Malaysian
Journal Of Civil
Engineering

PARAMETRIC STUDY OF DIAGRID STRUCTURE COMPARED WITH RIGID FRAME STRUCTURE SUBJECTED TO LATERAL LOADING

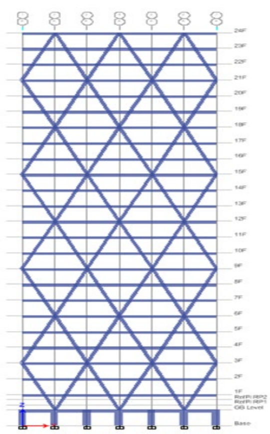
Md. Farhad Hossain[a]*, Md. Sohel Rana[a], Ahanaf Tahmid[b]

[a]Department of Civil Engineering, Rajshahi University of Engineering and Technology, Bangladesh
[b]Departmentof Civil Engineering, Ahsanullah University of Science and Technology, Bangladesh

Article history
Received
11 June 2022
Received in revised form
20 August 2022
Accepted
04 September2022
Published online
30 November 2022

*Corresponding author
1500045@student.ruet.ac.bd

Graphical abstract



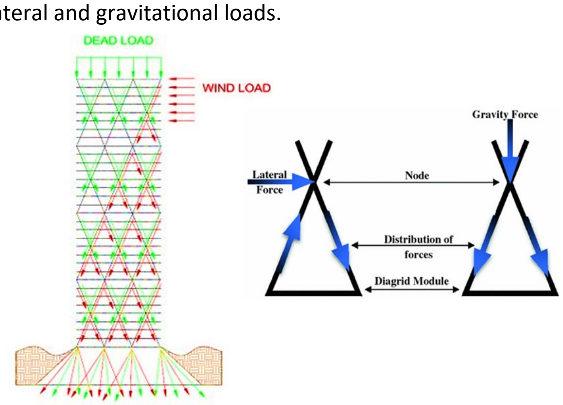
Abstract

Tall buildings are now preferred due to the scarcity of available land in cities and the rapid development of the urban population. People are now rising upward to avoid ongoing urban sprawl and to protect vital agricultural productivity. As the building's height increases, the lateral resisting system becomes just as important as the gravity supporting system. Diagrid has recently acquired favor for tall structures among the numerous lateral stability of tall buildings due to its structural efficiency and aesthetic possibilities given by the system's unusual geometric layout. Because of its triangulated construction, the diagonal components of the diagrid system can support both gravity and lateral loads. For this study, two structural models of 24-story buildings are used: one with a rigid frame structure and one with a diagrid structure. ETABS is used for modeling and analysis of buildings. The analytical findings are compared in terms of story drift and story displacement subjected to lateral loading. When compared to rigid framed structures, diagrid systems are far more effective at reducing drift and displacement. Because of the axial action of the diagonal parts, diagonal configurations carry shear. Shear is carried by rigid-framed constructions due to the bending of vertical columns.

Keywords: Tall buildings, Lateral resisting system, Diagrid building, Rigid frame building, Parametric study, Drift, Displacement, ETABS

1.0 INTRODUCTION

Due to the scarcity of available land in cities and the rapid development of the urban population, tall buildings are now preferred. As the height of the building increases, the lateral resisting system becomes as important as the gravity supporting system. In tall buildings, the main problem is that lateral load governs the design, but in the case of a shorter building, gravitational load governs. As a result, when constructing tall structures, structural methods that are more effective at producing stiffness against lateral stresses are preferred. The diagrid structural system is one of the most effective lateral resisting systems due to its different geometric configurations. Recently Structural engineers as well as architects have made significant progress in following diagrid structures. Peripheral vertical columns are omitted in diagrid systems. This is the primary distinction between diagrids and rigid frame structures. In this modern era, diagrid buildings have arisen as a new elegant design for tall buildings, with structural efficiency as a modified form of bracing systems. The triangular geometric configuration of diagrid structures as shown in Figure 1 effectively prevents structural failure due to lateral and gravitational loads.



(a) (b)

Figure 1: Distribution of loads in Diagrid Structure

1.1 Diagrid Structures

Diagrid structure is a distinct structural system among the various lateral structural systems that is becoming increasingly prominent in tall building design. The phrase "diagrid" is made up of the words "diagonal" and "grid." The bracing system includes a rather complex diagrid system. It evolved from the traditional bracing system. It is made up of massive diagonal bracings that sit on the building's periphery and are generally visible to the public. As a result, it becomes one of the aesthetical components used by architects.

In order to withstand both compression and tension, diagrids employ diagonal bracing members. Traditionally, the interior core and external diagonal bracings work together to produce more rigidity which enables the entire structure to achieve larger heights. Diagrid buildings can efficiently resist both lateral and gravitational loads without undergoing structural failure owing to its triangular form. Due to this distinctive quality, the need for columns—particularly corner columns—is significantly reduced as compared to traditional bracing. The following are the main benefits of diagrid structures:

i. Both gravitational and lateral loads are carried by the diagonal members, which improves design efficiency and reduces steel usage.
ii. The triangular shape increases stability by providing maximum resistance to torsion and overturning moment, hence minimizing core size.
iii. Minimizing the cost of the foundation by reducing the weight of the building.
iv. Because of the abundance of diagonal members, structures become more stable.
v. Reducing the number of peripheral columns allows the customer to build a more flexible area.

