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Seismic Action Reduction in Supertall Building Design
超高层建筑结构减小地震作用的方法


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Abstract

Per building design practice in China, structural engineer will carry on more detailed analysis in design development stage when schematic design is approved. For a supertall building, when its height exceed the code limitation, a structural engineer will mainly focus on performance based seismic design which is required by China seismic code, and prepare seismic expert review report in design development stage. It is a common method in the design to increase structural stiffness and member size to meet seismic performance requirement, which will in turn increase the seismic action. Therefore, it is necessary for a design engineer to carry on structural analysis to minimize seismic force in order to achieve a rational, high- efficiency and cost- effective structural design. In this paper the authors have studied the ways to reduce seismic action to a value which is as close as to the minimum base shear force specified in the code, through influence of mass, stiffness and damping of a structural system. The analysis result using this method is provided for an example of 310m tall building in a strong seismic zone.

Keywords: Supertall building; Seismic Design; Seismic Action Reduction; Mass; Stiffness; Damping

摘要

按照中国建筑设计流程，超高层建筑在方案审批通过后，进入初步设计阶段，进行更详细的结构分析。当建筑高度超出规范限值时，该阶段结构设计的主要内容之一是按照中国抗震规范要求，进行超限高层结构的抗震性能化分析，并准备抗震审查报告给专家审批。这个阶段为了满足抗震性能目标的最低要求，设计者往往采用原结构方案增加刚度和增大构件尺寸的方法，而刚度增加后实际上也加大了地震作用。因此，为了实现一个合理、高效、经济的结构设计，进行减小地震作用的分析十分必要。本文将探讨通过对质量、刚度和阻尼的干预，以达到减小地震力使其尽量接近规范规定的最小基底剪力的目的。按照本文提出的方法，并结合高烈度区一栋310米的超高层结构设计实例，给出了分析结果。

关键词: 超高层建筑; 抗震设计; 减小地震作用; 质量; 刚度; 阻尼

Introduction

In China a building design is normally divided into three stages – schematic design stage, design development stage, and construction documentation stage. In schematic design stage the designer shall explore several options and choose a best scheme according to given design parameters, codes and standards, loads, and materials. In design development stage, more detailed analysis will be carried out to optimize the structural elements based on the scheme chosen. For a building in seismic region, it is important to perform analysis on seismic action reduction to achieve a high efficient structural design.

For a supertall building under seismic action, in addition to static analysis, dynamic analysis and performance based design (including linear, non linear elasto-plastic methods) are also required in the design process. The dynamic response of a tall building is governed by several factors, including its shape, intrinsic and supplementary damping,

前言

在中国建筑设计过程一般被划分为方案、初步设计和施工图设计阶段等三个阶段。方案阶段的工作是在确定设计参数、规范、标准、荷载及材料后，设计者往往需要经过多方案比较，找出一个综合最佳的方案。 初步设计阶段的工作是在已确定的方案基础上，对结构构件进行深化和优化。对地震区建筑，要获得一个高效的结构设计，进行减小地震作用的分析是十分重要的。

对地震作用下的超高层建筑，除满足静力分析的规范要求外，还需满足动力分析和抗震性能化目标的要求(包括线性、非线性弹塑性分析方法)。高层建筑的动力反应主要由几个因素控制，包括本身的形状、固有和外加阻尼、质量及刚度等对地震作用有很大影响。超高层建筑结构的优化实际操作往往是结合以往工程经验，在已确定结构方案体系的基础上，通过调整结构质量、刚度和阻尼，以取得规范规定的最小地震力，并按此进行结构设计。

mass and stiffness. Therefore, in real design process of a supertall building, in order to obtain a result which is close to minimum seismic base shear force specified in the code a designer will use one's experience to adjust structural mass, stiffness and damping to reduce structural seismic response.

One of the main issues in a supertall building design is to control lateral deformation by providing a rational stiffness with minimum construction cost under wind and seismic action. When a seismic action takes control in the design, it is suggested to reduce the mass and stiffness, and use simple and regular structural system. When a wind load takes control in the design, it is suggested to increase the mass and stiffness, and use linked structures when it is possible, which could decrease the top level acceleration to meet comfort requirement. When both take control in the design, a balanced consideration shall be given to all relevant factors. For both wind and seismic loads, the structure will get benefit to reduce lateral deformation from increasing structural damping.

