Title: **Study on Structural Efficiency of Supertall Buildings**

Authors: Jianlong Zhou, ECADI
Lianjin Bao, ECADI
Peng Qian, ECADI

Subject: Structural Engineering

Keywords: Outriggers
Structural Engineering
Supertall

Publication Date: 2014

Original Publication: International Journal of High-Rise Buildings Volume 3 Number 3

Paper Type:
1. Book chapter/Part chapter
2. **Journal paper**
3. Conference proceeding
4. Unpublished conference paper
5. Magazine article
6. Unpublished

International Journal of High-Rise Buildings
September 2014, Vol 3, No 3, 185-190

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

Study on Structural Efficiency of Super-Tall Buildings

Zhou Jianlong†, Bao Lianjin, and Qian Peng

East China Architectural Design & Research Institute Co., Ltd, No.151 Hankou Road, 200002, Shanghai, China

Abstract

Based on a 405m high super-tall building, the influence of outriggers, different shapes and layouts of structural plane and elevation on structural efficiency under lateral forces is studied in this paper. A calculation formula concerning the structural efficiency is given. The study shows that structural efficiency can be improved by triangulating the plane shape, using mega columns, the peripherization of the plane layout, tapering the elevation shape and setting bracing structure in the elevation. The arrangement of outriggers between the core tube and flange frame can reduce the shear lag effect in order to improve structural efficiency. The essence of improving structural efficiency of super-tall buildings is to maximize the plane bending stiffness and to make its deformation approach to plane section assumption.

Keywords: Super-tall buildings, Structural efficiency, Shape, Layout, Outriggers

1. Introduction

In recent years, along with the development of the global economy, the number of high-rise building construction is increasing. According to elementary estimation, as for China, the total number of high-rise buildings under construction (above the height at 500 feet or 152 m), is more than 200. And in the next five years, it will be more than 800, which is four times of the total amount of U.S. skyscrapers now (Wang et al., 2012).

Because of the buildings height, long construction period and the huge investment, the cost of structure accounts for about a quarter of the total cost of construction. Therefore, reducing the cost of structure and improving the structural efficiency become an important topic in the design of super-tall buildings. So, this article is based on a super-tall structure with 90 stories, of which the height is 405 m, the aspect ratio is 7.5, and the story height is 4.5 m. This article studies the structural efficiency of six different peripheral lateral resisting systems with the same height, aspect ratio, core tube, floor layout under wind loads. The sizes of the structure and the core tube are squares of $54\ \mathrm{m} \times 54\ \mathrm{m}$ and $27\ \mathrm{m} \times 27\ \mathrm{m}$ respectively.

The six peripheral lateral resisting systems are: moment frame, mega frame, mega bracing tube, frame tube, diagonal grid tube and entity tube. These six systems have the same projection area of the vertical members and the bracing systems in the plan. In addition, there are belt trusses every 15 layers in the first three structural systems. The plans and elevations of 6 different systems are shown in Fig. 1.

The study on outer structures can be divided into three steps: the floor plan, 2-D system and 3-D system. Therefore, in this paper the intent of studying structural efficiency is: starting with floor planes, and then studying the

