STRUCTURAL ENGINEERING OF COMPLEX-SHAPED TALL BUILDINGS

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Abstract- Today's diverse architectural design directions have produced tall buildings of many different forms. This paper presents performance-based structural system design options for complex-shaped tall buildings, such as twisted, tilted and free form towers. For each complex form category, tall buildings of different heights are designed with various structural systems prevalently used for today's tall buildings, such as braced tube, diagrid and outrigger systems, to investigate the structural performance of each system comparatively in conjunction with its form. Parametric structural models are generated to study the impacts of varying important geometric configurations of complex-shaped tall buildings. The models are exported to structural engineering software for analyses and design. Based on the design studies, structural performance of each system in different complex form category is comparatively evaluated.

Keywords- Complex-Shaped Tall Buildings, Structural Design, Diagrids, Braced Tubes, Outrigger Structures.

I. INTRODUCTION

Today's architecture, including tall buildings, can be understood only through recognition of the dominance of pluralism. This contemporary architectural design trend has produced various complex-shaped tall buildings, such as twisted, tilted and freeform towers, as are the cases with the twisted Shanghai Tower in Shanghai, tilted Veer Towers in Las Vegas and freeform Phare Tower in Paris. This paper studies performance-based structural system design options for complex-shaped tall buildings.

Twisted, tilted and freeform tall buildings of various heights are designed with today's prevalent tall building structural systems, i.e., diagrids, braced tubes and outrigger systems, and their structural performances are studied comparatively. Considering that the structural design of tall buildings is generally governed by lateral stiffness rather than strength [1] [2], stiffness-based design methodologies are used to design tall building structures of various complex forms. Preliminary structural member sizes for conventional rectangular box form towers of diagrid, braced tube and outrigger systems of various heights are generated first to satisfy the maximum lateral displacement requirement of a five hundredth of the building height. Once the structural design and analyses of the rectangular box form tall buildings are completed, comparable complex-shaped tall buildings of each form category are designed again with diagrids, braced tubes and outrigger structures. For twisted, tilted and freeform tall buildings, parametric structural models are generated using Rhino/Grasshopper to investigate each system's structural performance depending on the rate of twist, angle of tilt and degree of fluctuation of free form. The models are exported to structural engineering software, SAP 2000, for analyses and design. Based on the design studies, this paper comparatively evaluates the performance of different structural systems employed for various complex-shaped tall buildings.

II. TWISTED TALL BUILDINGS

Twisted forms employed for today's tall buildings can be understood as a reaction to rectangular box form buildings prevalently designed in the mid-twentieth century. Twisted forms can be found in today's tall buildings, such as the Shanghai Tower in Shanghai designed by Gensler (Figure 1), Infinity Tower in Dubai by Skidmore, Owings and Merrill, and Turning Torso in Malmo by Calatrava.

Both diagrids and braced tubes, which carry lateral loads by axial actions of the primary structural members, are very efficient structural systems for tall buildings of conventional rectangular box forms. The studied rectangular box form tall buildings' plan dimensions are 36 m x 36 m, with an 18 m x 18 m core at the center and typical story heights of 3.9 m. Based on these dimensions, the height-to-width aspect ratios of the studied 60-, 80- and 100-story buildings are 6.5, 8.7 and 10.9, respectively. Core structures are designed to carry only gravity loads for these tube type structures. 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. In order to comparatively estimate the structural performances of diagrids and braced tubes employed for twisted structures, the preliminary structural member sizes determined for the conventional box form towers are also used for the twisted tall buildings. Figure 2 shows examples of twisted diagrid and braced tube structures of 60 stories with a rate of twist of 3 degrees per floor. When both diagrids and braced tubes are employed for twisted

tall buildings, the systems' lateral stiffness is decreased as the rate of twist is increased.



