Journal of Zhejiang University SCIENCE A
ISSN 1009-3095 (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Safety analysis of optimal outriggers location in high-rise building structures*

ZHANG Jie†, ZHANG Zhong-xian, ZHAO Wen-guang, ZHU Hong-ping, ZHOU Chun-sheng

(*Department of Civil Engineering and Mechanics, Huazhong University of Science and Technology, Wuhan 430074, China*)

†E-mail: little_knf@sohu.com

Received May 17, 2006; revision accepted Oct. 14, 2006

Abstract: This paper presents the restraining moments of outriggers acting on the core wall and the equation of the horizontal top deflection based on a simplified outrigger model. The deformation compatibility conditions between outriggers and core wall as well as the finite rigidities of outriggers are also considered. One case study was carried out to analyze the horizontal top deflection and the mutation of the restraining moments caused by the variation of outrigger location. The results showed that the method adopted in the paper is simple and reasonable. Some conclusions are valuable to the safety design of high-rise building structures.

Key words: High-rise building, Frame-core structure, Outrigger, Internal force mutation, Horizontal top deflection, Safety

doi:10.1631/jzus.2007.A0264 **Document code:** A **CLC number:** TU973$^+$.19

INTRODUCTION

Outriggers location has direct influence on the efficiency of the horizontal deflection control in high-rise building structures. An appropriate outrigger location will be more efficient in minimizing the horizontal deflection and reducing the restraining moments mutation. As a result, the safety of a structure subjected to lateral load is guaranteed to be better.

Presently, the so-called optimal location of outriggers is derived from the principle of minimum ultimate displacement (Zhao, 1992; Xu and Huang, 1999). However this mode is not suitable for high-rise structures with outriggers. The determination of optimal outrigger location should consider not only the restrict horizontal deflection but also the restraining moments mutation caused by varied outrigger locations. This paper gives emphasis on the analyzing of the relationship between horizontal deflection, restraining moments mutation and outrigger location. The influence of the varied outrigger's rigidities on the horizontal deflection and restraining moments mutation was also studied. Some methods on enhancing the safety design of high-rise building structures were obtained.

PROBLEM STATEMENT

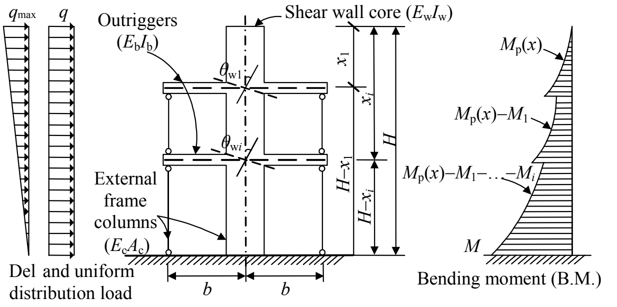
Basic assumptions and calculating sketch

Current researches (Hoenderkamp and Snijder, 2003; Smith and Salim, 1981; Smith and Coull, 1991; Liu, 1997) show that the theoretical analysis of the optimal outrigger location is mature. These analysis methods are based on the following assumptions: (1) The sectional properties of the core, columns, and outriggers are constant throughout their height; (2) The outriggers are hinged to the columns and the columns are hinged to the foundation; (3) The influences of the horizontal members are neglected except the outriggers; (4) The structure is linearly elastic.

The actual rigidities of outriggers are used in the current study, instead of the assumption of infinite rigidity in horizontal direction. Based on the above assumptions the analytical model is developed and shown in Fig.1.

