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Comparative Evaluation of Structural Systems for Tilted Tall Buildings

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Abstract

Employing tilted forms in tall buildings is a relatively new architectural phenomenon, as are the cases with the Gate of Europe Towers in Madrid and the Veer Towers in Las Vegas. This paper studies structural system design options for tilted tall buildings and their performances. Tilted tall buildings are designed with various structural systems, such as braced tubes, diagrids and outrigger systems, and their structural performances are studied. Structural design of today's tall buildings built with higher strength materials is generally governed by lateral stiffness. Tilted towers are deformed laterally not only by lateral loads but also by dead and live loads due to their eccentricity. The impact of tilting tall buildings on the gravity and lateral load resisting systems is studied. Comparative evaluation of structural systems for tilted tall buildings is presented.

Keywords: Tilted tall buildings, Diagrids, Braced tubes, Outrigger structures

1. Introduction

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. The leaning Tower of Pisa (Fig. 1) is a famous example of tilted buildings due to differential settlements. Today, however, tilted buildings are intentionally designed and built to produce more dramatic architecture, as are the cases with the Gate of Europe Towers of 1996 in Madrid (Fig. 2) designed by Philip Johnson/John Burgee, Veer Towers of 2010 in Las Vegas by Helmut Jahn, and the design of the Signature Towers in Dubai by Zaha Hadid (Fig. 3).

Tall buildings carry very large gravity and lateral loads. Therefore, structural impacts of tilting tall buildings are significant, and more careful studies are required for the design of tilted tall buildings. Though not uncommon these days, design and construction of tilted tall buildings are a still very recent architectural phenomenon, and only a limited amount of related research has been conducted. Scott et al. (2007) presented general design considerations for tall buildings of complex geometries, including leaning towers, with examples of the Songdo Northeast Asia Trade Tower and the Fiera Milano. Erakovic et al. (2010) studied the structural design and performance of the tilted Veer Towers in Las Vegas. Schofield (2012) performed a case study on the leaning Capital Gate Tower in Abu Dhabi. Kim and Hong (2011) estimated the progressive collapse potential of irregular buildings including tilted buildings of 30 stories. Kim and Jung (2012) presented progressive collapse resisting capacities of tilted tall buildings of 36 stories.

Structural design of tall buildings is generally governed by lateral stiffness (Connor, 2003; Ali & Moon, 2007). While a considerable amount of research has been carried out by many researchers and engineers about structural systems for conventional prismatic form tall buildings, impacts of tilting tall building structures on lateral stiffness have not been much investigated. This paper studies

Figure 1. Leaning Tower of Pisa (Courtesy of Stephen Staples).

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Figure 2. Gate of Europe Towers in Madrid (Courtesy of Antony Wood, CTBUH).

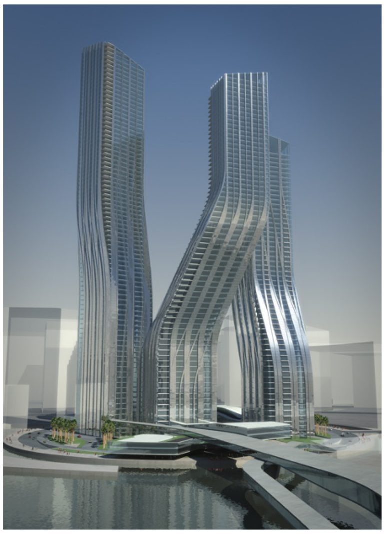

Figure 3. Signature Towers (Courtesy of Zaha Hadid Architects).

structural system design options for tilted tall buildings with various structural systems and evaluates their lateral performances comparatively.

Unlike vertical tall buildings, tilted tall buildings are subjected to large initial lateral deformations and localized stresses due to their eccentricity. This paper also discusses these important structural issues. Though tilted forms have emerged as a new form of tall building architecture, research on this subject is still very rare and more studies are needed. This paper systematically studies and evaluates structural systems for tilted tall buildings.

2. Parametric Modeling

In order to illustrate the concepts underlying the structural behavior of tilted tall buildings, sixty-story towers of various angles of tilt are designed with three different structural systems prevalently used for today's tall buildings, i.e., braced tubes, diagrids and outrigger structures. Structural steel is used for the design of all three structural systems in this study, though reinforced concrete or composite structures are also commonly used in real world. Each system's structural performance depending on various angles of tilt is investigated comparatively based primarily on lateral stiffness. Parametric structural models are generated using appropriate computer programs such as Rhino/Grasshopper to investigate the impact of varying angle of tilting. The models are exported to structural engineering software, SAP 2000, for design, analysis and comparative studies. Fig. 4 shows example

