International Journal of Civil and Structural Engineering – IJCSE 2018
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Volume 5 : Issue 1- [ISSN : 2372-3971] - Publication Date: 25 June, 2018

Outrigger Structural Systems for Tilted Tall Buildings

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***Abstract*— Structural design of tall buildings is generally governed by lateral stiffness. Outrigger structural systems, which produce lateral stiffness very effectively, are one of the most prevalently used structural systems for today's tall buildings. With abundant emergence of complex -shaped tall buildings, when the system is employed for twisted or freeform tall buildings, its lateral stiffness is typically reduced compared with the cases when they are used for prismatic tall buildings. However, when the system is employed for tilted tall buildings, its lateral stiffness is increased. This paper studies lateral performance of outrigger structures employed for tilted tall buildings. Parametric structural models are generated using appropriate computer programs for this study, and the models are exported to structural engineering software for design and analyses of tilted outrigger structures of various tilted angles.**

***Keywords*— tilted tall buildings, lateral stiffness, outrigger structures, parametric modeling**

I. Introduction

With its inherent structural efficiency, the outrigger structural system is among the most widely used structural systems for today's tall buildings. The system was first employed for tall buildings in 1960s. Compared with various tubular structures, which were also developed at the similar time, outrigger structures provide greater flexibility in façade design. While some of the tubular structures, such as framed tubes, are rarely used these days, the use of outrigger structures in tall buildings has recently been increasing continuously.

Outrigger structures were used mostly for prismatic tall buildings which were predominant especially in 1960 and 1970s. Today, however, with prevalent emergence of complex-shaped tall buildings, outrigger systems are often employed for the structural design of complex-shaped tall buildings such as twisted, tilted and freeform tall buildings. For example, the twisted Chicago Spire project by Santiago Calatrava in Chicago and tilted Signature Tower project by the late Zaha Hadid in Dubai employed outrigger structures for their primary lateral load resisting systems.

Structural design of tall buildings is generally governed by lateral stiffness. The outrigger system's lateral load carrying mechanism is conceptually explained in Figure 1. The overturning moment (M_o) caused by wind loads (W) is reduced due to the counteracting moment (M_c) provided by the mega-columns connected to the building core through the outrigger trusses. The counteracting moment can be expressed as

$$M_c = 2b^2 AE\chi$$

A is sectional area of mega-columns; E is modulus of elasticity of steel, assuming steel is used; χ is curvature. Since the modulus of elasticity of steel is almost constant regardless of its strength, the outrigger's bending rigidity is a function of the square of the building width and sectional area of the mega-columns.

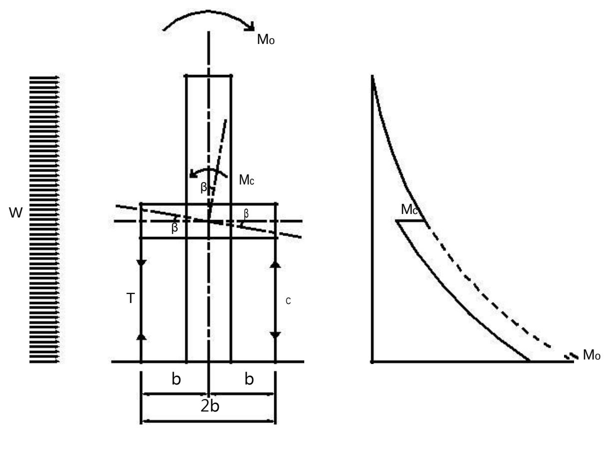

Figure 1. Lateral load carrying concept of outrigger system
Gravity Columns

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When outrigger structures are employed for twisted or freeform tall buildings, their lateral stiffness is reduced because the counteracting moments produced by the outrigger system tend to be reduced in tall buildings of these forms. If the system's mega-columns are located at the building's extreme perimeter in twisted or freeform tall buildings, they cannot be vertical in order to adjust them to the building forms. Alternatively, if vertical mega-columns are used, they must be located somewhat behind the building perimeter in order to be accommodated within the building forms, and

[illegible]

A considerable amount of research has been carried out by many researchers and engineers about structural performance of outrigger structures employed for conventional prismatic form tall buildings. However, the impact of tilting outrigger structural systems on their lateral stiffness has not been much investigated. This paper studies lateral performance of outrigger systems employed for tilted tall buildings of various angles of tilt.

II. Parametric Modeling and Structural Design of Outrigger Structures

In order to illustrate the concepts underlying the structural behavior of tilted outrigger structures, 60-story towers of various angles of tilt are designed with outrigger structures. Structural steel is used for the design of the structural system in this study, though reinforced concrete or composite structures are also commonly used in real world. Structural performance of the outrigger system depending on various angles of tilt is investigated 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, analyses and comparative studies.

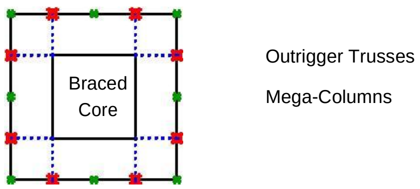

Figure 2. Simplified structural plan of the 60-story building of outrigger structure.