1.2 Difference between Bracing and Diagrid System

It's common to mix up the traditional bracing system and the diagrid structural system. The main difference between them is that peripheral vertical columns can be eliminated in a diagrid structure. Due to their triangular geometric shapes, diagrid bracings can withstand both gravity and lateral loads in diagrid buildings. However, the diagonals in the traditional bracing system could not sustain any gravity load.

1.3 Statement of the Project

This report represents a comparative study of 24 Story diagrid structures and rigid frame buildings with the same configuration. The floor plan was considered 24m x 24m for the structures. Modeling and Analysis of the structures were done by ETABS 16.2.1. All the load combinations for analysis such as dead load, live load, seismic and wind force are considered as per Bangladesh National Building Code 2006 (BNBC 2006) and Uniform Building Code 1994 (UBC 94). The comparison of results of the analysis regarding Maximum Story drift and Maximum Story displacement for seismic and wind forces is done and these properties are compared with rigid frame structure to determine the effectiveness of diagrid structure.

1.4 Objectives of the Study

i. To compare the response of diagrid structure with the rigid frame structure in terms of parameters - Story drift and Story displacement subjected to lateral loading.
ii. To evaluate the effect of drift and displacement on an RC-framed construction using diagrids.

1.5 Literature Review

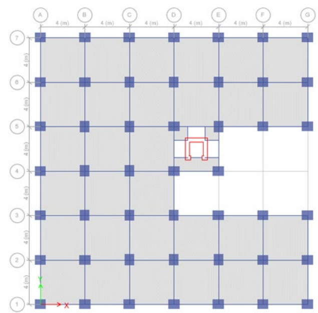
Significant study on the seismic behavior of the diagrid structural system has been conducted, and a few published papers are reviewed in this section. Nithin and Galer (2018) concluded that the diagrids give the structure the necessary stiffness, which reduces the storey displacement. Shankar and Priyanka (2018) found that the diagrid structure is observed to have less displacement, when compared to a traditional building. Yogeesh and Devaraj (2018) analyzed that the lateral displacement is decreased by 96.91% for RC diagrid frame in comparison with RC bare frame. Elena Toreno et al. (2014) commented on the most recent tubular structural mutation. Diagrid structures are important because of their structural efficiency, inherent aesthetic quality, and geometrical versatility. Diagrid structural systems can be differentiated from traditional bracing systems in such a way that practically all of the diagrid structure's periphery vertical columns are eliminated. The diagonal members of diagrid constructions are pin-jointed truss elements. Kwon and Kim (2014) discovered that when the twisting angle increases, diagrid structures are immune from progressive collapse. Jani and Patel (2012, 2013) revealed that the diagrid structural system is among the most successful free form structural systems. Kim et al. (2010) discovered that a diagrid construction has significantly less shear leg than a framed tube When the angle of twisting increases in a twisted diagrid building, the top story lateral displacement increases. As buildings become taller, the total structural material consumption increases fiercely were proposed by Mir and Moon (2007). Due to the accumulation of gravity force at the base, the size of the columns in a rigid frame building gradually grows towards the base, and the quantity of materials necessary to counteract lateral stresses likewise increases rapidly with increasing height. Mir and Moon (2007) discovered that when the structure's height exceeds 10 stores, a stiffness-based design concept takes precedence over a strength-based strategy. Diagrid structures, a sort of space truss, are a growing aesthetic trend in modern architecture for tall buildings. The diagrid system represents a unique outside design that is noticeable at first glance. Mir and Moon (2007) proposed that tubes, frames, or braced tubes are inefficient or economically unviable for 100-story buildings. In diagrid constructions, the expected angle range for diagonal members is 60° to 70°. Moon et al. (2007) demonstrated the derivation of a preliminary design approach and equations for the area of diagonals based on stiffness-based design. As a result, the diagrid system is the most effective structural system.

As per the literature review conducted here, a few scholars have investigated the usefulness of the diagrid structural system. As a result, a simulated results and evaluation of the efficiency of this lateral load resisting system are necessary.

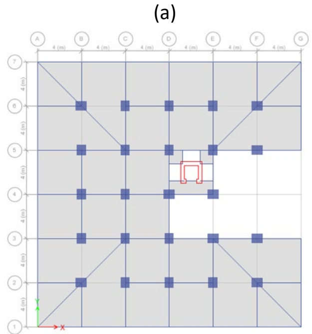
2.0 METHODOLOGY

2.1 Structural Models

Two structural models are taken for this study, one is a diagrid building and the other is a rigid frame building. 24 story building with 24m x 24m plan having 75m of total height with 3m height of each story is taken for both models. In diagrid building, the angle of diagrid is considered as 66° 2′ 15″. Figure 2 indicates the plan of rigid frame building and diagrid building and Figure 3 indicates the two different elevations of rigid frame building.

