07

BEHAVIOUR OF SLENDER BUILDING WITH VARIABLE ANGLE DIAGRID STRUCTURE UNDER LATERAL LOADS

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Abstract: *Following the industrial revolution, there was a rapid increase in the construction of slender buildings due to the challenges posed by urbanization and limited available space. Tall buildings prioritize lateral load-resisting systems over gravitational loads. While various systems exist, the 'diagrid' stands out for its structural efficiency and aesthetics. Unlike framed tube structures, diagrids employ inclined columns on the facade, relying on axial forces in diagonals for lateral load resistance. This innovative approach enhances both structural performance and aesthetics, making diagrids a popular choice in modern tall building construction. This paper explores the dynamic behavior of both constant angle and variable angle diagrid structures under lateral loads. Using the EATBS 21 software, a 64-story building model with a plan dimension of 24x24m, an overall height of 242.3m, an average story height of 3.8m, and a slenderness ratio of 10.13 is created. The study is conducted for a location in Delhi having seismic (zone-4). The aim is to determine the optimal angle for constant angle diagrid and create patterns of variable angle diagrid structures. These models are then compared to constant angle diagrids in terms of structural weight of diagrid and performance of the building.*

Keywords: *Slender building, Diagrid, Lateral displacement, Inter-story drift, Response spectrum, Wind analysis.*

1. INTRODUCTION

The allure of towering structures has been a perennial fascination for humanity, a fascination that gained momentum following the industrial revolution. The migration of individuals from rural landscapes to urban centers in pursuit of employment opportunities became a notable trend in the aftermath of the industrial revolution. As urban areas witnessed a surge in population density,

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there was a notable upswing in the demand for the construction of high-rise buildings. This increased demand gave rise to the concept of a vertical city.

Diagrid structures differ from traditional exterior-braced frames by reducing the number of vertical columns through diagonal members, which serve dual roles in supporting both gravity and lateral forces. In contrast to conventional braced frames that depend on vertical columns for lateral loads, diagrids employ diagonals for this function. When compared to framed tubular structures without diagonals, diagrids significantly diminish shear deformation by utilizing diagonal members for axial shear action. (Panchal & Patel, 2014). The perimeter "diagrid" system stands out for its ability to decrease structural steel weight by approximately 20% when compared to traditional moment-frame structures, thereby simplifying construction processes and underscoring the economic and environmental advantages. Renowned global examples of diagrid structures include Swiss Re in London, Hearst Tower in New York, Cyclone Tower in Asan (Korea), Capital Gate Tower in Abu Dhabi, and Jinling Tower in China. The new CCTV headquarters in Beijing exemplifies the efficient application of the diagrid structural system for complex architectural support (Leonard, 2007).

(Montuori et al., 2014) initiated on investigating geometrical patterns in diagrid buildings and introduced three categories: regular diagrid structures featuring a consistent angle of inclination, variable angle diagrid structures with angles changing along the height, and variable density diagrid structures with fluctuating member density.

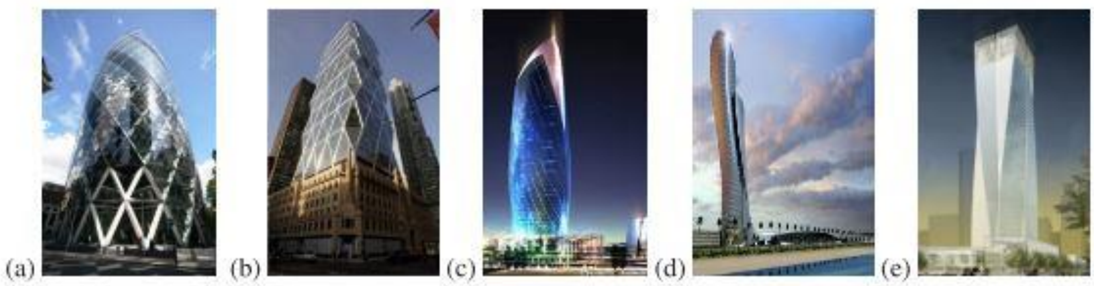

Figure 1: (a) Swiss Re in London (b) Hearst Tower in New York (c) Cyclone Tower in Asan (Korea) (d) Capital Gate Tower in Abu Dhabi

This study explores variable angle diagrid structures in slender diagrid buildings (H/B>10), examining different configurations achieved by adjusting the angle of inclination while maintaining height ratios constant. It compares structures with constant angles (68.45° (4 module), 78.85° (8 module), and 81.03° (10 module)) to those with varying diagonal inclinations. Structural performance evaluation of these diagrid structures is conducted, considering their varying heights and geometric properties, in accordance with Indian Standards

(IS 800, 2007; IS 875 (Part 3), 2015; IS 1893 (Part 1), 2016; IS 16700, 2017). The findings suggest that optimal diagonal geometries play a crucial role in achieving an efficient structural layout. The study has investigated the impact of both stiffness-based and strength-based design criteria on diagrid structures (Bhat & Danish, 2021; Montuori et al., 2014).

