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Diagrid Systems for Structural Design of Complex-Shaped Tall Buildings

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Abstract

Today's architectural design trend based on the recognition of pluralism has led to multiple design directions for all building types including tall buildings. This contemporary design trend has produced many complex-shaped tall buildings, such as twisted, tilted, tapered and freeform towers. Among many different structural systems developed for tall buildings, the diagrid system, with its powerful structural rationale and distinguished aesthetic potential, is one of the most widely used systems for today's tall buildings. This paper studies structural performance of diagrid systems employed for complex-shaped tall buildings. Twisted, tilted, tapered and freeform tall buildings are designed with diagrid structures, and their structural performances are investigated. For the twisted diagrid study, the buildings are twisted up to 3 degrees per floor. In the tilted diagrid study, the angles of tilting range from 0 to 13 degrees. The impact of eccentricity is investigated for gravity as well as lateral loads in tilted towers. In the study of tapered diagrid structures, the angles of tapering range from 0 to 3 degrees. In the study of freeform diagrid structures, lateral stiffness of freeform diagrids is evaluated depending on the degree of fluctuation of free form. The freeform floor plans fluctuate from plus/minus 1.5 meter to plus/minus 4.5 meter boundaries of the original square floor plan. Parametric structural models are generated using appropriate computer programs and the models are exported to structural engineering software for design, analyses and comparative studies.

Keywords: Twisted tall buildings, Tilted tall buildings, Tapered tall buildings, Freeform tall buildings, Diagrid structures

1. Introduction

Today's architecture, including tall buildings, can be best understood only through pluralism. Many tall buildings of unconventional and more complex building forms are prevalently designed and built throughout the world. Due to their enormous scale and symbolic power, tall buildings, especially those with unique forms, easily catch global attention and have great advertising effect. Though constructing an irregular complex-shaped tall building is a very challenging task, with rapid development of computer-aided design and advanced construction technologies, many complex-shaped tall buildings have recently been soaring in many cities worldwide.

Among many different structural systems developed for tall buildings, the diagrid system, with its inherent structural efficiency, powerful structural rationale and aesthetic potential, has been one of the most prevalently used structural systems for today's tall buildings throughout the world since its application for the Swiss Re Building of 2003 in London and Hearst Headquarters Tower of 2006 in New York. More recent applications of diagrid structures include supertall buildings such as the tapered 438 m tall Guangzhou International Finance Center of 2010 and tapered and morphing 555 m tall Lotte Super Tower project in Seoul. Other recent applications include irregular freeform tall buildings such as the Capital Gate Tower of 2011 in Abu Dhabi, which is also dramatically tilted by 18 degrees to the west.

This paper investigates structural performance of diagrid systems employed for twisted, tilted, tapered and freeform tall buildings through design studies. In order to study the impacts of different rates of twist, angles of tilt, angles of taper and degrees of fluctuation of free form, parametric structural models are generated using appropriate computer programs such as Rhino/Grasshopper. The parametric models are exported to structural engineering software SAP2000 for design, analyses and comparative studies.

2. Prismatic Diagrid Design

Prismatic diagrid structures of 60, 80 and 100 stories with a square floor plan are designed first. The building's typical plan dimensions are 36×36 meters with an 18×18-meter core at the center and typical story heights of 3.9 meters. The perimeter diagrid system is designed to carry the entire lateral loads, and the 18×18-meter building core is designed to carry only gravity loads, in order to more accurately estimate the impact of twisting, tilting, taper-

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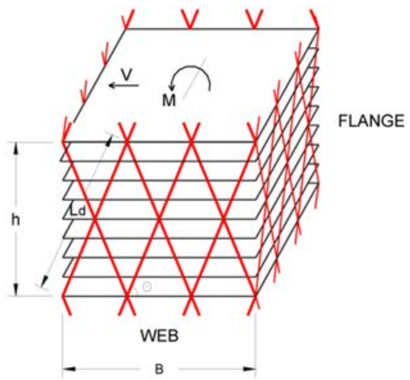

Figure 1. An 8-story diagrid module.

