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Multi-Constrained Outrigger Optimization
多约束条件下伸臂系统结构优化

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The outrigger system has been widely employed as an innovative and efficient structural lateral-load resisting system in supertall buildings in recent decades. The optimization of the outrigger system is desirable because it can significantly increase structural lateral stiffness, decrease steel tonnage, reduce construction periods and make extra space for building functions and equipment. Conventional trial-and-error procedure relies on engineers' experience and is laborious and time-consuming for the optimization of outrigger trusses. A sensitivity vector method (SVM) proposed by the authors (Zhao, Liu and Zheng (2011)) was further developed to find the optimal position and number of outriggers under multiple design constraints. The Multi-Constrained Sensitivity Number (MCSN) method can produce in-depth engineering understanding on how outriggers function under different design constraints and lead to a determination of the optimal placements and number of the outriggers in a project. The Suzhou Zhongnan Center is used as an example to show the application and effectiveness of the Multi-Constrained Sensitivity Vector Method. The Multi-Constrained Sensitivity Number and Vector methods aim at period and story-drift constraints respectively.

伸臂系统作为一种创新和高效的结构抗侧力体系，近几十年来在超高层建筑中得到了广泛应用。伸臂系统的优化可以有效增加结构抗侧刚度、降低用钢量、加快施工工期、增加建筑及设备空间。传统的伸臂结构优化方法通常是依靠工程师的经验来反复尝试，往往是耗时耗力的。作者对之前提出的灵敏度向量算法进一步探讨以确定在多约束条件下伸臂系统的最优布置位置和数量。简化的灵敏度数量法在周期约束条件求解伸臂最优数量和位置，可以加深设计人员关于不同设计约束条件对伸臂系统优化设计影响的理解。最后，通过对中南中心的案例分析阐述了该算法的运用过程及其有效性。

Introduction

The outrigger system has been widely applied in supertall buildings structures due to its high efficiency for enhancing overall lateral stiffness. The introduction of the outrigger system also has some disadvantages. For example, it can cause abrupt changes and stress concentration near the outrigger floors and requires huge steel consumption, large member dimensions and a longer construction period. To counteract these disadvantages, a structural optimization method is desirable for outrigger systems to introduce the following benefits: structural lateral stiffness increase, steel tonnage decrease, construction period reduction and extra space for building functions and equipment. In this chapter, optimized outrigger systems have the benefits of providing steel tonnage decreases and making extra space for building functions and equipment, compared to the original / conventional design scheme. Structural optimization for engineering applications has to consider different design constraints according to diversified performance requirements, such as overall stiffness, structural stability, minimum earthquake base shear, and vibration period, among many others. Although the number and placement of outrigger systems are commonly determined according to the stiffness requirement, it was found that the vibration-period requirement will also dominate the outrigger system design for supertall buildings with a height of more than 500 m. Thus, both stiffness constraint and vibration-period constraint have to be considered for the optimal design of an outrigger system.

The optimal design of outrigger systems for supertall buildings has been widely investigated in the past few decades. Smith and Nwaka (1980) analyzed the inner forces and displacements of the outriggers and advanced the simplified formula for reconciling the bending moment of the outriggers, the reduction of the top displacement and the optimal location of the outriggers. Coull and Lau (1988) analyzed the top displacement and the base bending moment of a structure with multiple outriggers under the concentrated horizontal load on the center of the top level, as well as the triangle-distributed horizontal load. A general formula was also given to determine the optimal location of outriggers by the linear regression method. Wu and Li (2003) introduced, in detail, the optimization design of frame tube structures with outriggers. Influences of the location of outriggers and the relative proportion of structural member

引言

伸臂系统作为一种创新和高效的结构抗侧力体系，近几十年来在超高层建筑中得到了广泛应用。伸臂系统的引入存在缺点：如导致设备层应力集中、用钢量巨大、构件尺寸过大及周期过长等。而伸臂系统的优化可以有效增加结构抗侧刚度、降低用钢量、加快施工工期、增加建筑及设备空间。由于实际工程设计中超高层建筑结构常常要满足多种约束条件，如整体刚度、结构稳定性、最小地震基底剪力及自振周期等，如何使伸臂系统优化时结构的各约束条件均能满足要求就很有意义。尽管伸臂系统的位置和数目常常由结构的刚度决定，研究发现对超过500m的超高层来说，自振周期同样会对伸臂系统的设计起控制作用。因此，在伸臂系统的优化设计中，需要同时考虑刚度和自振周期约束。