Predicting whether global stiffness or member strength will dominate diagrid member design is challenging, necessitating consideration of both criteria. Some scientific papers focus on non-regular diagrid geometries. The Lotte Super Tower exemplifies a diagrid structure with variable geometry, utilizing diagonals with varying inclinations to optimize the structure and enhance lateral load support. Variable-angle diagrids prove more efficient in design compared to constant-angle counterparts.(Moon, 2008; Zhang et al., 2012). An illustration for the analysis and design of tall steel structures featuring diagrids.(Deshpande et al., 2015; Jani & Patel, 2013).Examining and designing high-rise steel structures with diagrids provides a valuable example, aiding in the adaptation of these strategies for various models.(Jani & Patel, 2013). In this paper, the models undergo analysis and design using the ETABS software.

2. OBJECTIVE OF RESEARCH PAPER

This study aims to delve into the attributes of slender diagrid buildings (H/B>10) by examining their dynamic response under lateral loads, considering both constant and varying angles of diagrid members. The investigation involves the utilization of E-TABS software for modeling and analyzing tall and high-rise structures. The focus is on understanding how variations in diagrid member angles influence the structural performance of such buildings, particularly in the context of lateral loads.

3. DETAILS OF MODELLING AND ANALYSIS

The location of the structure is recognized as Delhi. An examination is conducted on a 64-storey diagrid building. The building, subject to analysis, has a plan with dimensions of 24m x 24m. Each storey has a consistent height of 3.8m, resulting in an overall structure height of 243.2m. The structure is uniformly distributed along both the X and Y axes. Instead of straight perimeter columns, diagrid columns are employed with constant and varying angles. The angle of the diagrid is determined by the storey height, which is set at 3.8m.

Example- Storey height- 3.8m, No. of storeys- 243.2m; (2 module); $\tan\theta = P/B$; $\tan\theta = 3.8/3$; $\theta = 51.70°$, (4 module); H = 7.6m; $\theta = 68.45°$, (6 module); H = 11.4m; $\theta = 75.25°$, (8 module); H = 15.2m; $\theta = 78.83°$, (10 module); H = 19m; $\theta = 81.03°$.

For variable angle diagrid angle inclination are $\theta = 81°$ for the top 10 storeys, $\theta = 75.25°$ for the middle 30 storeys, and θ = 68.45° for the bottom 24 storeys.

The structure is designed with M40 grade concrete and a 200mm slab thickness, incorporating diaphragms at each level for diaphragm action. It's assumed the structure is fixed at ground level. Dead loads, live loads, and live load reduction factors are assigned according to IS-875 (1987). The model meets all clauses of IS-456 (2000) and SP16. Additionally, as per IS-16700 (2017), lateral load drift should not exceed H/500 for wind and H/400 for seismic loads (IS 456, 2000; IS 800, 2007; IS 16700, 2017).

According to IS-1893 (2016) (Part 1), the equivalent static method and the response spectrum method are used in the analysis. All the combination used as per the standards are listed in IS 456:2000 & IS 1893:2016.

