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Exploring Diagrid Efficiency: A Modern Analysis of Lateral Load Resistance Across Building Heights

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Abstract

Modern architectural design and engineering often feature innovative structural systems, with diagrid structures standing out as an aesthetically appealing solution for tall buildings due to their geometrically complex patterns. Despite extensive global research on diagrids, a comprehensive study systematically comparing their structural efficiency is still lacking. The structural efficiency and seismic performance of diagrid lateral load-resisting systems were evaluated in this thesis. The study compared the diagrid system's effectiveness against conventional building designs across low-rise, mid-rise, and high-rise buildings under seismic loads. Using ETABS v17.0 software, response spectrum analysis was conducted to assess story displacement, story drift, base shear, and time period in both X and Y directions for 12 models. The study reveals that diagrid systems outperform conventional structures by significantly reducing story displacement and drift, increasing base shear capacity, and shortening the time period across varying building heights. Overall, these findings underscore the diagrid system's superiority in seismic conditions, urging its wider adoption in earthquake-prone regions for improved building safety and performance.

Keywords: Diagrid structures, seismic performance, structural efficiency, story displacement, story drift, base shear, time period, ETABS, low-rise buildings, mid-rise buildings, high-rise buildings

INTRODUCTION

Integrating innovative structural systems has been a defining feature of modern architectural design and engineering. Among these, diagrid structures have emerged as an intriguing and aesthetically appealing solution for tall buildings, characterized by their geometrically complex patterns. As the demand for sustainable, efficient, and visually striking high-rise structures continues to grow, the examination of diagrid systems in various building types and geometric plans becomes paramount. The integration of such novel approaches and advanced design methods can lead to the development of tall buildings that are both structurally robust and architecturally striking, while also optimizing the use of materials and resources.

Despite the extensive research on diagrids globally, there appears to be a lack of a comprehensive study that systematically compares the structural efficiency of these diagrid systems. Additionally, while diagrid structures have gained popularity in many developed and developing countries, they have not yet received the attention they deserve in our country. Therefore, this research aims to assess and compare the lateral load-resisting efficiency of diagrids with various geometric patterns and to determine their efficiency concerning different building heights.

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The study investigates the impact of height variation on the structural performance of diagrid buildings by considering three different types of buildings: low-rise (G+3), medium-rise (G+7), and high-rise (G+11). Each height category demands different design considerations and construction techniques to ensure safety, durability, and performance under varying environmental conditions. By analyzing these three height variations, the study aims to provide insights into the optimal design strategies for diagrid structures across different building scales.

AIM AND OBJECTIVES

The research aims to achieve the following specific objectives:

- Evaluate the seismic behavior of diagrid lateral load resisting systems, focusing on story displacement, story drift, time period, and story shear using ETABS v17.0 software.
- Analyze the structural performance of diagrid systems across low-rise, mid-rise, and high-rise reinforced concrete (RC) buildings.
- Investigate the influence of different materials, shapes of diagrid, and connection types on the performance of diagrid structures.
- Determine the overall efficiency of diagrids as lateral load resisting systems compared to other efficient systems in our country.

This project is significant as it has the potential to transform the design and construction practices of reinforced concrete buildings. By providing a comprehensive understanding of diagrid structures in varied contexts, the study supports the development of innovative, sustainable, and resilient building solutions that meet the evolving demands of modern cities and societies, addressing structural, environmental, and economic considerations.

LITERATURE REVIEW

The research conducted by various authors highlights the structural efficiency of diagrid systems under seismic and wind loads. Nayak et al. [1] found that braced tube structures with circular plans outperformed square and rectangular ones, while diagrid structures with square plans showed superior performance. Lacidogna et al. [2, 3] identified optimal diagonal inclinations for minimizing lateral displacements (64°–72°) and torsional stiffness (35°–38°). Heshmati et al. [4] demonstrated enhanced hardening behavior with diagrid cores under seismic loads. Mohsenian et al. [5] confirmed the seismic reliability of diagrid systems, proposing a new multilevel R-factor. Tirkey and Ramesh Kumar [6] used ETABS to show that diagrid systems are more effective in resisting lateral loads. Kamath et al. [7] found that a 71° brace angle improved base shear performance. Jani and Patel [8] determined optimal diagrid angles (65°–75°) and stiffness ratios (2–5) for tall buildings. Moon [9] studied the efficiency of diagrids in complex-shaped buildings, providing design considerations for twisted, tilted, and freeform structures. These studies collectively highlight the structural efficiency and aesthetic potential of diagrid systems, emphasizing their performance in seismic and wind conditions, and providing insights into optimal geometric configurations for different building shapes and heights.

SYSTEM DEVELOPMENT

The analysis of diagrid structures across low-rise, mid-rise, and high-rise RC buildings aims to offer a holistic view of their structural behavior and performance in diverse architectural configurations. This study employs the response spectrum method, a widely accepted technique in structural engineering for seismic analysis. This method provides a streamlined and effective approach to evaluating how buildings and other structures respond to earthquake-induced ground motions, thus serving as a crucial tool for seismic design and assessment. Loading considerations were considered following Indian Standards. Dead load (DL) of 1 kN/m^2, live load (LL) of 3 kN/m^2, and the load combination of 1. 2(DL+LL+EQ) were employed as per IS 875:1987 [10–14].