For a supertall building in a seismic region, in order to meet its performance design requirements, the structural design criteria in terms of concept, analysis, and detailing are more stringent than that of a normal tall building. As a result, the supertall building cost will be higher. Hence it is necessary to carry out special analysis on minimization of structural seismic response in detailed design stage.

Case Study

The project (see Figure 1, 2 and 3) is located in Xishan district of Kunming city, China. It is a 310 m high (structural roof level is 298 m) office building. The structural system using four strengthening levels (three outriggers and four belt trusses) in refuge floors is comprised of composite circular column (steel encased with high strength concrete) and composite core wall (concrete encased with steel columns)- a mixed structural system. The floor is made of composite steel deck on top of composite steel universal beam. The project is designed to resist 8 degree seismic fortification intensity (group 3). The basic design acceleration of ground motion is 0.2g, the site soil classification is type 3, and the characteristic period of the seismic response spectrum is 0.65 second. The wind pressure in 50 years return period is 0.3 KPa per China load code. The main member sizes and material used are as described below.

For composite column, the corner column size changes from 2400mm diameter at the bottom level to 1200mm diameter on the top level, and the other column changes from 2000mm diameter at the bottom level to 1000mm diameter on the top level. Steel grade is Q390GJ and concrete grade is C60. The columns on top one-third part are inclined.

For composite shear wall, the exterior wall thickness changes from 1300mm at the bottom level to 400mm on the top level, and the interior wall thickness changes from 500mm at the bottom level to 300mm on the top level. Steel grade is Q345B and concrete grade is C60.

For composite steel beam on typical floor, its height is 500mm and Q345B steel is used. For slab, 150mm concrete slab is placed inside the core, 110mm composite deck slab is placed outside the core, and 180mm composite slab is used in outrigger level and adjacent levels.

The composite spandrel beam is 1000mm in height and Q345 steel is used.

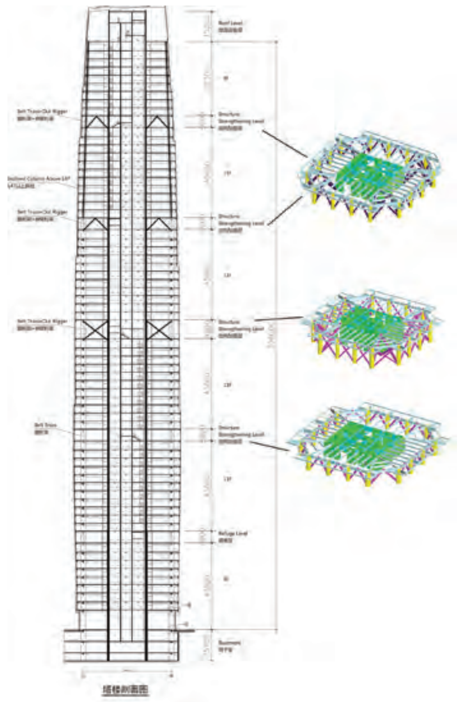

Figure 1. Section (Source: Buro Happold)
图1.结构剖面图 (出自: Buro Happld)

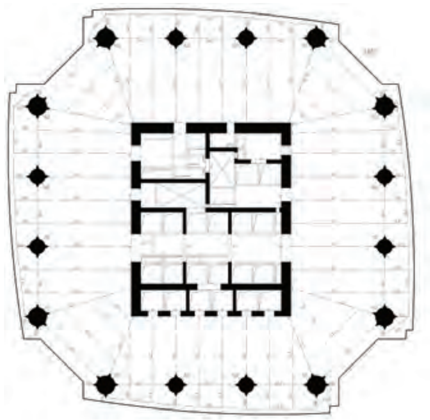

Figure 2. Typical floor pan(Source: Buro Happold)
图2. 标准层结构平面图(出自: Buro Happld)

Figure 3. Site construction (Source: Buro Happold)
图3. 现场结构施工(出自: Buro Happld)

For the bottom strengthening level, only belt truss is placed (as required by expert review comments). For other three strengthening levels, both belt truss and outrigger are placed. Q420GJC steel is used.

The design is governed by seismic action, and the wind load can be ignored as it is relatively small. Seismic performance objective is Class C, and seismic performance levels for all structural members are defined accordingly per China codes (reference 1, 2).

Both SATWE and ETABS software are used in linear analysis for frequent seismic (50 years) and moderate seismic (475 years) events, and ABAQUS is used in non-linear elasto-plastic dynamic analysis for rare seismic (2475 years) event.