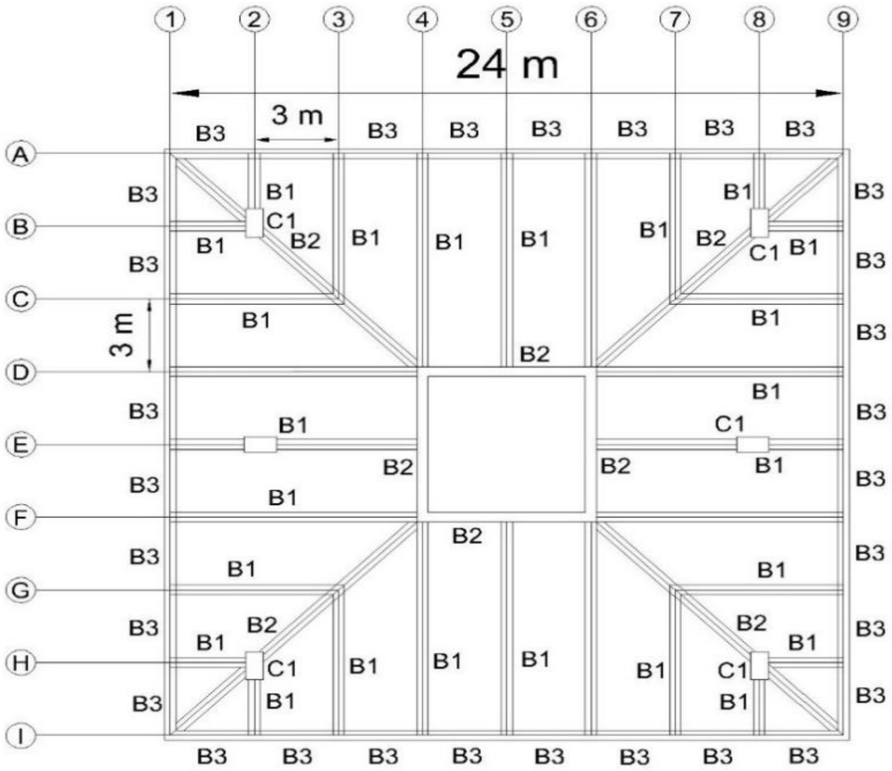

Figure 2: Plan of Building

Figure 2 shows the plan of a symmetrical building with dimensions of 24 × 24m. The plan includes eight bays on each side of 3m, and features diagrid (D1) of CHS 825mm with thickness 55mm, inner columns (C1) column measuring (900 x 1200) mm, Beams (B1 = 350x500) mm, (B2 & B3 = 350x650) mm and Shear Wall of 300mm thickness. The building is symmetric in both the x-axis and y-axis.