Building Specification

The primary building specifications considered for the models to be analyzed in ETABS v17.0 for investigating the design diversity of a diagrid structure which is the aim of this research are:

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The plan area for the proposed work is 18 m × 18 m in which the size of the panels is 3 m × 3 m for conventional and square diagrid buildings and similar areas considered for different levels G + 3, G + 7, G + 11. Figure 1 displays the plan views of both conventional and diagrid buildings, whereas Figure 2(a)–(c) presents the 3D views of conventional low-rise, mid-rise, and high-rise buildings, respectively. Figure 3(a)–(c) depicts the 3D views of diagrid buildings corresponding to low-rise, mid-rise, and high-rise configurations, respectively.

Design parameters used for the study

- *Model* G + 3, G + 7, G + 11
- *Seismic zone* III
- *Floor to floor height* 3.6 m
- *The configuration of both the models* Square 3 m × 3 m grid
- *Diagrid angle* 67.4°
- *Size of plan* 18 m × 18 m
- *Column size* 350 mm × 350 mm
- *Beam size* 250 mm × 250 mm
- *Slab thickness* 125 mm
- *Diagrid size* 300 mm × 400 mm
- *Grade of concrete* M30
- *Grade of steel* Fe 500

RESULTS AND DISCUSSION

This section presents a comprehensive analysis of the seismic performance of low-rise, medium-rise, and high-rise buildings, comparing conventional building designs with diagrid building designs. The data includes story displacement and drift in both X and Y directions, base shear in X and Y directions, and the time period for various mode shapes. The presented graphs illustrate the differences in structural responses between conventional and diagrid buildings across different story levels.

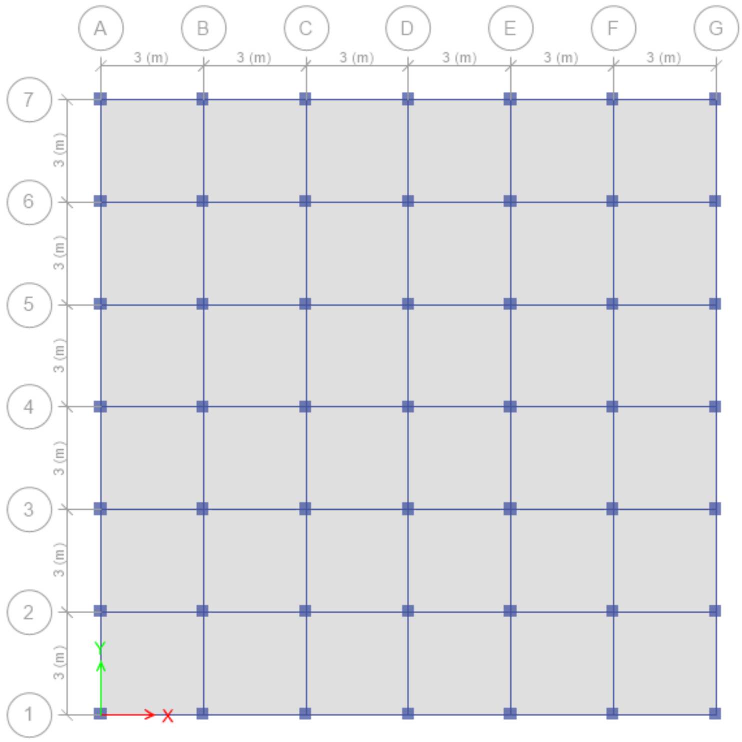

Figure 1. Building plan view.