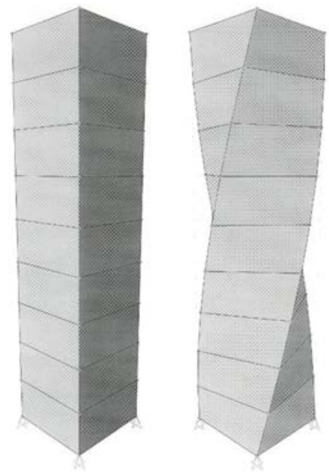

Figure 2. Prismatic and twisted solid towers.

ing and free-forming the prismatic diagrid buildings on their structural performance.

The SEI/ASCE document, Minimum Design Loads for Buildings and Other Structures, is used to establish the wind load. The building is assumed to be in Chicago, and within category III, which implies that there is a substantial hazard to human life in the event of failure. Based on the code, the basic wind speed is 90 mph (about 40 m/s). One percent damping is assumed for the calculation of the gust effect factor. The target maximum lateral displacement is set as a five hundredth of the building height, which is a value commonly used in practice.

In due consideration of the structural effectiveness and constructability, the diagrid modules in this study are configured to have three diamond-shaped sub-modules within the building width. Studies suggest that a configuration with a diagrid module height of 8 stories which results in a diagrid angle of 69 degrees as shown in Fig. 1 is close to the optimal condition for the 60-, 80- and 100-story diagrid structures studied in this paper. No corner columns are introduced in this study to provide the building with architecturally valuable column-free building corners.

Depending on the direction of loading, the faces act as either web planes (i.e., planes parallel to wind) or flange planes (i.e., planes perpendicular to wind). The diagonal members are assumed to be pin-ended, and therefore resist the transverse shear and moment through axial action only. With this idealization, the design problem reduces to determining the cross-sectional area of typical web and flange members for each module. Following the design methodology developed by Moon et al. (2007), Eqs. (1) and (2) expresses the diagrid module's shear and bending stiffness based on the web and flange plane members respectively.

$$K_t = 2N_w\left(\frac{A_{d,w}E}{L_d}\cos^2\theta\right) \qquad (1)$$

$$K_b = N_f\left(\frac{B^2A_{d,w}E}{2L_d}\right)\sin^2\theta \qquad (2)$$

Member sizes for the modules can be computed using Eqs. (3) and (4) customized for each design case.

$$A_{d,w} = \frac{VL_d}{2N_{d,w}E_dh\gamma\cos^2\theta} \qquad (3)$$

$$A_{d,f} = \frac{2ML_d}{(N_{d,f}+\delta)B^2E_d\chi h\sin^2\theta} \qquad (4)$$

$A_{d,w}$ is the area of each diagonal on the web; $A_{d,f}$ is the area of each diagonal on the flange; V is shear force; M is moment; L_d is the length of diagonal; E_d is the modulus of elasticity of steel; q is the angle of diagonal members; γ is transverse shear strain; χ is curvature; $N_{d,w}$ is the number of diagonals on each web plane; $N_{d,f}$ is the number of diagonals on each flange plane; d is the contribution of web diagonals for bending rigidity; B is the building width in the direction of applied force.

3. Twisted Digrid Structures

While structures of rectangular box forms are very common and have been one of the most extensively researched subjects, structures of twisted forms are relatively rare and have not been investigated much. Fig. 2 shows two solid vertical cantilever structures with the same square plan and height. The first one is prismatic and the second one is twisted by 90 degrees total. Moment of inertia of a certain square area is identical regardless of its different rates of rotation. When the two solid vertical structures are made of the same material and the identical concentrated force is applied laterally at the top of each structure, the maximum lateral displacements at the top of the two structures are also the same (Moon, 2014).

