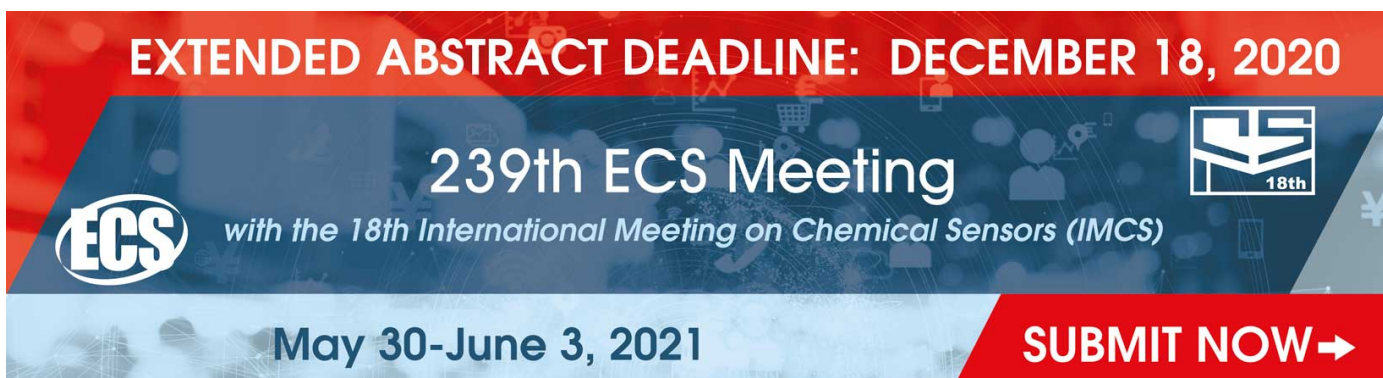


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# Comparative Structural Performance Of Diagrid and Bracing System in Mitigation of Lateral Displacement

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**Abstract.** The design of high rise building with more than 10 stories is controlled by lateral drift which increases the cost rapidly with the number of stories. Recently, the diagrid structural system has emerged and in fact has been widely used for high rise buildings. How effective is a diagrid system in mitigating the lateral displacement of a high rise building? Thus, the objective of this research is to compare the lateral displacement of high rise building that adopts diagrid system with those that use X-bracing and frame system, due to wind. This research also explored the effect of using diagrid, X-bracing and frame system to the natural frequency of high rise building. Two diagrid systems which are 60°-diagrid and 80°-diagrid that has an angle of inclination of 60 degrees and 80 degrees, respectively, were studied. STAAD Pro software was used to analyse twelve building models to determine the lateral displacement due to wind load and the natural frequency in the along wind, across wind and torsional directions. Building with 80°-diagrid has the least lateral displacement, followed by buildings with the X-bracing, 60°-diagrid and frame for 40 and 60 storey buildings. Further study showed that X-bracing became the most effective system to lower the lateral displacement compared with the diagrid and frame when the number of storey of the building exceeds 71 storeys. Natural frequency was not affected by the different systems used except for torsional natural frequency that increased substantially by the use of 60°-diagrid.

## 1. Introduction

The design of tall buildings is generally controlled by lateral serviceability criteria rather than by ultimate strength requirements. As modern tall buildings become taller and more slender, the effects of wind become more pronounced and the amount of structural materials needed to provide lateral resistance drastically increases [1]. This causes the emergence of new types of structural systems such as diagrid, braced tubes, outrigger, core wall, shear wall, beltwall, mega column and tube-in-tube which are some of the different types of lateral load resisting systems that are available today.

