 4. The diagrid structure with scheme 2 shows the minimum axial forces in the members.

Table 3. Provided sections for 40, 50 and 60 stories.

Module	Minimum Sections Provided (B×t)		
	40 Story	50 Story	60 Story
1	0.50×0.04	0.55×0.05	0.88×0.05
2	0.45×0.04	0.55×0.05	0.85×0.05
3	0.40×0.04	0.55×0.04	0.75×0.05
4	0.30×0.03	0.50×0.04	0.65×0.05
5	0.30×0.03	0.40×0.04	0.55×0.05
6	0.30×0.025	0.40×0.04	0.50×0.04
7	0.30×0.025	0.35×0.03	0.45×0.04
8	0.30×0.02	0.35×0.03	0.40×0.03
9	-	0.30×0.03	0.35×0.03
10	-	0.30×0.02	0.35×0.03
11	-	-	0.30×0.03
12	-	-	0.30×0.02

Table 4. Axial Forces Under Lateral Loads for All Three Schemes.

Stories	Diatrid Scheme	Maximum Axial Forces (KN)		
		1.5 (DL-WX)	DL+LL-WX	DL+LL-EX
40	1	16588.01	12625.97	5476.02
	2	16550.95	12407.66	5197.02
	3	18136.70	13512.67	5544.49
50	1	26214.45	19408.47	9271.86
	2	23656.57	17509.67	8631.41
	3	25381.56	18756.55	7348.53
60	1	37021.50	27088.45	13382.52
	2	32117.23	23520.16	11388.49
	3	34687.14	25407.50	10097.73

Fundamental Time Period

The first mode time period of the 40, 50, and 60 story diagrids with all three schemes and their corresponding time period values calculated from IS 1893 2002 are presented in Table 5. The time period of all three diagrid structures is found to be less than that calculated using provisions from IS 1893 2002. This indicates that diagrid structures are stiffer than conventional steel-framed structures.

Displacement at Top Story

Diagrids with scheme 2 show a comparatively lower value of both the time period and the top lateral displacement, as shown in Tables 6 and 7.

Table 5. First mode time period of diagrid structures.

Stories	Diagrid Scheme	Time Period (second)	
		SAP 2000	IS 1893 2002
40	1	3.6253	3.614
	2	3.5990	3.614
	3	3.5956	3.614
50	1	4.5173	4.272
	2	4.1979	4.272
	3	4.5192	4.272
60	1	5.2970	4.898
	2	4.7893	4.898
	3	5.0251	4.898

Table 6. Maximum Lateral Displacements Due to Wind and Earthquake Loads.

Stories	Diagrid Scheme	Maximum displacement Allowed (m)	Maximum deformation Observed (m)		
			1.5 (DL-WX)	DL+LL-WX	DL+LL-EQ X
40	1	0.5936	0.450	0.300	0.0939
	2	0.5936	0.4355	0.2903	0.0938
	3	0.5936	0.4451	0.2967	0.0940
50	1	0.742	0.6682	0.4454	0.142
	2	0.742	0.6241	0.4161	0.117
	3	0.742	0.730	0.4871	0.146
60	1	0.890	0.925	0.6166	0.209
	2	0.890	0.8527	0.5685	0.1668
	3	0.890	0.919	0.6126	0.184

Table 7. Drift Ratios for all three schemes of 40, 50, and 60 Stories.

Stories	Diagrid Scheme	Drift Ratio (%)		
		1.5×(DL-WX)	DL+LL-WX	DL+LL-EQ X
40	1	0.303	0.202	0.0632
	2	0.293	0.195	0.0632
	3	0.299	0.199	0.0633
50	2	0.360	0.240	0.1941
	2	0.336	0.224	0.1813
	3	0.393	0.262	0.2121
60	1	0.415	0.276	0.0938
	2	0.383	0.255	0.0749
	3	0.412	0.275	0.0826

Lateral Stiffness

As scheme 2 of the diagrid pattern shows good results, section sizes are further increased to limit the structure's lateral displacement and the time period and improve its lateral stiffness. The Lateral stiffness for scheme 2 of 40, 50, and 60 story structures have been calculated using the performance points obtained after plotting the curve as per FEMA 356 Coefficient method and FEMA 440 equivalent linearization [23] and represented in Table 8. The response of scheme 2 of the diagrid structure is presented in terms of the monitored displacement, spectral acceleration, spectral displacement, and the time period in Table 9.

Performance of Plastic Hinges

In a 40-story structure, the first IO performance level hinges observed in the web face, which is under shear action and at the top lateral displacement of 0.9117 m. After further lateral displacement, at 1.2679 m, nearly 0.85% of the building height, one plastic hinge crossed the CP performance level in the 1st

Table 8. Lateral Stiffness of 40, 50, and 60 Story Structures.

Story	Lateral Stiffness (KN/m)	
	FEMA 356 Coefficient Method	FEMA 440 Equivalent Linearization
40	128168.191	127528.033
50	97576.362	97302.877
60	77758.269	78099.854

Table 9. Response of Diagrid structures in Zone III.