关于伸臂系统设置对结构性能的影响以及伸臂系统优化问题已有大量研究。Smith和Nwaka (1980) 对加强层结构的内力和位移进行了分析，给出了加强层约束弯矩、顶部位移降低和加强层最优位置的简化公式。Coull和Lau (1988) 对设有多个加强层的结构在顶部水平集中荷载和三角形分布水平荷载作用下的顶部位移和基底弯矩进行了分析，并使用线性回归方法给出了确定加强层最优位置的一般性公式。Wu和

Figure 3.34. Geometric form of the tower (Source: Gensler)
图3.34. 塔楼型态 (来源: Gensler)

stiffness on the top displacement and base moment were investigated by Wu and Li.

Ding (1991) addressed the optimal design of tall buildings with a single outrigger. Several critical parameters were analyzed to see the impacts on the optimal location of the outrigger and the reduction factor of top displacement. However, most of the research findings described in that work apply only to tall buildings of regular shape comprising similar typical floors and moderate building height, and are not easily applied to highly irregular supertall buildings.

Zhao, Liu and Zheng (2011) in recent years developed a sensitivity vector method (SVM) that sought to identify the impact of different outrigger positions, focusing on the independence of each location on the story-drift distribution throughout the building height. The sensitivity vector method makes

Li (2003) 详细介绍了带加强层框筒结构的优化设计，研究了加强层结构位置、结构单元刚度的相对比例关系对结构顶部位移和基底弯矩的影响。

丁洁民 (1991) 以设置一个加强层的高层建筑为例，考察了多个关键结构参数对加强层最优位置和顶部位移折减系数的影响。然而很多研究都是针对某一特定荷载形式作用下，对结构进行简化，考虑核心筒及伸臂的转角变形协调关系得到的。

而赵昕，刘南乡等(2011)依据结构不同位置伸臂对结构影响的相对独立性，提出了灵敏度向量法，给出了快速求得层间位移角约束条件下伸臂桁架的最优道数及位置的方法。灵敏度向量法不需要对建筑形体以及体量分布进行假设，所以可以应用于形状极不规则的超高层建筑以及沿高度方向体量非均匀分部的建筑。

在作者的研究基础上，进一步发展了灵敏度向量算法以确定伸臂桁架同时满足层间位移角和周期约束条件下的最优布置数量和位置。该算法优化结论可以加深设计人员关于不同设计约束条件对伸臂系统优化设计影响的理解。最后，通过对中南中心的案例分析阐述了该算法的运用过程及其有效性。

灵敏度算法

本文针对周期约束条件下的伸臂最优位置及道数对该算法特例化，即灵敏度数量算法的基本原理介绍如下:

S_0表示不设置伸臂桁架的结构状态，T_0表示对应结构状态S_0的结构自振周期。S_i表示仅第

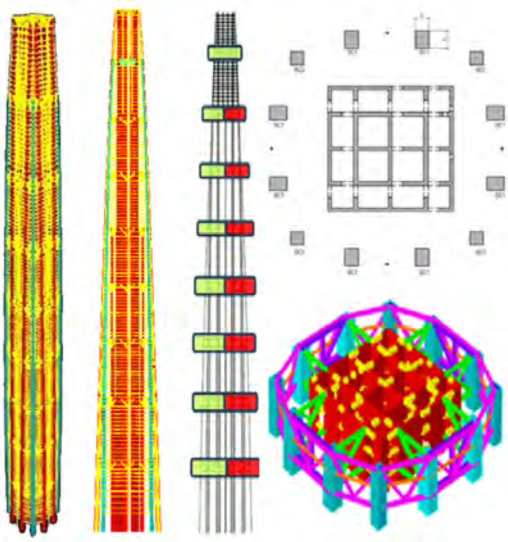

Figure 3.35. Structural system of Zhongnan Center(Source: Moukui Xu)
图3.35. 结构体系 (来源: 许谋奎)

no assumption about the building shape and mass distribution, and thus can be applied for supertall buildings of highly irregular shapes and uneven mass distribution along the building height.