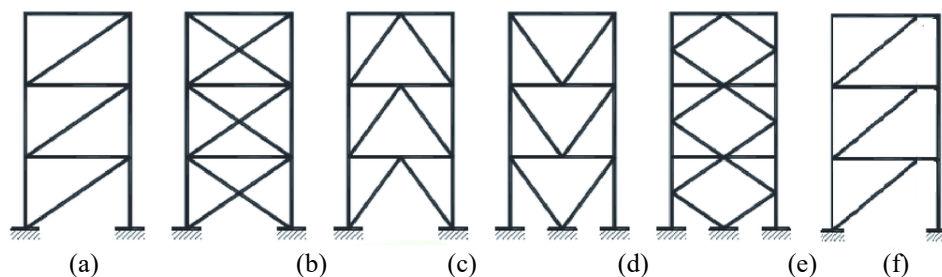
The most basic structures that are used to resist both lateral and vertical loads are moment resisting frame. Moment resisting frame is a system that combines columns and beams that are rigidly connected to increase the resistance of lateral forces, shear force and bending moment. Connection that is flexible between the column and beam may cause early nonlinear behaviour for the frame besides causing the frame to deform more than a frame with rigid connection between the beam and the column [2]. Combination of moment frame with non-structural element such as masonry increases the performance of the frames. Hotel San Diego, a six-story reinforced concrete infilled-frame structure resists



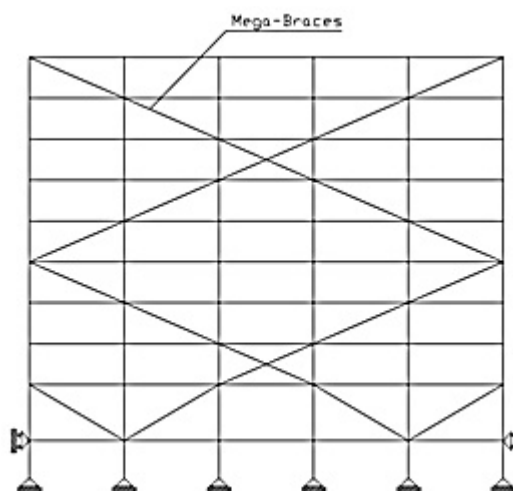
progressive collapse despite the removal of its two adjacent exterior columns [3]. Three-dimensional Vierendeel (frame) action of the transverse and longitudinal frames with the participation of infill walls was identified as the major mechanism for redistribution of loads in the structure.

The strength of frames can be upgraded with the installation of bracing that are connected with pinned connections. Braced frames have the extra of vertical steel trusses that are very efficient to resist lateral loads [4]. Bracing is a very effective global upgrading strategy as it enhances the global stiffness and strength of steel and composite frames [5]. The positioning of braces, however, can be problematic as they can interfere with the design of the façade and the position of openings. Braces can be aesthetically unpleasant where they change the original architectural features of the building [6,7]

There are many types of bracing such as single diagonal, cross-bracing, K-bracing, V-bracing, chevron bracing and eccentric bracing (Figure 1). Pushover and nonlinear time history analyses of chevron, X and V bracing shows that chevron bracing has higher stiffness compared to X and V bracing which had almost the same stiffness [8]. However, mega-braces which is huge X-braces as shown in Figure 2 is the most cost-effective bracing system under earthquake ground motions when compared to special concentrically braces (SCBFs) and buckling-restrained braces (BRBFs) [9].



**Figure 1.** (a) Single diagonal (b) cross (c) chevron (d) V-bracing (e) K-bracing (f) eccentric bracing.



**Figure 2.** Configuration of mega-braces studied by Sarno and Elnashai (2004)

The most recent tall building system that has been realized is diagrid system which is an exodiagonal system. Diagrid is characterized by a narrow grid of diagonal members that provide the strength of structures to resist both gravity and lateral loads [10]. Diagrid structural pattern does not use conventional vertical columns [11]. Unlike the conventional framed tubular structures that carry shear by the bending of the vertical columns, diagrid carries shear by axial action of the diagonal members [12, 13, 14], which is effective in minimizing shear deformation. Most of the lateral load is resisted by

diagrid columns on the perimeter of the buildings, while gravity load is resisted by both internal and perimeter diagonal columns [15].