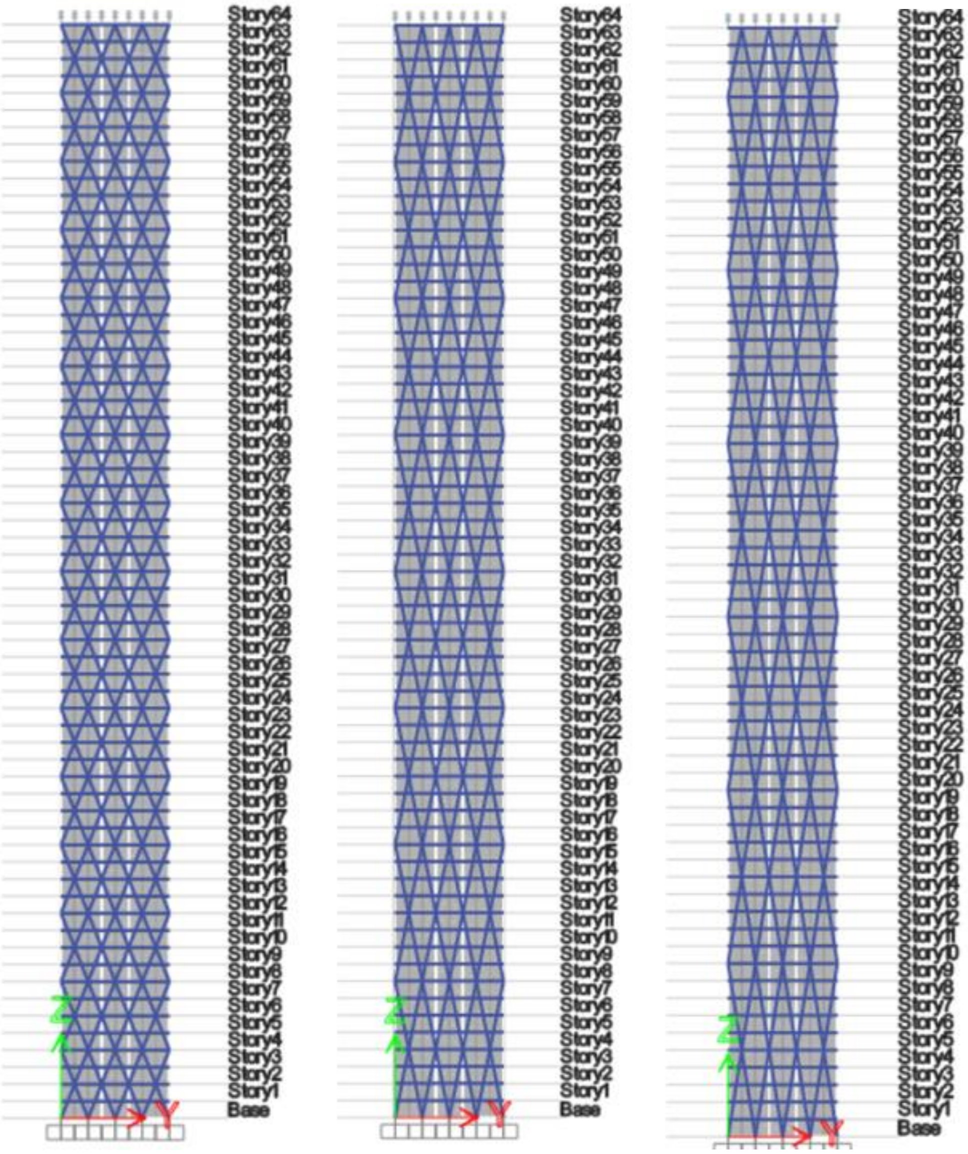

Figure 3: Elevation of building (a) 68.45 (b)78.85 (c)81.03

Figure 3 shows the building's elevation featuring a diagrid with inclinations of 68.45°, 78.85°, and 81.03°. The structure comprises a ground floor plus 63 additional storeys, each measuring 3.8m in height, leading to a total height of 243.2m.

Figure 4 illustrates the elevation of the building featuring a variable angle diagrid having angle inclination are θ = 81° for the top 10 storeys, θ = 75.25° for the middle 30 storeys, and θ = 68.45° for the bottom 24 storeys. Similar to Figure 3, the building comprises G+63 storeys, each with a height of 3.8m, resulting in an overall height of 243.2m.

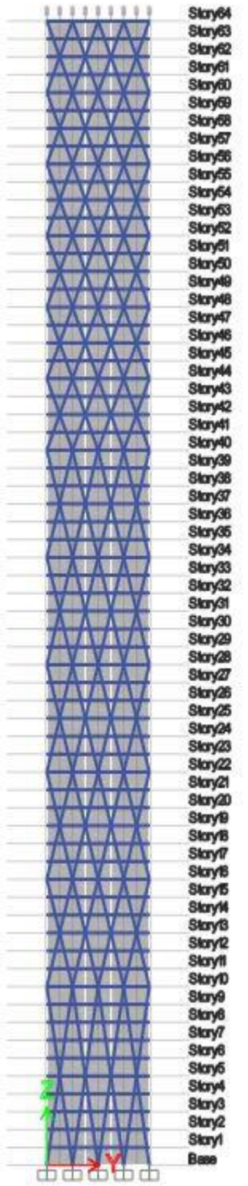

Figure 4: Elevation of variable angle diagrid building

4. METHOD OF ANALYSIS

4.1 Response Spectrum Analysis (RSA)

During seismic events, buildings experience displacement, velocity, and acceleration responses. The response spectrum curve illustrates the maximum response of a structure to earthquake-induced ground movement over time. Utilizing response spectrum analysis provides valuable insights into the structure's behavior and aids in determining seismic forces. This analysis is crucial for designing earthquake-resistant structures, particularly due to its linear nature, which limits responses to the elastic range.

In this particular investigation, following the guidelines of IS 1893 (Part 1)-2016, the earthquake load is computed for Delhi, categorized as "zone 4" (Z = 0.24), with an importance factor of 1.2 for the building. The assumed soil type is medium to stiff, and a uniform response reduction factor (R) of 3.0 is applied to all frames.

In dynamic analysis the determined design base shear V_B should not be lower than the design base shear V_B, which is derived through the fundamental natural time period (Ta). If V_B is less than V_B, then the response force parameters, including base shear, base reactions, and member stress resultants, should be scaled by the ratio V_B / V_B. The dynamic analysis of the structures is conducted using the Response Spectrum Method (IS 1893 (Part 1), 2016).

4.2 Wind Analysis (WA)

Wind, characterized as air movement relative to the earth's surface, varies temporally and spatially. Due to its unpredictable nature, it's crucial to design tall structures considering its significant impact. Wind force relies on factors like exposed area, terrain, wind characteristics, structure size, shape, and building dynamics. Designing should particularly address the fluctuating wind pressure component (IS 875 (Part 3), 2015).

In this research, Wind load calculations adhere to the standards specified in IS 875 (Part 3)-2015. For the location under review, Delhi, the design wind speed is 47 m/sec. The building's importance factor, as well as the probability and topography factors, are all designated as 1.0 (IS 875 (Part 3), 2015).

5. METHODOLOGY

The ETABS software is employed to create a model of a 64-storey building, where all stories have a uniform height of 3.8 meters. The slabs are 200 mm deep, and a concrete shear wall with a thickness of 300 mm is incorporated. The designated seismic zone is 4, with a zone factor of 0.24 and an importance factor of 1.2. The soil type considered is medium, and a response reduction factor of 3 is applied. The basic wind speed is determined to be 47 m/sec.