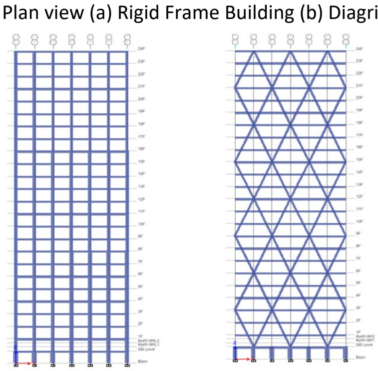


(a)



(b)

Figure 2 (a) Plan view (a) Rigid Frame Building (b) Diagrid Building



(a) (b)

Figure 3 Elevation view (a) Rigid Frame Building (b) Diagrid Building

2.2 Material Properties

Material properties are summarized in Table 1 as follows:

Table 1 Material Properties

Name	E (MPa)	Unit Weight (kN/m³)	Design Strengths
Concrete-20.7MPa	21383.71	24	F_c = 20.7 MPa
Concrete-24MPa	23025.20	24	F_c = 24 MPa
Steel-415MPa	199947.98	76.97	F_y = 415 MPa F_u = 620.53 MPa

2.3 Frame Sections

Frame sections are summarized in Table 2 as follows:

Table 2 Frame Sections

Name	Material	Shape
B-1	Concrete-20.7MPa	Concrete Rectangular
C-1	Concrete-24MPa	Concrete Rectangular
C-2	Concrete-24MPa	Concrete Rectangular
C-3	Concrete-24MPa	Concrete Rectangular

2.4 Shell Sections

Shell sections are summarized in Table 4 as follows:

Table 4 Shell Sections

Name	Design Type	Element Type	Material	Thickness (mm)
Slab-1	Slab	Shell-Thin	Concrete-20.7MPa	200
Stair-1	Slab	Shell-Thin	Concrete-20.7MPa	200
Wall-1	Wall	Shell-Thin	Concrete-24 MPa	350

2.5 Load Pattern

The loads applied on the model according to BNBC 2006 are shown in Table 5 as follows:

Table 5: Load Patterns

Name	Type	Self- Weight Multiplier	Auto Load	Applied Load (kN/m²)
DL	Dead	1	-----	Self-weight
LL	Live	0	-----	2.5
FF	Super Dead	0	-----	1.5
PW	Super Dead	0	-----	1.5
Stair	Live	0	-----	5
Roof	Live	0	-----	1.25
W_x	Wind	0	UBC 94	-----
W_y	Wind	0	UBC 94	-----
E_x	Seismic	0	UBC 94	-----
E_y	Seismic	0	UBC 94	-----

According to BNBC 2006, Uniformly distributed load shall not be applied simultaneously with the concentrated load.

3.0 RESULTS AND DISCUSSION

The analysis results of the rigid frame and diagrid building are provided in Table 6.

Table 6: Analysis Results of the Rigid Frame and Diagrid Building

Story (↓)	Maximum Story Drift (mm)								Maximum Story Displacement (mm)							
	Rigid Frame Building				Diagrid Building				Rigid Frame Building				Diagrid Building			
Load case (→)	W_x	W_y	E_x	E_y	W_x	W_y	E_x	E_y	W_x	W_y	E_x	E_y	W_x	W_y	E_x	E_y
24F	1.602	2.134	1.11	1.364	1.053	2.029	0.67	1.117	125.317	146.844	50.736	56.765	29.753	46.399	16.667	22.685
23F	1.875	2.432	1.245	1.496	1.065	1.42	0.675	0.85	124.028	144.709	49.736	55.4	28.841	45.181	16.064	21.932
22F	2.183	2.82	1.358	1.629	1.17	1.567	0.725	0.914	122.434	142.277	48.584	53.904	27.798	43.812	15.397	21.113
21F	2.526	3.268	1.473	1.768	1.18	2.069	0.734	1.102	120.463	139.457	47.291	52.276	26.651	42.303	14.679	20.233
20F	2.89	3.74	1.59	1.908	1.16	1.627	0.719	0.931	118.074	136.189	45.858	50.507	25.571	40.834	13.99	19.362
19F	3.275	4.226	1.71	2.046	1.248	1.758	0.755	0.965	115.247	132.449	44.285	48.599	24.422	39.268	13.275	18.466
18F	3.736	4.717	1.847	2.179	1.264	2.427	0.753	1.23	111.972	128.223	42.575	46.553	23.183	37.567	12.52	17.529
17F	4.227	5.226	1.987	2.313	1.262	1.97	0.751	1.039	108.236	123.507	40.729	44.374	22.001	35.846	11.794	16.586
16F	4.585	5.619	2.073	2.402	1.336	2.12	0.782	1.094	104.009	118.28	38.742	42.061	20.741	33.959	11.043	15.588
15F	4.96	6.028	2.175	2.503	1.358	2.345	0.787	1.157	99.424	112.662	36.669	39.659	19.407	31.938	10.262	14.542
14F	5.349	6.444	2.276	2.6	1.339	2.132	0.778	1.088	94.464	106.634	34.494	37.156	18.101	29.931	9.489	13.495
13F	5.74	6.855	2.373	2.691	1.387	2.173	0.788	1.078	89.115	100.19	32.218	34.556	16.763	27.886	8.712	12.449
12F	6.122	7.252	2.462	2.773	1.344	2.564	0.757	1.195	83.375	93.335	29.845	31.865	15.377	25.789	7.926	11.405
11F	6.49	7.625	2.543	2.842	1.328	2.272	0.734	1.079	77.253	86.084	27.382	29.093	14.054	23.708	7.175	10.383
10F	6.838	7.965	2.613	2.897	1.377	2.414	0.747	1.122	70.763	78.458	24.839	26.25	12.732	21.538	6.443	9.349
9F	7.164	8.269	2.669	2.936	1.368	2.428	0.747	1.133	63.925	70.493	22.227	23.353	11.359	19.245	5.7	8.279
8F	7.331	8.412	2.674	2.926	1.352	2.357	0.724	1.081	56.761	62.224	19.558	20.474	9.995	16.94	4.955	7.199
7F	7.489	8.536	2.683	2.916	1.336	2.254	0.696	1.007	49.43	53.813	16.884	17.632	8.647	14.684	4.234	6.16
6F	7.576	8.564	2.666	2.872	1.216	2.209	0.625	0.931	41.941	45.277	14.202	14.779	7.315	12.511	3.541	5.185
5F	7.548	8.448	2.61	2.782	1.122	2.084	0.562	0.883	34.365	36.713	11.536	11.944	6.111	10.484	2.917	4.293
4F	7.346	8.116	2.498	2.645	1.125	2.182	0.547	0.899	26.817	28.265	8.926	9.172	5.00	8.495	2.36	3.446
3F	6.884	7.464	2.304	2.422	1.168	2.295	0.57	0.945	19.471	20.149	6.429	6.526	3.884	6.425	1.819	2.59
2F	6.034	6.35	1.991	2.055	1.094	2.058	0.52	0.832	12.587	12.684	4.124	4.104	2.736	4.253	1.256	1.692
1F	4.588	4.581	1.497	1.481	1.144	1.675	0.515	0.657	6.553	6.334	2.133	2.049	1.705	2.279	0.758	0.889
GB	1.981	1.814	0.648	0.582	1.277	1.238	0.586	0.496	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