Building type structures are different from the solid structures shown in Fig. 2. They are composed of numerous frame elements, and their structural behavior is very much dependent upon the building forms and arrange-

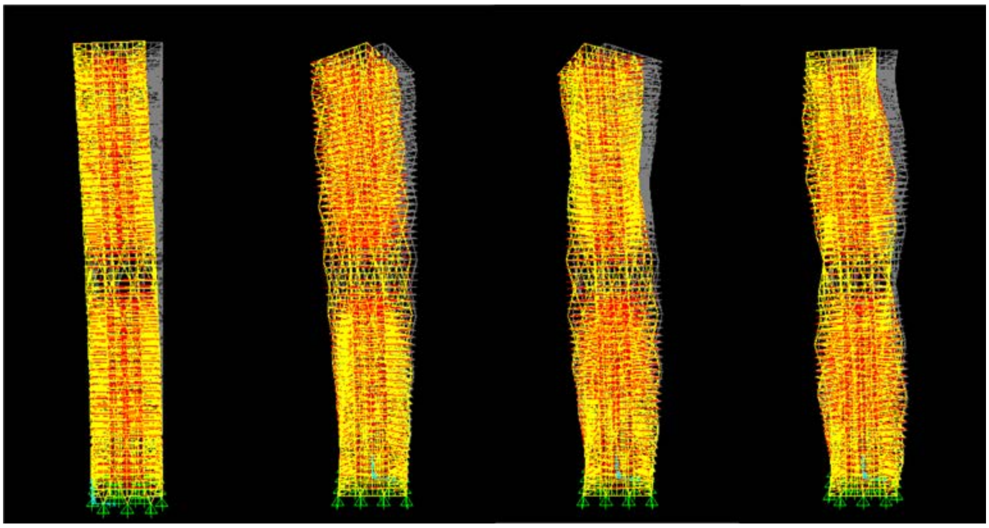

Figure 3. 60-story diagrids structures of various rates of twist.

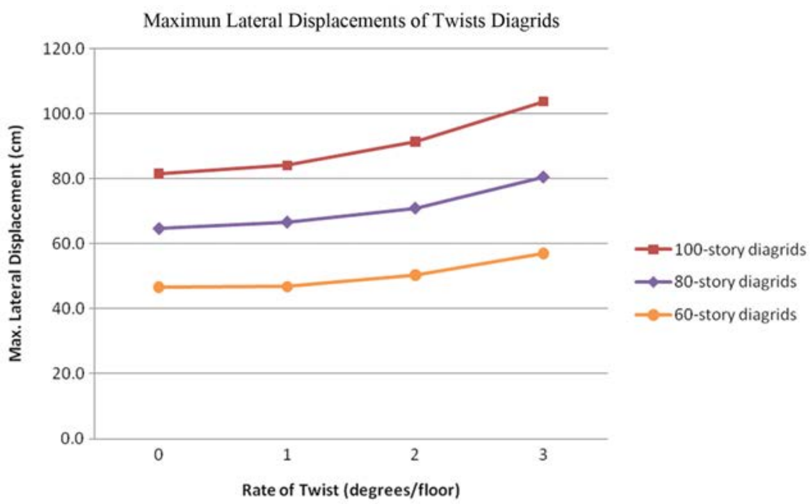

Figure 4. Maximum lateral displacements of twisted diagrids of various heights.

ments of the frame elements. The 60-story straight diagrid structure with a height-to-width aspect ratio of 6.5 is now twisted with three different rates of 1, 2 and 3 degrees per floor as shown in Fig. 3. Member sizes determined for the straight structure using Eqs. (3) and (4) are also used for the twisted diagrids to investigate comparative structural efficiency. As the rate of twist is increased, lateral stiffness of the diagrid structure is decreased, and, consequently, its lateral deformation is increased. The 60-story straight diagrid structure's maximum lateral displacement is 46.0 cm based on the SAP2000 analysis. The maximum lateral displacements of the diagrid towers with 1, 2 and 3 degrees-per-floor twists are 46.8, 50.4 and 56.1 cm respectively.

The straight rectangular box form diagrid tower was initially configured with diagonals placed at a near-optimal uniform angle, which is about 69 degrees for the studied case. As the rate of twist is increased, the diagrid angle deviates more and more from its original near-optimal condition and the lateral stiffness of the system is gradually reduced. And, consequently, the tower's lateral displacement is gradually increased and deviates from its targeted value.

