SUSTAINABLE STRUCTURAL ENGINEERING FOR COMPLEX-SHAPED TALL BUILDINGS

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ABSTRACT

Today's architecture can be best understood only through the recognition of pluralism. Consequently, as is true of other building types, multiple design directions are prevalent for tall buildings. This contemporary design trend has produced many complex-shaped tall buildings such as twisted, tilted and free form towers. Structural systems for tall buildings are constructed with an abundant amount of structural materials. As the height of a building becomes taller, the required amount of structural material becomes drastically larger due to the premium for height. Constructing complex-shaped tall buildings typically requires an even more amount of structural material. This paper studies performance-based structural design options for various complex-shaped tall buildings, and investigates more efficient structural solutions for each complex form category. For this purpose, tall buildings of complex forms are designed with different contemporary structural systems, such as diagrids, braced tubes and outrigger systems, and the structural efficiency of each system, in conjunction with the building form, is studied. Parametric structural models are generated using appropriate computer programs, and the models are exported to structural engineering software for analyses and design. With the prevalent emergence of complex-shaped tall buildings, it is important to investigate more efficient structural systems to construct sustainable built environments using less amount of materials and consequently to save our limited resources.

Keywords: Tall buildings, structures, complex forms, sustainable engineering, parametric design.

1. INTRODUCTION

Tall buildings emerged in the U.S. in the late nineteenth century as office towers of about ten stories. Today, they are constructed in major cities throughout the world as very tall towers of various functions. Many different design approaches were tested for early tall buildings until the dominance of the International Style in the mid-twentieth century. Today's pluralism, however, has produced tall buildings of various forms, including more complex forms such as twisted, tilted and free forms. The amount of available information on design and construction of complex-shaped tall buildings is relatively small due to the lack of accumulated experiences. This paper studies performance-based structural design options for various complex-shaped tall buildings, and investigates more efficient structural solutions in order to help construct them with less amount of structural materials.

Parametric structural models are generated using appropriate computer programs such as Rhino and Grasshopper to investigate the impact of varying important geometric configurations of complex-shaped tall buildings, including the rate of twist, angle of tilting and degree of fluctuation of free form. The models are exported to structural engineering software such as SAP 2000 for analyses, design and comparative studies.

2. TWISTED TALL BUILDINGS

2.1. Twisted Diagrids and Braced Tubes

Both diagrids and braced tubes carry lateral loads very efficiently by axial actions of their primary structural members. Sixty-story buildings of various rates of twist are designed with diagrids and braced tubes. The studied 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 structures, assumed to be in Chicago and subjected to the code defined wind loads, are designed with no twist first. Then the straight structures are twisted with three different rates of 1, 2 and 3 degrees per floor, as shown in Figures 1 for the diagrids and Figure 2 for the braced tubes.

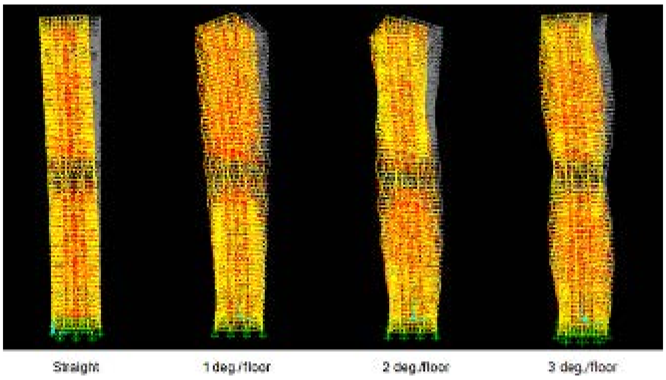

Figure 1: 60-story diagrids of various rates of twist.

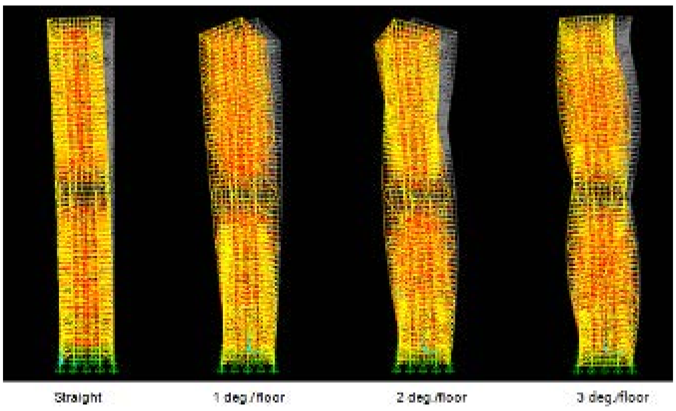

Figure 2: 60-story braced tubes of various rates of twist.