---

* Project supported by the National Natural Science Foundation of China (No. 50378041) and the Specialized Research Fund for the Doctoral Program of Higher Education (No. 20030487016), China



(a) (b)

Fig.1 (a) Multiple-outrigger analytical model diagram; (b) Core resultant moment diagram

Stress analysis and deformation calculation

Suppose $M_p(x)$ is the external moment of the structure subjected to a horizontal load; $\theta(x)$ is defined as the rotation function of the structure; $\delta(x)$ is the horizontal deflection function of the structure; x_1 and x_i are the respective heights of outrigger 1 and i from the top of the core; M_i is the restraining moment of outrigger i acting on the core; T_i is the frame column axial compression (tension) force produced by outrigger i; n is the number of outriggers; θ_{wi} is the angle of rotation of the core at outrigger i subjected to $M_p(x)$. E_w, E_c and E_b represent the elastic modulus of the core wall, frame column attached to the outriggers and outrigger beams respectively. A_c is the sectional area of the frame column attached to the outriggers; b is outrigger's horizontal distance from the centroid of the core. E_wI_w and H are the flexural rigidity of the core wall in horizontal direction and total height of the core respectively. E_cA_c is the axial rigidity of the frame column; E_bI_b is the effective flexural rigidity of the outriggers; θ_b is the outrigger's angle of rotation subjected to column forces, θ_c is the rotation produced by the differential axial deformations of the columns. The following analysis derives the restraining moments of the core and the horizontal top deflection equations.

According to the elastic deformation superposition, we obtain

$$\theta_{w1}=\theta_{c1}+\theta_{b1}, \tag{1}$$

$$\theta_{w1}=\frac{1}{E_wI_w}\int_{x_1}^{H}[M_p(x)-M_1]\mathrm{d}x. \tag{2}$$

Angle of rotation of outriggers subjected to the column forces is

$$\theta_{b1}=M_1b/(6E_bI_b). \tag{3}$$

From equation $M_i=2bT_i$, the rotation of the "inboard" ends of the outrigger caused by the differential axial deformations of the columns is

$$\theta_{c1}=M_1(H-x_1)/(2b^2E_cA_c). \tag{4}$$

Substitute Eqs.(2) and (3) into Eq.(1), to obtain

$$\begin{aligned}M_1\left[\left(\frac{1}{2b^2E_cA_c}+\frac{1}{E_wI_w}\right)(H-x_1)+\frac{b}{6E_bI_b}\right]\\=\frac{1}{E_wI_w}\int_{x_1}^{H}M_p(x)\mathrm{d}x.\end{aligned} \tag{5}$$

Introduce the segmentation line rigidity concept. We suppose $i_{c1}=E_cA_c/(H-x_1)$, $i_{w1}=E_wI_w/(H-x_1)$, $i_{b1}=E_{b1}A_{b1}/(2b)$, and then substitute them into Eq.(5), to obtain the equation

$$M_1=\frac{12b^2i_{c1}i_{b1}}{(b^2i_{c1}i_{w1}+6i_{w1}i_{b1}+12b^2i_{c1}i_{b1})(H-x_1)}\int_{x_1}^{H}M_p(x)\mathrm{d}x. \tag{6}$$

The top displacement of the structure is different from that under uniformly distributed load. Hence, the optimal locations of outriggers are also different. In the current study, the actual lateral loadings are applied to the high-rise structure based on the actual rigidities of outriggers, which approaches more to the actual situation. $M_p(x)$ is the external moment of the action of del distribution load,

$$M_p(x)=q(3x^2-x^3/H)/6. \tag{7}$$

Substituting Eq.(7) into Eq.(6), we obtain the restraining moment of outrigger

$$M_1=\frac{2qb^2i_{c1}i_{b1}(3H^4-4Hx^3+x^4)}{4H(H-x)(b^2i_{c1}i_{w1}+6i_{w1}i_{b1}+12b^2i_{c1}i_{b1})}. \tag{8}$$

The resultant deflection at the structure top is

$$\delta_1=\frac{1}{E_wI_w}\int_0^H M_p(x)x\mathrm{d}x-\frac{M_1(H^2-x_1^2)}{2E_wI_w}. \tag{9}$$