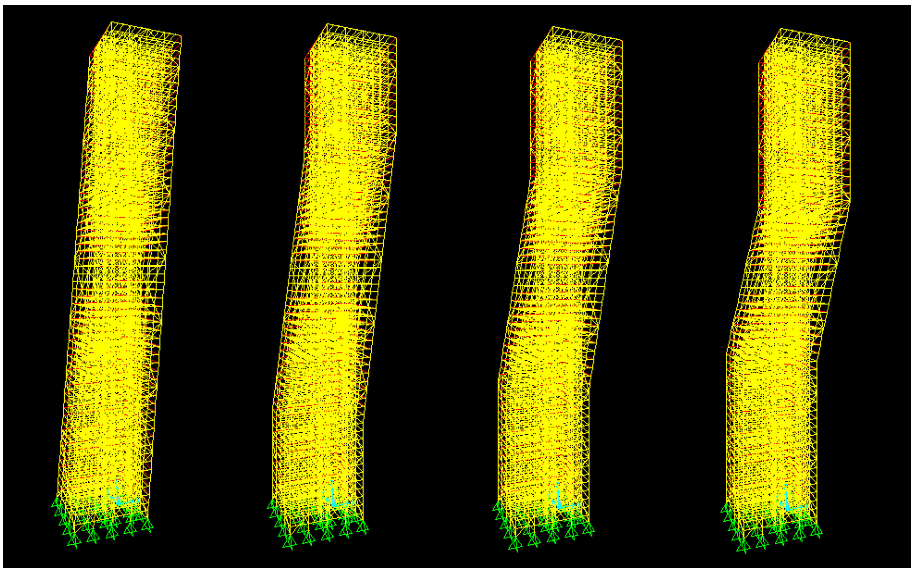

Figure 4. 3D structural models of variously tilted tall buildings generated using Rhino/Grasshopper and SAP 2000.

3D structural models of tilted tall buildings generated using Rhino/Grasshopper and SAP 2000.

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 meters per second (90 miles per hour). One percent damping is assumed for the calculation of the gust effect factor. Considering the fact that the structural design of tall buildings is generally governed by lateral stiffness, preliminary member sizes for the straight tower are generated first to satisfy the maximum lateral displacement requirement of a five hundredth of the building height. The maximum allowable displacement of tall buildings, one of the most important stiffness-based design parameters, is typically in the neighborhood of this value (Kowalczyk et al., 1995).

3. Tilted Braced Tubes

Braced tubes, with their superior structural efficiency, have often been used for tall buildings, such as the John Hancock Center in Chicago, Renaissance Tower in Dallas and 780 Third Avenue in New York to name a few. This section investigates structural performance of braced tubes employed for tilted tall buildings. A 60-story tall rectangular box form straight tall building is designed with the braced tube system first, and the building is tilted at four different angles as shown in Fig. 5. Case 1.1 is the straight braced tube tower. The building's typical plan dimensions are 36×36 meters with an 18×18-meter core at the center, which produces a floor depth of 9 meters between the building façades and the core perimeter walls. Typical story heights are 3.9 meters. The braced tube system on the building perimeter 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 estimate the impact of different angles of tilting on the performance of the perimeter braced tube.

Fig. 6, with simplified section drawings of the tilted braced tubes, clearly explains the relationship between the vertical building core and the tilted perimeter braced tube for each tilted case. Case 1.2 is a tilted case with no floor offset. While the 18×18-meter gravity core is kept vertical within the tilted perimeter braced tube, the building is tilted to its maximum angle of 4 degrees. Therefore, on the left side of the building as seen in Fig. 6, 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. Though this specific configuration produces some architectural issues regarding the space use as the distance between the exterior façade and the core perimeter wall nears 0 meter, this study is focused more on structural aspects and assumes architectural issues can be reasonably resolved in the end. The tilted form of this case is similar to that of the Gate of Europe Towers in Madrid shown in Fig. 2 or the Veer Towers in Las Vegas.

Case 1.3, 1.4 and 1.5 are tilted braced tube towers 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 shown in Fig. 3. In these cases, the 18×18-meter gravity cores are still kept vertical within the perimeter braced tube structures.

The preliminary structural design is performed based on the stiffness-based design methodology developed for braced tubes by Moon (2010). A braced tube building is

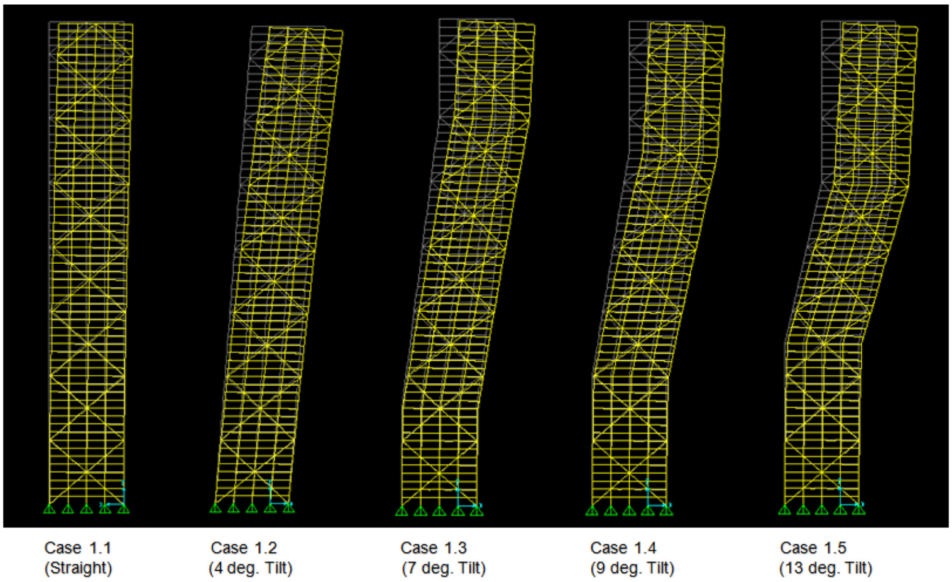

Figure 5. 60-story tilted braced tube structures of various tilted angles (elevation view).

