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COMPARATIVE EFFICIENCY BETWEEN STRUCTURAL SYSTEMS FOR COMPLEX-SHAPED TALL BUILDINGS

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This paper presents various structural system design options for complex-shaped tall buildings—such as twisted, tilted, and freeform tall buildings—and evaluates their comparative structural efficiency. For each complex form category, tall buildings are designed with different contemporary tall building structural systems, e.g., diagrids, braced tubes, and outrigger systems. Comparative structural efficiency between these systems in conjunction with building forms and height is studied. The heights of the studied buildings range from 60 to 100 stories, and the corresponding height-to-width aspect ratios range from 6.5 to 10.8. Parametric structural models are generated with Rhino/Grasshopper to investigate the impacts of various important geometric configurations of complex-shaped tall buildings, such as the rate of twist, angle of tilt, and degree of fluctuation of free form. The parametric models are exported to structural engineering software SAP2000 for analyses and design. Based on the study results, comparative structural efficiency between different structural systems of each complex form category is presented.

Keywords: Tall buildings, Twisted tall buildings, Tilted tall Buildings, Freeform tall buildings, Diagrids, Braced tubes, Outrigger structures.

1 INTRODUCTION

Today's architectural design trends based on pluralism have produced various complex-shaped tall buildings, such as the twisted Cayan Tower in Dubai, the tilted Gate of Europe Towers in Madrid, and the freeform Phare Tower in Paris. Complex-shaped tall buildings are a relatively new architectural phenomenon, and the amount of available information on design and construction of complex-shaped tall buildings is relatively little, due to the lack of accumulated experience and research. This paper systematically studies and comparatively evaluates structural system design options for various complex-shaped tall buildings.

Tall buildings carry very large gravity and lateral loads. Therefore, structural impacts of twisting, tilting and free-forming tall buildings are significant. More careful studies are required for the structural design of complex-shaped tall buildings. Tall buildings of various complex forms are designed with today's prevalent structural systems for tall buildings, such as diagrids, braced tubes and outrigger systems, and their comparative structural efficiencies are studied. Considering the fact that the structural design of tall buildings is generally governed by lateral stiffness rather than strength (Connor 2003), stiffness-based design methodologies are used to design the tall building structures of various complex forms.

2 COMPLEX-SHAPED TALL BUILDING STRUCTURE MODELING

Conventional rectangular box form tall buildings of 60, 80 and 100 stories were designed first with three different structural systems—braced-tube, diagrid, and outrigger systems—as the comparison basis. Preliminary member sizes for the conventional rectangular box-form tall buildings were determined to satisfy the maximum lateral displacement requirement of a five-hundredth of the building height. The SEI/ASCE Minimum Design Loads for Buildings and Other Structures was used to establish the wind load. The structures were assumed to be in Chicago.

The conventional rectangular-box-form tall buildings' plan dimensions were 36 m x 36 m, with an 18 m x 18 m core at the center and typical story heights of 3.9 m. With these basic dimensions, the height-to-width aspect ratios of the studied 60-, 80-, and 100-story buildings were 6.5, 8.7 and 10.9, respectively. The core was designed to carry only gravity loads for the tube-type structures, i.e., braced tubes and diagrids. For outrigger structures, the core was designed as the braced frame to carry gravity as well as lateral loads.

Once the design and analyses of the rectangular-box-form tall buildings were completed, complex-shaped tall buildings of each form category were designed with braced tubes, diagrids and outrigger structures. For twisted, tilted, and freeform tall buildings, parametric structural models were generated using Rhino/Grasshopper to investigate each system's structural performance depending on various rate of twist, angles of tilt, and degree of fluctuation of free form. The studied rates of twist ranged from 1 to 3 degrees per floor. The studied angles of tilt ranged from 4 to 13 degrees. For the freeform tall building studies, the degrees of fluctuation of free form, defined as deviation distance from the original square floor plan dimension of 36m x 36m, ranged from +/- 1.5 m to +/- 4.5 m.

The models were exported to structural engineering software, SAP 2000, for design, analysis, and comparative studies. In order to comparatively estimate the structural efficiencies of various structural systems employed for twisted, tilted and freeform structures, the member sizes used for the conventional box form towers were also used for the complex-shaped tall buildings with some minor adjustments when necessary.

3 TWISTED TALL BUILDINGS

Twisted diagrid, braced-tube, and outrigger structures of 60 stories are shown in Figure 1. Both the diagrids and braced tubes, which carry lateral shear forces and overturning moments by their perimeter tube members, are very efficient structural systems for tall buildings of conventional rectangular-box-form towers (Moon 2010, Moon et al. 2007). If these structural systems are employed for twisted tall buildings, the systems' structural efficiency decreases as the rate of twist increases. The stiffness reduction of braced tubes, composed of verticals and diagonals, is much more sensitive to the rate of twist, compared to that of diagrids, composed of only diagonals. And this sensitivity becomes accelerated as the building height increases. Figure 2 clearly shows this phenomenon with the maximum lateral displacements of twisted diagrids, and with braced tubes of various heights and rates of twist.