The SVM proposed by the authors is further developed in this chapter, finding the optimal placement and number of outriggers to meet both the story drift and period constraints. Named the Multi-Constrained Sensitivity Number (MCSN) by the authors, the method can produce in-depth engineering understanding of how the outriggers react to and create different design constraints, and then inform optimal placements and number of outriggers. The Zhongnan Center project will be used as an example to illustrate the application and effectiveness of the proposed Multi-Constrained Sensitivity Vector (MCSV) method.

Sensitivity Number Method

A brief introduction of the MCSN method is as follows:

Assuming that represents the state of non-outrigger structural scheme, T_0 represents the corresponding vibration period of S_0 x S_i represents the state of an outrigger located in the i_{th} zone in the structure and T_i represents the corresponding vibration period of S_i. So we can define a non-dimensional coefficient of period sensitivity r_i:

$$r_i = T_i/T_0$$

The outriggers are usually placed in different zones combined with the architectural functions. Different zones are divided into an interval of 10 stories, due to which we can assume that outriggers in different zones affect the overall structure stiffness independently and the following relationship is defined:

$$r_{i,j,k} = r_i \cdot r_j \cdot r_k$$

Thus, we can get the vibration period of multiple outrigger positions as:

$$T_{i,j,k} = r_{i,j,k} \cdot T_0$$

i区设置伸臂桁架的结构状态，T_i表示对应结构状态S_i的结构自振周期。定义无量纲周期灵敏度r_i为

$$r_i = T_i/T_0$$

伸臂桁架一般结合建筑分区设置，间隔约在10层以上，可以认为各区伸臂桁架对整体结构刚度的影响是相互独立的，可得以下关系:

$$r_{i,j,k} = r_i \cdot r_j \cdot r_k$$

进而可以获得在多区同时设置伸臂桁架的结构自振周期:

$$T_{i,j,k} = r_{i,j,k} \cdot T_0$$

假设超高层建筑结构共有n区可以设置伸臂桁架。其在周期约束条件下的最优伸臂道数及位置确定的灵敏度数量法步骤如下: 首先利用整体结构模型，计算在不同区设置单道伸臂桁架的周期，并与不设伸臂桁架的周期相比较，获得各区设置伸臂桁架的灵敏度。其次利用各区伸臂桁架灵敏度的数乘运算，获得设置n道伸臂桁架情况下最优的伸臂设置位置，即不同伸臂道数情况下的伸臂最优设置方案。最后比较不同伸臂道数情况下的伸臂最优设置方案，获得周期约束条件下道数最少的伸臂最优设置方案。

同时考虑多约束条件，应综合考虑层间位移角约束条件下的最优布置方案，而各种约束条件下的最优方案往往是不完全相同的，这时就需要设计人员搞清楚各控制因素在本项目中的重要性指标，从而综合考虑得出最优方案。

工程实例

以苏州中南中心为例，说明多约束条件下灵敏度方法获得伸臂桁架优化布置方案的流程。该结构为典型的巨柱框架核心筒结构体系，结构体系见图3.35，由核心筒、巨柱和角柱组成。沿高度方向划分为九个区，九区观光层尚未考虑布置伸臂，八区由于斜墙的存在仅考虑在X向布置伸臂桁架，其余各区设备层皆可以设置两个方向的伸臂桁架(n＝8)。结构层间位移角为风荷载控制，在伸臂桁架道数和位置优化时，采用风荷载下结构的最大层间位移角为优化目标。为准确反映伸臂桁架设置方案对结构刚度的影响，不考虑结构动力特性与风荷载的相关性。

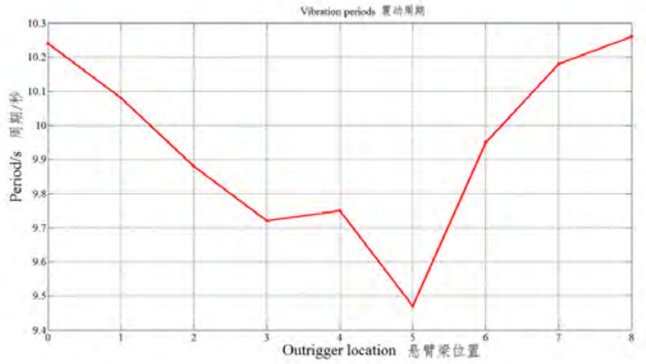

Figure 3.36. Vibration periods (Source: Moukui Xu)
图3.36. 单道伸臂结构一阶自振周期 (来源: 许谋奎)