Seismic Action Reduction

The analysis of the dynamics of structures is based upon the use of a set of linear second-order differential equations. For a structural model with n degrees-of-freedom, the equations can be written in the following form:

$$[m]\{\ddot{x}\}+[c]\{\dot{x}\}+[k]\{x\}=-[m]\{I\}\ddot{x}_g(t)$$

Where:

$[m]$= mass matrix

$[c]$= damping matrix

$[k]$= stiffness matrix

$[x]$= vector of displacements

These equations are a statement of Newton's Second law involving all of the DOFs which are chosen for the model. The coefficient matrices are mass, damping and stiffness. The inertial force is caused by ground acceleration.

Using superposition, the total response of the MDOF system can be obtained by solving the n uncoupled modal equations and superposing their effects. The time domain solution is expressed by the Duhamel integral. Per China seismic code (reference 1), mode-superposition response spectrum method is the basic method for tall building in seismic analysis. The standard value of seismic force on mass i caused by mode j without considering coupling can be expressed as:

$$F_{ji}=\alpha_j\gamma_j X_{ji}\,G_i \quad i=1,2,\ldots.n;\; j=1,2,\ldots.n$$

$$\gamma_j=\sum_{i=1}^{n}X_{ji}G_i\Big/\sum_{i=1}^{n}X_{ji}^2G_i$$

In which:

F_{ji} = Lateral seismic force standard value caused by mode j on mass i

α_j = Seismic influence coefficient due to mode j. It is related to seismic intensity, site classification, seismic group, structural period, and damping ratio

X_{ji} = Lateral displacement caused by mode j on mass i

γ_j = Mode j participation coefficient

According to above equation, following methods could be taken in order to reduce seismic action on a structure:

超高层结构设计的主要矛盾之一是侧向刚度和侧向位移的矛盾，具体是如何在最经济的情况下对风和地震作用产生的变形控制在合理的范围内。通常当地震作用控制结构设计时，宜减轻自重、减小刚度、并采用简单形体的单体建筑。但在风荷载控制设计时，宜加大自重、增加刚度、并在可能时采用连体建筑，以便减小结构顶部风振加速度，控制舒适度，反而能取得更好的效果。在特定情况下，地震和风共同控制结构设计，此时需要综合考虑各项因素。不论风荷载还是地震作用，增加结构的阻尼对控制结构反应和水平变形都是有效的。

对于地震区的超高层建筑，为满足抗震性能目标的要求，结构在概念设计、结构分析和抗震措施方面都比非地震区高层结构有所提高，导致结构造价较高。因此在初设阶段，对其专门进行结构地震反应的最小化分析显得十分必要。

工程案例

案例位于昆明市西山区 (见图1、图2和图3)，为一栋310m超高层写字楼(结构主屋面高度298米)，结构采用钢管混凝土框架柱和内插钢骨的钢筋混凝土剪力墙核心筒，并在避难层设置四道结构加强层(三道伸臂桁架和四道腰桁架)，形成框架-核心筒混合结构体系。楼面采用钢梁和压型钢板组合楼板体系。项目所在场地属8度设防地震区，地震分组为第三组，设计基本地震加速度值为0.2g，场地类别为III类，特征周期Tg=0.65秒。按中国荷载规范50年一遇的基本风压为0.3KPa。 主要构件材料及尺寸如下所述:

外框柱采用钢管混凝土柱，角柱直径为2400mm~1200mm，中间柱直径为2000mm~1000mm，钢材等级采用Q390GJ，内灌混凝土等级为C60。柱子在上部三分之一的楼层内倾成斜柱。

核心筒外墙厚度为1300mm~400mm，内墙厚度为500mm~300mm。核心筒内插型钢，型钢等级采用Q345B，混凝土等级为C60。

典型楼层楼面钢梁为500mm高工字型钢梁，钢材等级为Q345B 。核心筒内的楼板采用150mm厚混凝土楼板，核心筒外楼面板为110mm厚压型钢板--组合楼板，加强层及其上下相邻层的组合楼板加厚为180mm。

外围框架梁为1000mm高工字型钢梁，钢材等级为Q345B。

最下部加强层仅布置腰桁架 (专家审查后采取的加强措施)，其他三个加强层同时布置了腰桁架和伸臂桁架。钢材等级为Q420GJC。

本工程风荷载较小而地震作用较大，设计中地震荷载起控制作用。按照中国规范(文献1、2)，工程抗震设计性能目标定为C，并按对应的抗震性能目标对不同类型构件进行设计和校核。