Substitute Eq.(7) into Eq.(9), to obtain Eq.(10)

$$\delta_1=\frac{11qH^4}{120E_\mathrm{w}I_\mathrm{w}}-\frac{qb^2i_\mathrm{c1}i_\mathrm{b1}(3H^4-4Hx_1^3+x_1^4)(H+x_1)}{4HE_\mathrm{w}I_\mathrm{w}(b^2i_\mathrm{c1}i_\mathrm{w1}+6i_\mathrm{w1}i_\mathrm{b1}+12b^2i_\mathrm{c1}i_\mathrm{b1})}. \tag{10}$$

According to the compatibility conditions of outriggers and the core wall deformation, the equation with n outriggers case considering infinite rigidities of outrigger under arbitrary lateral load is as Eq.(11):

$$\begin{bmatrix} \frac{1}{12i_\mathrm{b1}}+\frac{1}{i_\mathrm{w1}}+\frac{1}{2b^2i_\mathrm{c1}} & \frac{1}{i_\mathrm{w2}}+\frac{1}{2b^2i_\mathrm{c2}} & \cdots & \frac{1}{i_{\mathrm{w}n}}+\frac{1}{2b^2i_{\mathrm{c}n}} \\ \frac{1}{i_\mathrm{w2}}+\frac{1}{2b^2i_\mathrm{c2}} & \frac{1}{12i_\mathrm{b2}}+\frac{1}{i_\mathrm{w2}}+\frac{1}{2b^2i_\mathrm{c2}} & \cdots & \frac{1}{i_{\mathrm{w}n}}+\frac{1}{2b^2i_{\mathrm{c}n}} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{1}{i_{\mathrm{w}n}}+\frac{1}{2b^2i_{\mathrm{c}n}} & \frac{1}{i_{\mathrm{w}n}}+\frac{1}{2b^2i_{\mathrm{c}n}} & \cdots & \frac{1}{12i_{\mathrm{b}n}}+\frac{1}{i_{\mathrm{w}n}}+\frac{1}{2b^2i_{\mathrm{c}n}} \end{bmatrix}\begin{bmatrix} M_1 \\ M_2 \\ \vdots \\ M_n \end{bmatrix}=\begin{bmatrix} \theta_\mathrm{w1} \\ \theta_\mathrm{w2} \\ \vdots \\ \theta_{\mathrm{w}n} \end{bmatrix}. \tag{11}$$

Suppose $\boldsymbol{S}$ is the coefficient matrix, the general expressions of restraining moments of outriggers and resultant top deflection are

$$M_i=\boldsymbol{S}^{-1}\theta_{\mathrm{w}i}, \tag{12}$$

$$\delta_n=\frac{1}{E_\mathrm{w}I_\mathrm{w}}\int_0^H M_\mathrm{p}(x)x\mathrm{d}x-\frac{1}{2E_\mathrm{w}I_\mathrm{w}}\sum_{i=1}^{n}M_i(H^2-x_i^2). \tag{13}$$

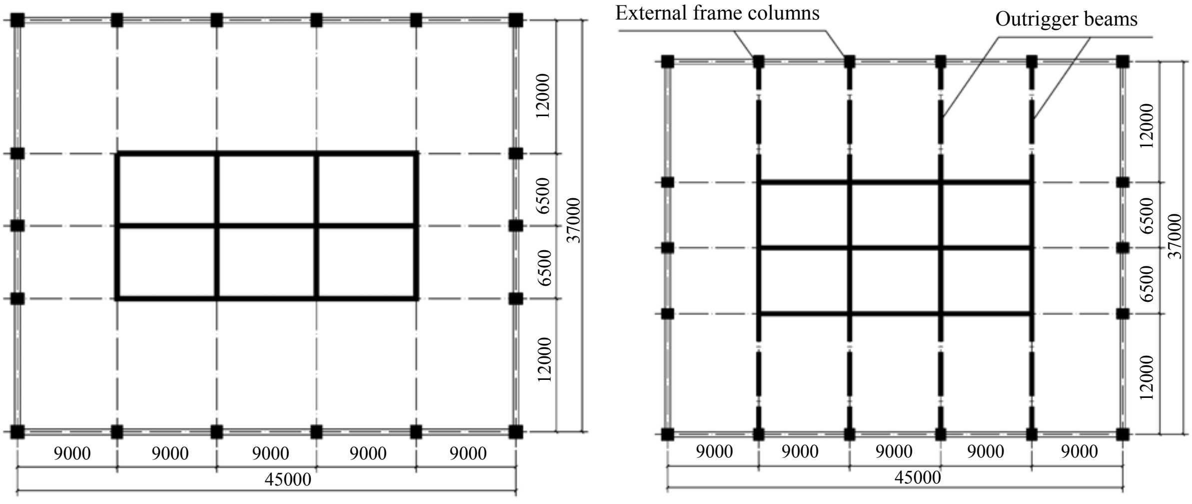
In practice, $M_\mathrm{p}(x)$ uses the actual load in Eq.(13). The determination of the number and rigidity of the outriggers is based on the restraining moment M and resultant top deflection δ.

