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Procedia Engineering 14 (2011) 1343–1350

Procedia Engineering

www.elsevier.com/locate/procedia

The Twelfth East Asia-Pacific Conference on Structural Engineering and Construction

# Diagrid Structures for Complex-Shaped Tall Buildings

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**Abstract**

Diagrid structures are prevalently used for today's tall buildings due to their structural efficiency and architectural aesthetic potentials. This paper studies structural performance of diagrid systems employed for complex-shaped tall buildings such as twisted, tilted and freeform towers. For each complex form category, tall buildings are designed with diagrid systems, and their structural efficiency is studied in conjunction with building forms. In order to investigate the impacts of variation of important geometric configurations of complex-shaped tall buildings, such as the rate of twisting and angle of tilting, parametric structural models are used for this study. Based on the study results, design considerations are discussed for the efficient use of diagrid structures for complex-shaped tall buildings.

**Keywords:** Tall buildings; diagrids; twisted towers; tilted towers; freeform towers.

## 1. INTRODUCTION

Today's architecture, including tall buildings, can be best understood through recognition of the dominance of pluralism. Early design of tall buildings culminated with the emergence of the International Style, which prevailed for decades. Today, however, as is true of other building types, many different design approaches are prevalent for tall buildings. This contemporary design trend has produced various building forms, such as twisted, tapered, tilted, and free forms. This paper investigates structural design solutions for these complex-shaped tall buildings.

Among various structural systems developed for today's tall buildings, diagrid structures are primarily studied in this paper. Due to their structural efficiency and architectural potential, diagrid structures have been used for many tall buildings worldwide, including the Hearst Tower in New York, Guangzhou West Tower in Guangzhou, Capital Gate Tower in Abu Dhabi and proposed Phare Tower in Paris to name a

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doi:10.1016/j.proeng.2011.07.169

few. The forms of these diagrid towers range from conventional rectangular box form to tilted, tapered or free form.

Characteristics and preliminary structural design methodology for rectangular box form diagrids were investigated by Moon et al. (2007), and optimal diagrid geometries were studied by Moon (2008), again, for conventional rectangular box form diagrids. With abundant emergence of complex-shaped tall buildings all over the world and increased interests in diagrid systems by many architects and engineers, this paper investigates structural performance of diagrids for tall buildings of various complex geometries.

In order to investigate the impacts of variation of important geometric configurations of complex-shaped tall buildings, such as the rate of twisting and angle of tilting, parametric structural models are generated using appropriate computer programs such as Rhino/Grasshopper. The models are exported to structural engineering software such as SAP 2000 for design and analyses. Based on the study results, design considerations are discussed for more efficient and integrative use of diagrids for complex-shaped tall buildings.

## 2. STRUCTURAL DESIGN OF DIAGRIDS

With the rapid advancement of materials science and consequently produced higher strength materials, building structures are more often governed by stiffness requirements because of the lag in material stiffness versus material strength (Connor, 2003). A specific structural system for a tall building with a certain height-to-width aspect ratio has a unique optimal mode of deformation, which is primarily a combination of a particular bending and shear deformation. With this optimal mode of deformation, structural design can meet the target stiffness criteria most efficiently. Based on this stiffness-based design concept, this section presents a preliminary design methodology for diagrid structural systems.

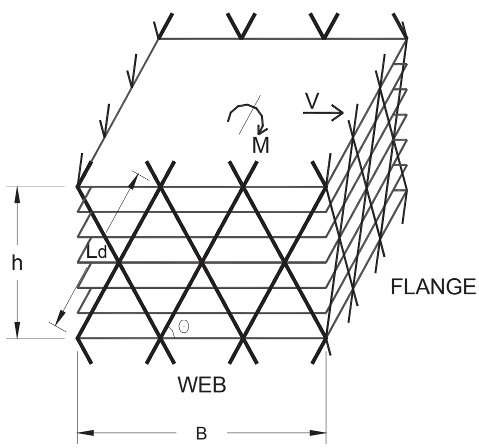



Figure 1: Typical diagrid module.