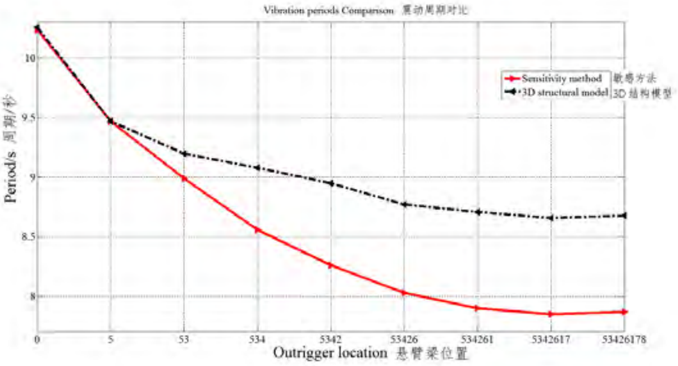

Figure 3.37. Vibration periods comparison (Source: Moukui Xu)
图3.37. 周期约束条件下不同伸臂桁架道数时伸臂设置的最优位置 (来源: 许谋奎)

For supertall buildings of *n* zones, the optimal number and location of the outriggers under the period constraint can be determined by the following steps: The vibration periods of the tower with a single outrigger will first be calculated for different zones. The obtained vibration periods of towers with single outriggers in different zones will then be compared with the vibration period of a tower without an outrigger to derive the vibration-period sensitivities of the outrigger system. The vibration period sensitivities will be multiplied to obtain the optimal arrangement of the outriggers for specific level numbers. The outrigger arrangement which satisfies the vibration period constraints and has the minimum level number will be the optimal outrigger arrangement.

For the optimization problem under multiple constraints, one may first find the optimal designs under different design constraints. It should be noted that the optimal design under one constraint will not necessarily be the optimal design under another constraint. The final optimal design under multiple constraints will be derived comprehensively by weighing the impacts of different constraints on the optimal design.

Case Study

The Suzhou Zhongnan center is used in this section to illustrate the application of the Multi-Constrained Sensitivity Member method for the optimal design of outriggers. The structural system is a typical megaframe-core wall structural system composed of megacolumns, belt trusses, outrigger trusses and central core walls. The structural system is shown in Figure 3.35. There are a total of nine zones along the building height. The outrigger trusses can be arranged within each zone in two directions, apart from the eighth and ninth zones. Due to the requirements for viewing locations and the existence of an inclined wall, the outrigger can only be arranged in an X-direction orientation within zones 8 and 9. Story drifts of this structure are dominated by the wind load. The coupling effect between the dynamic characteristics of the structure and the wind load is not taken into consideration, in order to reflect only the influence of different outrigger schemes on the overall structural stiffness.

In the original design scheme, the outriggers are installed in the mechanical floors of different zones, such as the 11th – 13th floor, 43rd – 45th floor, 59th – 61st floor (Y-direction only), 91st – 93rd floors, 107th and 108th floor, 123rd and 124th floor (X-direction only). There are five total outriggers installed in the X and Y directions. The vibration periods are 9.05 and 8.69 seconds for the X-direction and Y-direction respectively, and the periods in both directions satisfy the limit of 9.5 seconds by a big margin. However, the maximum story drift of the tower is 1/504, close to the drift limit of 1/500.

The sensitivity number method is adopted to optimize the number and placement of the outriggers under both story-drift and vibration-period constraints. The main conditions considered are as follows:

原伸臂设计方案利用机电层于位于11~13层，43~45层，59~61层 (仅Y向)，91~93层，107~108层，123~124层 (仅X向) 布置外伸臂桁架加强层，即X、Y向各布置了五道伸臂。结构X向一阶自振周期为9.05s，Y向一阶自振周期为8.69s，最大层间位移角1/504，与1/500的限值较为接近。

本文采用灵敏度向量算法对层间位移角及周期约束条件下伸臂桁架的布置道数和位置进行优化。主要优化参数为:

1. 优化目标: 结构材料用量最小化;
2. 约束条件: 最大层间位移角<1/500，一阶周期<9.5s，剪重比>1.0%。

周期约束条件下

对结构进行整体分析，计算仅设置单道伸臂桁架(n = 1) 和不设置伸臂桁架(n = 0) 时结构的自振周期，结果如图3.36所示。由图3.36可见，单道伸臂对结构自振周期最优布置方案在第五区，且八区设置X向的伸臂并不能使结构自振周期减小。