CASE STUDY

In the paper, a typical super high frame-core reinforced concrete structure is considered. The structure floor plan is shown in Fig.2. The high-rise structure has 50 stories with height of 3.5 m. The sectional areas of the external frame column, the corner column, the general story beam and the outrigger beam are 1200 mm×1000 mm, 1200 mm×1200 mm, 300 mm×800 mm and 450 mm×3500 mm respectively. The thickness of the concrete core wall is 450 mm. The concrete strength of the core wall and the external frame, the reference wind pressure and the roughness of the terrain are assumed as C50, 0.5 kN/m^2 and grade C respectively.

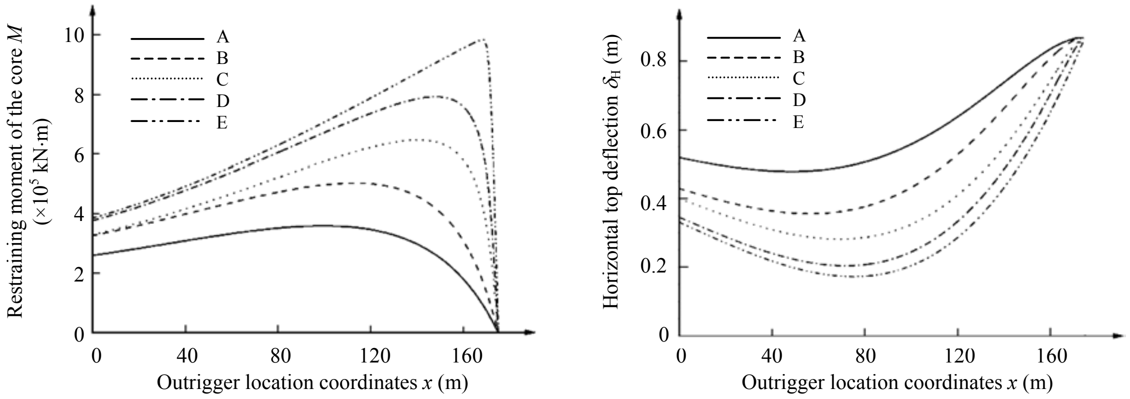
The wind load at the top of the structure is simulated as del distribution load which is the closest condition compared to the actual load applied on the structure. The maximum value of the del distribution load q_max is taken as 115 kN/m, $E_\mathrm{c}=E_\mathrm{b}=E_\mathrm{w}=3.45\times10^4$ N/mm^2, b=18.5 m, H=175 m. Analyzing Eq.(8) and Eq.(10) by varying the rigidity of outrigger from Cases A, B, C, D to E, the relationships between restraining moment of outriggers, M, resultant top deflection, δ_H, and locations of outriggers are obtained, and shown in Figs.3a and 3b respectively.