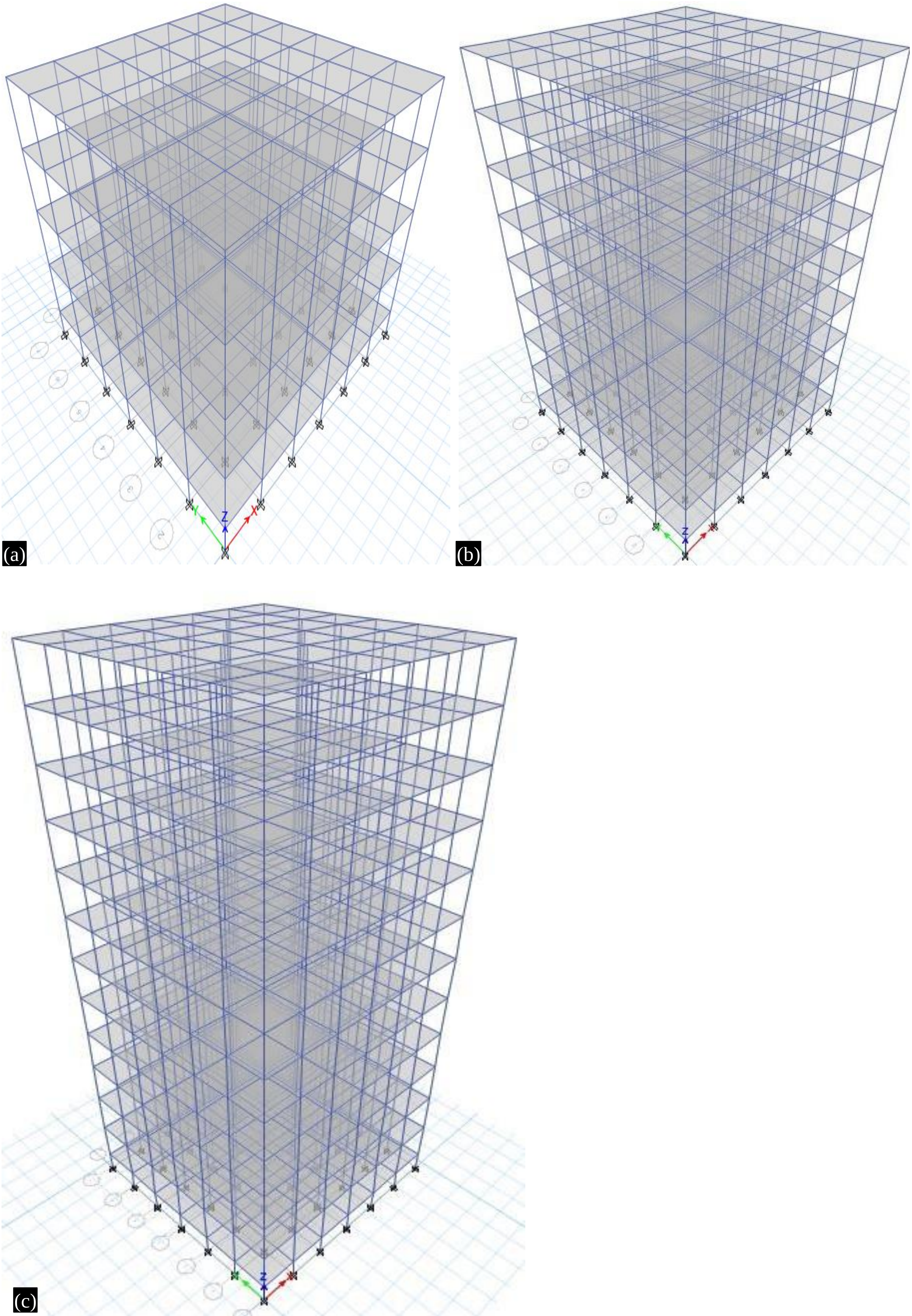

Figure 2. Conventional building 3D view: (a) low-rise, (b) mid-rise, and (c) high-rise.