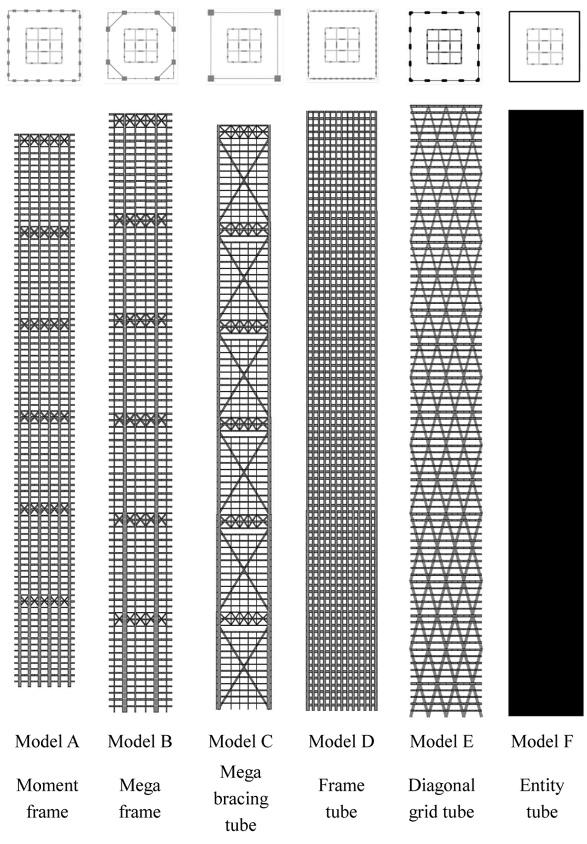

Figure 1. The plans and elevations of different systems.

†Corresponding author: Zhou Jianlong
Tel: +86-216-321-7420; Fax: +86-216-321-5908
E-mail: jianlong_zhou@ecadi.com

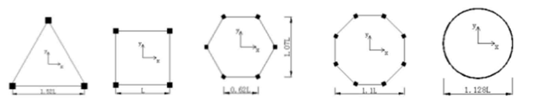

Figure 2. Floor plan of different shapes.

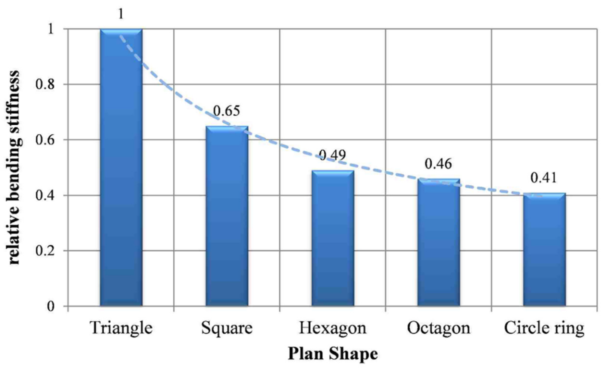

Figure 3. Relative bending stiffness of different plane shapes.

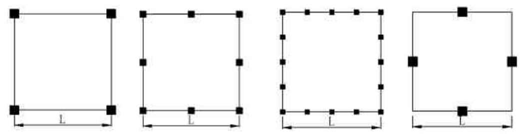

Figure 4. The floor plan of different layouts.

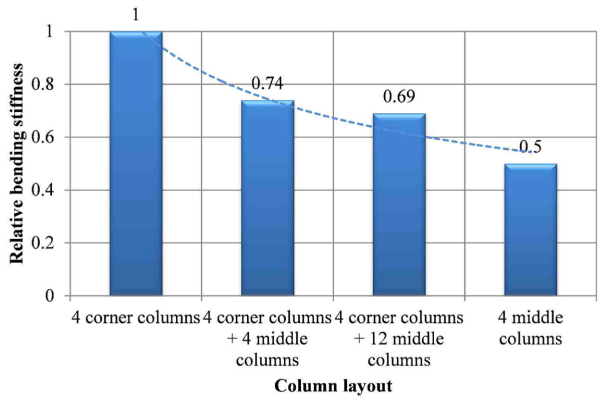

Figure 5. Relative bending stiffness of different layout.

elevations, and finally considering the impact of spatial action and outriggers on the structural efficiency. Besides, the definition structural efficiency of 3D structures and the comparison on the structural efficiency in different systems is given.

2. Study on Plane Structural Efficiency

2.1. Effects of plane shape

Five kinds of common regular polygon are studied to examine the influence of different floor plan shapes on bending stiffness and shear stiffness. With equal plan area and section area of vertical members, the vertical members are arranged uniformly in each of the polygon corners, as shown in Fig. 2.

With equal section areas of the vertical members and same material, each plane will have the same shear stiffness GA, and different bending stiffness EI. All of planes are assumed to meet the plane section assumption; the bending stiffness EI of the triangle is maximum. With the number of edges increasing, the bending stiffness will reduce correspondingly. When the number of edges tends to infinity, just as the ring plane, the plane bending stiffness will be to minimum. Assuming the bending stiffness of triangle plane is 1.0, the relative bending stiffness of the other plane can be calculated, as shown in Fig. 3.