In the outrigger structures with braced core structures, the braced core carries 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 the bending rigidity of the outrigger structure (Ali and Moon 2007). As the outrigger structure is twisted, the perimeter mega-columns wrap around the building spirally as can be seen in Figure 1. Lateral stiffness of the outrigger structures with these spirally slanted perimeter mega-columns is substantially reduced as the rate of twist increases. Consequently, the overall performance characteristics of the twisted outrigger structures are similar to those of the tube type structures.

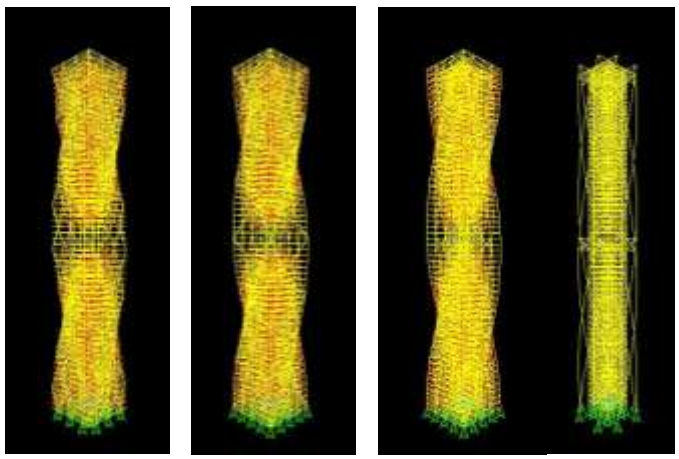

Fig. 1. Twisted braced-tube, diagrid and outrigger structures of 60 stories.

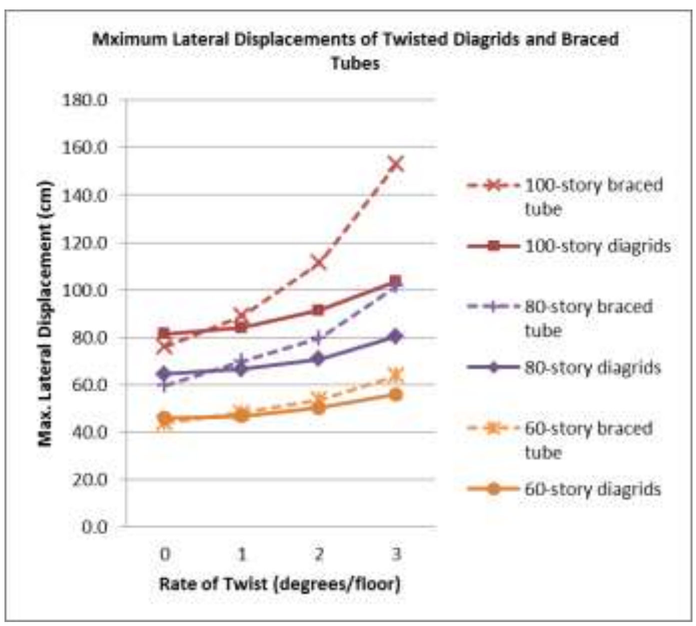

Fig. 2. Maximum lateral displacements of twisted diagrids and braced tubes.

3 TILTED TALL BUILDINGS

The performance of a tilted tall building is dependent upon its structural system and angle of tilt. Figure 3 shows tilted tall buildings designed with diagrid, braced-tube, and outrigger systems. The angle of tilt shown in Figure 3 is 13 degrees. Compared to the perimeter tube type structures, i.e., diagrids and braced tubes, the outrigger system provides greater lateral stiffness for tilted towers because of the triangulation of the major structural components—the braced core, outrigger trusses and mega-columns—caused by tilting the tower. Figure 4 summarizes wind-induced maximum lateral displacements of the 60-story tilted diagrid, braced-tube and outrigger structures, with the angles of tilt of 4, 7, 9 and 13 degrees. These angles of tilt correspond to 0, 12, 16 and 20 story offsets at the top and bottom of the building. The lateral stiffness of the braced-tube and diagrid systems is not substantially influenced by the angles of tilt between 0 and 13 degrees studied here. The lateral stiffness of the outrigger system is even increased by tilting the tower due to the triangulation of the major structural components.

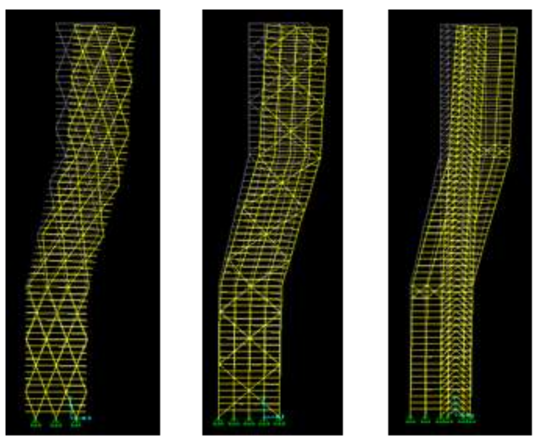

Fig. 3. Tilted diagrid, braced-tube and outrigger structures.