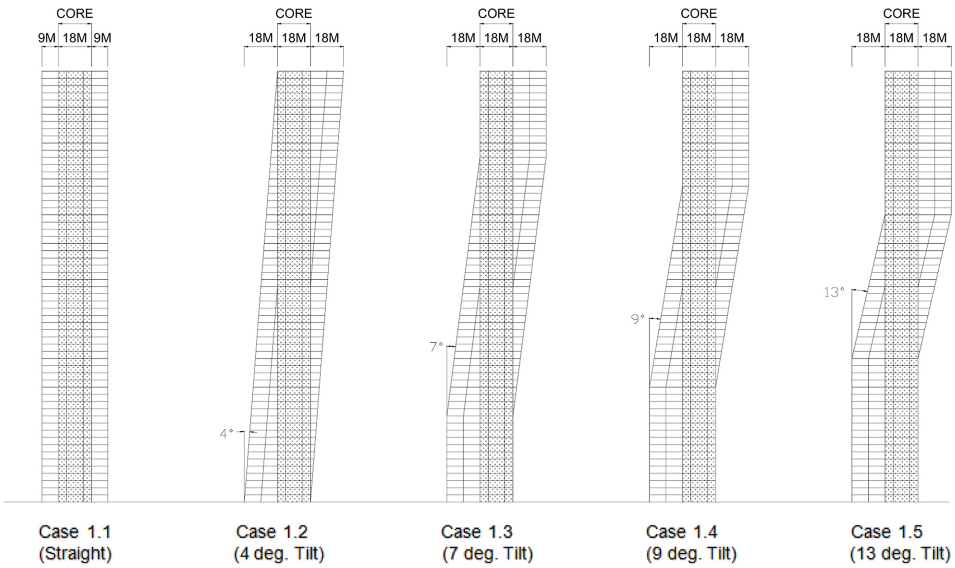

Figure 6. 60-story tilted braced tube structures (section view).

modeled as a cantilever beam, and subdivided longitudinally into modules according to the repetitive pattern. Each module is defined by a single level of diagonals that extend over multiple stories. Fig. 7 illustrates a 10-story braced tube module. Member sizes for the braced tube modules of a tall building can be computed using Eqs. (1) and (2) (Moon, 2010).

$$A_d = \frac{V}{4E\cos^2\theta\sin\theta\gamma} \tag{1}$$

$$A_c = \frac{2M}{(N_{c,f}+\delta_c)B^2E\chi} \tag{2}$$

A_d is area of each diagonal; A_c is area of each column; V is shear force; M is moment; E is modulus of elasticity of steel; θ is angle of diagonal member; γ is transverse shear strain; χ is curvature; $N_{c,f}$ is number of columns on each flange frame; δ_c is contribution of web columns for bending rigidity; B is building width in the direction of applied force.

In order to study the structural performances of braced tube systems of various tilted angles comparatively, the member sizes used for the straight tower are also used for the tilted towers for preliminary designs. The final design will obviously necessitate deferent sizes for each case to a certain degree. Some necessary adjustments are still made for the interior gravity column sizes because the tributary areas in the tilted zones change due to tilting the tower at different angles. However, the influence of the interior gravity columns on the tower's lateral stiffness is negligible.

Fig. 8 and Table 1 summarize the maximum lateral displacements of the tilted braced tubes in the direction parallel to the direction of tilting, when the wind load is applied also in the same direction. 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 angle between 0 and 13 degrees. However,

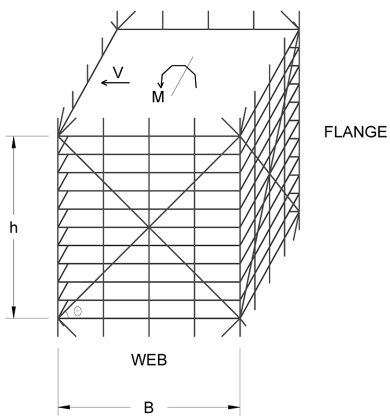

Figure 7. 10-story braced tube module.