In this study, three 3D models are generated, featuring angles of 68.45°, 78.85°, and 81.03°, each with a shear wall at the center, as depicted in Figure 3. These models are compared based on displacement, drift, and storey stiffness. Additionally, a model is created with a variable angle diagrid, featuring angles θ = 81° for the top 10 storeys, θ = 75.25° for the middle 30 storeys, and θ= 68.45° for the bottom 24 storeys, as shown in Figure 4. This model, with a shear wall at the center, is then compared with constant angle models.

6. RESULTS

The figures presented below exclude the response in the Y direction and focus solely on the results obtained in the X direction.

After analyzing the model with diagrid angles of 68.45°, 78.85°, and 81.03°, the building's displacement is determined to be 195.09mm, 240mm, and 268.28mm, respectively, in RSA. In wind analysis, the corresponding figures are 387.33mm, 413.77mm, and 448.16mm. Combining the variable angle diagrid building with angles θ = 81°, θ = 75.25°, and θ = 68.45°, the displacement values are 221.43mm (RSA) and 388.22mm (wind analysis), both below H/500 (486mm). (IS 16700, 2017) The drift of the building with angles 68.45°, 78.85°, and 81.03° is found to be 0.001069, 0.001239, and 0.001369, respectively, in RSA, and 0.00197, 0.001984, and 0.002155, respectively, in wind analysis. By combining the variable angle diagrid building with angles θ = 81°, θ = 75.25°, and θ = 68.45°, the drift values are 0.00112 (RSA) and 0.001843 (wind analysis), both less than 0.004hi; where hi represents the storey height. (i.e., 0.0152) (IS 1893 (Part 1), 2016).

6.1 Storey Displacement

Storey displacement pertains to the vertical movement or deflection of a building's floor levels in relation to one another, particularly during an earthquake or other seismic occurrences. This movement is typically induced by the response of the building's mass and stiffness to the forces generated by ground motion. It is essential to ensure that the maximum storey displacement of the building does not surpass H/500, where H represents the height of the building (IS 16700, 2017).

In Figures 5 and 6, the X-axis denotes displacement in mm, while the Y-axis signifies the storey number.

The Diagrid building exhibits maximum storey displacements at angles of 68.45°, 78.85°, and 81.03°, measuring 195.09mm, 240mm, and 268.28mm, respectively (Figure 5), for RSA. For wind analysis, the corresponding displacements are 387.33mm, 413.77mm, and 448.16mm (figure 6). In the case of a variable angle diagrid, the displacements are 221.43mm (RSA) and 388.22mm (wind analysis) in Figures 5 & 6, both of which are below the threshold of H/500 (486mm).

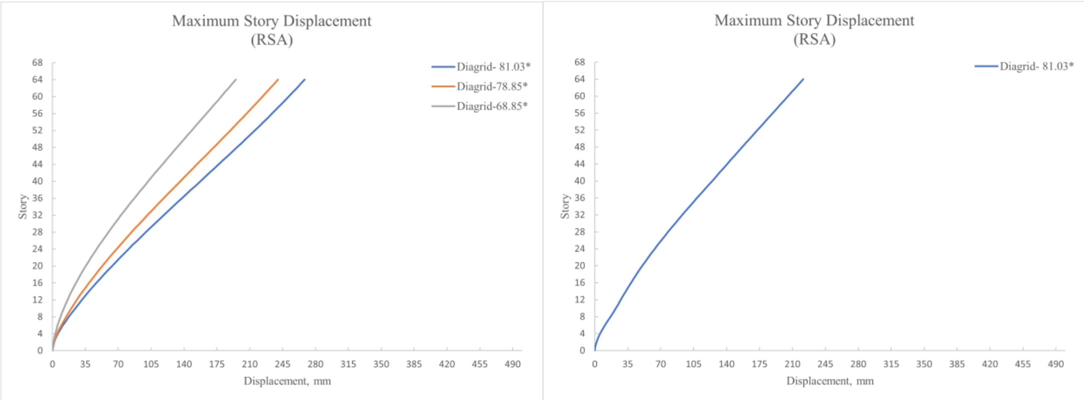

Figure 5: Displacement of building having angle 68.45, 78.85, 81.03 & variable angle diagrid (RSA)