In Fig.3a, the restraining moment of the core increases rapidly as the rigidity of outrigger beam increases, while the horizontal deflection decreases with increasing rigidity of outrigger beam (Fig.3b). The restraining moment mutation of the core gradually increases and the influence of the outrigger location on the reduction of the resultant top deflection gradually increases too as the rigidity of outrigger beam increases. With the height of the four outrigger plain girders varying from 3.5 m to 7 m, the rigidity of outrigger and the restraining moment of the core increase 8 times and 1.575 times, respectively. Accordingly, the resultant top deflection decreases 43% and reduced to 0.204 m, which meets the deflection requirement of the technical specification for concrete structures of tall building (MCC, 2002). Obviously, there exists a limited range of outrigger rigidity, which can reduce internal force mutation as well as decrease the horizontal top deflection. As the outrigger location is lower than 0.571H, the closer to the bottom of the structure, the bigger the restraining moment of the core and the effect to reduce the horizontal deflection will be worse. Small outrigger rigidity can reduce the internal force mutation more



(a) (b)

Fig.2 (a) Typical floor plan; (b) Outrigger floor plan (unit: mm)



(a) (b)

Fig.3 (a) Relation curves between horizontal top deflection and outrigger location coordinates; (b) Relation curves between restraining moment of the core and outrigger location coordinates

effectively. As the horizontal top deflection meets the horizontal deflection requirement of the technical specification for concrete structures of tall building (MCC, 2002), the smaller outrigger rigidity and higher location is more reasonable for one-outrigger structure. The method of conceptual design is to setup effective outrigger rigidity based on strengthening the original structure rigidity. Outrigger can make up for the lack of the whole structure's rigidity, reduce rigidity mutation and internal force leap, make the structure present "weak beam strong column" and "strong shear weak bending" ductile yield mechanism and prevent the adjacent story of the outrigger from forming the weak story (Xu and Huang, 1999).

Table 1 shows that the optimal outrigger location which minimizes the horizontal top deflection gradually moves toward the lower part of the high-rise structure. The optimal outrigger location with large outrigger rigidity (Case D) is close to the infinite outrigger rigidity. The optimal infinite outrigger rigidity location is at $0.571H$, which is consistent with the results from Yuan and Zhang (1996). The difference of optimal outrigger location is $0.152H$ as the outrigger rigidity varies from finite (Case A) to infinite (Case E). The smaller the outrigger rigidity, the greater the location error, especially for multiple-outrigger structures. Obviously, the optimal location obtained from the infinite outrigger assumption is not accurate. The outrigger location that maximizes the restraining moment of the core gradually moves toward the lower part of the high-rise structures. As the outrigger rigidity is infinite, the outrigger location

Table 1 The relative height of outrigger and the mutation of deflection and restraining moment in different outrigger case

Outrigger case	Relative height of outrigger (l/H)		Mutation quantity ($o-H$)	
	Minimum horizontal top deflection	Maximum restraining moment of the core	Horizontal tip deflection (%)	Restraining moment of the core (%)
A	0.723	0.431	8.0	18.8
B	0.677	0.354	17.1	24.2
C	0.606	0.197	29.6	33.0
D	0.591	0.154	40.9	34.6
E	0.571	0.023	47.9	36.9

A: Two 0.45 m × 3.5 m outrigger beams; B: Four 0.45 m×3.5 m outrigger beams; C: Two 0.45 m×7 m outrigger beams; D: Four 0.45 m×7 m outrigger beams; E: Infinite rigidity outrigger beam; l is the height from the outrigger location to the bottom of the structure; o is the height from the optimal outrigger location to the bottom of the structure

which maximizes restraining moment of the core is at the bottom of the structure. Hence, the analysis results based on infinite outrigger assumption are not reasonable and safe for construct the outrigger setting in practice.

As shown in Table 1, the mutation of the reduction of the horizontal top deflection and restraining moment of the core increase with a certain height range as the outrigger rigidity increases. As the outrigger rigidity is larger than a certain value, the outrigger rigidity has less influence on the reduction of the horizontal top deflection while the restraining moment mutation of the core increases fast. As the outrigger rigidity is smaller than a certain value, the effect on the reduction of the horizontal top deflection of outriggers is not definite and the stress state is not reasonable. The proper outrigger rigidity range can be gained from the analysis of the actual project.