The response of both buildings under the action of lateral loads are discussed in terms of maximum story drift and maximum story displacement. Firstly, the maximum story drift of rigid frame and diagrid buildings under the action of seismic and wind loads is compared and analyzed. The maximum story displacement results of both buildings under the action of seismic and wind loads are then compared and discussed.

3.1 Maximum Story Drift due to Lateral Loads

The response of both rigid frame and diagrid buildings in terms of maximum story drift under the action of wind and seismic load is discussed in section 3.1.1 and 3.1.2 respectively.

3.1.1 Maximum Story Drift due to Wind Load

(a) The alteration of story drift with respect to the story is presented in Figure 4. It is depicted from the figure that the story drift of rigid frame building increases in a non-linear manner and attains the maximum value of 7.576 mm at the sixth story and then decreases for the higher story. However, a little variation of story drift is observed for the diagrid building. Also, the story drift of the diagrid building is much lesser than the rigid frame building.

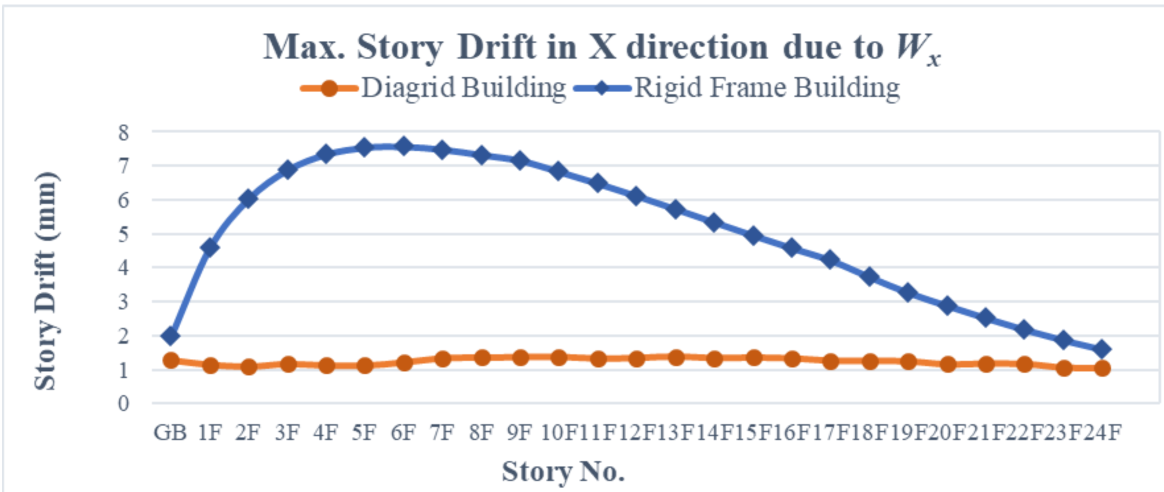


Figure 4: Maximum Story Drift in X direction due to W_x

(b) The alteration of story drift with respect to the story is presented in Figure 5. It is depicted from the figure that the story drift of rigid frame building increases in a non-linear manner and attains the maximum value of 8.564 mm at the sixth story and then decreases for the higher story. However, a little variation of story drift is observed for the diagrid building. Also, the story drift of the diagrid building is much lesser than the rigid frame building.