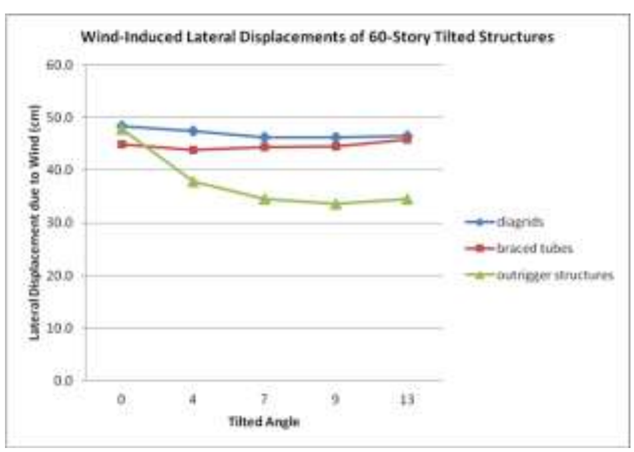

Fig. 4. Wind-induced lateral displacements of 60-story tilted tall buildings.

Tilted tall buildings are subjected to significant initial deformations due to eccentric gravity loads. While gravity-induced lateral displacements increase as the angle of tilt increases in all the three structural systems, the gravity-induced displacements of the outrigger structures are relatively small 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 increases, very large localized stresses are developed in tilted tall buildings due to the eccentricity. Though the structural design of tall buildings is generally governed by lateral stiffness, satisfying strength requirements is also essential, especially for tilted tall buildings. Large tensile forces, not very often found in conventional vertical tall buildings, can be developed in tilted tall buildings. Careful studies on the design and connection of the tensile members of tilted tall buildings are required.

4 FREEFORM TALL BUILDINGS

The number of freeform tall building projects has been rapidly increasing these days. As building's form becomes more irregular, finding an appropriate structural system for better performance and constructability is essential to successfully carry out the project. Though the supporting structural systems behind the free forms vary depending on the project-specific situations, diagrids are often employed as primary structures for freeform tall buildings, as can be observed from Daniel Libeskind's Fiera Milano Tower in Milan, and Thom Mayne's Phare Tower in La Defense. 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.

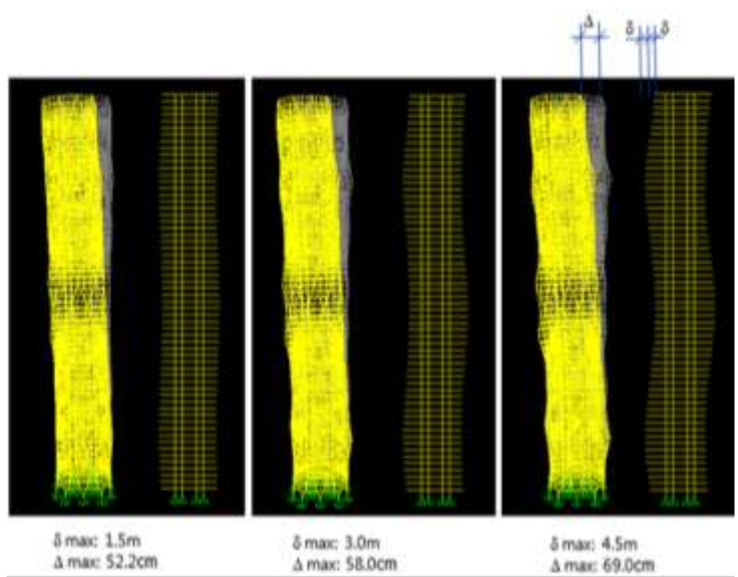

Fig. 5. Maximum lateral displacements of 60-story freeform diagrids.

Diagrid systems were employed for 60-story freeform tall buildings to investigate their structural performance. Freeform geometries were generated using sine curves of various amplitudes and frequencies. The degree of fluctuation of freeform was defined as deviation distance from the original square floor plan dimension of 36 m x 36 m. The studied deviation distances were +/- 1.5 m, +/- 3.0 m, and +/- 4.5 m. As can be seen in Figure 5, 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. This is very much related to the change of the diagrid angle caused by free-forming the tower. The straight tower designed first for comparison was configured with the optimal diagrid angle of about 70 degrees. As the degree of fluctuation of freeform increases, the diagrid angle deviated more from its original optimal condition, resulting 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 CONCLUSION

Today, complex-shaped tall buildings are designed and constructed in major cities throughout the world. Indeed, complex-form design has become a new strong direction in contemporary architecture. Complex-shaped tall buildings require more complicated system design, analysis and construction. This paper investigated static responses of structural systems employed for complex-shaped tall buildings. With regard to the across-wind direction dynamic responses due to vortex shedding, it should be noted that complex-shaped tall buildings, such as twisted and freeform towers, perform better than comparable prismatic ones, as the complex-shaped buildings can mitigate wind-induced vibrations by disturbing the formation of organized alternating vortexes. Well-organized coordination of complexity between architects and engineers to better satisfy architectural requirements and enhance structural performances will lead to higher-quality built environments.

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