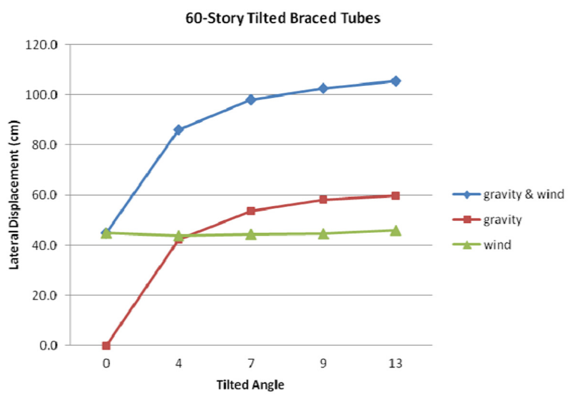

Figure 8. Maximum lateral displacements of the tilted braced tube structures shown in Fig. 5.

Table 1. Maximum lateral displacements of the tilted braced tube structures

	Tilted Angle (degrees)	Gravity-Induced Max. Lateral Displacement (cm)	Wind-Induced Max. Lateral Displacement (cm)	Combined Max. Lateral Displacement (cm)
Straight	0	0.0	44.9	44.9
0 Fl Offset	4	42.2	43.8	86.0
12 Fl Offset	7	53.7	44.4	98.1
16 Fl Offset	9	58.1	44.5	102.6
20 Fl Offset	13	59.7	45.9	105.6

initial lateral displacements of the tilted braced tubes 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 increases. The combined maximum lateral displacement of the braced tube is increased from 44.9 cm of Case 1.1 to 105.6 cm of Case 1.5. It should be noted, however, that gravity-induced lateral displacements of tilted tall buildings can be managed substantially during construction if planned carefully.

4. Tilted Diagrids

With their structural efficiency and powerful expression, diagrid structures have widely been used for recent tall buildings, such as the 30 St. Mary Axe in London, Hearst Tower in New York and Guangzhou International Financial Center in Guangzhou. This section investigates structural performance of diagrids employed for tilted tall buildings. The 60-story buildings are now designed with the diagrid structural system. Fig. 9 shows the straight diagrid structure and its four different tilted versions. The important dimensions and tilted angles of the diagrid structures are the same as those of the braced tube structures studied in the previous section. Design conditions including applied loads are also the same as before. The major difference is that the perimeter braced tubes studied in the previous section are replaced with diagrids.

The preliminary structural design is performed first for the straight diagrids shown in Case 2.1 of Fig. 9, based on the stiffness-based design methodology developed by Moon et al. (2007). A diagrid structure is modeled as a cantilever beam, and subdivided longitudinally into modules according to the repetitive diagonal pattern. Each module is defined by a single level of diagonals that extend over multiple stories. Fig. 10 illustrates an 8-story diagrid module. Member sizes for the diagrid modules can be computed based on the required lateral stiffness using Eqs. (3) and (4) (Moon et al., 2007).

$$A_{d,w} = \frac{VL_d}{2N_{d,w}Eh\gamma\cos^2\theta} \tag{3}$$

$$A_{d,f} = \frac{2ML_d}{(N_{d,f}+\delta_d)B^2E\chi h\sin^2\theta} \tag{4}$$

$A_{d,w}$ is area of each diagonal on the web; $A_{d,f}$ is area of each diagonal on the flange; V is shear force; M is moment; E is modulus of elasticity of steel; θ is angle of diagonal member; γ is transverse shear strain; χ is curvature; B is building width; L_d is length of diagonal; $N_{d,w}$

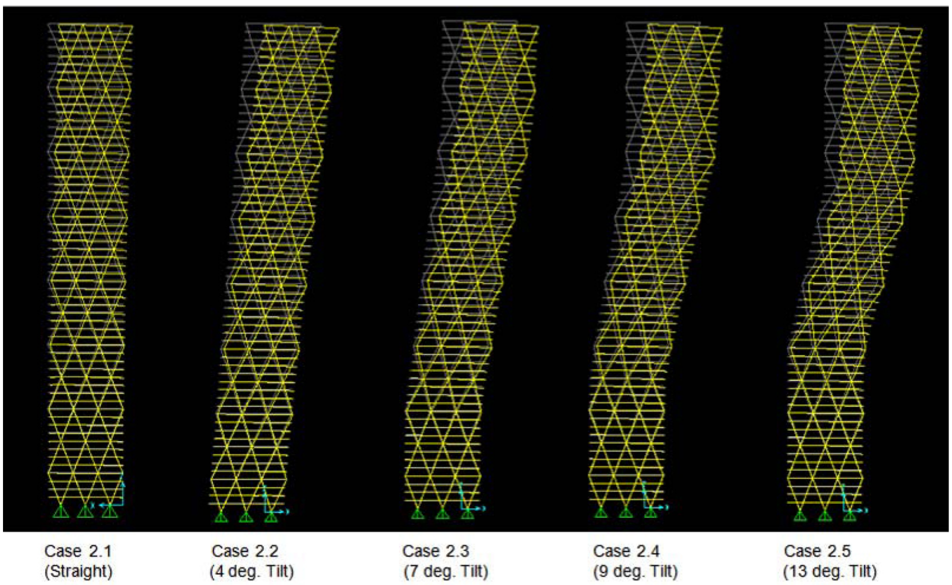

Figure 9. 60-story tilted diagrid structures of various tilted angles (elevation view).