Preliminary structural design of the diagrids and the braced tubes was performed based on the stiffness-based design methodology developed by Moon et al. (2007) and Moon (2010) respectively to satisfy the maximum lateral displacement requirement of a five hundredth of the building height. The maximum deflection at the top of the straight diagrids and braced tube is 46.0 cm and 44.0 cm respectively, which satisfies the stiffness design requirement. Figure 3 summarizes the maximum lateral displacements of the diagrids and braced tubes shown in Figures 1 and 2. Diagrid structures, which are gaining increased interests by many contemporary architects and engineers, lose their lateral stiffness as the rate of twist increases. The rectangular box form diagrid tower was designed first with diagonals placed at the optimal uniform angle, which is about 70 degrees. As the rate of twisting increases, the diagrid angle deviates more and more from its original optimal condition and the stiffness of the system reduces. However, the rate of stiffness reduction of the diagrids is smaller than that of the braced tubes as can be seen in Figure 3. Therefore, twisted buildings with higher rates of twist can be structured more efficiently with diagrids.

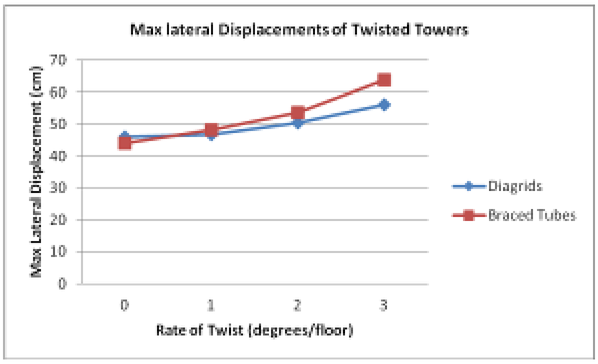

Figure 3: Maximum lateral displacements of 60-story twisted diagrids and braced tubes.

2.2. Twisted Outrigger Structures

Sixty-story buildings of various rates of twist are now designed with outrigger systems. The outrigger trusses are located at the top and mid-height of the tower. There are 8 perimeter mega-columns connected to the steel braced core through the outrigger trusses. The mega-columns are customized steel sections with sectional areas of 3,100 and 800 square cm for the lower and upper portions of the tower respectively. Based on the SAP2000 analysis, the maximum lateral displacement of the tower is 43.5 cm at the top, which satisfies the stiffness requirement.

The tower is twisted with two different rates. The first case twists the tower by 1.5 degrees per floor, which results in a total turn of 90 degrees, as shown in Figure 4. The mega-columns on the building perimeter wrap around the building spirally. Therefore, the position of the mega-columns on the flange planes (i.e., planes perpendicular to wind) at the base changes to those on the web planes (i.e., planes parallel to wind) at the top. And the position of the mega-columns on the web planes at the base changes to those on the flange planes at the top. These changes decrease the lateral stiffness of the system, and consequently the maximum lateral displacement is increased from 43.5 cm in the case of the straight tower to 48.8 cm in the case of the twisted tower.

The second case twists the tower by 3 degrees per floor, which results in a total turn of 180 degrees, as also shown in Figure 4. In this case, the position of the mega-columns on the flange planes at the base changes to those on the web planes at mid-height, and finally to those on the opposite flange planes at the top. This geometric configuration makes the structure behave more like a cantilever beam without outriggers, compared to typical outrigger structures in which curvature reversals occur around the outrigger truss levels. This increased rate of twist further decreases the lateral stiffness of the system, and consequently the maximum lateral displacement is increased from 43.5 cm in the case of the straight tower to 59.2 cm in the case of the twisted tower.