Other advantages of diagrid are its good appearance and its configuration which creates a lesser obstruction that provides the outside view of the tall buildings as well as natural light which saves cost in electricity. As diagrid allows interior, perimeter and corner columns to be removed, it saves the floor space besides providing more flexibility in planning interior space and façade of the building [15]. Further, the geometrical versatility of diagrid enables the construction of complex-shaped tall building such as twisted, tilted and tapered towers. Geometric configurations of complex-shaped tall buildings, such as the rate of twisting and angle of tilting affect the structural performance of these buildings [16]. Phare Tower in Paris, the Capital Gate in Dubai and Aldar Headquarters in Dubai are examples of complex shaped diagrid buildings (Figure 3).



**Figure 3.** (a) Phare Tower in Paris (b) the Capital Gate in Dubai and (c) Aldar Headquarters in Dubai.

Both mega X-bracing and diagrid are known to be efficient in resisting the lateral loading. Mega X-braces used the amount of structural steel 20% lower than in SCBFs, despite having almost the same displacement under seismic load [9]. Meanwhile, diagrid system saved approximately 20 percent of the structural steel weight if compared to conventional rigid frame structure when both systems have the same displacement when the structure is exerted by wind load. [17, 18]. A question arisen on whether the mega X-bracing or the diagrid is better in lowering the displacement of the tall building due to wind load. Thus, the first objective of this research is to compare the lateral displacement of high rise building that adopts diagrid system with those that use mega X-bracing and frame system, due to wind.

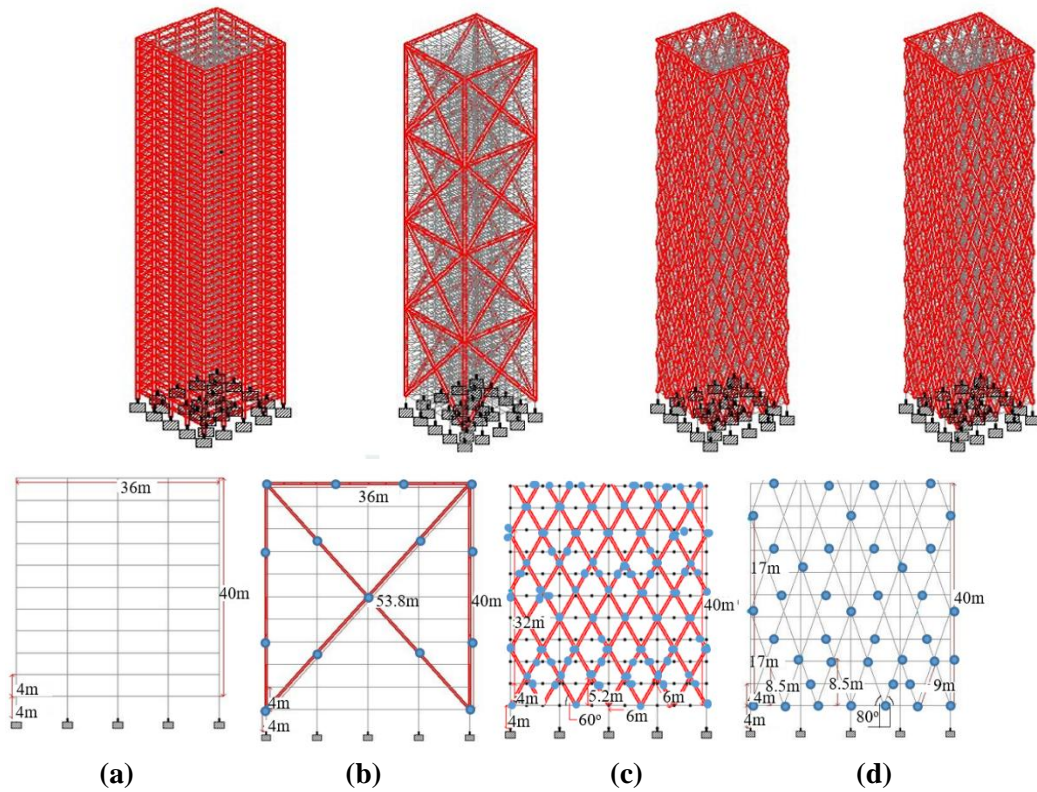
Tall building is classified as stiff or flexible depending on its value of natural frequency. A tall building is flexible when its natural frequency is less than 1 Hz [19]. Excessive response of a flexible building which are displacement and acceleration in the along wind and across wind as well as torsional acceleration may cause improper drainage, damage to windows and tenants to have nausea [20, 21]. Increasing the natural frequency will lower the value of displacement and acceleration due to wind [22]. Therefore, another objective of this research is to investigate the change of natural frequency in the along wind, across wind and torsional direction by employing X-bracing and digrid.