小震(重现期50年)和中震(重现期475年)采用软件SATWE和 ETABS进行分析， 大震(重现期2475年)采用软件ABAQUS 进行分析。

减小地震作用的方法

结构动力分析都是基于应用一组线性二阶导数方程。对于一个有n个自由度的结构，结构动力学方程如下:

$$[m]\{\ddot{x}\}+[c]\{\dot{x}\}+[k]\{x\}=-[m]\{I\}\ddot{x}_g(t)$$

- Reduce its mass
- Reduce its stiffness (but must meet displacement and comfort requirements), which will increase period and reduce seismic influence coefficient.
- Increase its damping (intrinsic and supplementary), which will reduce Seismic influence coefficient.

Therefore, when a structural system is determined, minimum seismic action specified by the code can be obtained by reducing structural mass and stiffness, or by increasing its damping ratio in structural analysis. For a performance based seismic design, this minimum action shall include frequent earthquake, moderate earthquake, and rare earthquake.

Thus the seismic action minimization problem can be simplified in following forms:

$$\min f(X)$$
$$X \in \Omega$$
$$h(X_i) = 0$$
$$S(X_j) \geq 0$$

$f(X)$ = objective function. Calculate the values of the objective function in different cases, and then compare all of them to find out the minimum value of the objective function. $X \in \Omega$ = a set of constraint. $h(X_i)$= equality constraint. $S(X_j)$=inequality constraint.

The purpose for this project is to obtain a minimum value of seismic action on the structure, which will minimize the structural material consumption and construction cost.

A practicable method in the design is to minimize seismic force under frequent seismic action, then to check the performance objectives under moderate and rare seismic action. For a member that can't meet the performance objective, it can be strengthened by increasing its size, reinforcement ratio or other methods. The building structure behavior is in elasticity under frequent seismic action, so linear method applies to frequent seismic analysis, commercial structural software can be used in minimizing seismic action process (see Figure 4).

The key index in output for assessment is that the seismic force calculated by the software shall be as close as the minimum value that can be measured by the base shear force over mass ratio given by the seismic code. The other indexes (constraints) will be checked to meet the code requirements to make sure the structure will not go extreme in irregularity and complexity , including top three primary frequencies(normally two translation and one torsion), inter-story drift to control lateral displacement, ratio of maximum displacement over average displacement of the plate to control torsion effect, wall and column axial compression ratio to provide suitable ductility, stiffness ratio between adjacent story to prevent "soft story", shear capacity ratio between adjacent story to prevent "weak story", torsion period over primary period ratio to ensure torsion capacity is relatively strong, and shear force taken by exterior frame for a frame- core wall system to ensure frame can work as secondary seismic resistant system. If the result can't meet the design requirement, the engineer will revise the input parameters (geometrical and physical) and run the model again. This process will be repeated until the seismic shear force is close to the minimum value given by the code.

其中:

$[m]$ 为质量矩阵;

$[c]$ 为阻尼矩阵;

$[k]$ 为结构刚度矩阵;

$[x]$ 为位移反应矩阵; [X.] 为速度反应矩阵; [X..] 为加速度反应矩阵; [X..] g为地面输入加速度矩阵

这个方程用牛顿第二定律表达了结构所有自由度的振动规律。质量、阻尼和刚度参数矩阵是结构固有性质的常量。结构惯性力由地面运动加速度引起。

采用振型分解法，多自由度结构体系的地震响应，可以通过n个独立的单自由度求解后叠加得出总反应。时域的解可以通过杜哈曼积分表达。按照中国规范 (文献1)，振型分解反应谱方法是高层建筑抗震分析的基本方法。采用振型分解反应谱法时，不进行扭转耦联计算的结构，结构 j 振型 i 质点的水平地震作用标准值，应按下列公式确定:

$$F_{ji} = \alpha_j \gamma_j X_{ji} G_i \quad i = 1,2,....n; \; j = 1,2,....n$$

$$\gamma_j = \sum_{i=1}^{n} X_{ji} G_i \Big/ \sum_{i=1}^{n} X_{ji}^2 G_i$$

式中:

F_{ji} 为j 振型 i 质点的水平地震作用标准值;