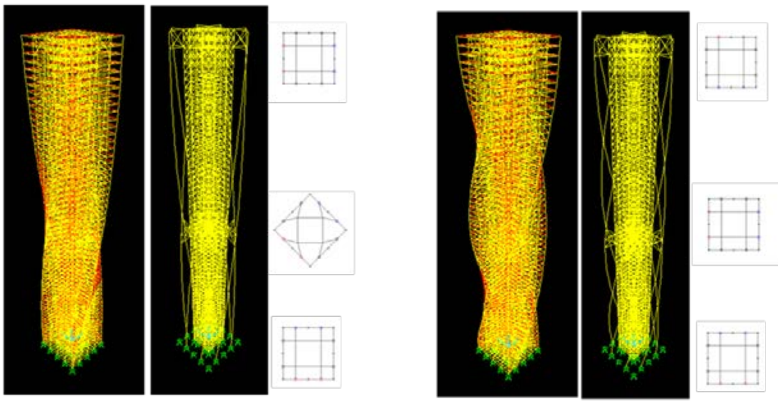

Figure 4: 60-story outrigger structures of two different rates of twist.

3. TILTED TALL BUILDINGS

3.1. Tilted Diagrids and Braced Tubes

The 60-story buildings are now tilted with various offsets and designed with diagrids and braced tubes. Tilted towers are deformed laterally not only by wind loads but also by dead and live loads due to their eccentricity. In fact, most of the studied tilted towers are laterally deformed more by dead and live loads than by wind loads. Figure 5 and 6 summarize the maximum lateral displacements of the tilted diagrids and braced tubes in the direction parallel to the direction of tilting, when the wind load is applied also in the same direction. The first, second and third cases, with offsets of 12, 16 and 20 floors, result in tilted angles of 7, 9 and 13 degrees, respectively.

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 angles. However, tilted diagrids' initial lateral displacements due to gravity load are significant. This gravity-induced lateral displacement, which is even larger than the wind-induced displacement, becomes greater as the angle of tilting increases. The combined maximum lateral displacement of the diagrids is increased from 46.0 cm of the straight tower case to 109.0 cm of the case with the tilted angle of 13 degrees.

The performance of the braced tubes is very similar to that of the diagrids. Lateral stiffness of the tilted braced tubes against wind loads is very similar to that of the straight braced tube regardless of the changes of the tilted angles. However, tilted braced tubes' initial lateral displacements due to gravity load are significant. This gravity-induced lateral displacement becomes greater as the angle of tilting increases. The combined maximum lateral displacement of the braced tube is increased from 44.0 cm of the straight case to 105.6 cm of the case with the tilted dangle of 13 degrees.

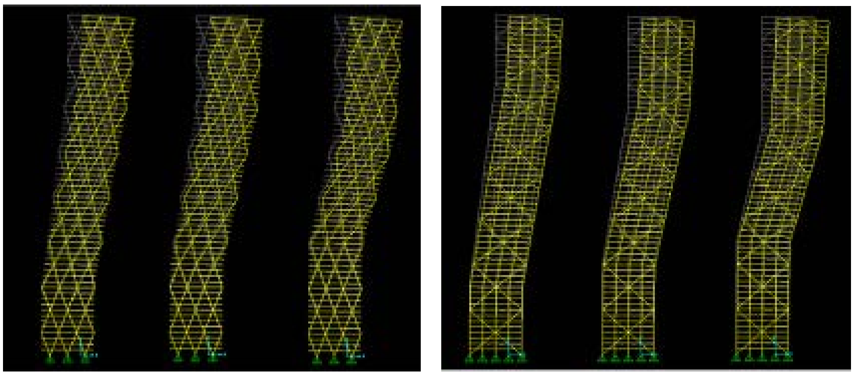

Figure 5: 60-story diagrids (left) and braced tubes (right) of various angles of tilting.

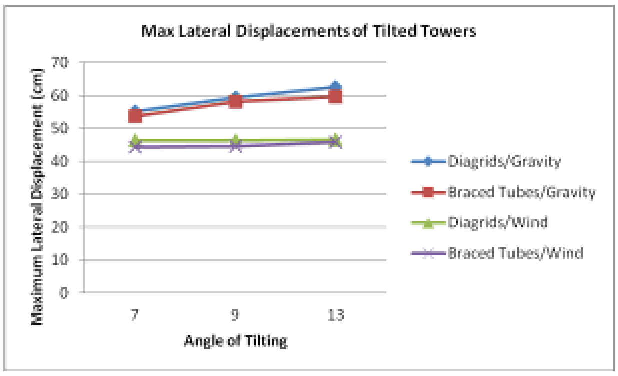

Figure 6: Maximum lateral displacements of tilted diagrids and braced tubes of 60-stories.

3.2. Tilted Outrigger Structures

A 60-story straight outrigger tower is tilted in three different configurations as can be seen in Figure 7. The straight outrigger structure in this section is similar to that in the previous section 2.2 except that the outrigger trusses are now located at one third and two third heights of the building.