Figure 1. Shanghai Tower (courtesy of author)

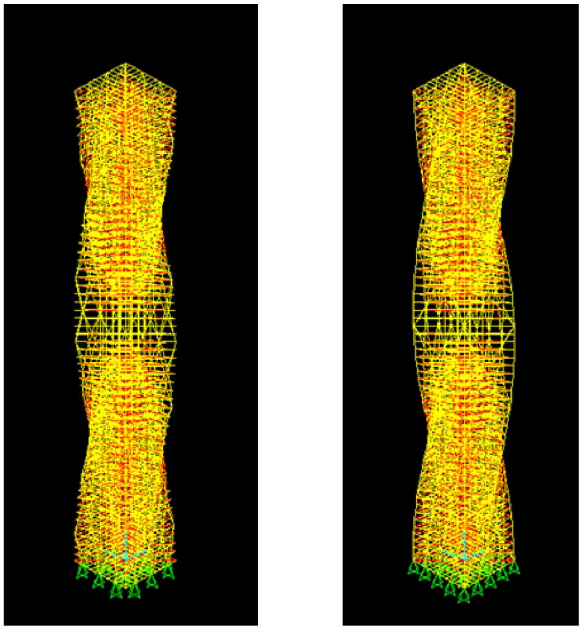


Figure 2. Structural models of twisted diagrid and braced tube structures of 60 stories.

The stiffness reduction of braced tubes, composed of verticals and diagonals, is more sensitive to the rate of twist, compared to that of diagrids, composed of only diagonals. This sensitivity is accelerated as the building height is increased. Figure 3 clearly shows this phenomenon with the

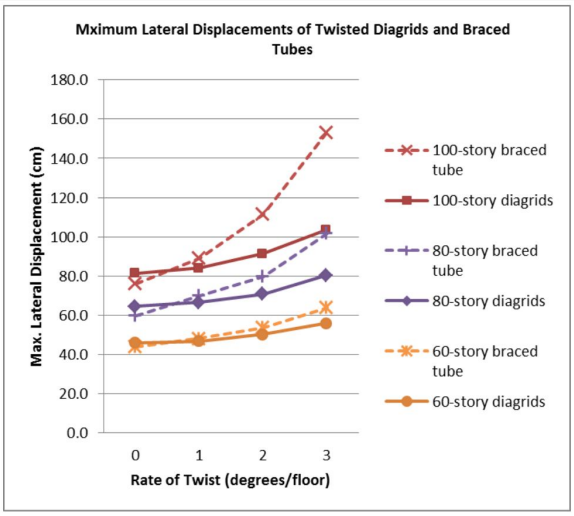


Figure 3. Maximum lateral displacements of twisted diagrids and braced tubes.

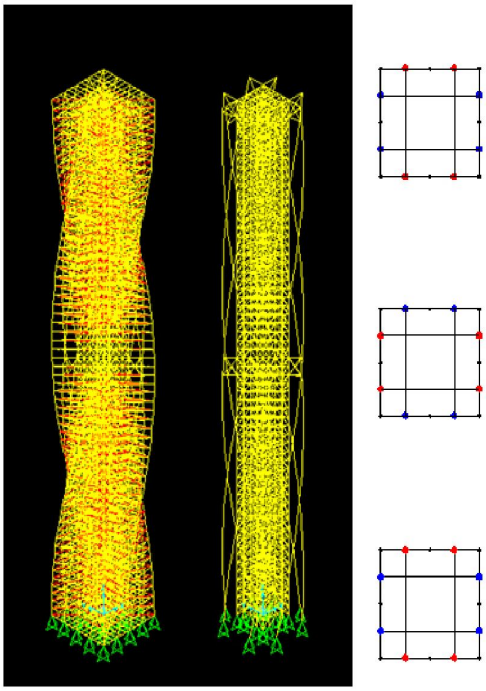


Figure 4. . Structural model of a twisted outrigger structure of 60 stories.

maximum lateral displacements of twisted diagrids and braced tubes of 60, 80 and 100 stories. The rates of twist studied are 1, 2 and 3 degrees per floor.

Lateral load-carrying mechanism of outrigger structures is different from that of tube type structures. Both lateral shear forces and overturning moments are carried by perimeter diagrids and braced tubes in the perimeter tube type structures [3] [4]. In outrigger systems, the braced cores carry lateral shear forces and a portion of overturning moments. Perimeter mega-columns connected to the stiff braced core through outrigger trusses also significantly contribute to carrying overturning moments [5].