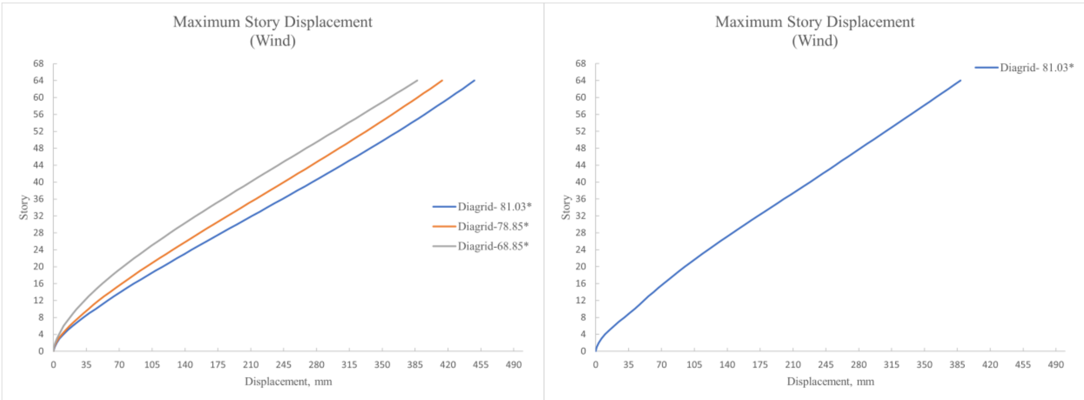

Figure 6: Displacement of building having angle 68.45, 78.85, 81.03 & variable angle diagrid (WA)

6.2 Storey Drift

Storey drift is commonly quantified as the maximum horizontal displacement of a specific storey in relation to the adjacent one. Excessive storey drift poses risks of structural damage, potential collapse, or impairment of the building's functionality. Therefore, designers and engineers must carefully consider the impact of storey drift in their designs and implement suitable measures to mitigate it. This may include the incorporation of diagrid systems, known for their effectiveness in reducing storey drift and enhancing the seismic performance of the building

In Figures 7 and 8, the X-axis represents storey drift in mm, while the Y-axis corresponds to the storey number.

The maximum storey drift of a Diagrid building at angles of 68.45°, 78.85°, and 81.03° are 0.001069, 0.001239, and 0.001369, respectively (as illustrated in Figure 7) for RSA. For wind analysis, the corresponding drift are 0.00197, 0.001984, and 0.002155 (as depicted in Figure 8).

In case of a variable angle diagrid, the drifts are 0.00112 (RSA) and 0.001843 (wind analysis) in Figures 7 & 8, both of which are less than 0.004hi, where h_i represents the storey height (i.e., 0.0152).

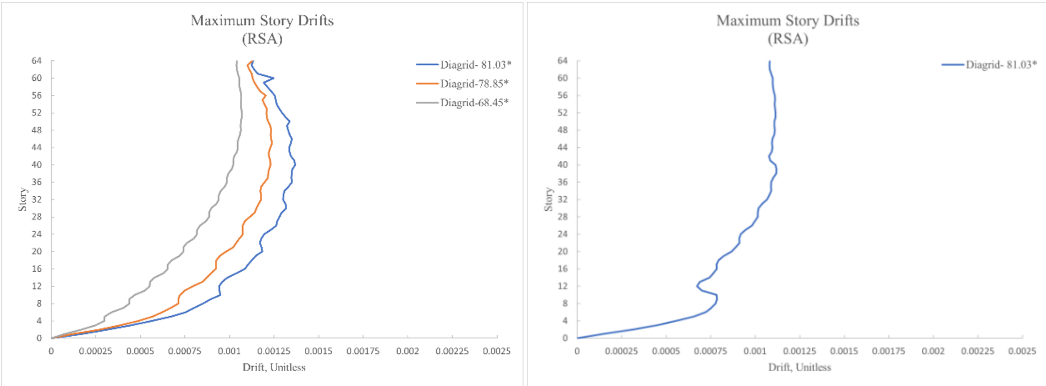

Figure 7: Storey drift of building having angle 68.45, 78.85, 81.03 & variable angle diagrid (RSA)

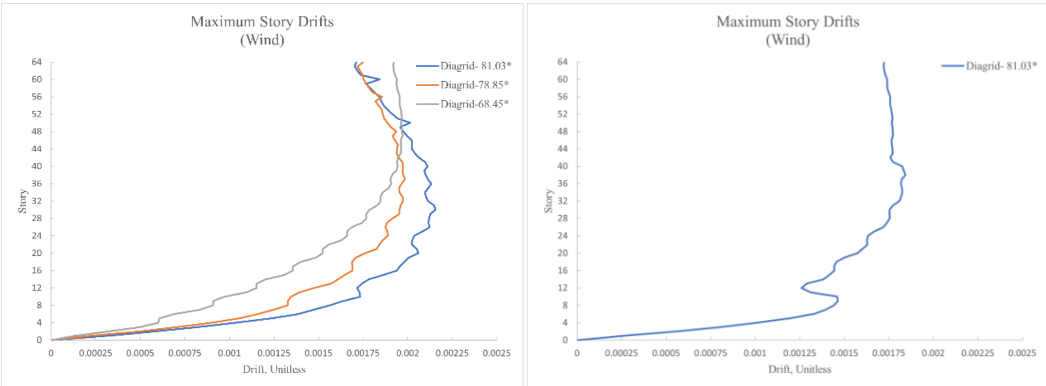

Figure 8: Storey drift of building having angle 68.45, 78.85, 81.03 & variable angle diagrid (WA)

6.3 Storey Stiffness

Storey stiffness denotes a building storey's capacity to withstand lateral forces, such as those induced by wind or seismic activities. A storey with greater stiffness can more efficiently resist lateral forces compared to a less stiff one. Buildings characterized by higher storey stiffness are generally regarded as more stable and less susceptible to damage during seismic events or strong winds.