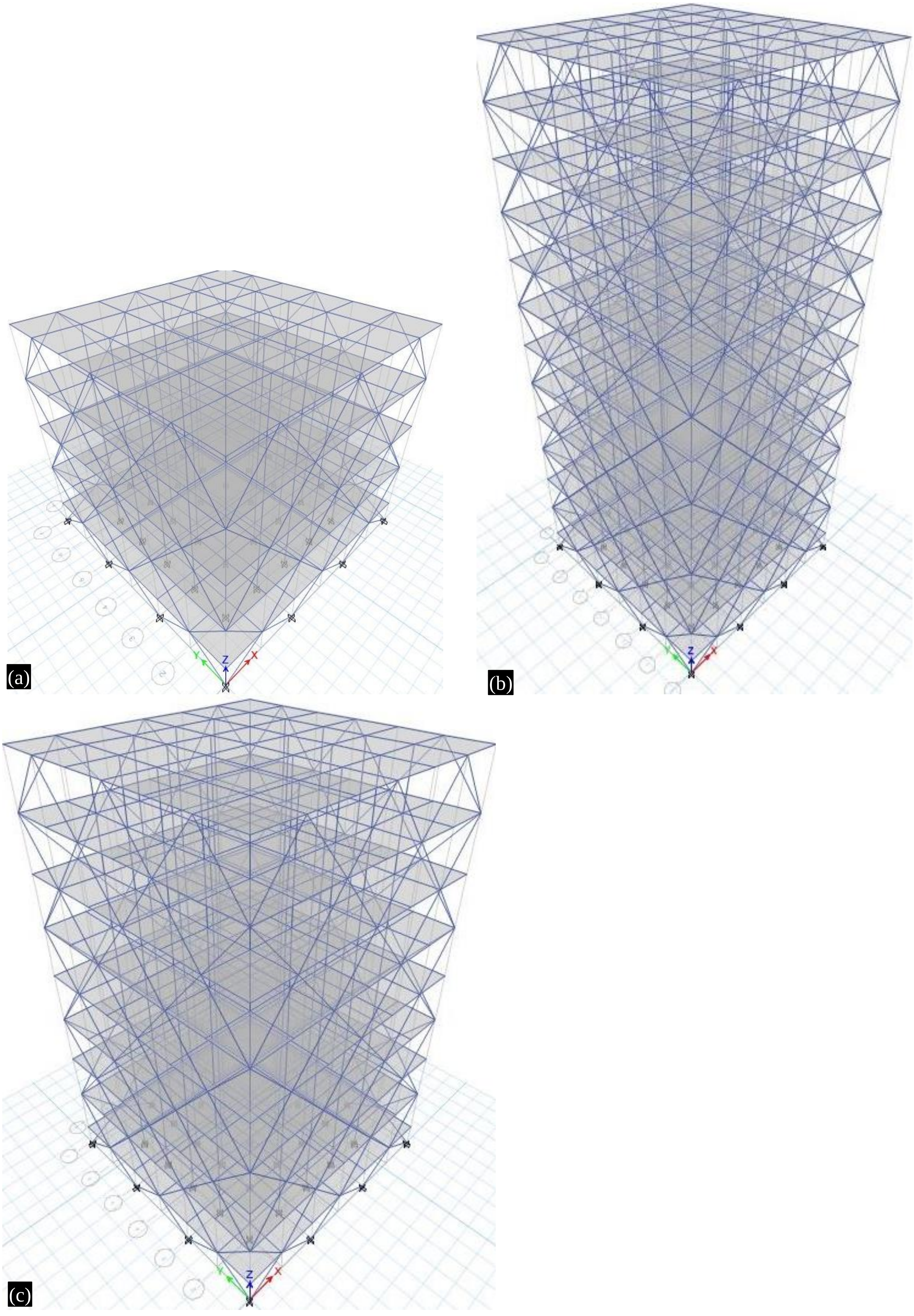

Figure 3. Diagrid building 3D View: (a) low-rise, (b) mid-rise, and (c) high-rise.

Low Rise

Story Displacement Comparison Between Conventional and Diagrid Building

Table 1 gives the results for story displacement in low-rise models and a graph is plotted for the same. Figure 4 shows graphical representation of story displacement in millimeters for low-rise conventional buildings and diagrid buildings. The X axis shows the story number and the Y axis shows the story displacement in millimeters. Conventional building shows the highest deformation, which is 4.953 mm, and the diagrid building shows the lowest deformation, which is 0.686 mm in story 1. This significant reduction in displacement indicates that diagrid buildings are far more stable under seismic loads.

Story Drift Comparison Between Conventional and Diagrid Building

Story drift values in millimeters for conventional building and diagrid building are given in Table 2 and the same are plotted in Figure 5. X axis shows the story number and Y axis shows the story drift in millimeters. The graph shows that conventional building shows the highest story drift, which is 2.83 mm, and diagrid building shows the lowest story drift, which is 0.397 mm in story 1.

Base Shear Comparison Between Conventional and Diagrid Building

A comparison of base shear for conventional building and diagrid building is given in Table 3 and Figure 6 shows the graphical representation for the same. X axis shows the story number and Y axis shows the base shear in kilonewtons (kN). Conventional building shows the lowest base shear, which is 3662.962 kN, and diagrid building shows the highest base shear, which is 6063.207 kN in story 1. This increased capacity suggests that diagrid structures have superior load-bearing capabilities.

Table 1. Story displacement in millimeters (low-rise).

SN.	Story Displacement (mm)		
	Story No.	***Conventional Building***	***Diagrid Building***
1	Base	0	0
2	Story 1	4.953	0.686
3	Story 2	33.573	3.791
4	Story 3	63.394	6.475
5	Story 4	86.526	9.083
6	Story 5	100.84	11.214

Table 2. Story drift in millimeters (low-rise).

S.N.	Story Drift in X Direction (mm)		
	Story No.	***Conventional Building***	***Diagrid Building***
1	Story 1	2.83	0.397
2	Story 2	7.954	0.899
3	Story 3	8.426	0.803
4	Story 4	6.868	0.777
5	Story 5	4.571	0.651

Table 3. Base shear in kilonewtons (kN) (low-rise).

S.N.	Base Shear (kN)		
	Story No.	***Conventional Building***	***Diagrid Building***
1	Story 1	3662.962	6063.207
2	Story 2	3525.932	5887.865
3	Story 3	2987.609	5094.638
4	Story 4	2394.024	3832.048
5	Story 5	1555.015	2046.443

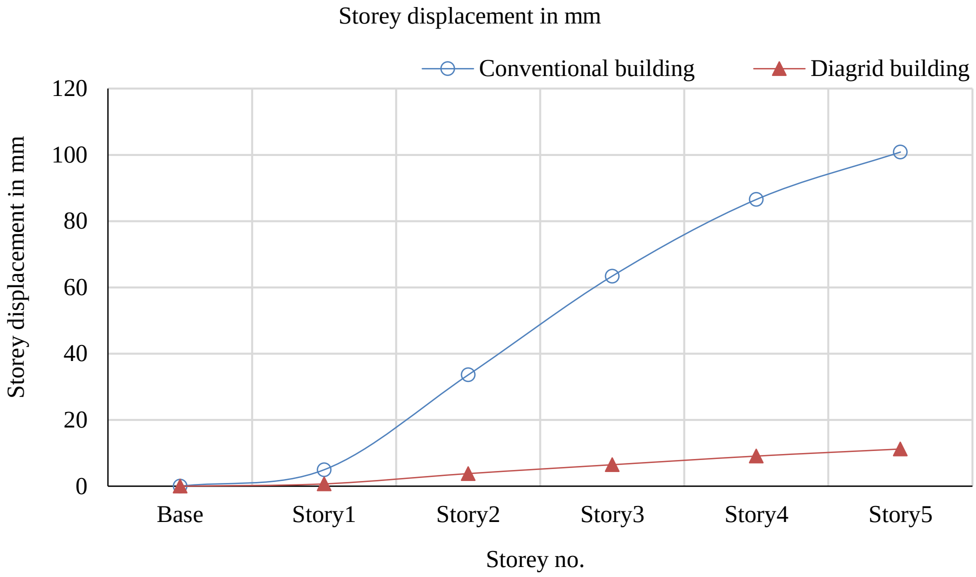

Figure 4. Story displacement in millimeters (low-rise).