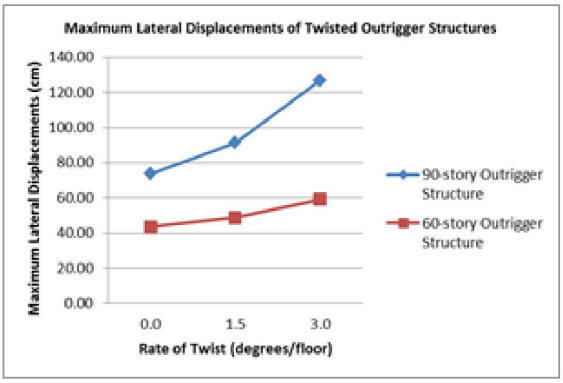


Figure 5. Maximum lateral displacements of twisted diagrids and braced tubes.

Figure 4 shows an example of twisted outrigger structures. As the outrigger structure is twisted, the perimeter mega-columns wrap around the building spirally. Lateral stiffness of the twisted outrigger structures with these spirally slanted perimeter mega-columns is substantially reduced as the rate of twist is increased. Figure 5 summarizes the maximum lateral displacements of twisted outrigger structures of different heights and rates of twist. It clearly shows the decreased lateral stiffness with the increased rate of twist.

Considering the substantial stiffness reduction caused by the spirally slanted mega-columns, outrigger structures with setback vertical mega-columns may be a feasible design alternative to enhance constructability. The twisted Chicago Spire project employs an outrigger structure with setback vertical mega-columns. With regard to the across-wind direction dynamic responses due to vortex shedding, it should be noted that a twisted tower generally performs better than a comparable prismatic one, as it can mitigate wind-induced vibrations by disturbing the formation of organized alternating vortexes. Considering the fact that the vortex-shedding-induced lock-in phenomenon often produces the most critical structural design condition for tall buildings [6], twisted building form's structural contribution can be significant.

III. TILTED TALL BUILDINGS

Buildings have traditionally been constructed vertically, orthogonal to the ground. Today, however, tilted buildings are designed and built to produce more dramatic architecture. Notable tilted tall buildings include the Gate of Europe Towers in Madrid designed by Philip Johnson/John Burgee, Veer Towers in Las Vegas by Helmut Jahn and the design of the Signature Towers in Dubai by Zaha Hadid.

Sixty story tilted tall buildings of various structural systems are studied in this section. The angles of tilt studied are 4, 7, 9 and 13 degrees, which correspond to offsets of 0, 12, 16 and 20 stories, respectively, at both top and bottom of the structure. Figure 6 shows braced tube structures with these angles of tilt.