In Figures 9 and 10, the X-axis represents storey stiffness in (KN/m), while the Y-axis signifies the storey number.

The maximum storey stiffness of a Diagrid building at angles of 68.45°, 78.85°, and 81.03° is 5915270 KN/m, 5365493 KN/m, and 6738450 KN/m, respectively (as indicated in Figure 9) for RSA. For wind analysis, the corresponding stiffness values are 4082775 KN/m, 4992594 KN/m, and 6617460 KN/m (as shown in Figure 10). In the case of a variable angle diagrid, the stiffness values are 5520896 KN/m (RSA) and 5239007 KN/m (wind analysis), as depicted in Figures 9 & 10.

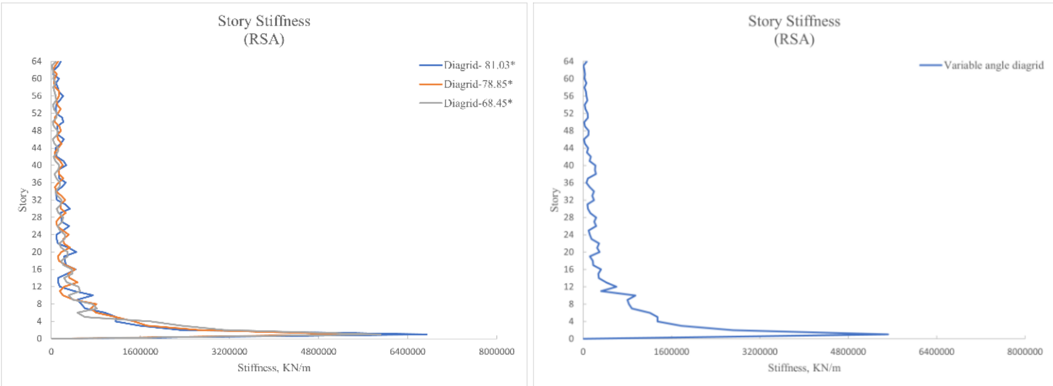

Figure 9: Storey stiffness of building having angle 68.45, 78.85, 81.03 & variable angle diagrid (RSA)

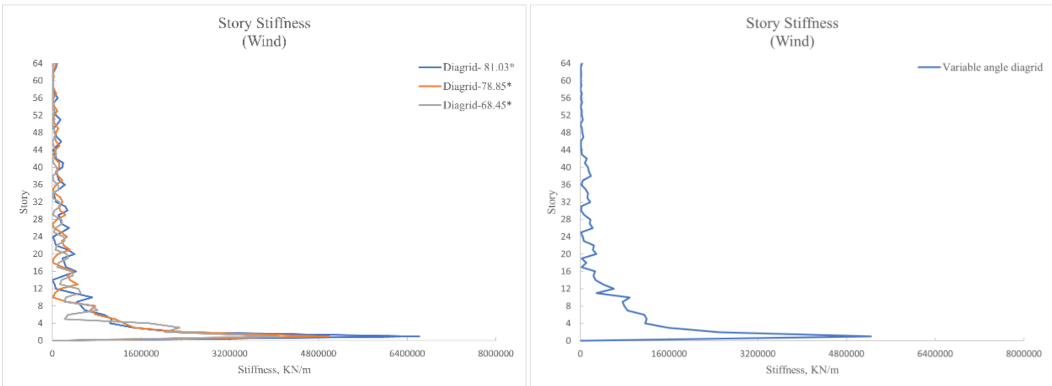

Figure 10: Storey stiffness of building having angle 68.45, 78.85, 81.03 & variable angle diagrid (WA)

6.4 Steel consumption

The amount of steel needed for a diagrid building with angles of 68.45°, 78.85°, and 81.03° is 85683.86 KN, 81236.78 KN, and 80721.04 KN, respectively (as depicted in Figure 11). For the variable angle diagrid, the required quantity of steel is 83369.72 KN, as shown in Figure 11.