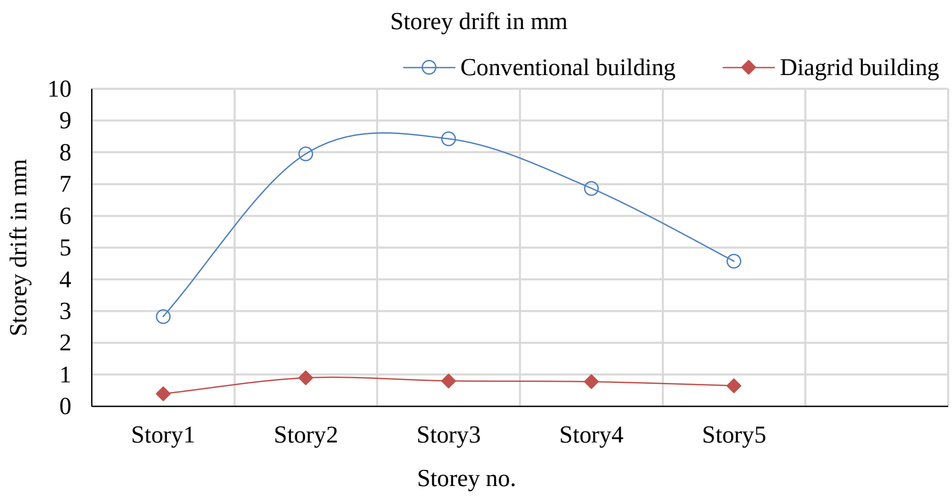

Figure 5. Story drift in millimeters (low-rise).

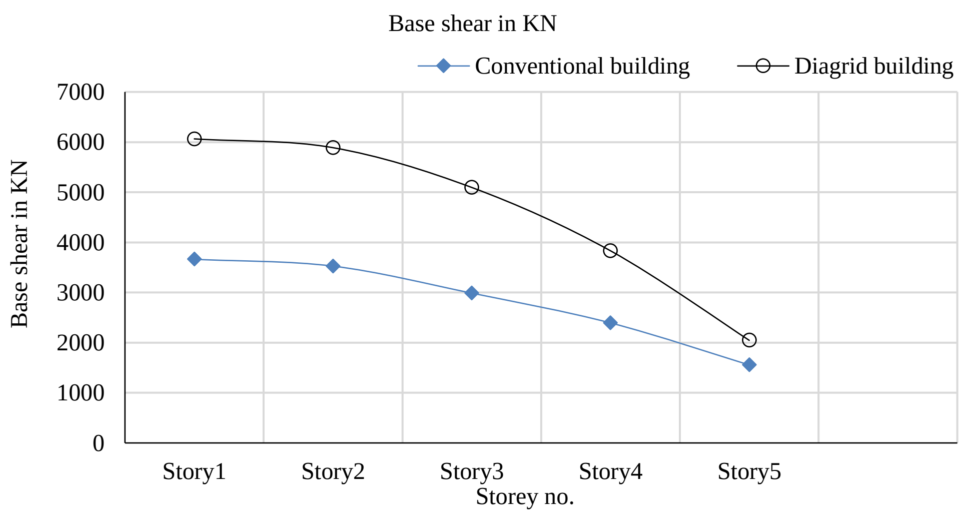

Figure 6. Base shear in kilonewtons (kN) (low rise).

Medium Rise

Story Displacement Comparison Between Conventional and Diagrid Building

Story displacement values for conventional building and diagrid building are tabulated in Table 4 and a graph of the same is depicted in Figure 7. X axis shows the story number and Y axis shows the story displacement in millimeters. Conventional building shows the highest deformation, which is 5.121 mm, and diagrid building shows the lowest deformation, which is 1.06 mm in story 1. This confirms the diagrid's efficacy in reducing displacement across different building heights.

Figure 8 illustrates the graphical comparison of story drift between a conventional building and a diagrid building, plotted based on the data provided in Table 5. The X axis denotes the story number, while the Y axis represents the story drift in millimeters. The conventional building exhibits the highest drift, reaching 2.927 mm, whereas the diagrid building demonstrates the lowest drift of 0.608 mm at story 1.

Base Shear Comparison Between Conventional and Diagrid Building

Table 6 gives the comparison of base shear values for conventional and diagrid buildings and Figure 9 represents those values in graphical format. The X axis denotes the story number, while the Y axis represents the corresponding base shear values. Notably, the conventional building exhibits a base shear of 3670.309 kN, whereas the diagrid building demonstrates significantly higher resilience with a base shear of 9147.7588 kN at story 1, underscoring its superior structural integrity.

Table 4. Story displacement in millimeters (medium-rise).

S.N.	**Story Displacement in X Direction (mm)**		
	Story No.	***Conventional Building***	***Diagrid Building***
1	Story 1	5.121	1.06
2	Story 2	35.638	7.377
3	Story 3	70.537	12.886
4	Story 4	103.095	20.246
5	Story 5	131.972	27.069
6	Story 6	156.588	34.502
7	Story 7	176.421	41.517
8	Story 8	190.926	48.235
9	Story 9	199.836	54.51

Table 5. Story drift in millimeters (medium-rise).