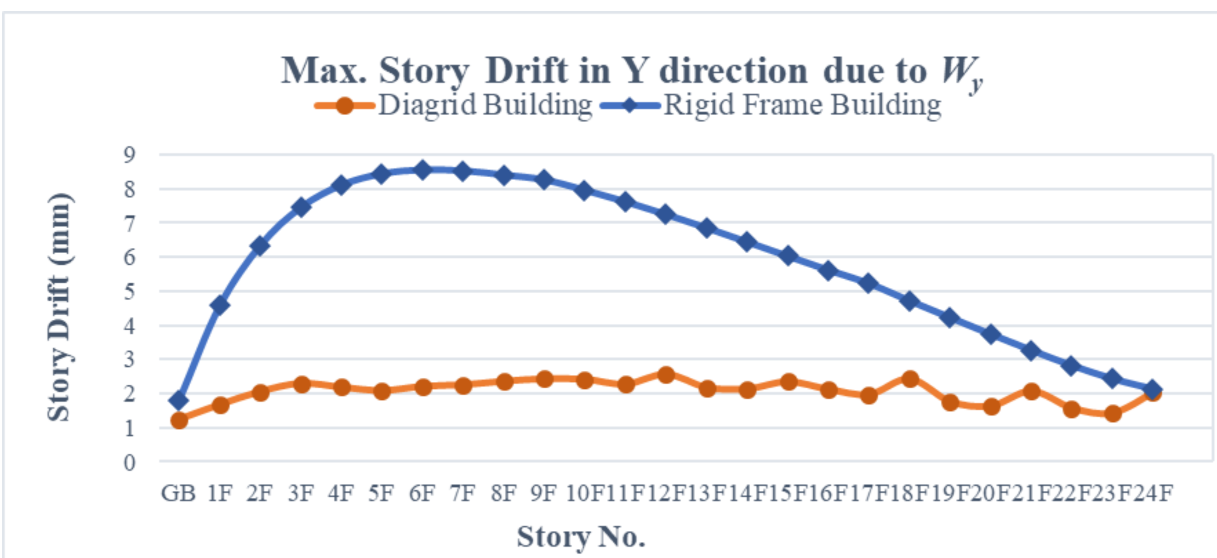


Figure 5 Maximum Story Drift in Y direction due to W_y

In section 3.1.1, It clearly indicates that, the story drift of the diagrid building under the action of wind loading is much lesser than the rigid frame building. This fact indicates that the diagrid building shows higher resistance against wind loading.

3.1.2 Maximum Story Drift due to Seismic Load

(a) The alteration of story drift with respect to the story is presented in Figure 6. It is depicted from the figure that the story drift of rigid frame building increases in a non-linear manner and attains the maximum value of 2.68 mm at the seventh story and then decreases for the higher story. However, a little variation of story drift is observed for the diagrid building. Also, the story drift of the diagrid building is much lesser than the rigid frame building.

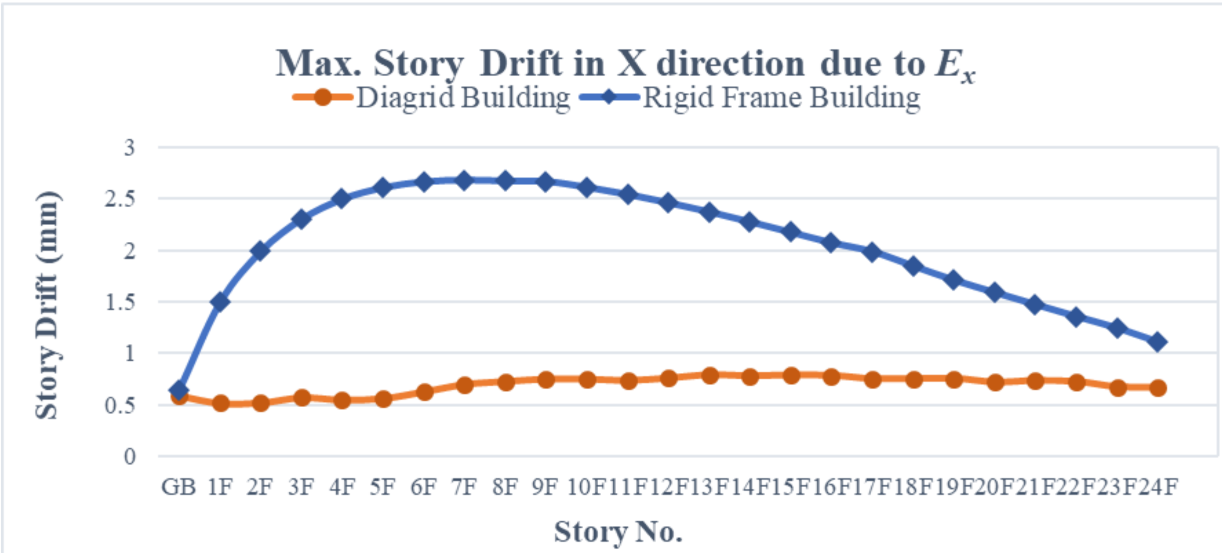


Figure 6 Maximum Story Drift in X direction due to E_x

(b) The alteration of story drift with respect to the story is presented in Figure 7. It is depicted from the figure that the story drift of rigid frame building increases in a non-linear