Similar studies are conducted for the diagrids of 80 and 100 stories with height-to-width aspect ratios of 8.7 and 10.9 respectively. Study results of these taller diagrid structures are very similar to those of the 60-story diagrids. Fig. 4 summarizes the maximum lateral displacements of the diagrids of 60, 80 and 100 stories with rates of twist of 0, 1, 2 and 3 degrees per floor. As the rate of twist is increa-

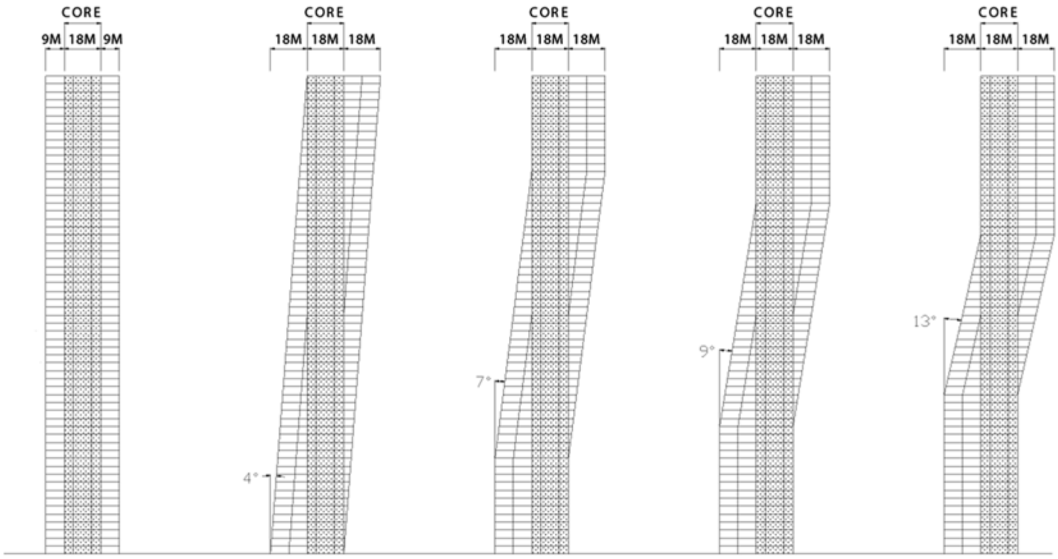

Figure 5. 60-story tilted diagrid structures with tilted angles of 0, 4, 7, 9 and 13 degrees (section view).

sed, the lateral stiffness of the tower is decreased. The stiffness reduction rate is accelerated as the rate of twist is increased. However, this stiffness reduction rate in relation to the rate of twist is not much influenced by the height of diagrid structures.

4. Tilted Diagrid Structures

Buildings have traditionally been constructed vertically, orthogonal to the ground. When a building is found to be tilted, it is typically an indication of some serious problems occurred to the building. Today, however, tilted buildings are intentionally designed and built to produce more dramatic architecture, as are the cases with the Gate of Europe Towers in Madrid designed by Philip Johnson/John Burgee, Veer Towers in Las Vegas by Helmut Jahn, and Signature Towers proposed for Dubai by Zaha Hadid.

The previously studied prismatic diagrid structure of 60 stories is now tilted at four different angles. Fig. 5, with simplified section drawings of the tilted diagrid structures, explains the relationship between the vertical building core and the tilted perimeter diagrids for each tilted case. The first case is the straight 60-story rectangular box form diagrid structure. The second case is a tilted diagrid tower