S.N.	**Story Drift in X Direction (mm)**		
	Story No.	***Conventional Building***	***Diagrid Building***
1	Story 1	2.927	0.608
2	Story 2	8.479	1.76
3	Story 3	9.775	1.715
4	Story 4	9.362	2.056
5	Story 5	8.599	1.989
6	Story 6	7.655	2.104
7	Story 7	6.553	2.006
8	Story 8	5.232	1.922
9	Story 9	3.486	1.802

Table 6. Base Shear in kilonewtons (kN) (medium-rise).

S.N.	Base Shear (kN)		
	Story No.	***Conventional Building***	***Diagrid Building***
1	Story 1	3670.309	9147.7588
2	Story 2	3606.501	9070.2432
3	Story 3	3303.807	8675.7048
4	Story 4	3044.921	8077.8657
5	Story 5	2779.549	7302.5925
6	Story 6	2478.038	6362.6461
7	Story 7	2133.701	5206.2636
8	Story 8	1745.899	3769.7062
9	Story 9	1101.174	1944.775

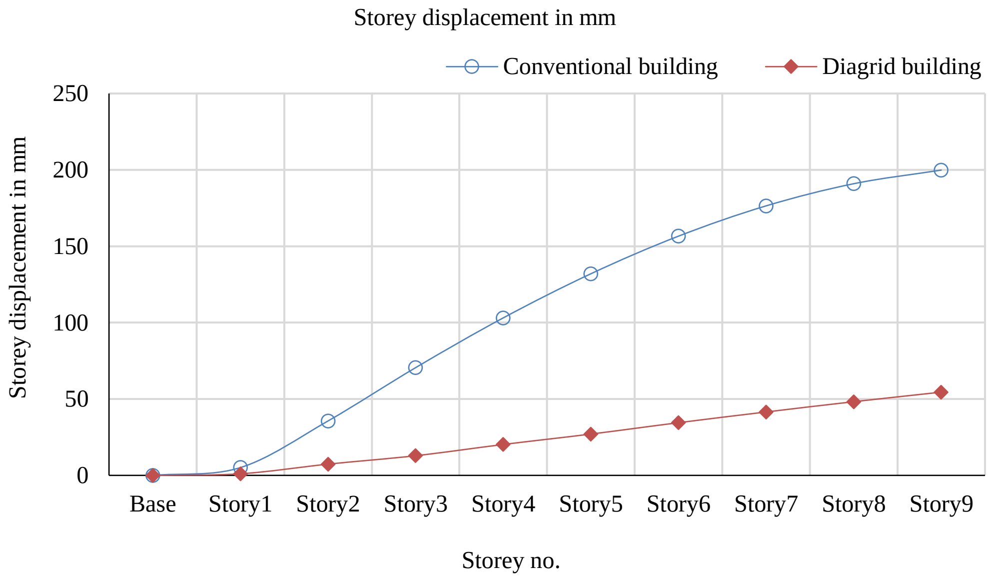

Figure 7. Story displacement in millimeters (medium-rise).

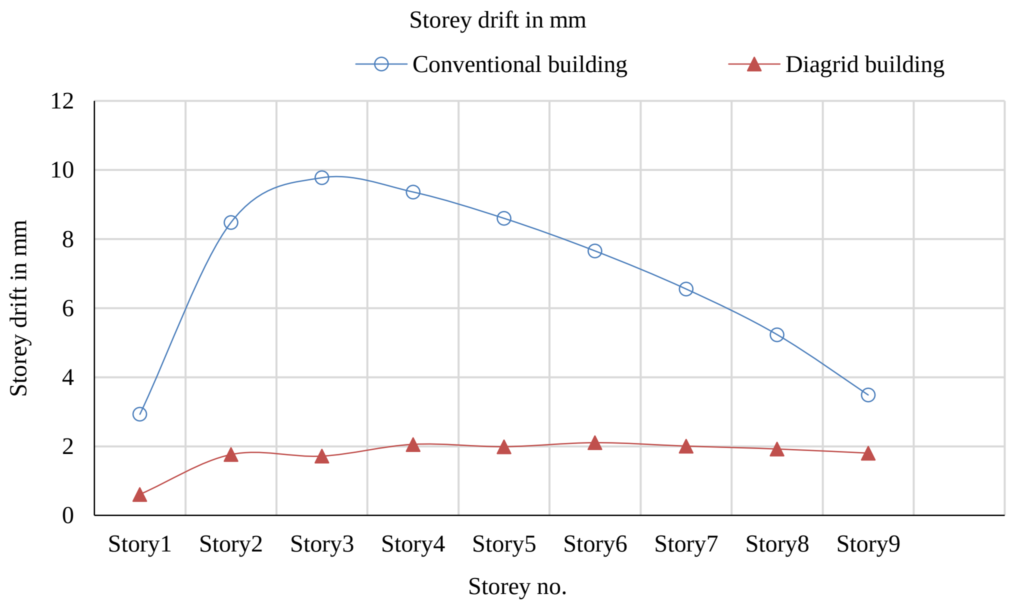

Figure 8. Story drift in millimeters (medium-rise).