A diagrid structure is modeled as a vertical cantilever beam on the ground, and subdivided longitudinally into modules according to the repetitive diagrid pattern. Each module is defined by a single level of diagrids that extend over multiple stories. Figure 1 illustrates the case of a 6-story module. In order to more accurately estimate the lateral rigidity provided by diagrids, all the required lateral stiffness is allocated to the perimeter diagrids, and core structures, omitted in Figure 1, are only gravity systems in this study.

Depending upon 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), member sizes for the modules can be computed using Equations (1) and (2) customized for each design case.

$$A_{d,w} = \frac{VL_d}{2N_{d,w}E_d h\gamma \cos^2\theta} \tag{1}$$

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

$A_{d,w}$ 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; θ is the angle of diagonal members; $\gamma$ is transverse shear strain; $\chi$ 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; δ is the contribution of web diagonals for bending rigidity; B is the building width in the direction of applied force.

Optimal stiffness-based design corresponds to a state of uniform shear and bending deformation under the design loading. Uniform deformation states are possible only for statically determinate structures. Tall building structures can be modeled as vertical cantilever beams on the ground, and uniform deformation can be achieved for these structures (Connor, 2003). Then, the deflection at the top, $u(H)$, is given by

$$u(H) = \gamma^* H + \frac{\chi^* H^2}{2} \tag{3}$$

*H* is the building height; $\gamma^*$ is the desired uniform transverse shear strain; $\chi^*$ is the desired uniform curvature.

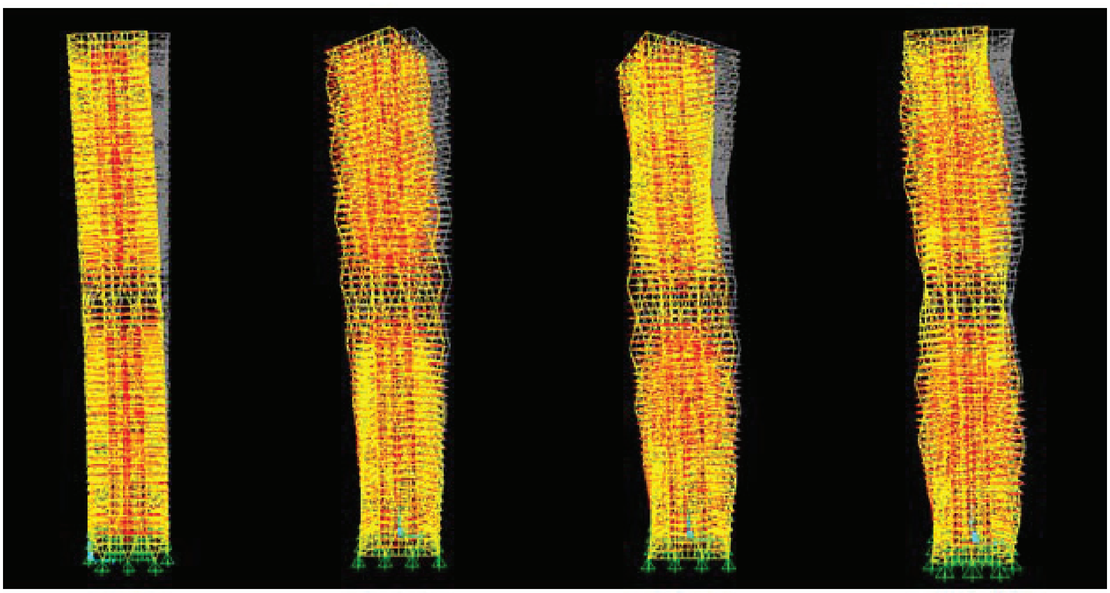
The maximum allowable deflection at the top is generally determined in the neighborhood of about a five hundredth of the building height. Then, the design begins by specifying the desired bending and shear deformation of the structure. Taller buildings behave more like bending beams and shorter buildings behave more like shear beams. Consequently, taller buildings should be designed to have more bending deformation than shorter buildings, and vice versa.