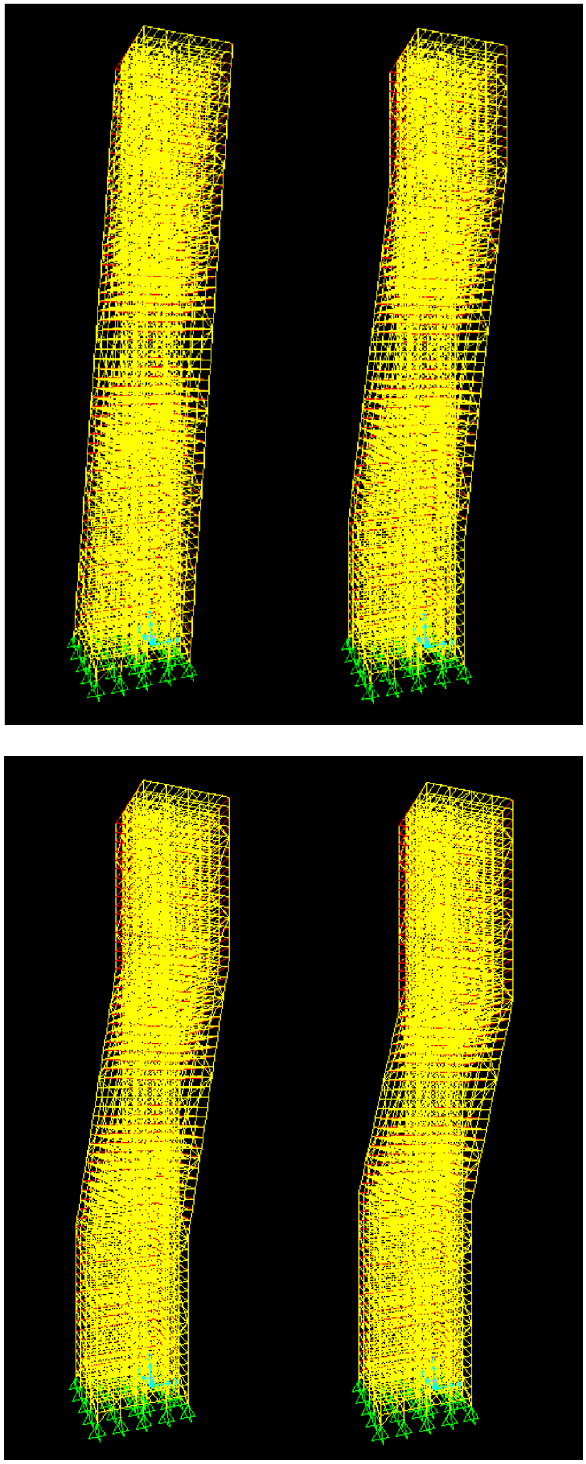


Figure 6. Structural models of 60-story tilted braced tubes of various tilted angles

Diagrids and outrigger structures are also tilted with these angles. Figure 7 summarizes wind-induced maximum lateral displacements of the 60-story tilted braced tubes, diagrids and outrigger structures. The lateral stiffness of the braced tube and diagrid systems is not substantially influenced by the angle of tilt

between 0 and 13 degrees studied here. The lateral stiffness of the outrigger system is somewhat increased by tilting the tower due to the triangulation of the major structural components – the braced core, mega-columns and outrigger trusses – caused by tilting the tower, as can be seen in Figure 8. The 18 m x 18 m core structures are kept vertical within the tilted buildings, regardless of the different angles of tilt.

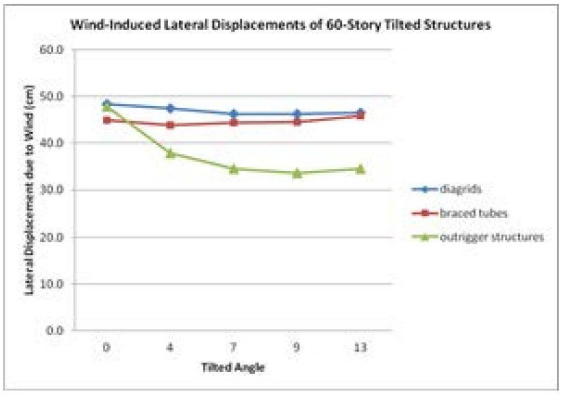


Figure 7. Maximum lateral displacements of tilted diagrids, braced tubes and outrigger structures

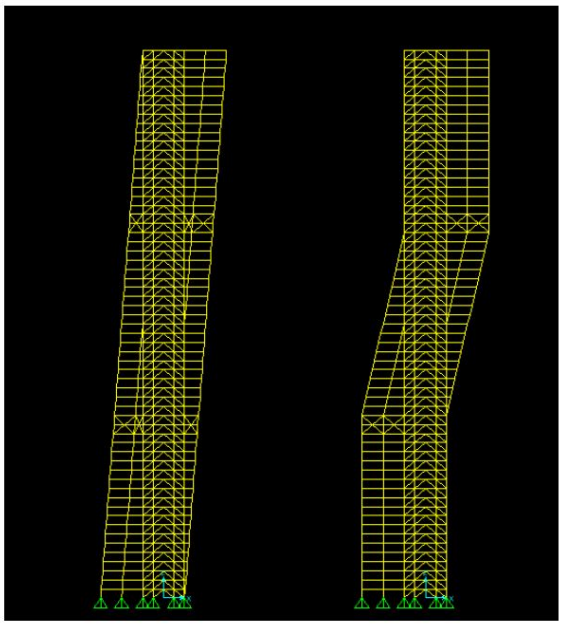


Figure 8. Structural models of 60-story tilted outrigger structures (section view)