High Rise

Story Displacement Comparison Between Conventional and Diagrid Building

A tabular comparison of story displacements between conventional and diagrid buildings is provided in Table 7, while Figure 10 graphically represents these values. The X axis denotes the story number, and the Y axis indicates the story displacement in millimeters. It is evident that the conventional building exhibits the highest deformation at 4.068 mm, whereas the diagrid building shows the lowest deformation at 0.922 mm in story 1. This highlights the superior effectiveness of diagrid systems in tall structures.

Story Drift Comparison Between Conventional and Diagrid Building

Table 8 presents story drift comparison for conventional and diagrid buildings whereas Figure 11 gives the graphical representation of the same. X axis shows the story number and Y axis shows the story drift in millimeters. Notably, conventional building shows the highest drift, which is 2.324 mm, and diagrid building shows the lowest drift, which is 0.527 mm in story 1.

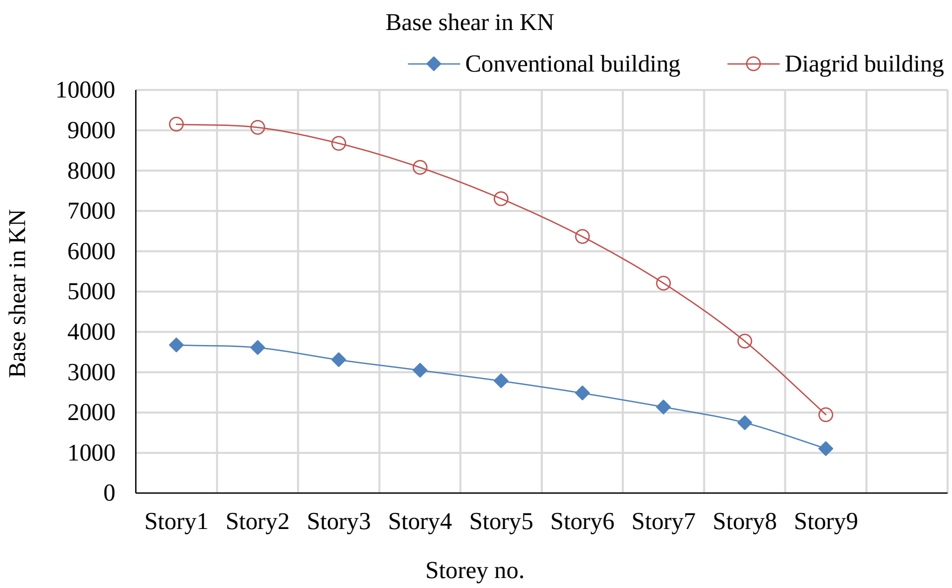

Figure 9. Base shear in kilonewtons (kN) (medium-rise).

Table 7. Story displacement in millimeters (high-rise).

S.N.	Story Displacement in X Direction (mm)		
	Story No.	***Conventional Building***	***Diagrid Building***
1	Base	0	0
2	Story 1	4.068	0.922
3	Story 2	28.647	6.589
4	Story 3	57.755	12.327
5	Story 4	86.075	19.637
6	Story 5	112.6	26.92
7	Story 6	137.179	35.17
8	Story 7	159.664	43.353
9	Story 8	179.866	52.014
10	Story 9	197.591	60.562
11	Story 10	212.609	69.177
12	Story 11	224.683	77.604
13	Story 12	233.545	85.775
14	Story 13	239.128	93.658

Journal of Construction Engineering, Technology & Management
Volume 14, Issue 2
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Table 8. Story drift in millimeters (high-rise).

S.N.	Story Drift in X Direction (mm)		
	Story No.	***Conventional Building***	***Diagrid Building***
1	Story 1	2.324	0.527
2	Story 2	6.828	1.58
3	Story 3	8.11	1.596
4	Story 4	7.997	2.045
5	Story 5	7.674	2.037
6	Story 6	7.29	2.326
7	Story 7	6.83	2.306
8	Story 8	6.322	2.46
9	Story 9	5.757	2.423
10	Story 10	5.124	2.452
11	Story 11	4.411	2.389
12	Story 12	3.467	2.31
13	Story 13	2.223	2.215