根据单道伸臂桁架的结构周期即可获得相应的周期灵敏度。应用灵敏度数量法可知，周期约束条件下伸臂桁架设置位置依次为5区、3区、4区、2区、6区、1区、7区、8区，从而得到周期约束条件下不同伸臂桁架道数时伸臂设置的最优位置。为验证灵敏度数量算法的正确性，对多道伸臂方案的实际模型进行计算，灵敏度方法及实际模型结果如图3.37所示。

由图3.37可见，可看做向量积算法特例的数量积算法显示了其合理性，虽然灵敏度数量积算法获得的周期与实际模型的误差很大，但对伸臂道数周期相对关系的判断是准确的，伸臂数目并不是越多越有利，多道伸臂方案增加8区时确实导致了自振周期的增大，这是由于增加8区伸臂时结构质量增大的幅度超过了伸臂对结构刚度的增

Outrigger number **悬臂梁号**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Original** **原始数据**
Optimal location 最优位置	6	67	678	5,678	15,678	125,678	1,235,678	12,345,678	134,678
Y direction period Y方向周期	9.93	9.88	9.88	9.34	9.22	9.03	8.83	8.7	9.05
X direction period X方向周期	9.46	9.41	9.32	9.09	8.98	8.74	8.5	8.38	8.69
Maximum story drift 最大层间位移	1/465	1/504	1/510	1/511	1/509	1/504	1/502	1/500	1/504

Table 3.19. Comparison results (Source: Moukui Xu)
表3.19. 灵敏度算法不同伸臂布置的最优方案对比 (来源: 许谋奎)

Outrigger number **悬臂梁号**	**X1Y1**	**X2Y2**	**X3Y2**	**X4Y3**	**X4Y4-1**	**X4Y4-2**	**X5Y4**	**X5Y5**	**X7Y6**	**X8Y7**
X direction X方向	6	67	678	5678	5678	5678	15678	15678	1235678	1.2E+07
Y direction Y方向	6	67	67	567	1567	2567	1567	12567	123567	1234567
Y direction period Y方向周期	9.93	9.88	9.88	9.34	9.22	9.16	9.22	9.04	8.83	8.7
X direction period X方向周期	9.46	9.41	9.32	9.09	9.07	9.06	8.98	8.81	8.5	8.38
Maximum story drift 最大层间位移	1/465	1/504	1/510	1/511	1/510	1/507	1/509	1/504	1/502	1/500
Y direction shear-weight ratio Y方向剪力重量比	1.11%	1.11%	1.10%	1.11%	1.11%	1.11%	1.11%	1.12%	1.13%	1.04%
X direction shear-weight ratio X方向剪力重量比	1.11%	1.12%	1.12%	1.13%	1.13%	1.13%	1.16%	1.16%	1.18%	1.08%
Notes 备注					Recommended scheme 2 推荐方案2	Recommended scheme 1 推荐方案1	Recommended scheme 2 推荐方案2			

Table 3.20. Optimal schemes by the sensitivity method (Source: Moukui Xu)
表3.20. 最优伸臂道数和布置方案 (来源: 许谋奎)

1. The objective of the optimization is the minimum usage of material
2. The constraints considered are that the maximum story drift should be below 1/500, the fundamental vibration period should be below 9.5 seconds and the shear-to-weight ratio should be above 1.0%.

Vibration Period Constraint

The vibration periods of the towers with single-outrigger schemes in different zones and those of non-outrigger schemes are shown in Figure 3.36. It can be seen from Figure 3.36 that the optimal outrigger placement under the vibration period constraint is zone 5, if only one outrigger is considered. Besides, the installation of outriggers in zone 8 has almost no influence on the vibration period compared with non-outrigger scheme.

The period sensitivity of each outrigger can be obtained by comparing the vibration periods of single-outrigger schemes and non-outrigger schemes. It can be found that the optimal outrigger locations for the vibration periods are in this order: zones 5, 3, 4, 2, 6, 1, 7 and 8. The vibration periods of the optimal schemes with different numbers of outriggers can then be derived by using the proposed sensitivity number method. To verify the accuracy of the sensitivity number method, the vibration periods are also calculated for the optimal schemes with different numbers of outriggers using 3D structural models. The vibration periods obtained from both methods are shown in Figure 3.37.