## 2. Methodology

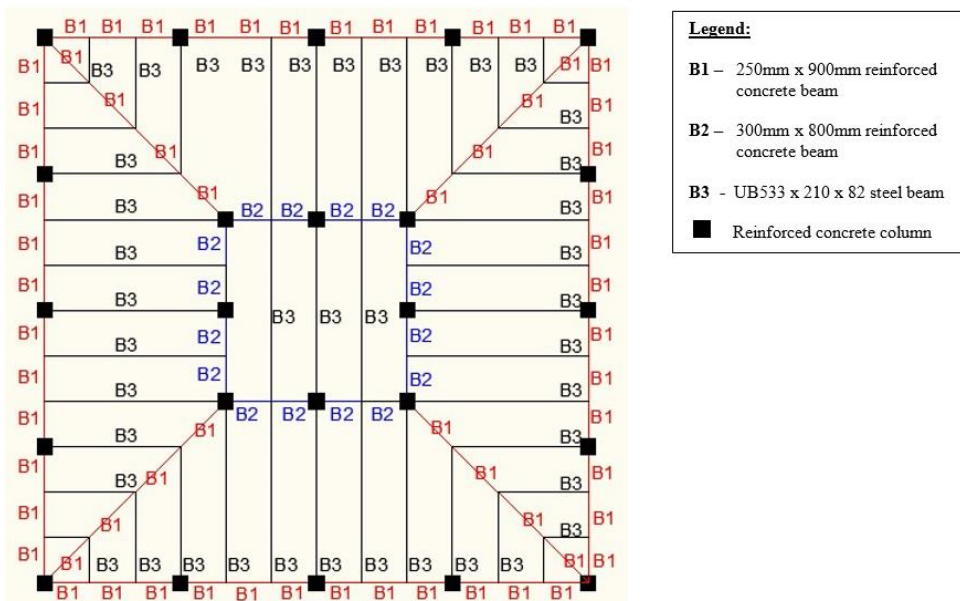
Four different types of models which are frame, mega X-bracing, diagrid with 60 degree angle and diagrid with 80 degree angle as shown in Figure 4 were analysed. Each model has three different numbers of storeys: 40 storeys, 60 storeys and 80 storeys with storey height of 4 m. All models have 36m x 36m foot print with a typical floor plan as shown in Figure 5. Reinforced concrete main beams, steel secondary beams and reinforced concrete columns were used to support the floor slab and live loads. Several different sizes of the reinforced concrete columns: 700 mm x 700 mm, 750 mm x 750 mm, 800 mm x 800 mm and 1000 mm x 1000 mm were used, depending on which level the columns were. High strength concrete with modulus of elasticity of  $4.83 \times 10^7$  kN/m<sup>2</sup> and compressive strength of 80000 kN/m<sup>2</sup> were used. These models were fix supported at the base.

The bracing and diagrid members were connected to the main structure (the original frame structure) at the blue dots in the elevation view in Figure 4. The bracing and diagonal members are assumed to be pin-ended, and therefore resist the transverse shear and moment through only axial action which allows

to determine the cross-sectional area of each member. The sizes of the steel sections used for the bracings and diagrid members are shown in Table 1 and Table 2, respectively, for each of the 40, 60 and 80 storey building.



**Figure 4.** Isometric and elevation view of : (a) frame (b) X-bracing (c) diagrid 60° (d) diagrid 80° models that were analysed.