α_j 为相应于 j 振型自振周期的地震影响系数，根据地震烈度、场地类别、设计地震分组和结构地震周期以及阻尼比确定。

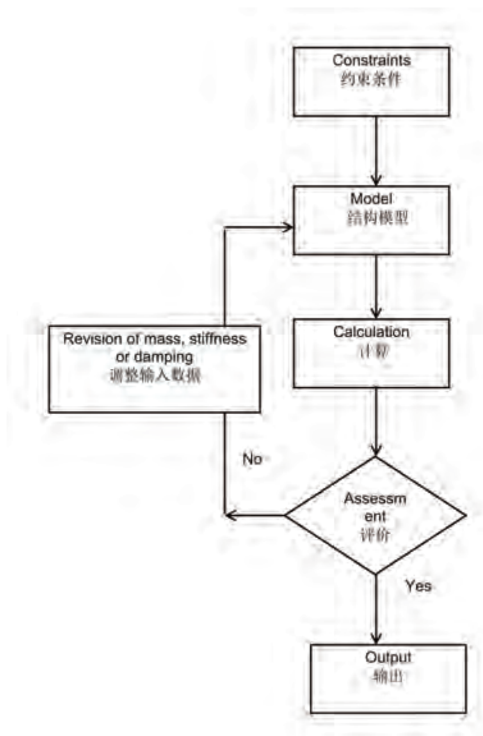

Figure 4. Minimization seismic action process
图4. 地震作用最小化设计流程

Source of mass 质量来源	Column 柱	Shear wall 剪力墙	Beam 楼面梁	Slab 楼板	SDL 附加恒载	50%LL 50% 活载	SUM 合计
Mass (t) 质量	41,000	65,000	22,000	46,000	44,000	26,000	244,000

Table 1. Mass from Different Sources
表1. 结构质量的构成

Influence of mass

The project is located in a high seismic intensity zone and the seismic force is large. As the base shear force will increase with the mass, so it is necessary to reduce the mass, especially the mass on top levels, to reduce the seismic action.

The mass used in seismic analysis is composite of column, wall, beam, slab, partition, façade, super imposed dead load, and 50% live load (see Table 1). Following rules are found in the structure analysis model:

- For shear wall, due to wall thickness variation the mass on each floor is reduced from 1250t at the bottom level to 500t on the top.
- For column, due to size variation the mass on each floor is reduced from 780t at the bottom to 300t on the top.
- The mass of beam and slab is about 300t for typical floors. The top floor is 200t due to gradually reduction of floor area on top part of the tower. The mass on MEP/refuge level is significantly larger than that on typical floor.
- The mass due to super- imposed dead load and live load is proportional to the area of each floor plate.

Using above method and following a pattern that the stiffness of the structure varies from large to small along its height in order to resist lateral load efficiently, i.e. the shear wall and column size shall be decreased gradually along the structural height. Considering all constraints, the seismic force calculated by the software shall be as close as to the minimum base shear force measured by the force over mass ratio given by the seismic code. In this case, the shear force to mass ratio is about 2.7% which is a slightly larger than 2.4% of the minimum base shear force to mass ratio stipulated by the code (see Table 2).

Owing to the total mass reduction by about 7.8%, the base shear force is reduced by 8.3% in both directions.

Influence of Stiffness Due to Different Outrigger Configuration

Structural stiffness is a key factor in a supertall building design in high seismic intensity zone. For a structure when its stiffness is decreased, which means smaller vertical member, less mass and less seismic force, the structure may not meet the requirements of lateral resistance. When its stiffness is increased, which means it will attract more seismic force, the structure may not cost effective. In this case, configuration of outriggers will be studied as it has a great impact on structural stiffness, and a best structural scheme will be obtained through analysis on different configuration of outriggers. Considering all constraints, the seismic force calculated by the software shall be as close as to the minimum shear force measured by the force over mass ratio given by the seismic code.

Outrigger configuration study is performed after many time revisions of vertical structural member size (core wall and column) to reduce structural seismic response. Following the minimization seismic action

Model 模型		Original model 原方案模型	Optimization model 优化后模型
Mass (t) 总质量		244,268	225,213
Period (s) 周期	T1(s)	5.5587	5.4348
	T2(s)	5.4757	5.3318
	T3(s)	3.128	3.2857
Max. displacement (mm) 最大位移	X	415	413.5
	Y	416.7	410.5
Max. inter-story displacement angle 最大层位移角	X	1/550	1/540
	Y	1/543	1/560
Base shear (KN) 基底剪力	X	67,163	61,620
	Y	66,574	60,871
Shear/Mass ratio 剪重比	X	2.75%	2.74%
	Y	2.73%	2.70%