加。可说明伸臂桁架数量的增多并不一定导致结构自振周期的降低。

层间位移角约束条件下

图3.38列出了在不同位置设置伸臂桁架结构的最大层间位移角。对限制最大层间位移角的最优布置方案在第六区。设置单道伸臂桁架和不设置伸臂的九种方案结构的层间位移角见图3.39。灵敏度算法获得的设置不同数目伸臂桁架最优位置组合层间位移角见图3.40。以灵敏度算法获得的最优方案建立实际模型，获得的实际计算结果如图3.41。

由图3.40、3.41补充的整体结构模型计算及上图曲线走势可知，灵敏度向量算法对伸臂最优位置的确定是准确的。由灵敏度算法获得的不同伸臂布置的最优方案对比见表3.19。

Figure 3.38. Maximum story drift (Source: Moukui Xu)
图3.38. 设置单道伸臂桁架时结构的最大层间位移角 (来源: 许谋奎)

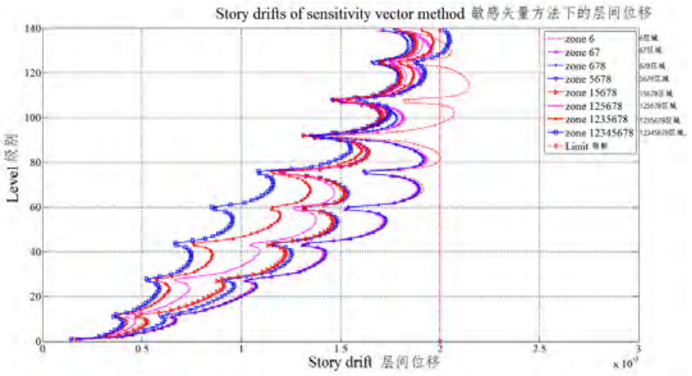

Figure 3.40. Story drift of sensitivity vector method (Source: Moukui Xu)
图3.40. 设置不同数目伸臂桁架的最优位置组合层间位移角 (来源: 许谋奎)

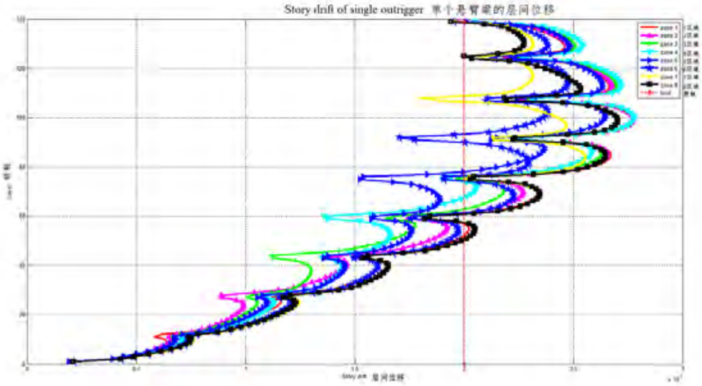

Figure 3.39. Story drift of single outrigger scheme(Source: Moukui Xu)
图3.39. 设置单道伸臂桁架和不设置伸臂时结构的层间位移角 (来源: 许谋奎)

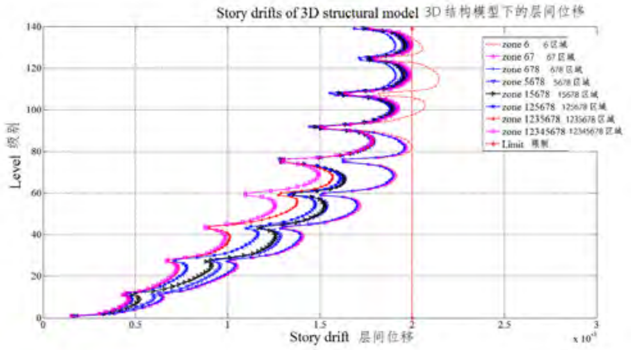

Figure 3.41. Story drift of 3D structural model (Source: Moukui Xu)
图3.41. 设置不同数目伸臂桁架最优位置组合实际模型的层间位移角 (来源: 许谋奎)

From Figure 3.37 it is seen that, although the errors between the vibration periods obtained from the sensitivity number method and the 3D structural model are relatively large, the optimal placements of the structural schemes with a different number of outriggers are precisely the same. It can also be seen that the increase of the outrigger of Zone 8 does not reduce the vibration period, due to the fact that the increase of structural mass exceeds the increase of structural stiffness for Zone 8. It also can be verified that the increase of the outrigger trusses will not necessarily reduce the structural periods.