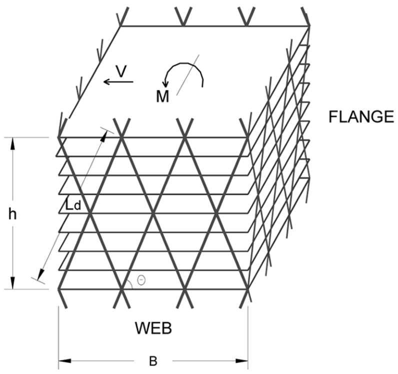

Figure 10. An 8-story diagrid module.

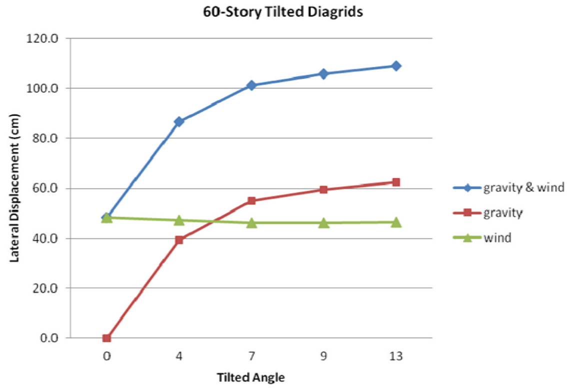

Figure 11. Maximum lateral displacements of the tilted diagrid structures shown in Fig. 9.

is number of diagonals on each web plane; N_{df} is number of diagonals on each flange plane; δ_d is contribution of web diagonals for bending rigidity.

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. 11 and Table 2 summarize 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. The performance of the diagrids is very similar to that of the braced tubes previously studied. 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 increases.

5. Tilted Outrigger Structures

Outrigger structures are another prevalently used structural system for today's tall buildings. Notable examples include the Jin Mao Building in Shanghai, Taipei 101 in Taipei, International Commerce Center in Hong Kong to name a few. The 60-story tilted buildings are now designed with the outrigger system. Fig. 12 shows the straight outrigger structure and its four different tilted versions. The important dimensions and tilted angles of the outrigger structures are the same as those of the braced tube or diagrid structures studied in the previous sections. Other design conditions, including the applied wind loads, are also the same as before. The major differences are that the primary lateral load resisting system is changed to the outrigger system. Consequently, lateral load resisting braced frames are employed for the core structures of the outrigger systems, instead of the gravity core structures without bracings, employed for the previously studied braced tubes and diagrids. For the straight outrigger tower shown in Case 3.1 of Fig. 12, the outrigger trusses, which connect the braced core and perimeter mega-columns, are placed at a third and two-thirds heights of the building. The locations of the outrigger trusses are adjusted for enhanced constructability depending on the offset locations of different cases as can be seen in Fig. 12.

Structural design is performed for Case 3.1 first to satisfy the maximum lateral displacement requirement of a five hundredth of the building height. Based on preliminary studies on the optimal lateral stiffness distribution between the braced core and perimeter mega-columns, 40% of the required bending stiffness is provided by the braced core and the rest by the mega-columns, connected to the braced core through the outrigger trusses. The steel braced core is designed based on Eqs. (1) and (2) presented earlier. The member sizes for the braced core and mega-columns of the straight outrigger structure are also used for the tilted outrigger structures, for preliminary designs. The outrigger truss member sizes are adjusted according to the length of the trusses. Overall, similar

Table 2. Maximum lateral displacements of the tilted diagrid structures

	Tilted Angle (degrees)	Gravity-Induced Max. Lateral Displacement (cm)	Wind-Induced Max. Lateral Displacement (cm)	Combined Max. Lateral Displacement (cm)
Straight	0	0.0	48.3	48.3
0 Fl Offset	4	39.3	47.4	86.7
12 Fl Offset	7	55.1	46.2	101.3
16 Fl Offset	9	59.4	46.3	105.7
20 Fl Offset	13	62.5	46.5	109.0