Tilted tall buildings are subjected to significant initial lateral deformations due to eccentric gravity loads. Gravity-induced lateral displacements increase as the angle of tilt is increased in all the three structural systems. Among them, the outrigger structures produce relatively small gravity-induced lateral displacements again because of the triangulation of the major structural components. These gravity-induced deformations can be managed substantially through careful construction planning. As the angle of tilt is increased, very large localized stresses are developed in tilted tall buildings. Though structural design of tall buildings is generally governed by lateral stiffness, careful studies on satisfying strength requirements are also essential for tilted tall buildings. Large tensile forces, not very often found in conventional vertical tall buildings, can be developed in tilted tall buildings. Careful design studies on the connections of the tensile members of tilted tall buildings are required.

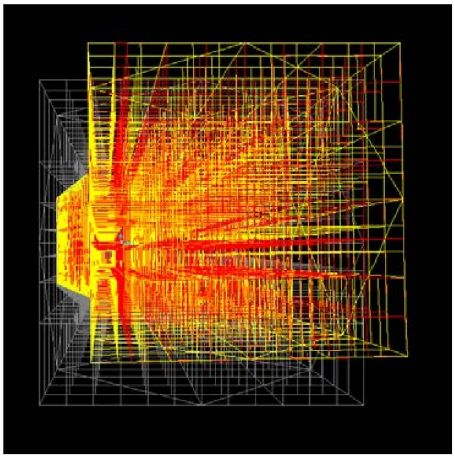


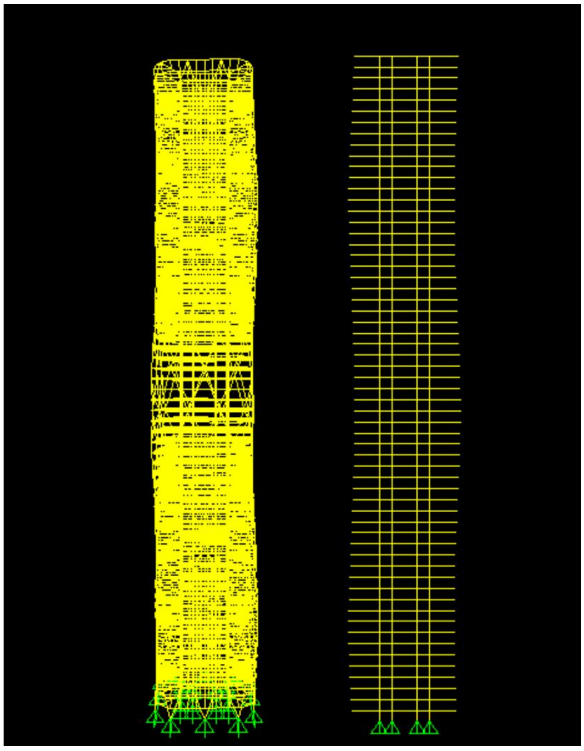
Figure 9. Deformed shapes of the 60-story tilted braced tube seen from above with wind in the direction perpendicular to the direction of tilting