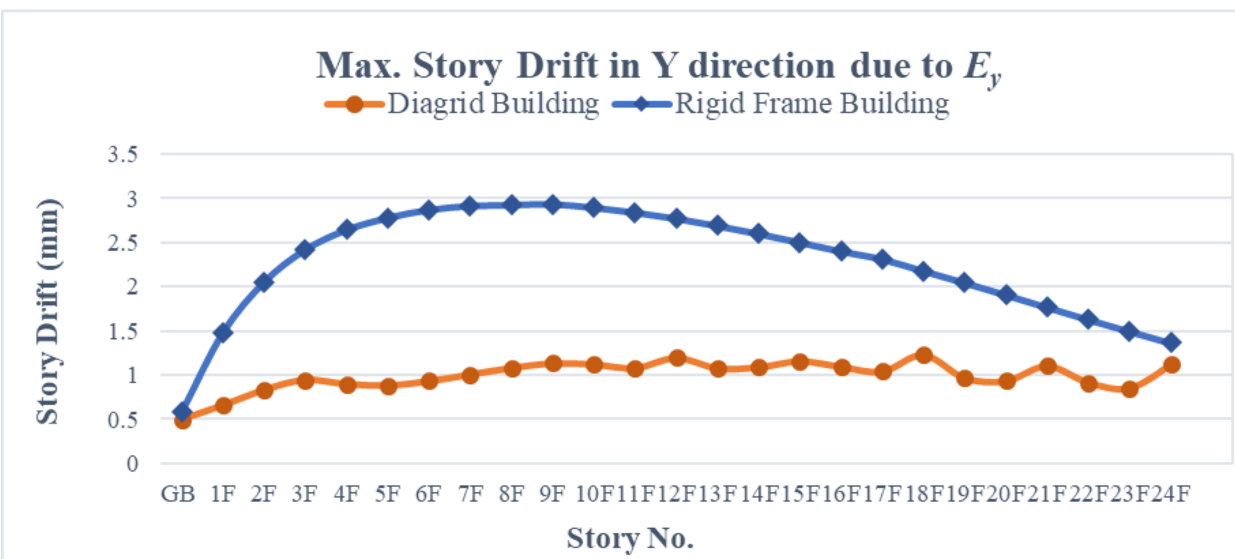


Figure 7 Maximum Story Drift in Y direction due to E_y

In section 3.1.2, It clearly indicates that, the story drift of the diagrid building under action of seismic loading is much lesser than the rigid frame building. This fact indicates that the diagrid building shows higher resistance against seismic loading.

It can be concluded that, As the story drift of the diagrid building under action of lateral loading is much lesser than the rigid frame building, the diagrid building shows higher resistance against lateral loading.

3.2 Maximum Story Displacement due to Lateral Loads

The response of both rigid frame and diagrid buildings in terms of story displacement under the action of wind and seismic load is discussed in section 3.2.1 and 3.2.2 respectively.

3.2.1 Maximum Story Displacement due to Wind Load

(a) The alteration of story displacement with respect to the story is presented in Figure 8. It is depicted from the figure that the story displacement of rigid frame building increases in a non-linear manner when the number of stories increases. However, in the case of the diagrid building, story displacement increases almost linearly and much lesser than the rigid frame building. This fact indicates that the diagrid building shows higher stiffness against wind loading.

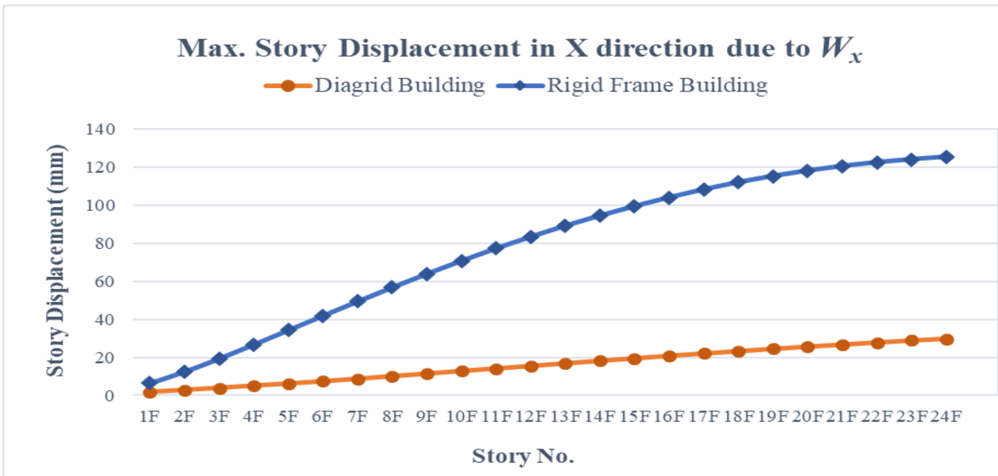


Figure 8 Maximum Story Displacement in X direction due to W_x

(b) The alteration of story displacement with respect to the story is presented in Figure 9. It is depicted from the figure that the story displacement of rigid frame building increases in a non-linear manner when the number of stories increases. However, in the case of the diagrid building, story displacement increases almost linearly and much lesser than the rigid frame building. This fact indicates that the diagrid building shows higher stiffness against wind loading.