Table 2. Results Influenced by Revision of Mass
表2. 质量调整对分析结果的影响

X_{ji} 为j 振型 i 质点的水平相对位移;

γ_j 为j 振型的参与系数。

根据以上方程，对一个已确定结构体系的建筑来说，减小地震作用的方法一般有:

- 减小质量
- 减小刚度 (须满足位移和舒适度等要求)，可增大周期，减小地震影响系数
- 增加阻尼 (外加阻尼器或固有阻尼)，可减小地震影响系数

因此在初步设计阶段，在结构抗力体系基本确定的情况下，结构地震作用最小值可以通过减小质量和刚度，或增大阻尼实现。对抗震性能化设计，这个地震作用分别对应小震、中震和大震。

因此这个地震作用最小化问题一般可简化为如下形式:

$$\min f(X)$$
$$X \in \Omega$$
$$h(X_i) = 0$$
$$S(X_j) \geq 0$$

其中: $f(X)$ 求其最小值; 优化过程就是优选X向量，使目标函数达到最小值; $X \in \Omega$为集约束，是其优选向量的可行取值范围。 $h(X_i)$ 为等式约束， $S(X_j)$ 为不等式约束。

本工程的目标就是通过最小化结构地震反应，在满足规范要求的情况下使得结构造价最低，材料用量最少。

比较实用的方法是对小震作用下结构的地震作用最小化后，再按弹塑性分析方法对中震和大震的抗震性能目标进行复核。对于少数大、中震时性能目标不满足的构件，可以通过加大构件尺寸和提高配筋率等实现。小震时结构工作处于弹性状态，所以小震设计属于线形分析，所以可以利用目前的高层结构设计通用软件实现地震作用的最小化 (见图4) 。

Scheme 方案		Scheme 1 方案1	Scheme 2 方案2	Scheme 3 方案3
Outrigger floor 设加强层楼层		10, 22, 34, 46, 58	22, 34, 46, 58	34, 46, 58
Total mass (t) 模型总质量		241,749	241,143	240,665
Periods (s) 周期	T1(s)	5.5325	5.6285	5.828
	T2(s)	5.4911	5.5917	5.7616
	T3(s)	2.8069	2.8672	2.9207
Max displacement (mm) 最大位移	X	414.1	424.5	442.3
	Y	412.7	421.8	433.9
Max story drift angle 最大层位移角	X	1/505	1/505	1/502
	Y	1/529	1/526	1/523
Base shear (KN) 基底剪力	X	70,811	68,854	66,533
	Y	70,599	68,446	67,093
Shear/Mass ration 剪重比	X	2.93%	2.86%	2.76%
	Y	2.92%	2.84%	2.79%

Table 3. Comparison Results of Different Outrigger Numbers
表3. 不同数量加强层方案计算结果比较

Scheme 方案		Scheme 1 方案1	Scheme 2 方案2	Scheme 3 方案3	Scheme 4 方案4
Outrigger floor 设加强层楼层		22, 46, 66	10, 34, 58	34, 46, 58	22, 34, 46
Total mass (t) 模型总质量		240,482	240,511	240,665	240,660
Periods (s) 周期	T1(s)	5.8322	5.8228	5.828	5.6767
	T2(s)	5.7461	5.746	5.7616	5.6346
	T3(s)	2.8491	2.878	2.9207	2.8915
Max displacement (mm) 最大位移	X	440.3	443.3	442.3	439.5
	Y	429.4	433.6	433.9	432.5
Max story drift angle 最大层位移角	X	1/485	1/477	1/502	1/487
	Y	1/510	1/502	1/523	1/510
Base shear (KN) 基底剪力	X	67,995	67,868	66,533	68,005
	Y	67,736	68,592	67,093	67,544
Shear/Mass ration 剪重比	X	2.83%	2.82%	2.76%	2.83%
	Y	2.82%	2.85%	2.79%	2.81%

Table 4. Comparison Results of Different Outrigger Configuration
表4. 不同加强层布置方案计算结果比较

process, first the number of outrigger is studied and then its location. After studying on five, four and three outrigger configurations, it is found that three outrigger configuration can not only meet the design requirements, but also has the most effectiveness (see table 3). Based on three outrigger configuration, four different schemes have been studied (see table 4). It can be seen by sensitive study that the seismic force of scheme 3 gives smallest value. In this case, the shear force to mass ratio in X- way is about 2.76% which is a slightly larger than 2.4% of the minimum base shear force to mass ratio stipulated by the code.