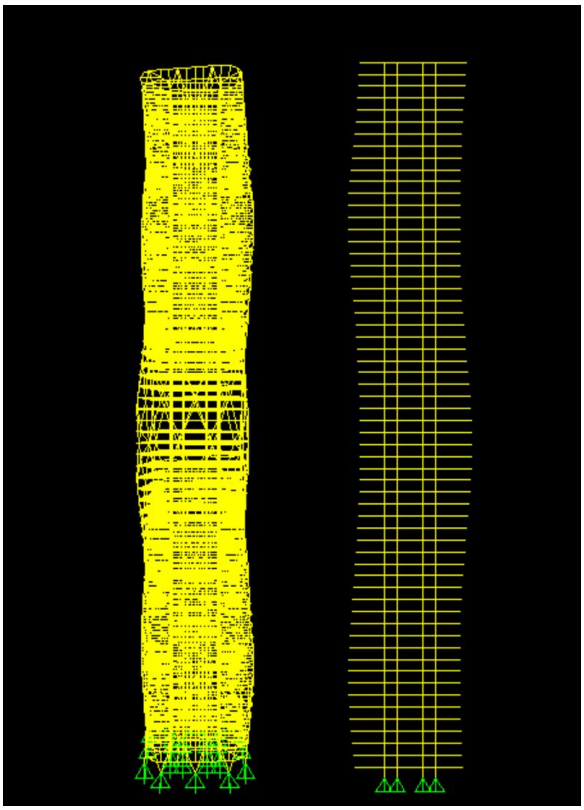
When wind load is applied in the direction perpendicular to the direction of tilting, the tilted tower is not only deformed laterally but also twisted. As the angle of tilting is increased, the rate of twisting is also increased. Figure 9 shows the deformed shape, seen from above, of the 60-story braced tube with an angle of twist of 13 degrees, subjected to the code-defined wind load in the direction perpendicular to the direction of tilting. The maximum twisted angle is 0.03 degrees at the top in this case. The maximum twisted angle of the corresponding tilted diagrid structure is 0.02 degrees, which is similar to that of the braced tube. The maximum twisted angle of the corresponding tilted outrigger structure is 0.07 degrees. This angle is much larger than the angles observed from the same studies with the tilted braced tube and diagrid structures because torsional stiffness of the outrigger structure is much smaller than that of the perimeter tube type structures with diagonals, such as braced tubes and diagrids.

IV. FREEFORM TALL BUILDINGS

The number of freeform tall building projects has been rapidly increasing these days. Relying on the powerful support of structural engineers and structural engineering software, some architects often find their design solutions in free forms. These architects include Daniel Libeskind, Zaha Hadid and Thom Mayne to name a few. Even though the supporting structural systems behind the free forms vary depending on the project-specific situations, diagrids

are often employed as primary structural systems for freeform tall buildings, as can be observed from the Fiera Milano Tower in Milan by Daniel Libeskind and the Phare Tower in La Defense by Thom Mayne. As building form becomes more irregular, finding an appropriate structural system for better performance and constructability is essential to successfully carry out the project.





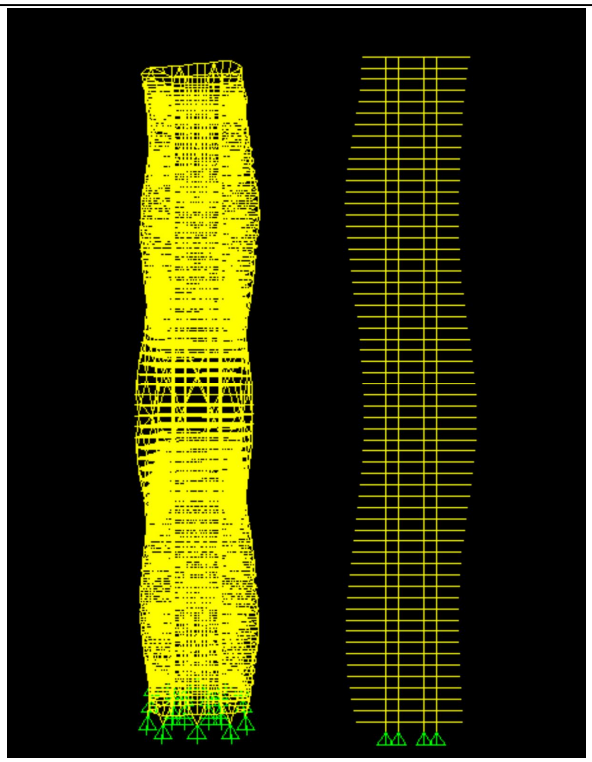


Figure 10. Structural models of freeform diagrid structures of 60 stories (3D and section views)

The diagrid structural system has great potential to be developed as one of the most appropriate structural solutions for irregular freeform towers because triangular structural geometric units naturally defined by diagrids can specify any irregular freeform tower more accurately without distortion.