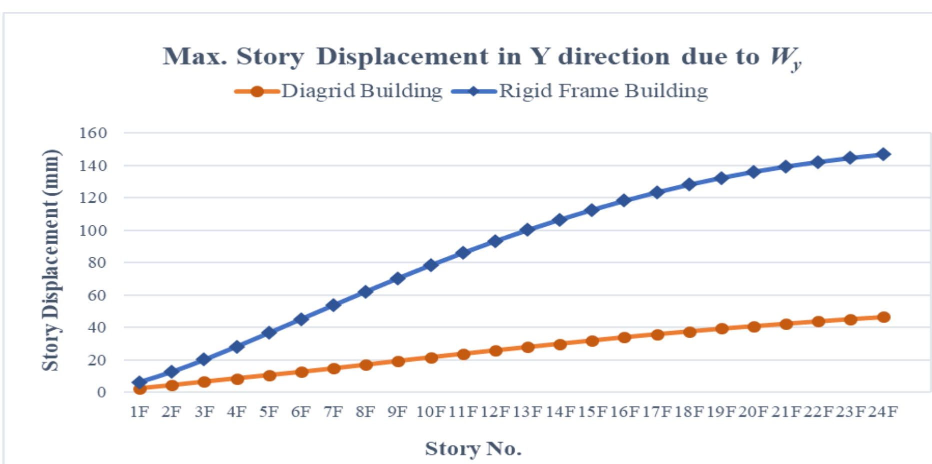


Figure 9 Maximum Story Displacement in Y direction due to W_y

In section 3.2.1, It clearly indicates that, the story displacement of the diagrid building under action of wind loading is much lesser than the rigid frame building. This fact indicates that the diagrid building shows higher resistance against wind loading.

3.2.2 Maximum Story Displacement due to Seismic Load

(a) The alteration of story displacement with respect to the story is presented in Figure 10. It is depicted from the figure that the story displacement of rigid frame building increases in a non-linear manner when the number of stories increases. However, in the case of the diagrid building, story displacement increases almost linearly and much lesser than the rigid frame building. This fact indicates that the diagrid building shows higher stiffness against seismic loading.

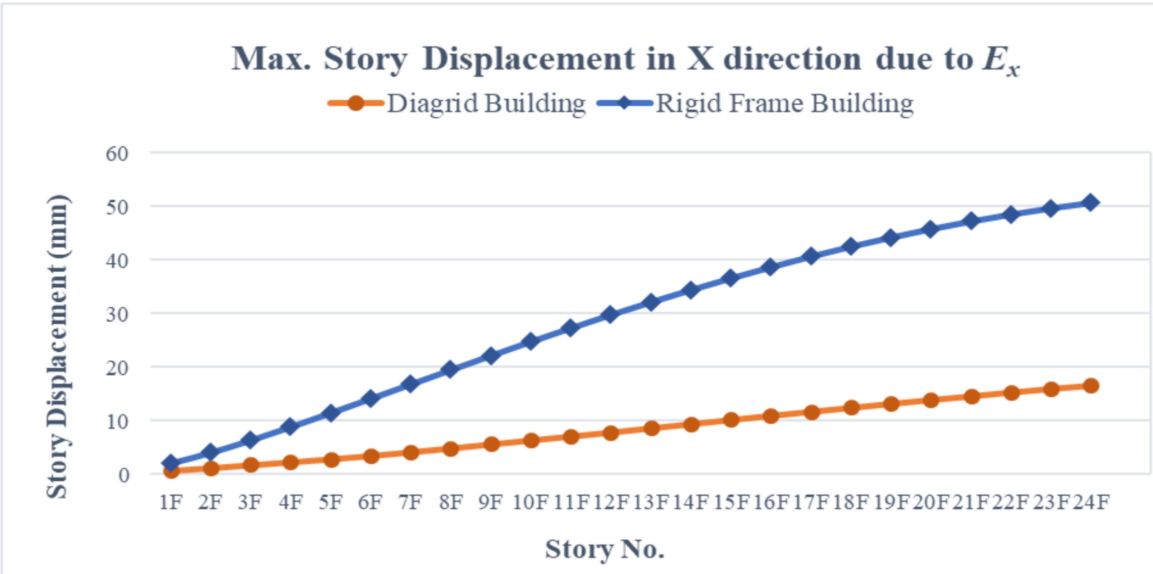


Figure 10: Maximum Story Displacement in X direction due to E_x

(b) The alteration of story displacement with respect to the story is presented in Figure 11. It is depicted from the figure that the story displacement of rigid frame building increases in a non-linear manner when the number of stories increases. However, in the case of the diagrid building, story displacement increases almost linearly and much lesser than the rigid frame building. This fact indicates that the diagrid building shows higher stiffness against seismic loading.