The result from performance based seismic design using elasto- plastic time-history method shows that the optimized structure can meet the performance objective in moderate and rare seismic levels.

Influence of Damping

Damping is the degree of energy dissipation that a structure can provide, helping to reduce build-up of the resonant response. It comes from two main sources: intrinsic and supplementary. All buildings have intrinsic damping - from the structural materials, the foundations, the cladding, etc - but it is very difficult to calculate. For a supertall building, the intrinsic damping of buildings has high variability, and the trend is for expected damping to reduce with building height according to reference 3.

Increasing structural damp will decrease seismic influence coefficient, thus decrease seismic force and reduce construction cost. Supplementary damper has been more and more commonly used to increase structural damp in recent years. Viscous Damper and BRB (Buckling restrained brace) are two kinds of dampers in the market. By adding an engineered supplementary damping system to a building, it is possible to reduce dependence on the low and uncertain intrinsic damping. This improves the reliability of dynamic response predictions and, by supplying higher levels of damping, substantially reduces the required stiffness of the building and at the same time improving the performance.

The total stiffness of an energy dissipation structure is sum of structural stiffness and effective stiffness provided by the damper. The total damping ratio of an energy dissipation structure is sum of structural damping ratio and effective damping ratio provided by the damper.

采用结构分析软件对结果评价的主要指标，是计算出来的楼层最小地震剪力要尽量接近规范要求的最小剪重比。为保证 结构不至于严重不规则，其他指标 (约束) 的复核还包括前三阶周期(通常是两个平动周期及一个扭转周期)、层间位移角、位移比、墙和柱的轴压比、相邻楼层刚度比和抗剪承载力比(避免软弱层)、扭转和平动周期比(控制扭转)、外框架承担的剪力比(要达到一定比列以保证形成第二道防线)等指标。 如结果不满足设计要求，则需要对输入条件 (几何和物理) 进行调整，在修改分析模型和参数后，重新计算，然后对结果再次进行评价。经反复试算， 直到计算所得地震剪力接逼近规范给出的最小地震剪力为止。

质量的影响

案例位于高烈度地震区，地震荷载大。结构的基底剪力随结构质量增加而增大。故为了减少地震作用，需要减小结构的质量，尤其是减少上部结构的质量十分必要。

结构质量包括柱、剪力墙、梁、板、内隔墙、外幕墙的自重荷载，以及附加恒载和50%活荷载 (见表1) 。具体到每一楼层质量分布有以下规律:

- 剪力墙厚度随楼层高度逐渐减薄，质量也逐渐减小，从下部典型楼层的每层约1250t逐渐减小到上部楼层的每层约500t。
- 柱直径随高度逐渐减小，质量也逐渐减小，从下部典型层的每层约780t逐渐减小到上部楼层每层约300t。
- 各层楼面质量变化幅度较小，每层基本为300t左右。在上部楼层斜向收进区域，逐渐减小到每层约200t。但在设备层和避难层楼面，楼板较厚质量较大。
- 附加恒载、活荷载的对质量的贡献基本同楼板面积的变化趋势一致。

按照本节所述的方法，为有效抵抗侧向荷载，结构体系竖向构件刚度需遵循上小下大的原则，即结构剪力墙和柱尺寸沿高度逐渐变小。在满足其他约束条件下，尽量使计算所得楼层最小地震剪力接近规范要求的最小基底剪重比。本案例基底剪重比约2.7%，略大于规范给出的2.4%的最小剪重比 (见表2) 。

由于结构总质量减少约7.8%，在两个平动方向上的基底剪力均减小8.3%以上。

Seismic records 地震波	S0256		S0257		S8651		S8652	
	X	Y	X	Y	X	Y	X	Y
Without damper 设阻尼器前	1/342	1/448	1/653	1/740	1/712	1/801	1/570	1/633
With damper 设阻尼器后	1/464	1/489	1/833	1/803	1/1081	1/971	1/784	1/672
Reduction ratio 减振效果	35.67%	9.15%	27.57%	8.51%	51.83%	21.22%	37.54%	6.16%

Table 5. Maximum Story Drift Angle
表5. 层间位移角最大值

Seismic records 地震波	S0256		S0257		S8651		S8652	
	X	Y	X	Y	X	Y	X	Y
Without damper 设阻尼器前	70,327	47,622	42,969	39,915	41,566	39,730	54,787	54,449
With damper 设阻尼器后	56,557	49,161	37,360	28,848	37,332	37,388	44,788	49,696
Reduction ratio 减振效果	19.58%	-3.23%	13.05%	27.73%	10.19%	5.89%	18.25%	8.73%

Table 6. Maximum Base Shear Force (KN)
表6. 基底剪力最大值 (KN)

60 viscous dampers are placed on 5 refuge levels. On each level there are 8 dampers are placed in X direction and 4 in Y direction.