## 3. TWISTED DIAGRID TOWERS

Twisted forms are often employed for tall buildings such as the Chicago Spire in Chicago, Infinity Tower in Dubai and Shanghai Tower in Shanghai. While none of these twisted towers have been designed with diagrid structures, this section investigates the structural potential of diagrids for twisted towers. Sixty-story towers of different twisted rates are designed with diagrid structures based on the stiffness-based design methodology presented in the previous section.

The buildings' typical plan dimensions are 36 x 36 meters with an 18 x 18-meter gravity core at the center and typical story heights of 3.9 meters. The SEI/ASCE Minimum Design Loads for Buildings and Other Structures is used to establish the wind load. The structures are 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 40.2 meter per second (90 mile per hour). One percent damping is assumed for the calculation of the gust effect factor. Preliminary member sizes for the rectangular box form digrid tower are generated first to satisfy the maximum lateral displacement requirement of a five hundredth of the building height. In order to comparatively estimate the lateral stiffness of diagrid structures employed for twisted structures, the member sizes used for the straight tower are also used for the twisted ones. Thus, each structure is designed with very similar amount of structural materials.

Figure 2 illustrates four different cases studied. The first case is the 60-story diagrid structure of straight box form. The maximum deflection at the top of the structure in this case is 46.8 cm, which satisfies the stiffness design requirement. The second case is a twisted version of the tower with a twisted rate of 1 degree per floor. The third and fourth case is another twisted version of the tower with a twisted rate of 2 degrees and 3 degrees per floor, respectively. The maximum deflection at the top of the structure of the second, third and fourth case is 47.5 cm, 51.2 cm and 57.0 cm, respectively. As the rate of twisting increases, the building's lateral stiffness decreases, and, consequently, its deflection increases. The stiffness reduction from the straight tower to the twisted one with 1 degree per floor turn is minimal. However, as the twisted rate increases to 2 and 3 degrees per floor, the stiffness reduction becomes much more substantial. Figure 3, with a summary of the maximum deflection at the top of each tower, clearly shows this phenomenon, which is very much related to the change of the diagrid angle caused by twisting the tower. The straight tower designed first is configured with the optimal diagrid angle of about 70 degrees. As the rate of twisting increases, the diagrid angle deviates more from its original optimal condition, which results in substantial reduction of the lateral stiffness of the tower.



Straight ($\Delta$max: 46.8 cm) | 1 deg./ floor ($\Delta$ max: 47.5 cm) | 2 deg./floor ($\Delta$ max: 51.2 cm) | 3 deg./floor ($\Delta$ max: 57.0 cm)

Figure 2: 60-story diagrid structures of various twisted rates.