Story Drift Constraint

Figure 3.38 shows the maximum story drift when outriggers are placed in different zones. It is seen that the optimal placement for a single-outrigger scheme is Zone 6 under the story drift constraint. Story drifts of single-outrigger schemes and the non-outrigger scheme are shown in Figure 3.39. Story drifts of different combinations of the optimal single-outrigger schemes can be obtained by the sensitivity vector method and are shown in Figure 3.40. Figure 3.41 gives the story drifts of different combinations of the optimal single-outrigger schemes obtained from the 3D structural model.

Comparing Figures 3.40 and 3.41, it is seen that the optimal outrigger placements obtained by the sensitivity method are almost the same as those obtained by the 3D structural model as shown in Table 3.19, although the amplitudes of the story drifts are different.

Considering the vibration period limit of 9.5 seconds, schemes with less than three levels of outriggers shall not be considered as optimal outrigger schemes under both story drift and vibration period constraints. The vibration period is reduced to 9.34 seconds with four outrigger levels, and the vibration period was not the controlling factor for four outrigger levels. Considering both the story drift limits and the even distribution of outriggers along the building height, the recommended optimal schemes were obtained (see Table 3.20). Therefore, the three recommended schemes, according to the results of the outrigger analysis of different optimal numbers and placements, are as follows (see also Table 3.21):

由于方案有周期9.5s的限值，布置伸臂桁架少于三道的方案可不考虑。四道伸臂时周期已降至9.34s，说明本项目中周期并不起控制作用。综合考虑时以层间位移角约束条件为主，并考虑结构竖向刚度均匀性，从而根据伸臂桁架分析结果得出了如下三种推荐的不同伸臂道数和位置的布置方案 (见表3.20) 。

推荐方案1

伸臂最优布置方案为在5678区X向、2567区Y向布置伸臂桁架，即X向4道、Y向4道，较原方案在X方向减少一道伸臂，Y方向减少两道伸臂，用钢量减少2032t。

推荐方案2

伸臂最优布置方案为在5678区X向、1567区Y向布置伸臂桁架，即X向4道Y向4道，较原方案在X、Y方向均减少一道伸臂，用钢量减少1948t。

推荐方案3

伸臂最优布置方案为在15678区X向、1567区Y向布置伸臂桁架，即X 5道Y向4道，较原方案在Y向减少一道伸臂，用钢量减少1009t。

从上述几种推荐方案来看，节约大量用钢量的同时，结构的整体指标变化并不大，

Schemes 方案		Original Scheme (X5Y5) 原始方案	Recommended Scheme 1 (X4Y4-2) 推荐方案	Recommended Scheme 2 (X4Y4-1) 推荐方案	Recommended Scheme 3 (X5Y4) 推荐方案
Optimal outrigger location 最佳悬臂位置	X direction X方向	13,678	5,678	5,678	15,678
	Y direction Y方向	13,467	2,567	1,567	1,567
Y direction period Y方向周期		9.05	9.16	9.22	9.22
X direction period X方向周期		8.69	9.06	9.07	8.98
Maximum story drift 最大层间位移		1/504	1/507	1/510	1/509
Y direction shear-weight ratio Y方向剪力重量比		1.13%	1.11%	1.11%	1.11%
X direction shear-weight ratio Y方向剪力重量比		1.14%	1.13%	1.13%	1.16%
Steel saved(t) 钢材节约量		--	2032	1948	1009

Table 3.21. Recommended schemes (Source: Moukui Xu)
表3.21. 原设计方案与推荐方案对比 (来源: 许谋奎)

Recommended Scheme 1

The optimal approach would be to place outriggers in the X-direction at the 5th, 6th, 7th and 8th zones, and in the Y-direction at the 2nd, 5th, 6th and 7th zones; providing four outriggers in both the X- and Y-direction. This scheme reduces by one outrigger level in both the X and Y direction, compared to the original scheme without optimization. This represents a saving of 2,032 metric tons of structural steel compared with the original design.