Story	Base Shear (KN)	Displacement (m)	Sa (g)	Sd (m)	T (s)
40	11477.523	0.090	0.160	0.074	1.362
50	11092.528	0.114	0.128	0.093	1.706
60	10699.538	0.137	0.107	0.112	2.053

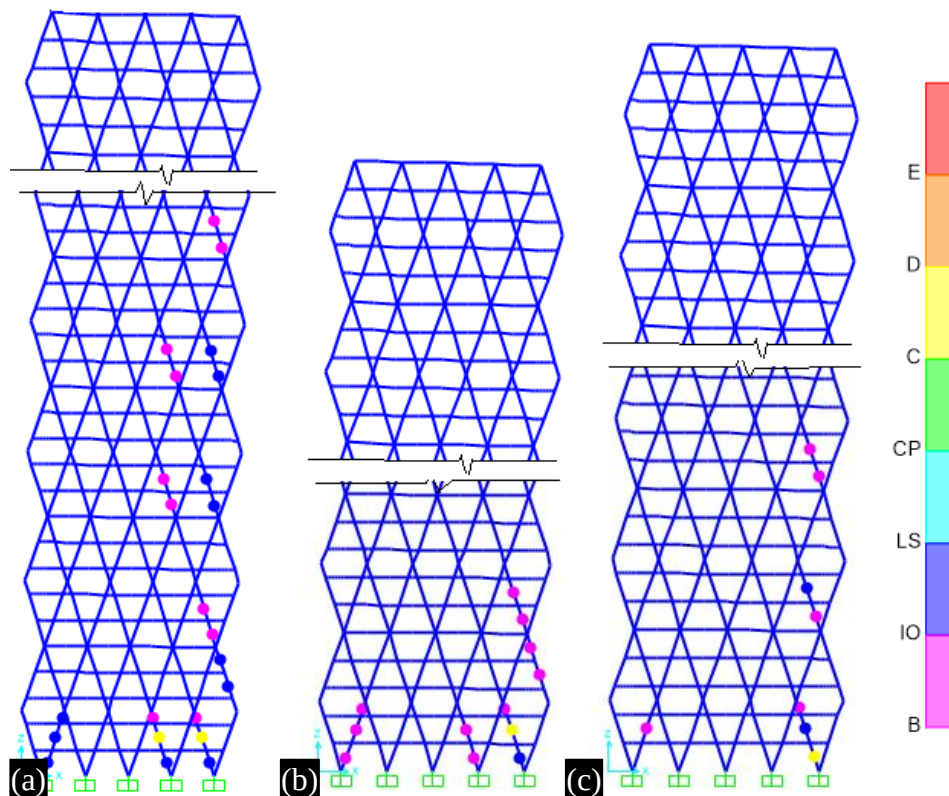


Figure 8. Plastic hinge formed at Web faces in (a) 40-Story; (b) 50-story; (c) 60-Story.

module. In a 50-story structure, the first IO performance level was observed in the 1st module diagonals and in web faces at the top lateral displacement of 1.257 m. The first hinge crossed the CP level in the 1st module diagonal at 1.576 m of lateral displacement, which is 0.85% of building height. In a 60-story structure, the first IO performance level observed in 1st module diagonals at the top lateral displacement of 1.831 m. Soon after, at a displacement of 2.312 m which is 1% of building height, the first hinge crossed CP performance level. The plastic hinges formed at the web face of 40, 50, and 60 stories are shown in Figure 8. An equal number of plastic hinges formed on both the web faces. And more critical plastic hinges formed on web faces than those on flange faces. The compression flange side of the diagrids showed more plastic hinges at LS level than the tension flange side.

CONCLUSIONS

After the structures are designed safely, non-linear static analysis has been performed to study the behavior of the proposed diagrid geometry by making the structure deform laterally at a monotonical rate. The behavior of the 40, 50, and 60 story structure is studied, and the following conclusions have been made:

- Scheme 2 of the diagrid pattern, which is proposed diagrid geometry, gives better results than other schemes studied, in terms of the time period and drift ratio, up to a height of 222.6 m or up to an aspect ratio of 7.42.
- As the height of the diagrid structures increases, their lateral stiffness goes on reducing.
- The 60-story structure shows lower seismic demand because of the more tendency to sway due to increased height.
- The value of 's' and ' α ' for 40, 50, and 60 story structures are 4 and 500; 3 and 400; and 3 and 400 respectively.
- More plastic hinges formed at web faces than that of flange face in 40, 50, and 60 story diagrid structures.
- In non-linear analysis, diagrid members in all three structures remained well below the IO performance level at their corresponding maximum top lateral displacement.
- In all three structures, first collapse level plastic hinges in diagrid members are observed at an average drift ratio of 0.9%.
- Diagrid members first show non-linearity under shear and then under axial compression.

Scope for Future Study

The diagrid structures show a slightly larger time period than that of conventional steel frame structures. Efforts can be made to reduce the time period by making use of a diagrid structural system coupled with an outrigger system. Also, this study only focuses on the material non-linearity of diagrid members. Research can be done on the geometric non-linearity of diagrids.

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