**Figure 5.** Typical Floor Plan for all models.

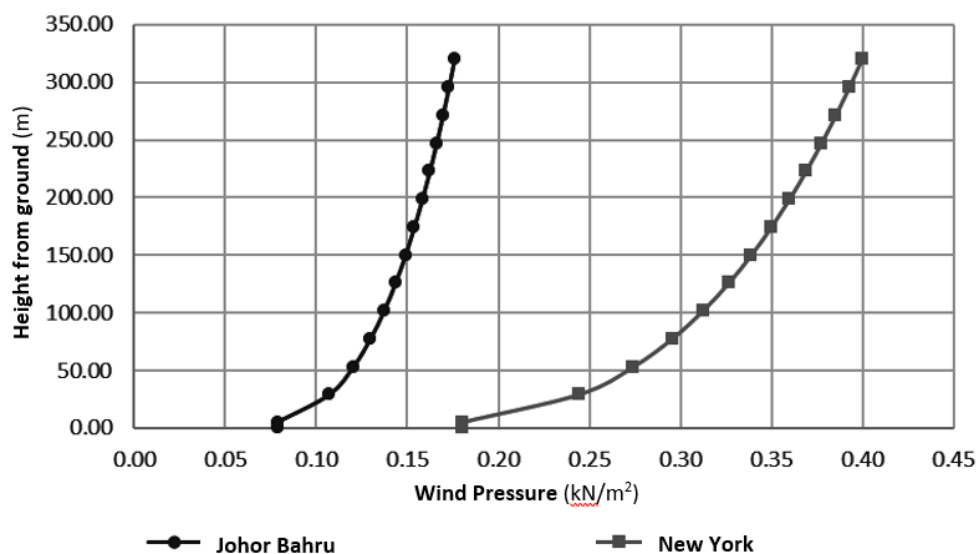
**Table 1.** Steel sections used for each member of the X-bracing.

Buildings Heights	Horizontal	Vertical	Diagonal
40 Storeys	UB406X178X60 kg/m	UC305X305X198 kg/m	UB457X191X98 kg/m
60 Storeys	UB457191X133 kg/m	UC356X406X634 kg/m	UB533X312X219 kg/m
80 Storeys	UB533X312X219 kg/m	UC356X406X634 kg/m	UB914X419X343 kg/m

**Table 2.** Steel sections used for each member of the diagrid system.

Diagrid Type	40 storey buildings	60 storey buildings	80 storey buildings
60°-diagrid	UB203 x 133 x 30 kg/m	UB254 x 102 x 22 kg/m	UB406 x 140 x 39kg/m
80°-diagrid	UB254 x 146 x 37 kg/m	UB406 x 140 x 46 kg/m	UB610x 229 x 113 kg/m

These models were loaded by wind load in two different wind environments which were Johor Bahru and New York. The wind speed used were 32.5 m/sec and 49 m/sec at 10 metre height for Johor Bahru and New York wind environment, respectively. The wind load was calculated in accordance with ASCE 7-16 [19]. The building was assumed to be located in a city, and thus, was considered to be in Exposure Category B. Wind loads were applied at two surfaces which are: windward and leeward wall. The wind pressure which acted at the windward surface varied parabolically as shown in Figure 6.



**Figure 6.** Wind load distribution in Johor Bahru and New York wind environment that was applied to the windward surface.

The leeward surface was subjected to uniform distributed wind suction of 0.1029 kN/m<sup>2</sup>, 0.1149 kN/m<sup>2</sup> and 0.1242 kN/m<sup>2</sup> for buildings with 40, 60 and 80 storeys, respectively, in Johor Bahru wind environment. The wind suction in New York wind environment that was applied is 0.2340 kN/m<sup>2</sup>, 0.2613 kN/m<sup>2</sup> and 0.2824 kN/m<sup>2</sup> for buildings with 40, 60 and 80 storeys, respectively.