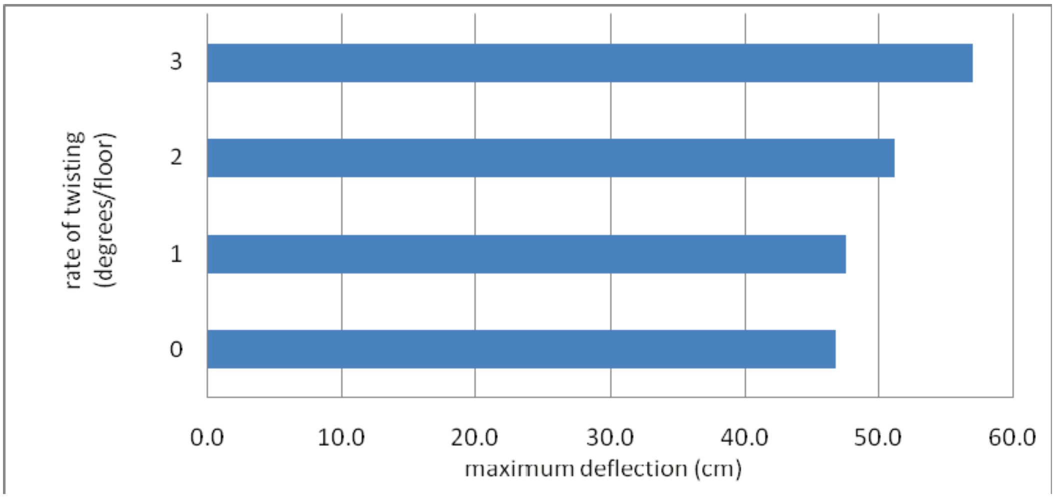



Figure 3: Maximum deflection comparison between the towers shown in Figure 2.

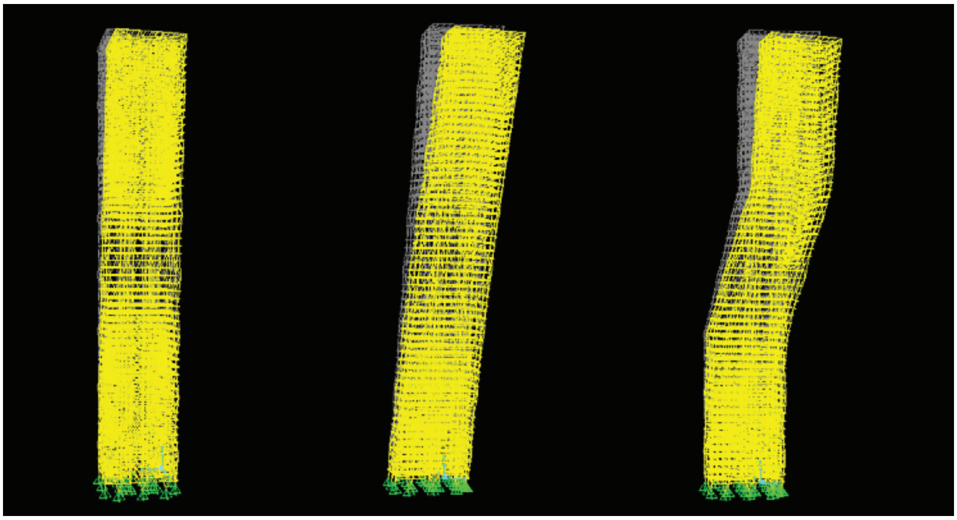


Figure 4: 60-story tilted diagrid structures of different configurations

With regard to the across-wind direction dynamic response due to vortex shedding, however, a twisted tower generally performs better than a straight one. In fact, there exists the optimal rate of twisting for a particular tower of a certain geometric configuration, as can be observed from the design studies of the Shanghai Tower, which is a 632m tall twisted tower. The total 120 degree twisting of the tower was determined based on the wind tunnel tests with multiple models of various twisted rates ranging from 90 to 210 degrees (Gensler, 2009). Another important issue to be considered for twisted towers is its constructability. As the rate of twisting increases, construction of the tower becomes more challenging. In deed, many aspects should be considered in an integrative way with multidisciplinary collaboration to successfully carry out twisted or other complex-shaped tall building projects.

## 4. TILTED DIAGRID TOWERS

This section investigates the structural performance of diagrid structural systems employed for tilted towers. The 60-story straight tower designed for the twisted building study in the previous section is now tilted in two different ways shown in Figure 4. The first case tilting, with zero floor offset, is similar to that of the Gate of Europe Towers in Madrid designed by Philip Johnson and John Burgee. The second case tilting, with 20 floor offset, is similar to that of the Signature Towers (formerly known as Dancing Towers) designed by Zaha Hadid. While these towers do not employ diagrids as their structural systems, this section employs diagrid systems for the tilted towers shown in Figure 4 and investigates their structural performance.