These tilted outrigger towers are also significantly deformed laterally by dead and live loads due to their eccentricity. As the angle of tilting increases, the lateral deformation caused by the gravity loads also increases. Gravity-induced maximum lateral deformation values obtained by SAP 2000 analyses for the three tilted cases shown in Figure 7 are 42.7 cm, 52.0 cm and 53.9 cm for the towers with tilted angles of 7, 9 and 13 degrees respectively. Lateral deformations caused by wind loads are reduced in tilted outrigger towers. Wind-induced maximum lateral deformation values obtained by structural analyses are 34.6 cm, 33.6 cm and 34.6 cm respectively, compared to the maximum lateral displacement of 47.8 cm in the case of the straight outrigger tower. Increased lateral stiffness of outrigger structures in tilted towers is caused by triangulation of major structural components – braced core, outrigger trusses and mega columns - by tilting the tower as can be seen in Figure 7. Figure 8 and 9 summarize lateral displacements of the tilted outrigger structures due to gravity and wind loads in comparison with the tilted diagrids and braced tubes. The outrigger structure can be a very efficient structural system option for tilted towers.

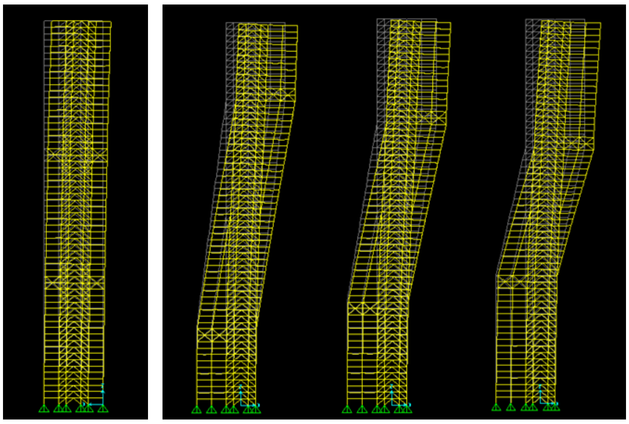

Figure 7: 60-story outrigger structures of various angles of tilting.

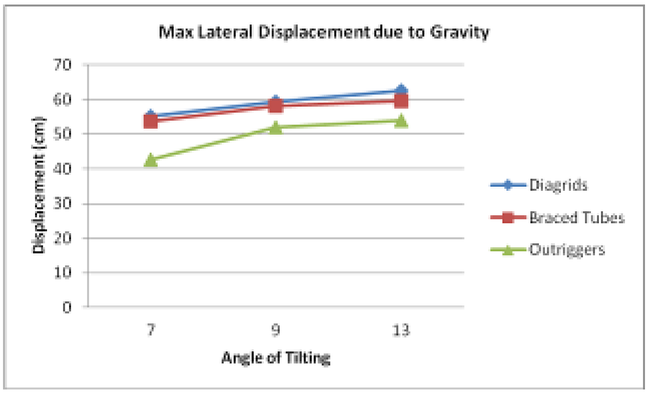

Figure 8: Max. lateral displacements of the 60-story tilted structures due to gravity loads.

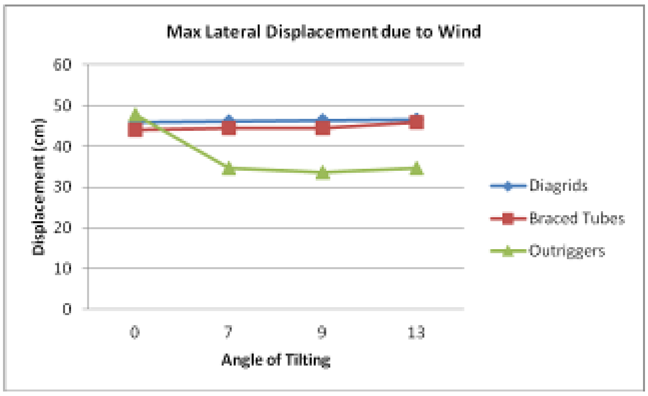

Figure 9: Max. lateral displacements of the 60-story tilted structures due to wind loads.