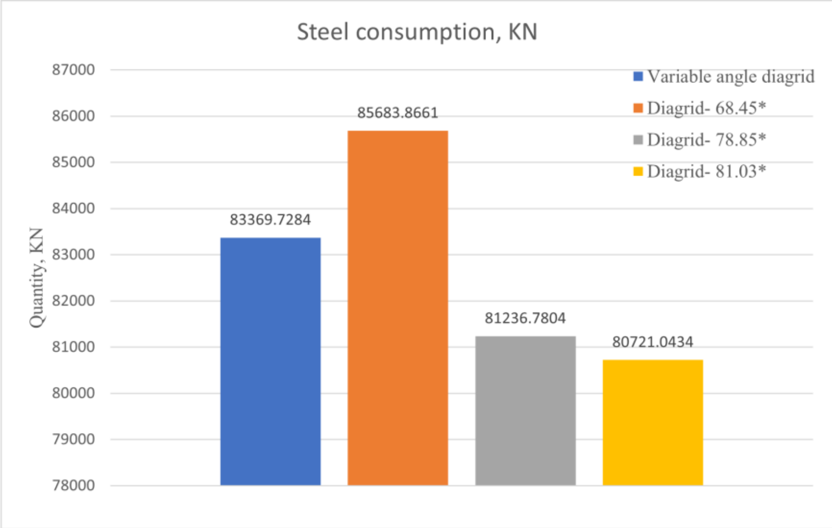

Figure 11: Steel consumption

6.5 Efficiency Factor

Based on these parameters, the efficiency factor for both the Optimized and Non-Optimized models was calculated using the provided formula (Table 1), As per (Montuori et al., 2014).

Efficiency Factor= $\frac{1}{(unit\ weight\ X\ Max\ drift)}$

A higher efficiency factor for a model signifies improved performance per structural unit employed in the diagrid pattern. Here, "unit weight" refers to the weight of the model in the diagrid per gross floor area of the building.

Table 1 indicates that the efficiency factor for the Variable Angle Diagrid is 42.05, surpassing all other models. This signifies that the Variable Angle Diagrid demonstrates superior performance under lateral loads. Moreover, this performance advantage has the potential to contribute to a reduction in material consumption.

Table 1: Efficiency factor of models

Model	Max Drift	Displacement, mm	Unit Weight, KN/m^2	Efficiency Factor, m^2/KN
Diagrid- 68.45°	0.00197	387.33	12.9657	39.15
Diagrid- 78.85°	0.001984	413.77	12.8451	39.23
Diagrid- 81.03°	0.002155	448.16	12.8311	36.16
Variable angle diagrid	0.001843	388.22	12.9029	42.05

7. CONCLUSION

In conclusion, employing Variable angle diagrid structures in high-rise buildings proves to be an effective strategy for enhancing structural stiffness, minimizing displacement, and reducing storey drift. This research demonstrates that these systems contribute significantly to improving the seismic performance of tall structures by offering lateral stability and mitigating the effects of earthquake-induced forces.

The analysis of the Diagrid building with diagrid angles of 68.45°, 78.85°, and 81.03° yields notable findings regarding displacement, drift, stiffness, and steel consumption. Storey displacement in both RSA and wind analysis falls within acceptable limits when examined individually. Furthermore, the variable angle diagrid, combining angles θ = 81°, θ = 75.25°, and θ= 68.45°, demonstrates displacement values below the specified threshold of H/500 (486mm).

Storey drift, a crucial parameter for seismic performance, is also well within acceptable limits for both RSA and wind analysis. The variable angle diagrid further demonstrates lower drift values, confirming its effectiveness in minimizing lateral movement.

Storey stiffness, an indicator of a building's ability to resist lateral forces, is substantial for the Diagrid building at various angles, ensuring stability during seismic events or high winds. The variable angle diagrid maintains commendable stiffness values, further contributing to the structural integrity of the building.

The quantity of steel required for the Diagrid building is well-documented for each angle, with the variable angle diagrid also showcasing efficient steel consumption. These results collectively suggest that the Diagrid structural system, especially with variable angles, offers a promising combination of structural efficiency and material economy.

Furthermore, the efficiency factor calculation, considering unit weight and maximum drift, highlights the superiority of the Variable Angle Diagrid with an efficiency factor of 42.05. This indicates better performance per structural unit used in the diagrid pattern, with the potential for reduced material consumption. The optimal results or the most efficient angles for constant diagrids fall within the range of 65° to 78°.

In conclusion, the comprehensive assessment of storey displacement, drift, stiffness, steel consumption, and efficiency factor underscore the viability and resilience of the Diagrid building, especially when incorporating variable angles in its design. These results provide valuable insights for architects and engineers seeking optimal solutions for tall building constructions in seismic-prone or windy regions.

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