The influence coefficient of plane shapes α_S can be defined: as the total area of vertical members are equal, and they are uniformly arranged in each polygon corners, the ratio of I (the bending stiffness) to I_{tri} (the bending stiffness of equilateral triangle plane which has the same area), can be expressed as:

$$\alpha_S = \frac{I}{I_{tri}} \tag{1}$$

Among them, I is the moment of inertia of a plane polygon. I_{tri} is the moment of inertia of an equilateral triangle, which has the same area. According to this definition, the plane shape influence coefficients of each polygon can be calculated respectively: 1.0, 0.65, 0.49, 0.46 and 0.41.

2.2. Effects of plane layout

The effects of different layout of vertical members on bending stiffness and shear stiffness are studied, with the same plan shape, area and the total area of vertical members. Assuming the plane shape is a square, the different layout of the vertical members for 4 models are shown in Fig. 4.

As the previous section, with the same shear stiffness, and different bending stiffness EI, EI of model (a) is supposed to be 1.0, and then the relative bending stiffness of the other planes can be calculated as shown in Fig. 4:

Fig. 5 shows that, as vertical members are arranged in four corners of the square, the bending stiffness reaches to the maximum. On the contrary, if they are arranged in two neutral axis, the bending stiffness will be the minimum, only 50% of the maximum. The bending stiffness of section is proportional to square of the distance between vertical members and the neutral axis.

Similarly, the influence coefficient of plane layout can be defined:

the ratio of I (the bending stiffness) to I_{cor} (the bending stiffness which has same total area of vertical members, same plane shape and the columns arranged on the corners of plane), can be expressed as:

$$\alpha_L = \frac{I}{I_{cor}} \tag{2}$$

Among them, I is the moment of inertia of plane. I_{cor} is the moment of inertia of plane, with the same total area of columns, plane shape and arrangement of the columns focus in all corners of plane. According to this definition, the influence coefficients of plane layout for each layout in Fig. 4 can be calculated respectively: 1.0, 0.74, 0.69 and 0.5.

2.3. Coefficient of structural plane efficiency

According to the above analysis, the effect of the shape and arrangement of plane on the lateral stiffness is mainly related to the bending stiffness. The coefficient of structural plane efficiency α_M can be defined as:

$$\alpha_M = \alpha_S \cdot \alpha_D \tag{3}$$

Therefore, the coefficient of structural plane efficiency α_M of six of peripheral lateral resisting systems is listed as follows:

3. Study on Elevation Structural Efficiency

Under the lateral load, the structural lateral displacement results from three forms of deformations: the overall structural bending deformation; local bending deformation of components; shear deformation (racking). Fazlur Khan considered optimal structural efficiency in a tall tubular building as the lateral displacement of the building due to axial column shortening only. Bending and shear deformation of frame elements only reduces the structural efficiency leading to higher material quantities and therefore costs (Mark et al. 2006).

As the proportion of lateral displacement produced by structure overall bending deformation grows with the increase of aspect ratio of structure, the structural efficiency can be expressed by the specific value of the ratio of the proportion of lateral displacement produced by structure overall bending deformation of the other structural system to the reference value which is the proportion of lateral displacement produced by structure overall bending deformation of the entity tube with the same aspect ratio.

Table 1 Coefficient of dilatation of lateral resisting stiffness efficiency α_M of six kinds of peripheral lateral resisting systems (Referring to Fig. 1)

Model	Model A	Model B	Model C	Model D	Model E	Model F
α_S	0.65	0.65	0.65	0.65	0.65	0.65
α_D	0.73	0.69	1.00	0.76	0.76	0.74
α_M	0.475	0.449	0.650	0.494	0.494	0.481

3.1. Effects of elevation shape

This section will focus on the relation between the lateral stiffness and elevation shapes. The overall displacement is studied on different shapes of structural elevation under the same wind load and with the same elevation area and structure height. The models are shown in Fig. 6.