CONCLUSION

The mutation of the core moment occurs at the location where the outrigger is setup. The mutation of the restraining moment and the reduction of the horizontal top deflection depend on the outriggers locations. The optimal outrigger location exists if we only consider the maximum reduction of the horizontal top deflection but the corresponding mutation of the restraining moment of the core is very large, the weak story will occur at the location where internal force is mutative, especially under earthquake action. Therefore, the optimal outrigger location is unsafe in seismic zone. We should comprehensively consider the top deflection reduction and small internal force mutation. From the analysis above, the following conclusions are obtained:

(1) The outrigger system is very effective in increasing the structure's flexural stiffness. Outrigger causes the structure's internal force redistribution. It is also very effective in decreasing the horizontal top deflection of high-rise frame-core structures and developing safe, economic and reasonable design of high-rise building structures.

(2) Outrigger will cause rigidity mutation when subjected to lateral load. It is recommended to choose proper outrigger rigidity and location according to the seismic fortification criterion. The lower outrigger rigidity and the location higher than the optimal location should be chosen for meeting the requirement of the higher seismic fortification criterion in order to reduce the internal force mutation and prevent the adjacent story of the outrigger from forming the weak story. The proper outrigger rigidity and location which meet the requirement of less horizontal deflection and less internal force mutation can be obtained by using the equation derived from the current study.

(3) Theory analysis of optimal outrigger location of all existing analytical models was carried out at certain assumption premise. The outrigger's infinite rigidity assumption has great influence on the analysis of the structure's horizontal deflection. The optimal location deduced from that assumption is unreasonable and unsafe. Optimization analysis based on the actual outrigger rigidity is needed before it is used to guide the actual engineering.

(4) Most research on optimal outrigger location

ignored the influence of horizontal members except the outriggers. The practical situation is the horizontal beam connected the external frame to the core, the belt girder connected to the external frame columns and corner columns have definite rigidities, they contribute to the reduction of the horizontal deflection (Zhou and Zhang, 2006; Zhang and Zhou, 2006). Their influence should be considered based on the safety of the structures. Further optimization is needed for structural analysis model.

References

Hoenderkamp, J.C.D., Snijder, H.H., 2003. Preliminary analysis of high-rise braced frames with facade outriggers. *Journal of Structural Engineering, ASCE*, **129**(5):640-647. [doi:10.1061/(ASCE)0733-9445(2003)129:5(640)]

Liu, J.X., 1997. Optimal position of rigid outriggers in high-rise structure. *Journal of Yantai University*, **27**(8):25-29 (in Chinese).

MCC (Ministry of Construction of the People's Republic of China), 2002. Technical Specification for Concrete Structures of Tall Building. JGJ3-2002, J186-2002, 2002 (in Chinese).

Smith, B.S., Coull, A., 1991. Tall Building Structures: Analysis and Design. Jone Willey & Sons Inc., New York, p.355-421.

Smith, B.S., Salim, I., 1981. Parameter study of outrigger-braced tall building structures. *Journal of the Structural Division, ASCE*, **107**(10):2001-2013.

Xu, P.F., Huang, J.F., 1999. Seismic design analysis of frame-core structures with outriggers. *Journal of Building Structures*, **20**(4):2-10 (in Chinese).

Yuan, X.L., Zhang, Y., 1996. Optimal outrigger location analysis of tall building structures. *Building Science Research of Sichuan*, **24**(1):15-18 (in Chinese).

Zhang, Z.X., Zhou, C.S., 2006. Sidesway analysis method of high-rise frame-tube structure with strengthened stories under lateral load. *Journal of Wuhan University of Technology*, **28**(4):52-55 (in Chinese).

Zhao, X.A., 1992. Reinforced Concrete Design of Tall Building Structures. China Architecture & Building Press, Beijing, p.409-451 (in Chinese).

Zhou, C.S., Zhang, Z.X., 2006. Strain energy analysis of high-rise frame-tube structure with top-strengthened story under lateral load. *Journal of Wuhan University of Technology*, **28**(3):86-88 (in Chinese).