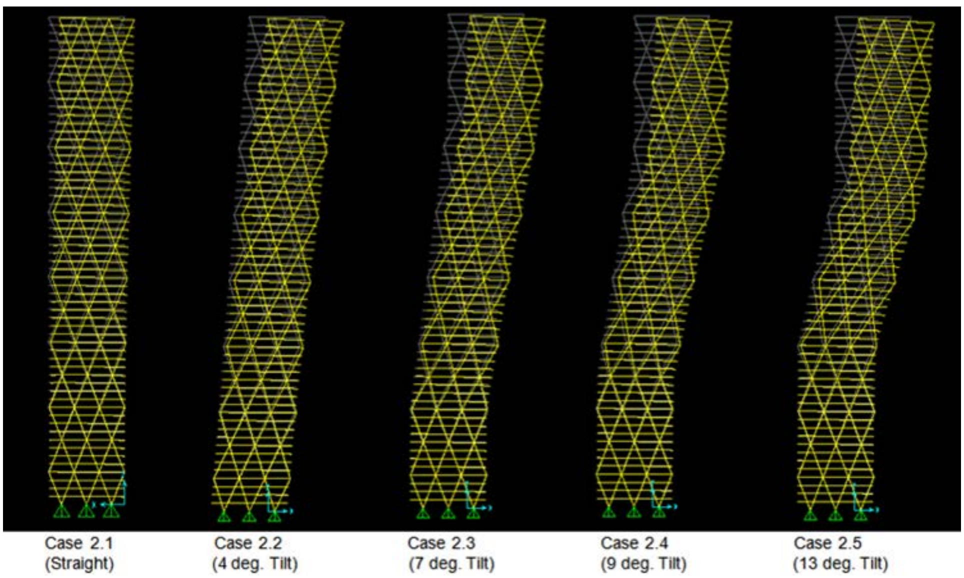

Figure 6. 60-story tilted diagrid structures with tilted angles of 0, 4, 7, 9 and 13 degrees.

with no floor offset. While the 18×18-meter gravity core is kept vertical within the tilted perimeter diagrids, the building is tilted to its maximum angle of 4 degrees. Therefore, on the left side of the building as seen in Fig. 5, the distance between the exterior façade and the core perimeter wall reduces from 18 meters on the ground to 0 meter at the top. On the right side, this distance increases from 0 meter on the ground to 18 meters at the top. The tilted form of this case is similar to that of the Gate of Europe Towers in Madrid or the Veer Towers in Las Vegas. The third, fourth and fifth cases are tilted diagrid structures with floor offsets of 12, 16 and 20 stories at both the top and bottom, resulting in tilted angles of 7, 9 and 13 degrees, respectively. Tilted forms of these cases are similar to those of the Signature Towers proposed for Dubai by Zaha Hadid. In these cases, the 18×18-meter gravity cores are still kept vertical within the perimeter diagrid structures.

In order to study the structural performances of diagrid systems of various tilted angles comparatively, the member sizes used for the straight diagrids are also used for the tilted diagrids for preliminary designs. Fig. 7 summarizes the maximum lateral displacements of the tilted diagrid towers in the direction parallel to the direction of tilting, when the wind load is also applied in the same direction. Lateral stiffness of the tilted diagrids against wind loads is very similar to that of the straight diagrids regardless of the changes of the tilted angle between 0 and 13 degrees. However, initial lateral displacements of the tilted diagrids due to gravity loads are significant. This gravity-induced lateral displacement, which is even larger than the wind-induced displacement in most cases, becomes greater as the angle of tilting is increased.

When wind load is applied in the direction perpendicular to the direction of tilting, the tilted tower is not only deformed laterally but also twisted. As the angle of tilting is increased, the rate of twisting is also increased. The maximum twisted angle of the tilted diagrid structure of the fifth case is 0.02 degrees.

Structural design of tall buildings is generally governed by lateral stiffness rather than strength (Ali & Moon, 2007; Connor, 2003). This study has focused on the lateral stiffness of tilted diagrid structures. Tilted towers are subjected to much larger localized stresses than conventional vertical towers. Much larger compressive and tensile member forces are developed in the tilted diagrids than in the straight diagrids. Tensile forces developed in tall buildings due to wind loads are often cancelled by compressive forces caused by gravity loads (Smith and Coull, 1991; Taranath, 1998). In the tilted diagrids studied here, however, substantial tensile forces are developed in perimeter diagrids due to the eccentricity and these tensile forces may not be cancelled by gravity loads. More careful studies are required for the design and construction of the connections of these members.

5. Tapered Diagrid Structures

Compared with prismatic forms, tapered forms provide many advantageous aspects for structural systems of tall buildings. For very tall buildings, it is common that lateral stiffness requirements against wind loads govern the structural design. The magnitudes of lateral shear forces and overturning moments due to lateral loads become larger toward the base of the building. Consequently, greater lateral stiffness is required at lower levels. Tapered forms provide greater lateral stiffness toward the base because tapered forms naturally produce greater structural depth toward the base. Tapered forms also help reduce wind loads applied to tall buildings. When a building is tapered, the exterior surface area where the wind load is applied is reduced at higher levels, and increased at lower levels.