According to the above analysis, the overall displacement is minimum with the triangle elevation, while maximum with the inverted trapezoid. Thus, the relation between β_S (the influence coefficient of elevation shapes) and the specific ratio of D (the lateral stiffness of different elevation shapes) to D_{tri} (the lateral stiffness of triangle elevation) can be expressed as:

$$\beta_S = \frac{D}{D_{tri}} \tag{4}$$

Fig. 7 shows the influence coefficient of different elevation shapes, β_S decreasing from 1 to 0.29 with the ratio of the trapezoid's upper line to the lower line increasing from 0 to 2.

3.2. Effects of elevation layout

This section mainly focuses on the different structural systems' influence on the structural efficiency with same elevation shape. In order to calculate the displacement caused by the overall structural bending deformation, we

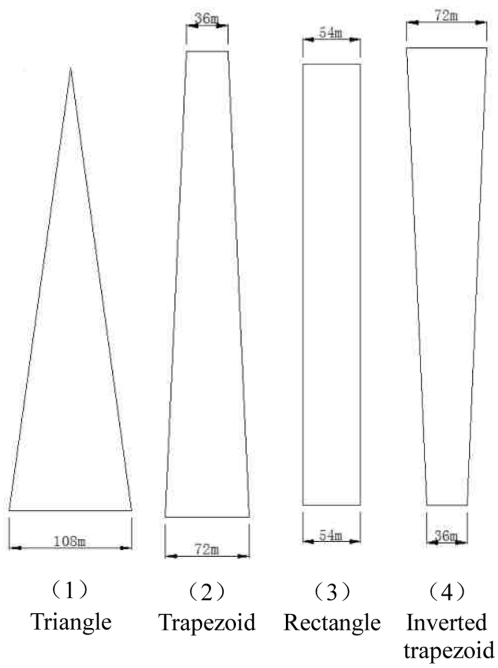

Figure 6. Model of different elevation shapes.

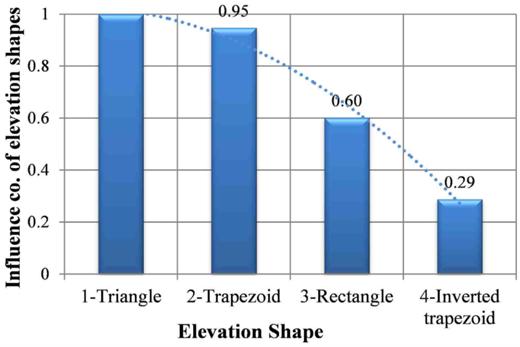

Figure 7. Influence coefficient of elevation shapes.

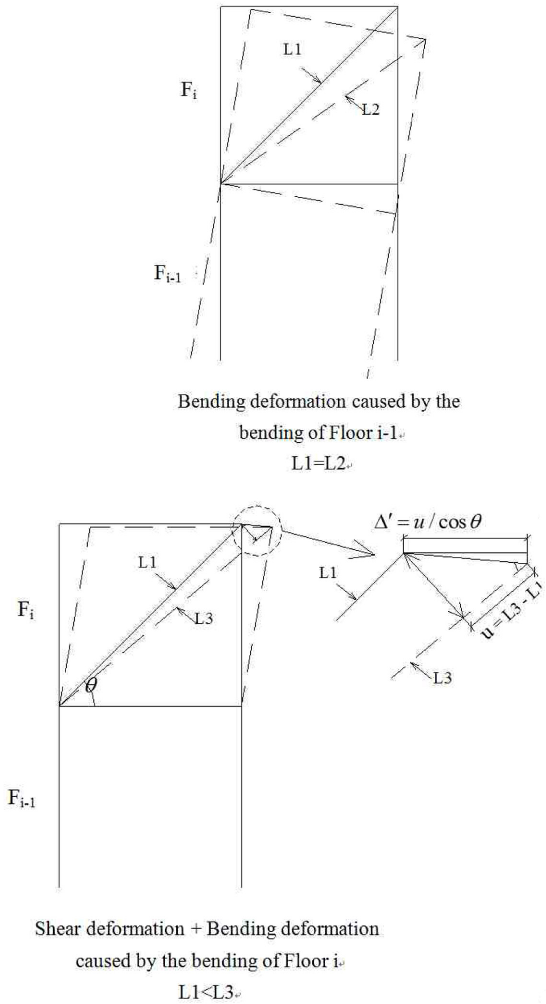

Figure 8. Calculation schematic diagram.