STAAD Pro software was used to analyse these buildings under wind load to obtain the lateral displacement. The values of the displacements of the models were compared to identify which system had reduced the displacement most effectively. The lowest natural frequencies of the models in different modes, which were in the along wind, across wind and torsional directions were also determined by using STAAD Pro software. The system which is most effective in increasing the value of the natural

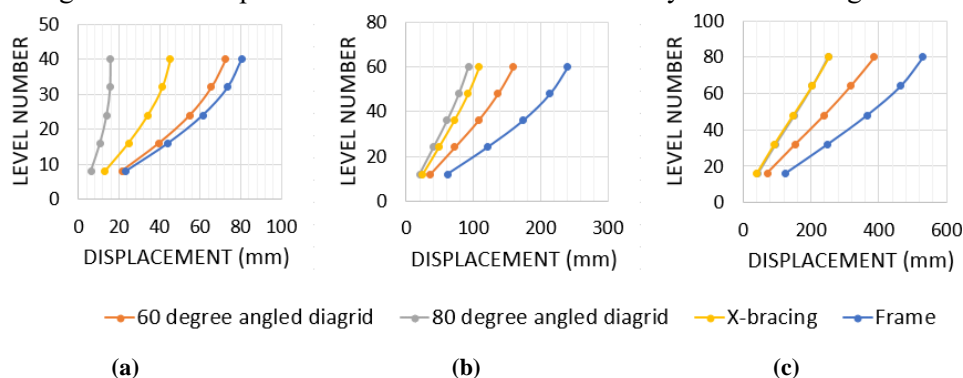
frequencies in all modes were identified and concluded as the most effective system to reduce the response of dynamically active tall buildings.

### 3. Results

Results from the dynamic analysis of all the models shows that all models had natural frequency more than 1 Hz. Thus, the buildings are categorized as stiff buildings, and static analysis is sufficient to determine the lateral displacement of the models, as in accordance with building code in United States of America, ASCE 7-16 [19].

#### 3.1. Lateral Displacement

The displacement of the building models with 60°-diagrid system, 80°-diagrid system, X-bracing and frame with different numbers of storeys is plotted in Figure 7. The 80°-diagrid system is better in reducing the displacement of the building compared to the 60°-diagrid system. The building with frame system has the largest displacement. Meanwhile, the 80°-diagrid system reduced the displacement due to wind most effectively compared to the rest of tall building systems studied, but only when the building has 40 and 60 storeys. When the building has 80 storeys, both X-bracing and 80°-diagrid system had almost the same displacement as shown in Figure 7(c). This proves that X-bracing became most effective in reducing the lateral displacement when the number of storey of the building is 80 storeys.



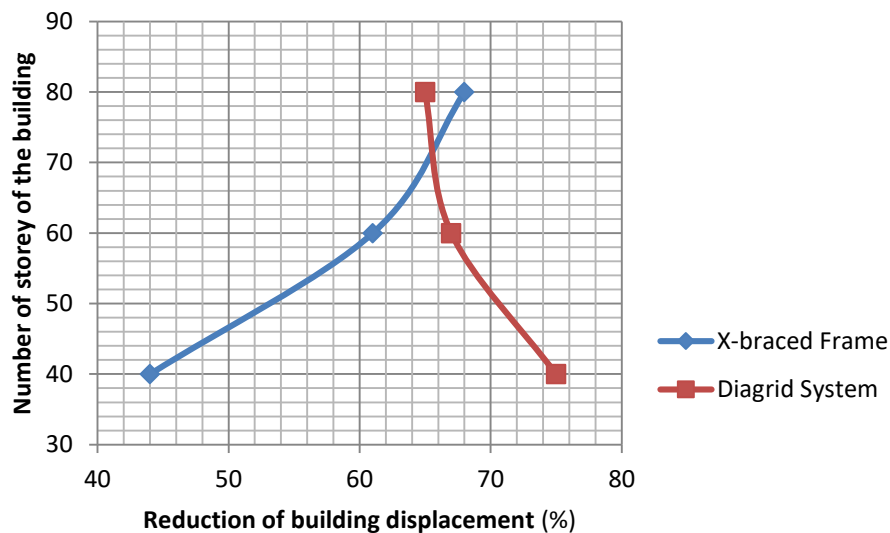
**Figure 7.** Lateral displacement of buildings that have different tall building systems: diagrid, X-bracing and frame, with height of (a) 40 storey (b) 60 storey (c) 80 storey.