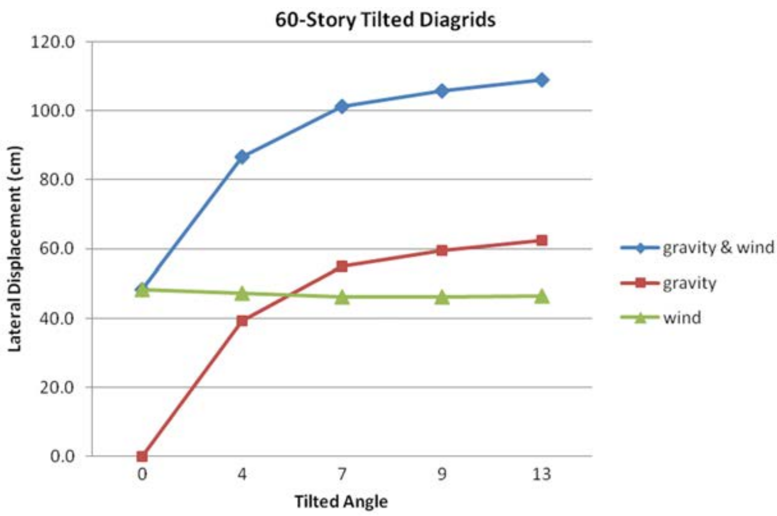

Figure 7. Maximum lateral displacements of the tilted diagrid structures shown in Fig. 6.

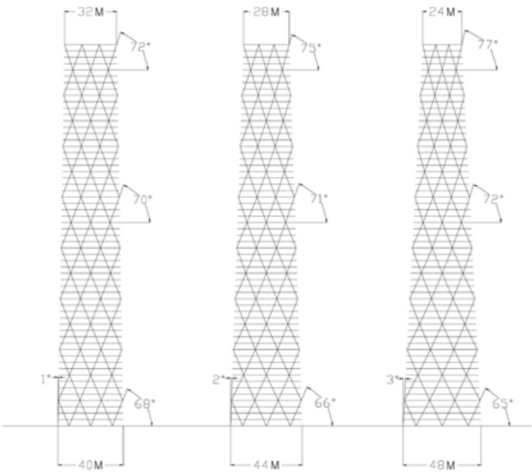

Figure 8. 60-story tapered diagrids design Alt.1: diagrid members are placed at angles steeper toward the top.

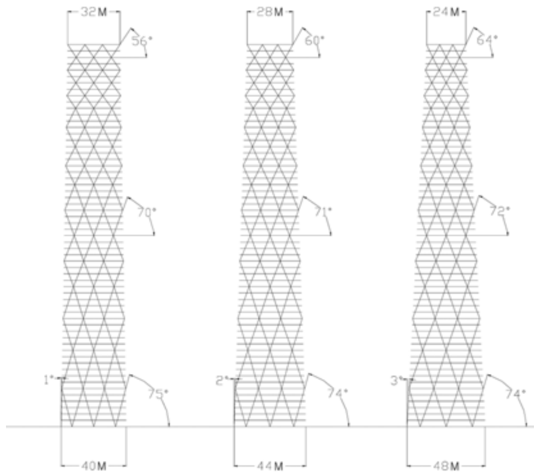

Figure 9. 60-story tapered diagrids design Alt.2: diagrid members are placed at angles steeper toward the base.

Since wind pressure is greater at higher levels and lesser at lower levels, the shear forces and overturning moments at each level is decreased as the angle of taper is increased.

Fig. 8 shows the 60-story diagrid structures tapered with three different angles of 1, 2 and 3 degrees. Since the building width at the mid-height is maintained to be the same, each building's gross floor area is the same regardless of the different angles of taper. Member sizes determined for the straight diagrids are also used for the tapered diagrids for preliminary design purposes to investigate the impact of tapering the structure comparatively.