can use L1 referring to the typical bracing, whose stiffness is set as 0, then get its axial displacement u, thus according to the formula $\Delta' = u / \cos\theta$ we can get the lateral displacement (as Fig. 8). Then the lateral displacement value caused by structure overall bending deformation can be calculated by overall displacement minus Δ',

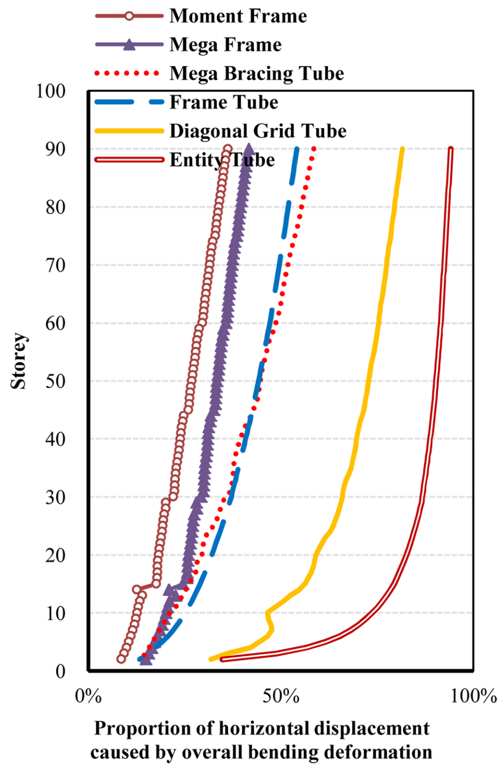

Figure 9. Proportion of horizontal displacement caused by overall bending deformation.

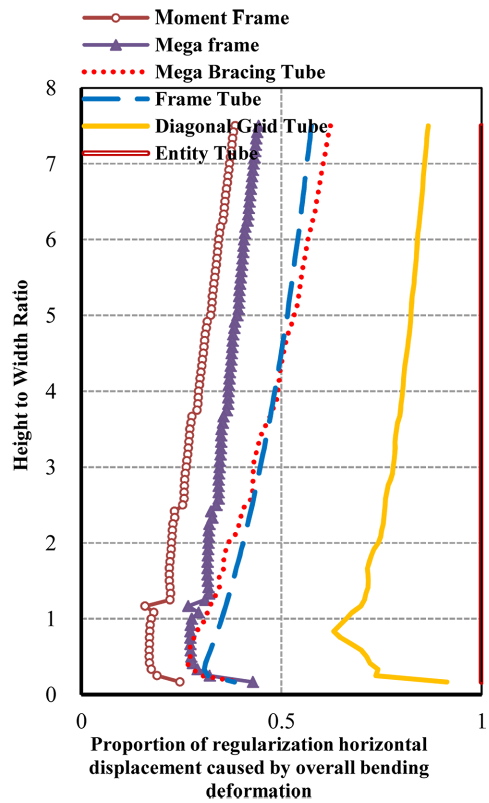

Figure 10. Proportion of regularization horizontal displacement caused by overall bending deformation.

θ referring to the horizontal included angle before the deformation (Jiang, 2014).

With a guarantee of an equal total projection area of vertical components, as for the 6 models shown by Fig. 1, the above method is adopted to respectively calculate the proportion of its horizontal displacement caused by overall structure bending deformation to the overall horizontal displacement. Their ratio curve and regularization curve are shown as Figs. 9 and 10.

As shown by Figs. 9 and 10, the lateral displacement of each story increases with the increase of number of story and the tube gets the maximum value, the diagonal grid tube comes second and the moment frame comes the last. Thus, β_L (the elevation layout's influence on structural efficiency) can be expressed by the specific value of R (proportion of horizontal displacement caused by overall bending deformation of different (other) structural systems) to R_{wall} (proportion of horizontal displacement caused by overall bending deformation of tube system) as follows:

$$\beta_L = \frac{R}{R_{wall}} \tag{5}$$

β_L considers the fit degree between plane deformation and "plane section assumption" and reflects the lateral resistance efficiency of structure materials. Fig. 11 shows different β_L in various systems. We can see that, it's 0.87 for diagonal grid system which is the closest to tube, sequentially followed by mega bracing tube: 0.62, frame tube: 0.58 which is the medium value, and moment frame: 0.39, mega frame: 0.44 which are the minimums. And the result of mega bracing tube fits well with shearing stiffness coefficient mentioned in (Bungale, 1997).