The first tower of Figure 4 is the straight one with the maximum displacement of 46.8 cm at the top. The tilted towers are significantly deformed laterally by dead and live loads due to their eccentricity. Between the two tilted towers of different geometric configurations, the one with 20 floor offset deforms more by about 23 cm than the one without offset due to the gravity loads. Lateral deformations caused by wind loads are similar in both tilted cases. These wind induced deformations of the tilted towers are also similar to that of the straight tower. Actual deformation values obtained by SAP2000 analyses are summarized in Table 1. Even though dead and live load induced deformations are large, they can be adjusted during the construction process if planned carefully. Therefore, if other non-structural design requirements can be met successfully by diagrid structures, they can be a feasible option for tilted towers.

Table 1: Lateral displacements of tilted towers

| | Lateral Displacement due to Dead & Live Load | Lateral Displacement due to Wind Load | Total Displacement due to Dead, Live & Wind Load |
|---|---|---|---|
| Case 1 | N/A | 46.8 cm | 46.8 cm |
| Case 2 | 39.3 cm | 47.4 cm | 86.7 cm |
| Case 3 | 62.5 cm | 46.5 cm | 109.0 cm |

## 5. FREEFORM DIAGRID TOWERS

As building forms become more irregular, finding appropriate structural systems for better performance and constructability is essential to successfully carry out the projects. The diagrid structural system has great potential to be developed as one of the most appropriate structural solutions for freeform towers. It is a very challenging task to accurately define and construct any freeform tower due to its complex geometry. If a freeform tower's geometry is defined by polygons other than triangles, it is very vulnerable to distortion. Triangular structural geometric units naturally defined by diagrid structural systems can specify any freeform tower more accurately without distortion.

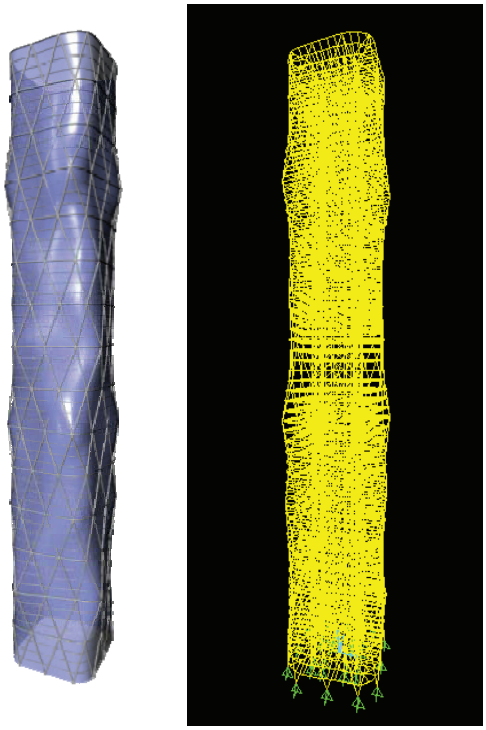


Figure 5: 60-story freeform diagrids: 3D rendering (left) and structural analysis model (right)

Research on structural performance of diagrids employed for freeform towers is in progress by the author. Notable freeform diagrid towers include the design of the Phare Tower in Paris and the Capital Gate Tower in Dubai. Figure 5 shows an example tower of freeform diagrids studied by the author. Not only structural performance but also constructability of the structural and façade systems of freeform towers will be studied in depth, and the results will be presented in the next EASEC.

## 6. CONCLUSIONS

Diagrid structures have been prevalently used for tall buildings worldwide. The unique compositional characteristics of diagrids provide great structural efficiency and aesthetic potential as an accentuating element in any existing urban context generally composed of buildings of orthogonal components. This paper presented structural performance and constructability issues of diagrid structures employed for complex-shaped tall buildings such as twisted, tilted and freeform towers. Though widely used today, application of diagrid structures for tall buildings is relatively new. With abundant emergence of complex-shaped tall buildings all over the world, more studies on their potential structural systems and multidisciplinary collaboration are very much required to construct built environments of higher performance.

## Acknowledgement

This research was supported by a grant (Code# '09 R&D A01) from Cutting-edge Urban Development Program funded by Ministry of Land, Transport and Maritime Affairs of Korean government.

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