4. FREEFORM TALL BUILDINGS

It is a very challenging task to accurately define and construct any freeform tower due to its complex geometry. The diagrid structural system has great potential to be developed as one of the most appropriate structural solutions for irregular freeform towers. If a freeform tower's geometry is defined by polygons other than triangles, its originally designed form is more vulnerable to distortion during construction. Triangular structural geometric units naturally defined by diagrid structural systems can specify any irregular freeform tower more accurately without distortion.

Diagrid systems are employed for 60-story freeform tall buildings to investigate their structural performance. Freeform geometries are generated using sine curves of various amplitudes and frequencies. For the purpose of comparison, preliminary member sizes for the 60-story conventional rectangular box form diagrid tall building are generated first to satisfy the maximum lateral displacement requirement of a five hundredth of the building height.

Once the conventional rectangular box form diagrid structure is designed using the methodology developed by Moon et al. (2007), these member sizes are also used for the freeform diagrids. Thus, each structure is designed with very similar amount of structural materials. Compared to the rectangular box form diagrid structure, which has 36 x 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 maintained to be the same.

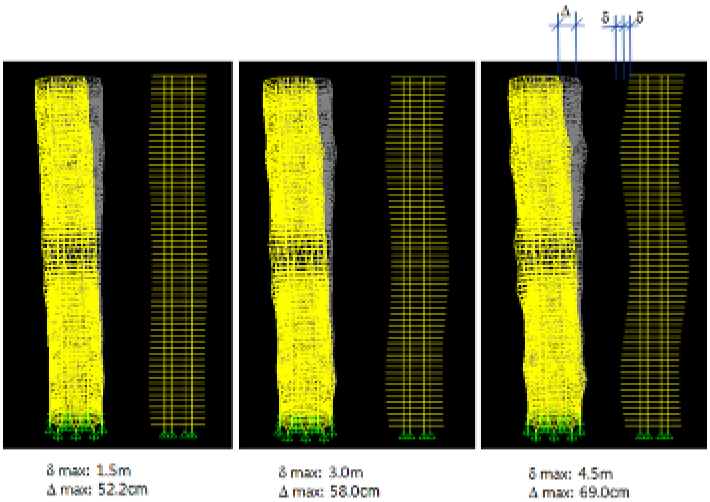

Figure 10: 60-story freeform diagrids.

As can be seen in Figure 10 which shows the deformed shape of each 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 deflections at the top of the structures of the first, second and third cases are 52.5 cm, 58.0 cm and 69.0 cm, respectively, compared to 46.0 cm in the case of the straight tower. This is very 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 of about 70 degrees. As the degree of fluctuation of freeform increases, 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.

5. CONCLUSIONS

As a building's form becomes more complicated, finding an appropriate structural system for better performance and constructability is essential to successfully carry out the project. This paper studied various structural design options for twisted, tilted and free form tall buildings. The lateral stiffness of twisted towers is decreased as the rate of twist is increased, and the rate of the stiffness reduction is different depending on the structural system employed. The systems with lower stiffness reduction rates may be considered as structural system options to build twisted towers using less amount of material. Tilted towers are deformed laterally not only by wind but also by dead and live loads due to their eccentricity. The gravity load-induced deformations can be managed substantially during construction process if planned carefully. Through the most appropriate system selection, design optimization and construction planning, tilted towers can be constructed more efficiently. For freeform towers, diagrid structures have greater potential than other systems because the diagrid system, with its triangular configuration, can better define freeform structures without distortions.

REFERENCES

Ali, M. M. and Moon, K. (2007). Structural Developments in Tall Buildings: Currents Trends and Future Prospects. *Architectural Science Review*, Vol. 50.3, pp. 205-223.

Connor, J. J. (2003). *Introduction to Structural Motion Control.* New York: Prentice Hall.

Kowalczyk, R., Sinn, R., and Kilmister, M. B. (1995). *Structural Systems for Tall Buildings.* Council on Tall Buildings and Urban Habitat Monograph. New York: McGraw-Hill.

Moon. K. (2010). Stiffness-Based Design Methodology for Steel Braced Tube Structures: A Sustainable Approach, *Engineering Structures*, Vol. 32, pp 3163-3170.

Moon, K., Connor, J. J. and Fernandez, J. E. (2007). Diagrid Structural Systems for Tall Buildings: Characteristics and Methodology for Preliminary Design, *The Structural Design of Tall and Special Buildings,* Vol. 16.2, pp. 205-230.

Schueller, Wolfgang. (1990). *The Vertical Building Structure.* New York: Van Nostrand Reinhold.