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 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 building's typical plan dimensions are 36 x 36 meters with an 18 x 18 meter braced frame core at the center and typical story heights of 3.9 meters. The outrigger trusses are located at a third and two third heights of the tower to perform most effectively. There are 8 perimeter mega-columns connected to the steel braced core through the outrigger trusses as can be seen in Figure 2. 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 core structure and the rest by the mega-columns, connected to the core through the outrigger trusses.

III. Design Studies of Tilted Outrigger Structures

The 60-story outrigger structure is now tilted with various angles of tilt. Figure 3 shows the straight outrigger structure first and its four different tilted versions. The second case is a tilted case with no floor offset. While the 18 x 18 meter braced core is maintained vertical within the tilted building mass, the building is tilted to its maximum angle of 4 degrees. The third, fourth and fifth cases are tilted outrigger 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. In these cases, the 18 x 18 meter gravity cores are still maintained vertical within the tilted building mass.

For the straight outrigger tower shown in the first structure, the outrigger trusses, which connect the braced core and perimeter mega-columns, are placed at a third and two third heights of the building. The locations of the outrigger trusses are somewhat adjusted for enhanced constructability depending on the offset locations of different cases depending on different angles of tilt. The member sizes for the braced core and mega-columns of the straight outrigger structure determined using the code defined wind loads are also used for the tilted outrigger structures for preliminary designs though the outrigger truss member sizes are adjusted according to the length of the trusses. Overall, similar amount of structural materials are used for the five cases studied.

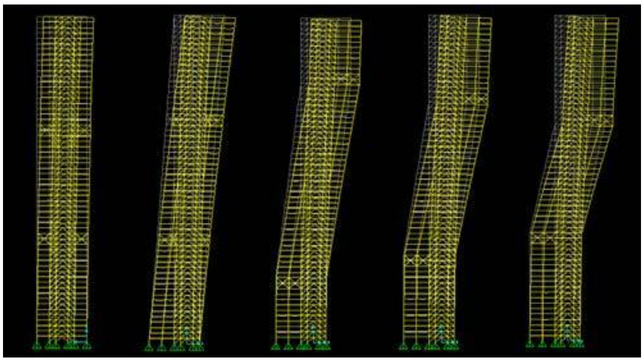

Figure 3. 60-story tilted outrigger structures of various tilted angles (section view

Figure 4 summarizes 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 tilted outrigger structures are substantially deformed initially due to dead and live loads. This gravity- induced lateral deformation is increased as the angle of tilt is increased. However, gravity-induce lateral deformations of tilted tall buildings can substantially be managed during construction if planned and executed carefully.

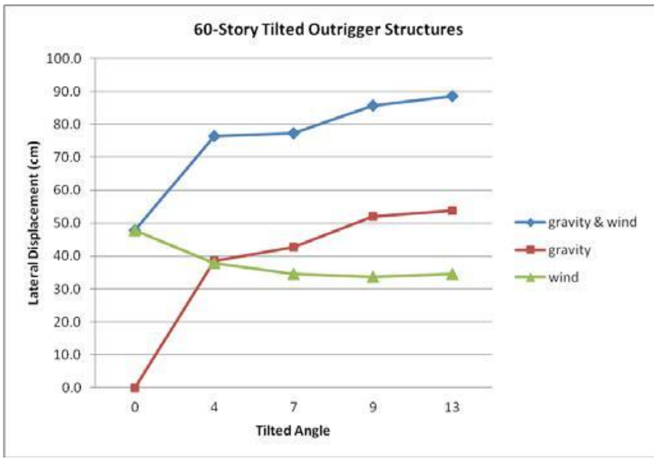

Figure 4. Maximum lateral displacements of the tilted outrigger structures shown in Figure 3.

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 Figure 3 carry lateral loads more effectively because tilting the tower results in triangulation of the major structural components – the vertical braced frame core, slanted mega -columns and horizontal outrigger trusses. As the angle of tilt is increased from 0 to 13 degrees, the geometry of the triangles, formed by the major structural components, becomes more effective to resist wind loads, and, consequently, the wind-induced maximum lateral displacement of the outrigger structure is decreased.

IV. Conclusion

This paper presented lateral stiffness-based structural performance of the outrigger system employed for tilted tall buildings. The outrigger system provides greater lateral stiffness when used for tilted towers because of the triangulation of the major structural components – the core, outrigger trusses and mega-columns – caused by tilting the tower. As the angle of tilt is increased, the lateral stiffness of the system is increased and consequently the lateral displacement is decreased. However, as the tilted angle is increased, the gravity-induced lateral deformation is also increased. Gravity-induce lateral deformations of tilted tall buildings can substantially be managed during construction if planned and executed carefully. Further research, such as dynamic analyses of tilted towers are required to more comprehensively understand their structural behavior. With prevalent emergence of complex-shaped tall buildings, including tilted towers, more rigorous research is necessary to construct higher quality built environments.

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