A very important design issue associated with tapering the diagrid towers is that, if the module height and the number of the diamond-shaped sub-modules within the building width are maintained to be the same regardless of the different angles of taper, the diagrid angles become steeper at higher levels, and shallower at lower levels in the tapered diagrid structures, as can be seen in Fig. 8 (Alt. 1). Studies suggest that varying angle diagrid structures with diagrid members placed at angles shallower toward the base are less efficient than optimal uniform angle diagrid structures for tall buildings. Further, varying angle diagrid structures with diagrid members placed at angles steeper toward the base could be more efficient for very tall buildings because taller structures behave more like bending beams and diagrid members placed at steeper angles at lower levels provide higher bending rigidity (Moon, 2008). Thus, the configurations of the tapered diagrid structures shown in Fig. 8 are adjusted by changing the module heights. Fig. 9 (Alt. 2) shows a group of adjusted diagrid structures with diagrid members placed at angles steeper toward the base of the buildings.

As the angle of taper is increased, the lateral stiffness of the diagrid structures is increased. Consequently, the maximum lateral displacements of the tapered diagrid structures are decreased substantially. Once the angles of the diagrid members are adjusted to be steeper toward the base (Alt. 2), the lateral stiffness of the tapered diagrid structures is further increased.

Similar studies are repeated for the 80- and 100-story diagrid structures. In terms of reducing lateral displacements, the impact of taper becomes greater as the structure becomes taller. The stiffness increase based on the diagrid angle adjustments becomes also greater as the structure becomes taller. Fig. 10 summarizes the maximum lateral displacements of the 60-, 80- and 100-story tapered diagrids of Alt. 2 type. It clearly shows that the impact of taper becomes greater as the diagrid structure becomes taller.

6. Freeform Diagrid Structures

As a building's form becomes more irregular, finding

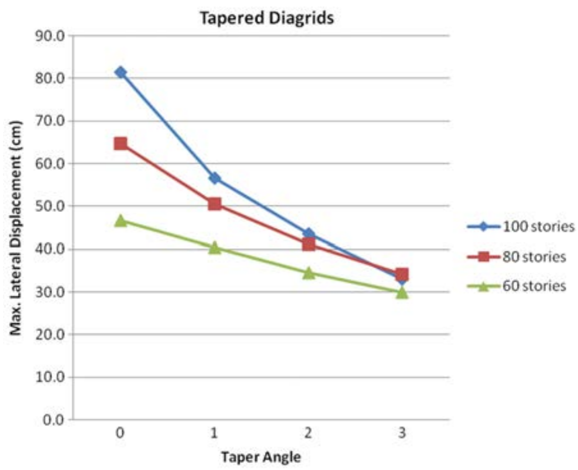

Figure 10. Maximum lateral displacements of 60-, 80- and 100-story tapered diagrids.

an appropriate structural system for better performance and constructability is essential to successfully carry out the building project. The diagrid structural system has great potential to be developed as one of the most appropriate structural solutions for irregular freeform towers. Triangular structural geometric units naturally defined by diagrid structural systems can specify any irregular freeform tower more accurately without distortion.

The 60-story prismatic diagrid structure is now modified into freeform diagrids to investigate the structural performance of freeform diagrids in comparison with the prismatic diagrids. Freeform geometries are generated using sine curves of various amplitudes and frequencies. In order to comparatively estimate the lateral stiffness of diagrids employed for freeform structures, the member sizes used for the prismatic diagrids are also used for the freeform diagrids. Thus, each structure is designed with very similar amount of structural materials. Compared with the rectangular box form diagrid structure, which has 36×36 meter square plan on each floor, the first freeform case's floor plans fluctuate within the plus/minus 1.5 meter boundaries of the original square. The second and third cases' floor plans fluctuate within the plus/minus 3 and 4.5 meter boundaries of the original square respectively. Despite these geometry changes, total floor area of each case is kept to be the same.