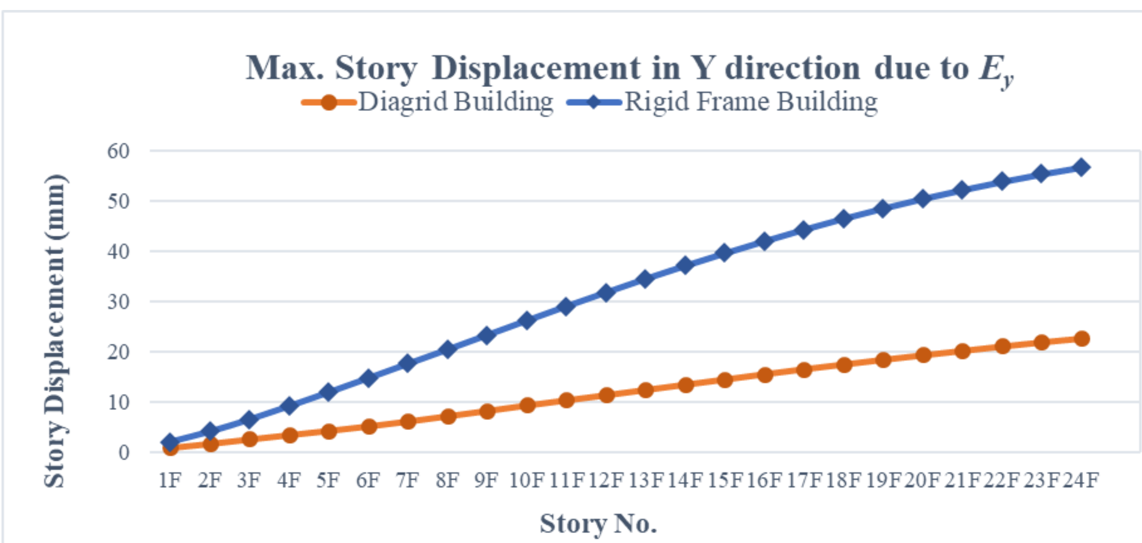


Figure 11 Maximum Story Displacement in Y direction due to E_y

In section 3.2.2, It clearly indicates that, the story displacement of the diagrid building under action of seismic loading is much lesser than the rigid frame building. This fact indicates that the diagrid building shows higher resistance against seismic loading.

In both section 3.1.1 and 3.1.2, It can be concluded that, As the story displacement of the diagrid building under action of lateral loading is much lesser than the rigid frame building, the diagrid building shows higher resistance against lateral loading.

4.0 CONCLUSIONS

Based on the analysis of results carried out in the previous chapter, the following are the findings,

i. The value of story drift of rigid frame building increases in a non-linear manner as the number of stories increases up to a certain level and then reduces. However, the diagrid building shows higher stiffness against story drift, and the magnitude of story drift is found to be more or less parallel to the X-axis and much lesser than the rigid frame building.

ii. The value of story displacement of rigid frame building increases in a non-linear manner as the number of stories increases. In a diagrid building, the value of story displacement increases almost linearly and much lesser than the value of rigid frame building. This fact indicates that the diagrid building shows higher resistance against story displacement.

Acknowledgements

First and foremost, praises and thanks to Almighty Allah. The authors would like to express gratitude to all teachers of Department of Civil Engineering, RUET, specially, Late Professor Dr. Tarif Uddin Ahmed for his suggestions and constructive criticisms throughout this research work.

References

[1] Ali, M. M., and Moon, K. S. 2007. Structural Developments in Tall Buildings: Current Trends and Future Prospects. *Architectural Science Review*, 50(3): 205-223.

[2] BNBC, 2006. Bangladesh National Building Code, Ministry of Housing and Public Works, Government of the People's Republic of Bangladesh, 6(2): 19-68

[3] Elena, M., Toreno M., Brandonisio G., and De Luca, A. 2014. Diagrid Structures for Tall Buildings: Case Studies and Design Consideration. *The Structural Design of Tall and Special Buildings*. 124-145.

[4] Feng F. 2018. Design and Analysis of Tall and Complex Structures, *Elsevier Ltd*. 81-156.

[5] Jani, K. D. and Patel, P. V. 2013. Design of Diagrid Structural System for High Rise Steel Buildings as per Indian Standards. *Structures Congress 2013 © ASCE 2013*, 1070-1081.

[6] Jani, K. D. and Patel, P. V. 2012. Analysis and Design of Diagrid Structural System for High Rise Steel Buildings. *Procedia Engineering*. 51: 92-100.

[7] Kwon, K. and Kim, J. 2014. Progressive Collapse and Seismic Performance of Twisted Diagrid Buildings. *International Journal of High-Rise Buildings*, 223-230.

[8] Moon, K. S. 2014. Comparative Evaluation of Structural Systems for Tilted Tall Buildings. *International Journal of High-Rise Buildings,* 89-98.

[9] Moon, K. S. 2011. Diagrid Structures for Complex-Shaped Tall Buildings. *Procedia Engineering*, 14: 1343-1350.

[10] Moon, K. S. 2008. Optimal Grid Geometry of Diagrid Structures. *Architectural Science Review*, 51(3): 239-251.

[11] Moon, K. S., Connor, J. J., and John, E. F. 2007. Diagrid Structural Systems for Tall Buildings: Characteristics and Methodology for Preliminary Design. *The Structural Design of Tall and Special Buildings*. 16(2): 205-230.

[12] Nithin, M. and Galer, P. S. 2018. Parametric Study on the Behavior of Diagrid Structures Subjected to Dynamic Loading. *International Research Journal of Engineering and Technology (IRJET).* 5(7): 56-72.

[13] Shankar, B. and Priyanka, M. V. 2018. Comparative Study of Concrete Diagrid Building and Conventional Frame Building Subjected To Seismic Force. *International Research Journal of Engineering and Technology (IRJET). 5*(6): 56-72.

[14] UBC, 1994. Uniform Building Code – Structural Engineering Design Provisions, International Conference of Building Officials, Whittier, California.

[15] Yogeesh, H. S. and Devaraj, V. 2018. A Seismic Study on Diagrid Structure. *International Journal for Research in Applied Science & Engineering Technology (IJRASET).* 6(6): 2321-965.