3.3. Coefficient of structural elevation efficiency

With the results from the previous analysis in this paper, a conclusion can be drawn that, the shape and layout of elevation mainly affect the lateral resistance stiffness of super-tall building structure by bending stiffness. So we can define the coefficient of structural elevation efficiency, β_M, as:

$$\beta_M = \beta_S \cdot \beta_L \tag{6}$$

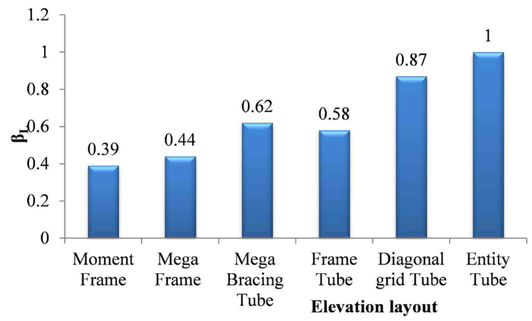

Figure 11. Influence coefficient of elevation layout.

Table 2. Coefficient of lateral resisting stiffness efficiency β_M of six kinds of peripheral lateral resisting systems (referring to Fig. 1)

Model	Model A	Model B	Model C	Model D	Model E	Model F
bS	0.60	0.60	0.60	0.60	0.60	0.60
bL	0.39	0.44	0.62	0.58	0.87	1.00
bM	0.234	0.264	0.372	0.348	0.522	0.60

Therefore, the coefficient of structural elevation efficiency, β_M, for all 6 systems are as follows:

4. Lateral Resistance Efficiency of Structural System

4.1. Outriggers Influence Coefficient

For the first and second structures of the 6 models, due to the shear lag effect, the column of flange frame usually doesn't fully involve in overall bending during the actual force process, which leads to low efficiency (Qian et al., 2013). So we normally set proper number of outrigger in the equipment storey - in the case of 405 m tall building, it's economical to set 3 outriggers. Based on moment frame and mega frame systems, outriggers are set every 30 floors, and there are altogether 3 of them (Fig. 12 shows its section view) for us to study its influence on structural efficiency.

According to Fig. 13, after setting outrigger between the core and flange frame, the elevation of structural efficiency of moment frame and mega column have improve 40%, from 0.39 to 0.44, from 0.55 to 0.62 respectively. So the outrigger influence coefficient, γ_O, can be defined as the

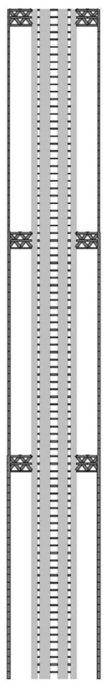

Figure 12. Illustration of outriggers.

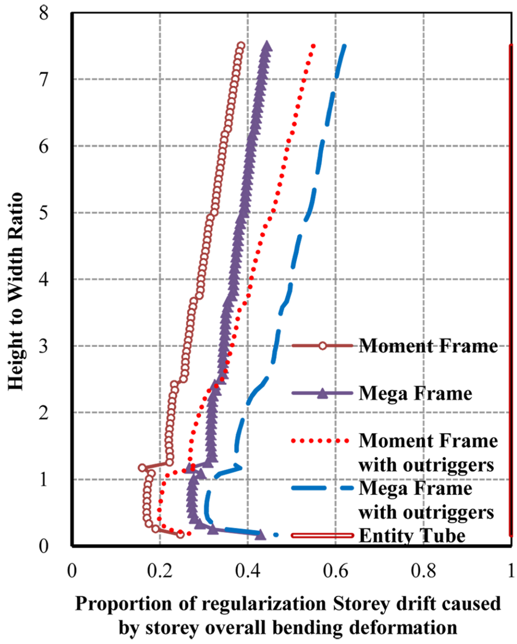

Figure 13. Proportion of regularized horizontal placement.