As can be seen in Fig. 11 which shows the deformed shape of each freeform diagrid structure in a scale factor of 20, the lateral displacement of the structure becomes larger as the freeform shape deviates more from its original rectangular box form. The maximum deflection at the top of the structure of the first, second and third case is 52.5 cm, 58.0 cm and 69.0 cm, respectively, compared with 46.6 cm in the case of the straight tower. This is much related to the change of the diagrid angle caused by free-forming the tower. The straight tower designed first for the comparison is configured with the optimal diagrid angle. As the degree of fluctuation of freeform is increased, the diagrid angle deviates more from its original optimal condition, which results in substantial reduction of the lateral stiffness of the tower. Therefore, freeform shapes should be determined with careful consideration of their not only architectural but also structural performance.

7. Conclusions

The diagrid structural system is one of the most prevalently used structural systems for today's tall buildings. The unique compositional characteristics of diagrid structures provide lateral stiffness very efficiently and at the same time produce distinguished architectural aesthetics in any existing cityscapes. In addition, the diagrid structural system is one of the most appropriate structural solutions for non-prismatic complex-shaped tall buildings. Triangular structural geometric units naturally defined by diagrid structural systems can specify any irregular form tower more accurately without distortion. Today's diverse architectural design directions have produced various non-prismatic building forms such as twisted, tilted, tapered and free forms. This paper studied lateral performance of diagrid structures employed for these complex-shaped tall buildings of various form categories.

When diagrid structures are employed for twisted and freeform tall buildings, their lateral stiffness is reduced as the rate of twist and degree of fluctuation of free form are increased. With regard to the across-wind direction dynamic responses due to vortex shedding, however, it should be noted that twisted or freeform towers generally perf-

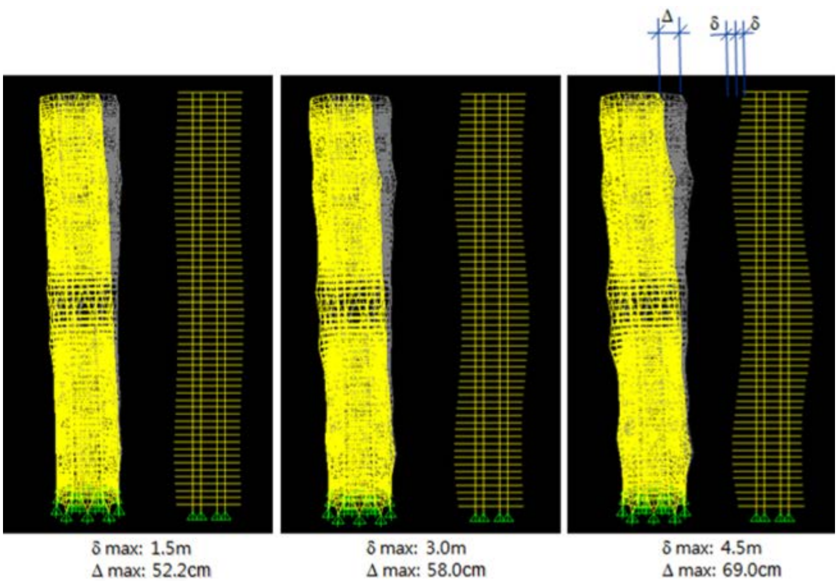

Figure 11. 60-story freeform diagrids' deformed shape in 3D (left), undeformed section through core in 2D (right).

orm better than a prismatic one, as they can mitigate wind-induced vibrations by disturbing the formation of organized alternating vortexes. Considering the fact that the vortex-shedding-induced lock-in condition often produces the most critical structural design condition for tall buildings, twisted or irregular free forms' structural contribution can be significant.

When the diagrid system is used for tapered tall buildings, its lateral stiffness is increased as the rate of taper is increased. Due to the geometric characteristics of diagrid structures, the module heights of the diagrids should be adjusted in tapered diagrid tall buildings in order to maximize their lateral stiffness. Diagrids placed at appropriately steeper angles towards the base of the building produce greater lateral stiffness especially for very tall and slender buildings.

Lateral stiffness of the tilted diagrids against wind loads is very similar to that of the prismatic diagrids regardless of the changes of the tilted angles between 0 and 13 degrees studied in this paper. However, initial lateral displacements of the tilted diagrids due to gravity loads are significant. These gravity-induced deformations can be managed substantially through careful construction planning.

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