# Optimal Design of Outrigger Systems for Super Tall Buildings

**Xin ZHAO**
PhD , Senior Engineer
Department of Structural Engineering, Tongji University
Tongji Architectural Design (Group) Co., Ltd.
Shanghai, China
*22zx@tjadri.com*

**Lang QIN**
Research Student
Department of Structural Engineering, Tongji University
Shanghai, China
*qlxhzy999@sina.com*

**Yaomin DONG**
Research Student
Department of Structural Engineering, Tongji University
Shanghai, China
*dongluoyaomin@163.com*

**Xiang JIANG**
Research Student
Department of Structural Engineering, Tongji University
Shanghai, China
*786379623@qq.com*

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## Abstract

Applied widely to increase the lateral stiffness of supper tall buildings, outriggers can effectively reduce vibration period as well as the structural lateral deflection under wind loads and earthquake actions. Although increasing number of outriggers contributes to better overall stiffness, it will induce significant structural cost premium and cause serious delay in construction stage. In structural design of super tall buildings, the setting number, location and cross-section sizes of outriggers must be determined to meet the requirements of both structural safety and cost control. Based on the feature of mega frame-core wall structures, this paper discussed the optimal design of outrigger trusses.

The location and number of outriggers are optimized by adopting sensitivity vectors algorithm (SVA) method proposed by the authors. The sensitivity vectors of one outrigger truss at different locations on the overall structural stiffness are firstly obtained. As outrigger trusses are commonly set in mechanical floors with a more than 10-floor interval, it is assumed that the influences of single outrigger truss at different locations on story drift distribution are independent of each other. Under such an assumption, the sensitivity vectors of multiple outrigger trusses on story drift distribution can be obtained by simply multiplying the sensitivity vectors of single outrigger truss at different locations. Calculate the story drifts of building with outriggers in various number and location using SVA method, and determine location of outriggers with minimum story drifts when setting *m*-level outriggers. Comparing the story drifts and fundamental vibration period of the various models, the model with minimum number of outriggers satisfying story drifts and fundamental vibration period limitation is obtained, thus the number and location of outriggers are determined.

Using the principle of virtual work and Rayleigh method, the relationships between the structural member sectional dimensions and the design criteria, such as the story drift and vibration period, are established.

Story drift is one of the principal design criteria for super tall building design. The story drift $\delta_s$ can be expressed by the principle of virtual work in terms of the cross sectional properties as follows:

$$\delta^{(s)} = \frac{1}{6Q^{(s)}}\sum_{m=1}^{N}\left( [\mathbf{F}_i^{(m)}\ \mathbf{F}_j^{(m)}] \begin{bmatrix} 2\mathbf{C}^{(m)} & \mathbf{C}^{(m)} \\ \mathbf{C}^{(m)} & 2\mathbf{C}^{(m)} \end{bmatrix} \begin{bmatrix} [\mathbf{f}_i^{(m)}]^T \\ [\mathbf{f}_j^{(m)}]^T \end{bmatrix} L^{(m)} \right) \quad (1)$$

Where $Q^{(s)}$ is the virtual couple acting on the story *s*; *N* is the quantity of total structural members; $L^{(m)}$ is the length of member *m*; $\mathbf{F}_i^{(m)}$ and $\mathbf{F}_j^{(m)}$ are nodal force vectors of member *m* due to the actual

loading condition; $\mathbf{f}_i^{(m)}$ and $\mathbf{f}_j^{(m)}$ are nodal force vectors of member $m$ due to the virtual load $Q^{(s)}$; and $\mathbf{C}^{(m)}$ is diagonal matrix of member $m$, and the diagonal elements are $1/EA$, $1/GA_Y$, $1/GA_Z$, $1/GI_X$, $1/EI_Y$, and $1/EI_Z$.

Fundamental vibration period is a another principal criterion in the design of super tall buildings. Using the Rayleigh method, the fundamental circular frequency of vibration $w$ can be expressed as:

$$w^2 = W = \frac{1}{6}\sum_{m=1}^{N}\left( [\mathbf{F}_i^{(m)}\ \mathbf{F}_j^{(m)}] \begin{bmatrix} 2\mathbf{C}^{(m)} & \mathbf{C}^{(m)} \\ \mathbf{C}^{(m)} & 2\mathbf{C}^{(m)} \end{bmatrix} \begin{bmatrix} [\mathbf{F}_i^{(m)}]^T \\ [\mathbf{F}_j^{(m)}]^T \end{bmatrix} L^{(m)} \right) \quad (2)$$

Where $\mathbf{F}_i^{(m)}$ and $\mathbf{F}_j^{(m)}$ are nodal force vectors of member $m$ in the modal force condition; and $\mathbf{C}^{(m)}$ is diagonal matrix of member $m$.

The optimization problem of minimizing the steel construction cost of outriggers can be explicitly written as:

Minimize: $Volume = \sum_{i=1}^{n} A^{(m)} L^{(m)} \qquad m = 1, 2, ..., n$ (3)

Subject to $\qquad x_L^{(m)} \le x^{(m)} \le x_U^{(m)} \qquad m = 1, 2, ..., n$ (4)

$\qquad \delta^{(s)} \le [\delta] \qquad s = 1, 2, ..., n$ (5)

$\qquad T \le T^U$ (6)

Equation(3) defines the volume of outriggers; Equation(4) defines the sizing constraints for the cross-section, where $x_L{}^{(m)}$ and $x_U{}^{(m)}$ correspond to the lower and upper size bounds for the variable $x^{(m)}$; Equation(5) defines the set of story drift constraints under specified earthquake ground motions and wind load; and Equation(6) defines the set of fundamental vibration period constraints.

Upon formulating the explicit design optimization problems, Eqs.(3)-(6), a Matlab-based computer programe is developed on the basis of SQP approach to minimize the volume of outrigger truss members under multiple constraints.

A 729-meter real super tall building project is employed to illustrate the applicability and effectiveness of the proposed optimal design method. The scheme to satisfy story drifts and fundamental vibration period limitation with minimum number of outriggers is obtained using SVA method, as listed in Table 1. After optimizing cross-section size, the volume of exterior outriggers has been reduced by 153.2m$^3$, which means the optimization results have saved 676 tons of steel, as presented in Fig. 1.

*Table 1: The location of outriggers*

| | |
|---|---|
| the number of outriggers | X4Y4 |
| x-directional outrigger positions | 1,6,7,8 |
| y-directional outrigger positions | 1,2,6,7 |
| fundamental vibration period(s) | 9.30 |
| maximum story drift | 1/534 |

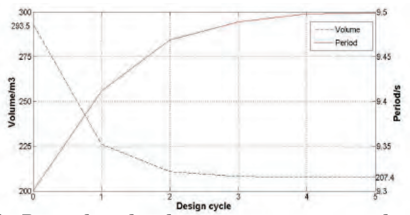


*Fig. 1: Period and volume in optimization history*

This paper presents a optimal design procedure for the minimum material cost design of outriggers under multiple constraints. The location and number of outriggers are optimized by SVA method. Using the principle of virtual work and Rayleigh method, the relationship between the story drifts and sectional dimension, vibration period and sectional dimension are established. Furthermore, SQP approach are adopted to solve the explicit design problem. At optimum, the lateral stiffness demand with the minimum material cost of outriggers is achieved. It is also believed that this optimal design methodology provides a powerful computer-based technique for design of super tall buildings with outriggers. The design optimization procedure provides a good basis for more comprehensive optimization of structures.