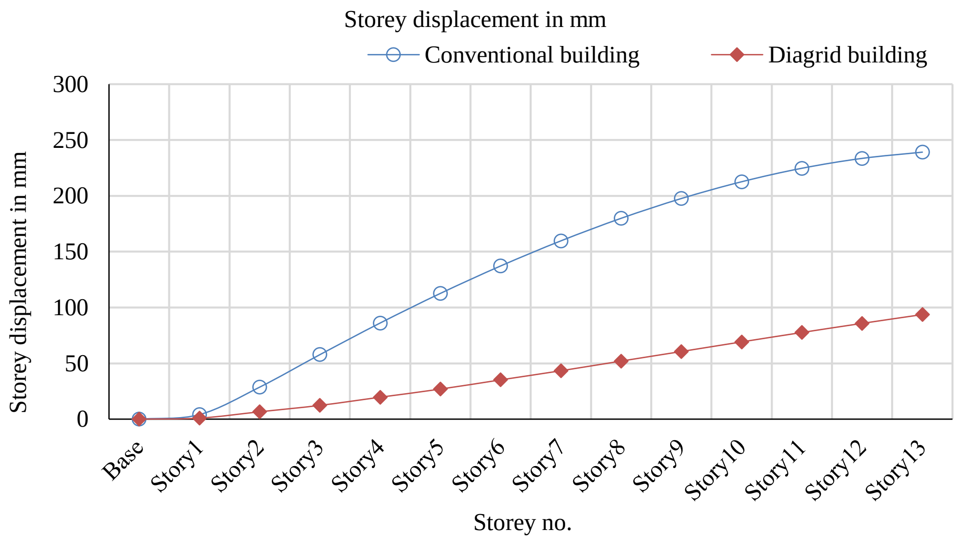

Figure 10. Story displacement in millimeters (high-rise).

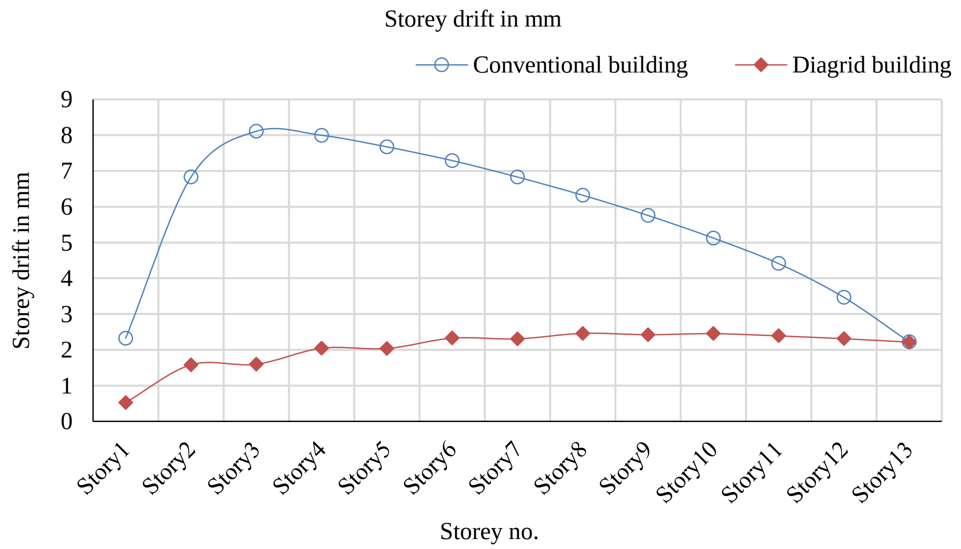

Figure 11. Story drift in millimeters (high-rise).

Table 9. Base shear in kilonewtons (kN) (high-rise).

S.N.	Base Shear in X Direction (kN)		
	Story No.	**Conventional Building**	**Diagrid Building**
1	Story 1	2869.938	8023.2877
2	Story 2	2846.613	7957.1699
3	Story 3	2705.095	7660.4237
4	Story 4	2538.37	7233.3117
5	Story 5	2411.682	6749.7104
6	Story 6	2280.385	6253.6546
7	Story 7	2121.688	5782.6607
8	Story 8	1957.616	5342.1917
9	Story 9	1777.608	4887.4245
10	Story 10	1576.891	4361.4105
11	Story 11	1371.064	3671.2382
12	Story 12	1084.603	2732.2925
13	Story 13	597.0624	1435.5599

Figure 12. Base shear in kilonewtons (kN) (high-rise).

Base Shear Comparison Between Conventional and Diagrid Building

Figure 12 presents the base shear in X direction in kilonewtons (kN) for conventional building and diagrid building. X axis shows the story number and Y axis shows the base shear in kN. Evidently, conventional building shows the lowest base shear, which is 2869.938 kN, and diagrid building shows the highest base shear, which is 8023.2877 kN in storey 1. This significantly higher capacity enhances the ability of diagrid structures to withstand lateral forces (Table 9).

CONCLUSIONS

The study comprehensively examined the structural efficiency and seismic performance of diagrid lateral load-resisting systems compared to conventional building designs across various building heights. Using advanced computational tools like ETABS v17.0 and employing response spectrum analysis, the research evaluated critical parameters such as story displacement, story drift, base shear, and time period. Based on the results, the following conclusions were obtained:

- Story displacement increases as number of stories are increased whereas story shear is maximum at base, reducing gradually towards the top.

- In low-rise buildings, diagrid systems demonstrate a story displacement that is twice lower than that observed in conventional buildings, and a base shear capacity marking an increase of 65.32% compared to that of conventional structures.
- For medium-rise buildings, diagrid surpasses conventional buildings by showing a displacement thrice lower and a base shear twice higher.
- In high-rise diagrid buildings, displacement represents a reduction of 60.89% compared to the conventional counterparts. The base shear capacity in diagrids is nearly twice as high as that recorded in conventional high-rise buildings.
- Diagrid structures exhibited superior stability and load-bearing capacity in low-rise buildings, reinforced structural integrity in mid-rise constructions, and effective performance under seismic loads in high-rise settings as compared to conventional structures.

These findings highlight the diagrid system's superior performance in seismic conditions, advocating for its broader adoption in earthquake-prone regions to enhance building safety and performance.

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