#### 3.2. Effective Tall Building System

As the 80°-diagrid system and the X-bracing managed to reduce the most of the lateral displacement compared with the other two systems, further study was conducted to determine the effectiveness of the two systems in reducing the lateral displacement. The volume of steel used in X-bracings system were calculated, before the cross sectional area of the diagrid members were selected such that the total volume of steel used for the diagrid system was almost the same as the volume of steel used for the X-bracing system as shown in Table 3. Wind load was applied to both models and the reduction of the displacement is plotted in Figure 8. Both 40 and 60 storey tall building with diagrid system are efficient because it had less lateral displacement compared to the X-braced building, even though it had equal amount of steels as the amount of steel used by the X-braced building. The diagonal arrangements of diagrid system provide better lateral stiffness compared to X-bracings system and conventional frames. Further, as the number of storey was increased, the reduction of the lateral displacement decreased when the diagrid system was employed. In contrast, the reduction of the lateral displacement of X-braced building increased with increasing number of storeys. The two curves which are the curve of the diagrid system building intersected with the curve of the X-braced system at about 71 storeys. At the point of intersection, when the buildings are 71 storey high, both the diagrid and the X-braced buildings had the same efficiency. The diagrid systems are therefore, effective in resisting lateral force when the number of storeys does not exceed 71 storeys (284 m).

**Table 3.** The volume of steel used for X-braced frame and diagrid system for building with different number of storeys.

Number of Storeys	X-braced Frame (m <sup>3</sup> )	Diagrid System (m <sup>3</sup> )
40	45.89	45.89
60	241.91	231.94
80	322.5	328.64



**Figure 8.** Percentage of the reduction of the displacement of the building with different number of storey the building has when X-brace frame and diagrid system that are utilized have the same volume of steel displacement consumption.

### 3.3. Natural Frequency

A building is considered as flexible and dynamically active when the natural frequency is less than 1 Hz. A building that has large natural frequency is better in resisting the lateral loads, both wind load and seismic load. The displacement of a building due to lateral loads is reduced when its natural frequency is increased. Figure 9 shows that the natural frequencies in all directions: along wind, across wind and torsional, become smaller as the taller the building is. This is as expected because buildings that are taller are more flexible, and thus, the smaller the stiffness becomes. As, natural frequency, is defined as,  $\sqrt{k/m}$ , where,  $k$  is stiffness and  $m$  is mass, natural frequency will reduce as the stiffness becomes smaller. Further, it is observed that the 80°-diagrid system has the largest natural frequency in both the along wind and across wind directions. The X-braced has natural frequency slightly less than the 80°-diagrid system in all the three directions. However, in general, the difference in the values of the natural frequency with the different tall building systems is small and insignificant. Interestingly, the 60°-diagrid system, is found to have the largest natural frequency in the torsional direction.





**Figure 9.** The natural frequency in (a) along wind (b) across wind (c) torsional direction, of building models with different tall building systems.

#### 4. Conclusion

As a conclusion, 80°diagrid system is the most effective structural system to reduce lateral displacement for building that has less than 71 stories while the X-bracing is the most effective system to reduce the lateral displacement for building that is more than 71 stories. Diagrid does not improve the natural frequency of building much which indicates, it is not economical to use diagrid to reduce lateral displacement and acceleration of flexible building except for 60°-diagrid system which increased the torsional natural frequency significantly compared to the rest of the building systems. The torsional natural frequency was increased by 20 percent for 80 story building when the 60°-diagrid system was used. Thus, 60°-diagrid system can be used if torsional acceleration is an issue for a high rise building.

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