Recommended Scheme 2

The optimal approach would be to place outriggers in the X-direction at the 5th, 6th, 7th and 8th zones, and in the Y-direction at the 1st, 5th, 6th and 7th zones, providing four outriggers in both the X- and Y-direction. This scheme calls for one less outrigger in both the X and Y direction as compared to the original scheme without optimization. This represents a savings of 1,948 tons of structural steel compared to the original design.

Recommended Scheme 3

The optimal approach would be to place outriggers in the X-direction at the 1st, 5th, 6th, 7th and 8th zones, and in the Y-direction at the 1st, 5th, 6th and 7th zones, providing five outriggers in the X-direction and four outriggers in the Y-direction. This scheme calls for one less outrigger in the Y-direction compared to the original scheme without optimization. This equates to a savings of 1,009 metric tons of structural steel compared to the original design.

From the above-recommended schemes, the design indices remain almost the same, while the steel tonnages are greatly reduced when compared with the original outrigger scheme without optimization. This case shows the importance of the optimal design for the outrigger system, and the Multi-Constrained Sensitivity Method is effective for the optimal outrigger design of supertall buildings.

Conclusions

The optimal design of outrigger systems depends upon the optimal number and placements of the outrigger trusses. A Multi-Constrained Sensitivity Method is proposed in this chapter for finding the optimal placement and number of outriggers under multiple constraints, especially the story drift and vibration period. The Suzhou Zhongnan Center was employed as an example to show the applicability and effectiveness of this method.

The following conclusions can be drawn from this study:

1. The optimal design of the outrigger system under one constraint does not necessarily capture the optimal design under other constraints
2. The optimal combination of multiple outriggers can be effectively obtained by using the sensitivity number method under a vibration-period constraint
3. The optimal design of outrigger systems for engineering application purposes can only be achieved by comprehensively considering multiple design constraints
4. The optimal design of an outrigger system can greatly reduce the structural steel tonnage; the proposed Multi-Constrained Sensitivity method is effective for the optimal outrigger design of supertall buildings

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伸臂系统优化的重要性可见一斑。多约束条件下的灵敏度方法在超高层结构伸臂桁架最优设计中是高效的 。

结论

伸臂系统的优化设计由伸臂桁架布置的最优数量和位置构成。本文提出了一种灵敏度方法来获取在多约束条件 (尤其层间位移角和周期约束) 下伸臂桁架布置的最优数量和位置。

通过对中南中心的案例分析阐述了该算法的运用过程及其有效性，获得了以下结论:

1. 伸臂系统在某一约束条件下的最优布置方案在另一约束条件下并不一定是最优的
2. 伸臂系统在周期约束条件下的最优布置方案可以通过灵敏度数量算法获得
3. 只有对各种约束条件有全面的理解才能在实际工程中获得伸臂系统的最优方案
4. 伸臂系统的优化设计可以大幅降低结构用钢量，文章提出的多约束条件下的灵敏度方法在超高层结构伸臂桁架最优设计中是高效的。

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References (参考书目):

Coull, A. and Lau, W.H.O., (1998) **Outrigger Braced Structures Subjected to Equivalent Static Seismic Loading**, Proc. 4th Int. Conf. on Tall Buildings, Hong Kong and Shanghai, Y.K. Cheung and P.K.K.Lee (Eds.), vol.1, Hong Kong, pp. 395-401.

Ding, J.M., (1991) "The Optimal Location of Horizontal Belt Truss and Lateral Displacements Reduction Factor in High-Rise Building," **Building Structure**, vol. 2, pp. 10-13 /In Chinese

Smith, B.S. and Nwaka, I.O., (1980) **Behavior of Multi-Outrigger Braced Tall Building Structures**, ACI Special Publication SP-63 (Reinforced concrete structures subjected to wind and earthquake forces), pp. 515-541.

Wu, J.R. and Li, Q.S., (2003) "Structural Performance of Multi-Outrigger-Braced Tall Buildings," **The Structural Design of Tall and Special Buildings**, vol. 12, pp. 155-176.

Zhao, X, Liu, N.X. and Zheng, Y.M., (2011) "Sensitivity Vectors Algorithm for the Optimal Arrangement of Outriggers for Supertall Buildings," **Building Structure**, vol. 41, 5, pp. 20-23/In Chinese