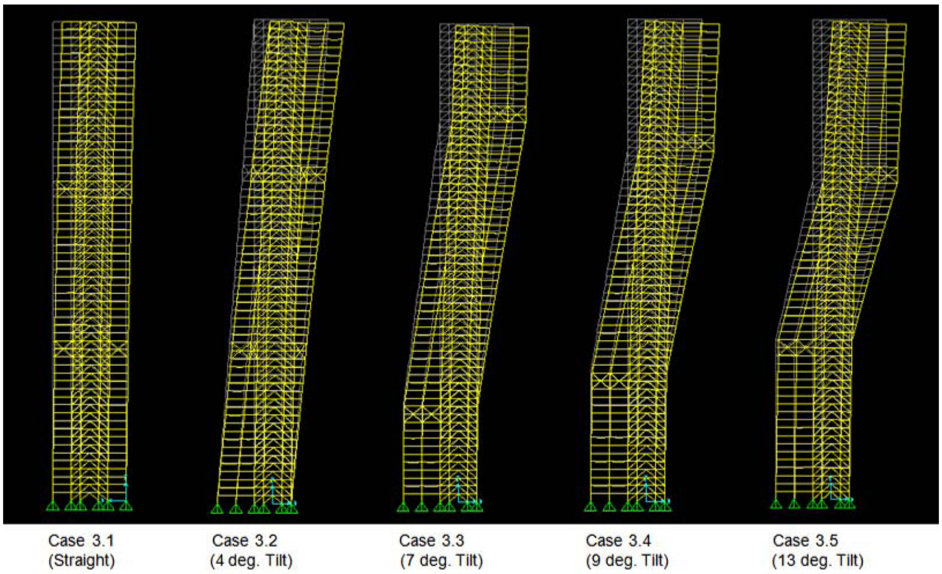

Figure 12. 60-story tilted outrigger structures of various tilted angles (section view).

amount of structural materials are used for the five cases studied.

Fig. 13 and Table 3 summarize the maximum lateral displacements of the tilted outrigger structures in the direction parallel to the direction of tilting, when the wind load is also applied in the same direction. The performance of the tilted outrigger structures is different from that of the tilted braced tubes or diagrids. Lateral stiffness of the tilted outrigger structures against wind loads is greater than that of the straight outrigger structure. The tilted outrigger structures configured as shown in Fig. 12 carry lateral loads more effectively because tilting the tower results in triangulation of the major structural components - the braced core, mega-columns and outrigger trusses. As the angle of tilting increases from 0 to 13 degrees, the geometry of the triangles, formed by the major structural components, becomes more effective to resist the wind load, and, consequently, the wind-induced maximum lateral displacement of the outrigger structure decreases. Fig. 14 shows wind-induced lateral displacements of Cases 3.1, 3.2 and 3.5.

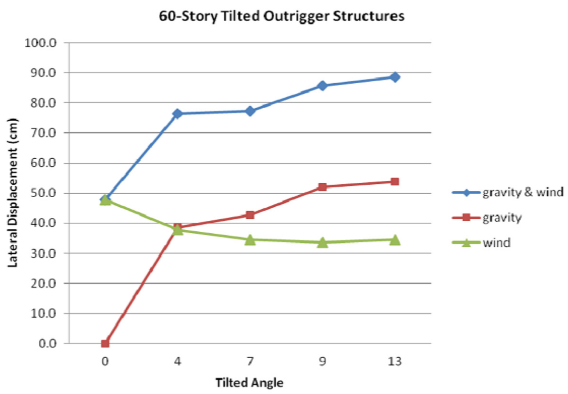

Figure 13. Maximum lateral displacements of the tilted outrigger structures shown in Fig. 12.

As in the cases with the braced tubes or diagrids, the tilted outrigger structures are also substantially deformed initially due to dead and live loads. This gravity-induced lateral deformation increases as the angle of tilting increases. However, gravity-induced lateral displacements of tilted outrigger structures are smaller than those of the tilted braced tubes or diagrids, again, due to the triangulation of the major structural components. Because of the increased lateral stiffness against wind loads and relatively small gravity-induced deformation, the total lateral displacements of the tilted outrigger structures are smaller than those of the tilted braced tubes or diagrids. The maximum lateral displacements of the braced tube,

Table 3. Maximum lateral displacements of the tilted outrigger structures

	Tilted Angle (degrees)	Gravity-Induced Max. Lateral Displacement (cm)	Wind-Induced Max. Lateral Displacement (cm)	Combined Max. Lateral Displacement (cm)
Straight	0	0.0	47.8	47.8
0 Fl Offset	4	38.6	37.9	76.5
12 Fl Offset	7	42.7	34.6	77.3
16 Fl Offset	9	52.0	33.6	85.6
20 Fl Offset	13	53.9	34.6	88.5

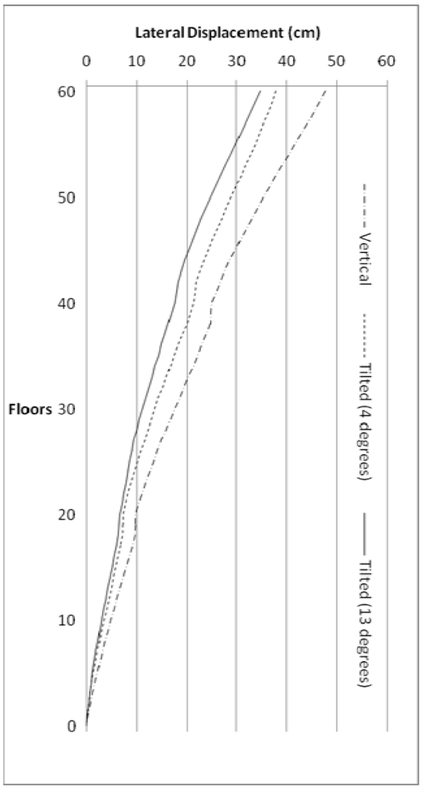

Figure 14. Wind-induced lateral displacements of Cases 3.1, 3.2 and 3.5 shown in Fig. 12.

diagrid and outrigger structures due to the combined gravity and wind loads are 105.6, 109.0 and 88.5 cm respectively, with a tilted angle of 13 degrees.