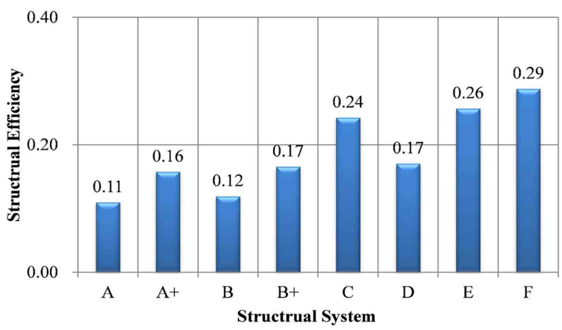

Figure 14. Structural efficiency of each model.

ratio between coefficient of structural elevation efficiency with outrigger, $\beta_{M,O}$, and coefficient of structural elevation efficiency, β_M, without outrigger.

$$\gamma_O = \frac{\beta_{M,O}}{\beta_M} \tag{7}$$

Usually γ_O is greater than 1, and it relates to the bending stiffness of outer tube, the relationship between lateral resistance stiffness of outrigger and axial stiffness of column, and numbers of outriggers and their layout.

According to previous analysis, the structural efficiency, E, can be defined as:

$$E = \gamma_O \cdot \alpha_M \cdot \beta_M = \gamma_O \cdot \alpha_S \cdot \alpha_L \cdot \beta_S \cdot \beta_L \tag{8}$$

So, the lateral resistance efficiency of the 6 structural systems (shown in Fig. 1) can be calculated according to Eq. (8), and result is entity tube (F) > diagonal grid tube

Table 3. Structural efficiency of each peripheral lateral resisting systems (referring to Fig. 1)

Model	A	A+	B	B+	C	D	E	F
α_M	0.47	0.47	0.45	0.45	0.65	0.49	0.49	0.48
β_M	0.234	0.234	0.264	0.264	0.372	0.348	0.522	0.6
γ_O	1.00	1.42	1.00	1.40	1.00	1.00	1.00	1.00
E	0.111	0.158	0.118	0.166	0.242	0.172	0.258	0.289

(E) > mega bracing tube (C) > frame tube (D) > mega frame with outriggers (B+) > moment frame with outriggers (A+) > mega frame (B) > moment frame (A), as Fig. 14:

5. Conclusions

Based on a 405 m high super tall building with an aspect ratio of 7.5 and story height of 4.5 m, with the same height, aspect ratio, core tube, story arrangement and wind load, the effect of different shapes and layouts of structural plane and elevation, outriggers on structural efficiency is studied, and a calculation formula concerning the structural efficiency is defined.

The following conclusions are noted:

- According to the study on plane shape and layout, in order to acquire the maximal lateral resistance in story plan, the plan shape should be triangulated, and the use of mega columns and the peripherization of layout is recommended.
- According to the study on elevation shape and layout, tapering the elevation shape and setting truss structure in the elevation can improve structural efficiency in elevation.
- The arrangement of outriggers between the core and flange frame can reduce the shear lag effect and improve lateral resistance efficiency.
- The essence of improving lateral resistance of super-tall buildings is to maximize the plane flexural stiffness and to make its deformation approach to plan section assumption.

References

Wang, D. S., Zhou, J. L., and Bao, L. J. (2012). “Analysis on the cost of structural construction in super-tall buildings.” *Building Structure*, 42(5), pp. 1~7.

Mark, S., and Neville, M., et al. (2006). “Jin Mao tower’s influence on China’s new innovative tall buildings.” *Shanghai International Seminar of Design and Construction Technologies of Super High-rise Buildings*.

Jiang, Y. (2014). “Allocation of Viscous Damper and Seismic Fragility Analysis Based on Harmful Story Drift.” Dissertation for the Master Degree, Tongji University, 2014.

Bungale, S. T. (1997). “Steel, Concrete and Composite Design of Tall Buildings.” *McGraw-Hill Professional*, 1997.

Qian, J. R., Zhao, Z. Z., and Ye, L. P.(2013). “Design of tall buildings.” *China Architecture & Building Press*, China.