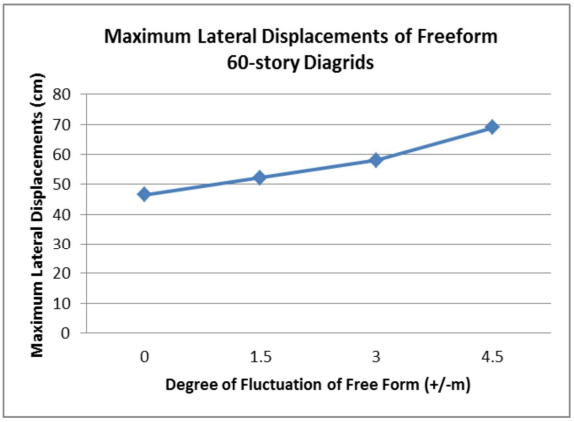


Figure 11. Maximum lateral displacements of 60-story freeform diagrids

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. Compared to the rectangular box form diagrid structure, which has 36 x 36 meter square plan on each floor, the floor plans of the first, second and third freeform case shown in Figure 10 fluctuate within the +/- 1.5, 3 and 4.5 meter boundaries of the

original square respectively. Each building is designed to have the identical gross floor area regardless of these geometry changes. In order to comparatively estimate the structural performances of freeform diagrids, the preliminary structural member sizes determined for the conventional box form towers are also used for the freeform towers.

The lateral displacement of the structure becomes larger as the freeform shape deviates more from its original rectangular box form as can be seen in Figure 11. The maximum lateral displacements of the first, second and third cases are 52.2, 58.0 and 69.0 cm, respectively, compared to 46.6 cm in the case of the prismatic tower. Similar to the cases of twisted diagrids, this stiffness reduction is very much related to the changes of the diagrid angle caused by free-forming the tower. The prismatic tower designed first is configured with diagonals placed at an angle close to the optimal. As the degree of fluctuation of free form is increased, the diagrid angle deviates more from its original optimal condition, and, consequently, lateral stiffness of the diagrids is substantially reduced.

Therefore, freeform shapes should be determined with careful considerations of not only architectural but also structural performance. With regard to the across-wind direction dynamic responses due to vortex shedding, irregular free forms also help tall buildings prevent shedding organized alternating vortices, which can cause the lock-in condition, along the building height. Therefore, freeform tall buildings are generally less susceptible to severe across-wind direction vibrations than prismatic tall buildings.

CONCLUSION

Today's diverse architectural design directions in conjunction with rapid evolution of technologies have produced many tall buildings of complex forms. This paper presented comparative lateral performances of diagrids, braced tubes and outrigger structures, employed of twisted tilted and freeform tall buildings. Lateral stiffness of diagrids, braced tubes and outrigger structures is reduced when they are employed for twisted tall buildings. As the rate of twist is increased, the rate of stiffness reduction is also increased. Lateral stiffness of tilted diagrids and braced tubes is not substantially influenced by the angle of tilt ranging from 0 to 13 degrees studied in this paper. Lateral stiffness of outrigger structures is somewhat increased as they are tilted because of the triangulation of the major components of the lateral load resisting system – the braced core, mega-columns and outrigger trusses. Tilted tall buildings are laterally deformed by not only wind loads but also eccentric distribution of gravity loads. The gravity-induced lateral displacements can be substantially managed through careful construction planning. For freeform tall buildings, the diagrid structural system has great potential to be developed as one of the most appropriate structural solutions because triangular structural units naturally defined by diagrids can specify any irregular freeform tower more accurately without distortion. Lateral stiffness of diagrid structural systems employed for freeform tall buildings is decreased. As the degree of fluctuation of free form is increased, the rate of lateral stiffness reduction is also increased.

Vortex-shedding-induced lock-in phenomenon often produces the most critical structural design condition for tall buildings. Regarding the across-wind direction dynamic responses, complex-shaped tall buildings, such as twisted and freeform towers, generally perform better than comparable prismatic tall buildings, as they can mitigate wind-induced vibrations by disturbing the formation of organized alternating vortexes. Today's complex-shaped tall buildings require more complicated system design, analysis and construction. Not only architectural but also structural and other related performance issues should be considered holistically to produce better performing and higher quality built environments.

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