6. Comparison between the Systems

The performance of a tilted tall building is dependent upon its structural system and angle of tilting. Fig. 15 summarizes wind-induced maximum lateral displacements of the tilted braced tubes, diagrids and outrigger structures shown in Figs. 5, 9 and 12, respectively, when the wind load is applied in the direction of tilting. The lateral stiffness of the braced tube and diagrid systems is not substantially influenced by the angle of tilting between 0 and 13 degrees studied here. The lateral stiffness of the outrigger system is increased by tilting the tower due to the triangulation of the major structural components - the braced core, mega-columns and outrigger trusses. Fig. 16 summarizes gravity-induced maximum lateral displacements of the tilted braced tubes, diagrids and outrigger structures. While gravity-induced lateral displacements increase as the angle of tilting increases in all the three structural systems, the gravity-induced displacements of the outrigger structures are relatively small because of the triangulation of the major structural components. Fig. 17 summarizes the total maximum lateral displacements of the tilted braced tubes, diagrids and outrigger structures.

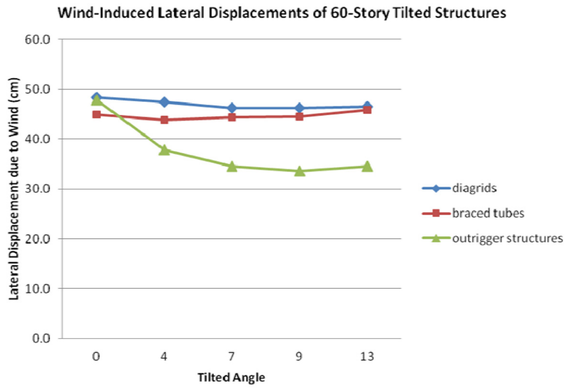

Figure 15. Wind-induced maximum lateral displacements of the tilted braced tubes, diagrids and outrigger structures shown in Figs. 5, 9 and 12.

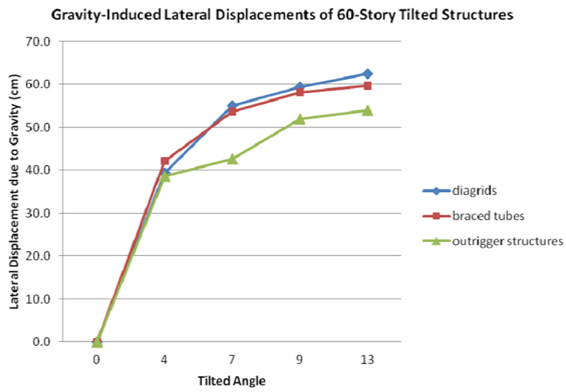

Figure 16. Gravity-induced maximum lateral displacements of the tilted braced tubes, diagrids and outrigger structures shown in Figs. 5, 9 and 12.

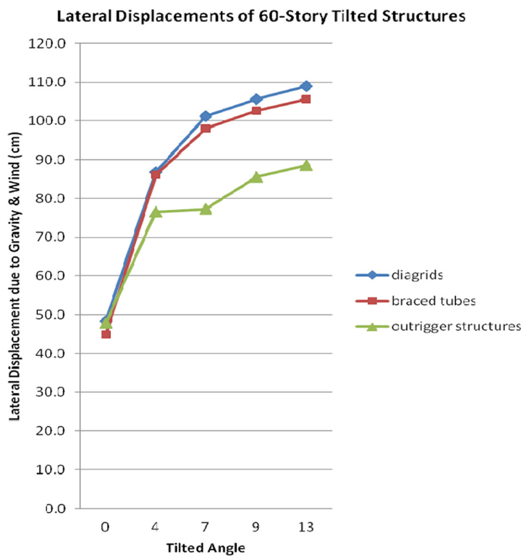

Figure 17. Total maximum lateral displacements of the tilted braced tubes, diagrids and outrigger structures shown in Figs. 5, 9 and 12.

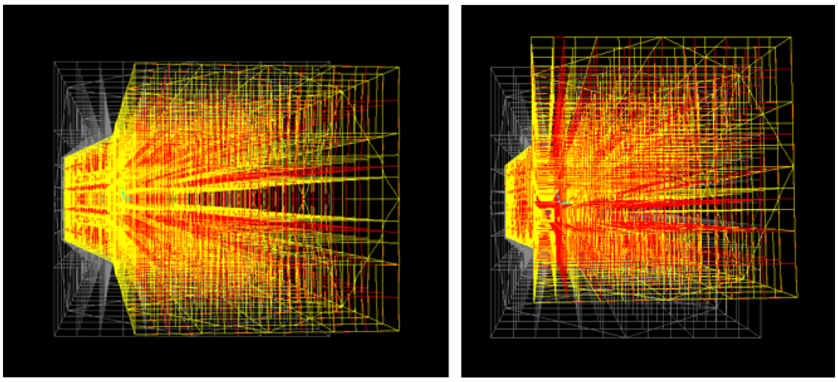

Figure 18. Deformed shapes of the 60-story tilted braced tube of Case 1.5 seen from above with wind in the direction parallel to the direction of tilting (left) and in the direction perpendicular to the direction of tilting (right).

The studies presented thus far have been about tilted tall buildings subjected to wind loads applied in 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 increases, the rate of twisting also increases. The right image of Fig. 18 shows the deformed shape, seen from above, of the 60-story braced tube of Case 1.5 subjected to the code-defined wind load in the direction perpendicular to the direction of tilting. In this case, the tower's maximum lateral displacement of the upper left corner is 49.3 cm, while that of the upper right corner is 51.4 cm at the top due to the twisting action. The maximum twisted angle is 0.03 degrees at the top in this case. As a comparison, the left image of Fig. 18 shows the deformed shape with no twisting action of the same structure subjected to the wind load in the direction of tilting. The maximum twisted angle of the tilted diagrid structure of Case 2.5 is 0.02 degrees, which is similar to the twisted angle of the braced tube. The maximum twisted angle of the tilted outrigger structure of Case 3.5 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.

7. Strength Consideration for Tilted Tall Buildings

Structural design of tall buildings is generally governed by lateral stiffness rather than strength. This study thus far has focused on the lateral stiffness of the structural systems for tilted tall buildings. Tilted towers are subjected to much larger localized stresses than conventional ver-

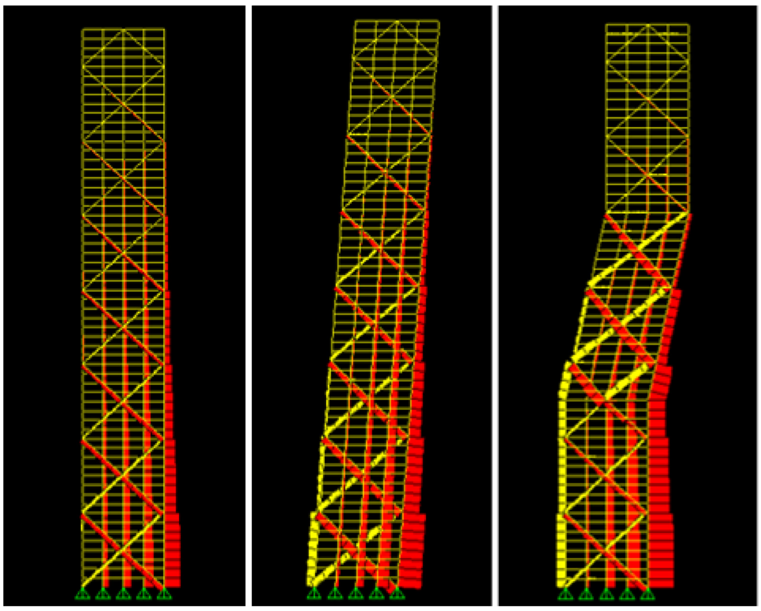

Figure 19. Axial member forces of the tilted braced tubes subjected to dead, live and wind loads.

tical towers. As examples, Fig. 19 shows axial member forces of the vertical and two tilted braced tube structures (Cases 1.1, 1.2 and 1.5 of Fig. 5) subjected to combined dead, live and wind loads. Much larger compressive and tensile member forces are developed in the tilted braced tubes than in the straight braced tube.

Tensile forces developed in tall buildings due to wind loads are often cancelled by compressive forces caused by dead and live loads (Smith and Coull, 1991; Taranath, 1998). In the tilted braced tubes studied here, however, substantial tensile forces are developed in perimeter columns and bracings due to the eccentricity. More careful studies are required for the design and construction of the connections of these members.

8. Conclusions

This paper presented lateral stiffness-based structural performance of contemporary structural systems employed for tilted tall buildings. The lateral stiffness of a tilted tower is dependent upon the structural system and angle of tilting. Compared to the perimeter tube type structures, such as braced tubes and diagrids, the outrigger system provides greater lateral stiffness when used 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. Torsional stiffness is greater in the perimeter tube type structures than in the outrigger structures. Thus, the tube type tilted structures are less twisted against wind loads applied in the direction perpendicular to the direction of tilting.

Tilted towers are significantly deformed due to dead and live loads. These gravity-induced deformations can be managed substantially through careful construction planning. As the angle of tilting increases, very large localized stresses are developed in tilted tall buildings due to the eccentricity. 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.

Many studies have been carried out for tall buildings of conventional forms. However, complex-shaped tall buildings, the structural behavior and design of which are more complicated, have not been much investigated. This paper presented comparative evaluation of structural systems for tilted tall buildings based on static analysis. Further research, such as studying on bi-axially tilted towers and dynamic analysis of tilted towers with various angles of tilt, is required to more comprehensively understand the structural behavior of tilted tall buildings. With prevalent emergence of complex-shaped tall buildings, including tilted towers, in the major cities throughout the world, more rigorous research is necessary to construct higher quality built environments.

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