Four frequent seismic intensity records are input in time- history analysis, and the result of story drift angle and the base shear force are compared with that of a model without supplementary damper (see Table 5 and Table 6).

It can be seen that adding damper to a structure is an efficient way to reduce seismic force. Since more dampers are placed in X- direction the reduction of structural response is more obvious. The engineer shall study damper number, location and design parameters according to one's experience in seismic design.

Though structural analysis in seismic zone in regarding to mass, stiffness and damping are separately discussed above, all these factors can be considered together in design process. The degree of convergence will much depend on engineer's experience and knowledge. Therefore, there is no unique solution for minimization of seismic action.

Conclusion and Recommandation

In order to minimize structural seismic action, a practical analysis method based on model analysis has been studied with a supertall building in high seismic intensity zone in design development stage. The preliminary conclusion and suggestion are:

加强层布置的影响

高烈度区超高层的结构刚度控制十分关键。在同一个结构体系下，结构刚度减小意味着竖向构件尺寸减小，结构质量减小，地震作用减小，但减小竖向构件尺寸后不容易满足抗侧能力的要求; 而结构刚度增大，意味着会吸引更大的地震作用力，导致设计不经济。对本项目，不同加强层布置方案对结构刚度的影响较大，应重点加以研究，以找到最佳方案。在满足其他约束条件下，尽量使计算所得楼层最小地震剪力最接近规范要求的最小剪重比。

加强层的研究经过了多次对竖向构件 (核心筒墙和柱) 尺寸的调整以减小地震反应的基础上进行的。按照本节所述取得最小地震作用的流程，首先对所需加强层数量进行分析，然后对其位置进行优化。经过对比采用5道、4道和3道加强层分析后发现，3道加强层方案可以满足设计要求，且效率最高 (见表3) 。在此基础上，对3道加强层的四个布置方案的分析结果进行对比 (见表4) 。经过敏感性分析，加强层采用方案3时，结构在两个平动方向上的地震力最小。本案例X方向基底剪重比约2.76%，略大于规范给出的2.4%的最小剪重比。

根据确定的抗震性能目标和构件对应的中震和大震的抗震性能水准，对优化后的结构进行弹塑性分析，校核构件的承载力和变形指标。结果表明质量和刚度优化后的结构完全满足性能化设计的要求。

阻尼的影响

阻尼是结构对能量耗散的程度，有助于减少结构在外荷载下的共振响应。 它来自两个方面: 固有阻尼和外加阻尼。所有结构具有固有阻尼: 来自结构材料、基础、外幕墙等，但很难准确计算。根据文献3的研究，超高层建筑的实际阻尼比变化很大，而且有随高度减小的趋势。

增大结构的阻尼比，会降低结构的地震响应，从而节约造价。近年来越来越常用的方法是采用外置阻尼器来增大结构阻尼。目前比较成熟的阻尼器有粘滞型阻尼器和约束屈曲型支撑。通过在结构上设置阻尼器，可以减少对较小的和不确定的固有阻尼的依赖。提供较大的外部阻尼不仅会增加动力分析的可靠度，而且减低了对结构侧向刚度的需求，提高结构抗震性能。

耗能减震结构的总刚度应为结构刚度和耗能部件有效刚度的总和。耗能减震结构的总阻尼比应为结构阻尼比和耗能部件附加给结构的有效阻尼比的总和; 多遇地震和罕遇地震下的总阻尼比应分别计算。

本项目选用60套粘滞型阻尼器，并将其分别设在5个避难层。每层横方向8套，纵方向4套。

选用了4条记录地震波作小震弹性时分析，分别对设置阻尼器前后的层间位移角和基底剪力计算结果进行比较 (见表5、表6) 。

可见阻尼器对减小地震作用是十分有效的。由于X方向刚度较弱，因此布置的阻尼器数量也较多，减震效果也更为明显。阻尼器的布置、数量和选型对结构地震反应的影响，结构工程师需根据经验和计算确定。

虽然上述案例分别对质量、刚度和阻尼进行了结构抗震分析，实际设计时也可以同时考虑各因素。最终收敛程度取决于设计人员的经验和知识水平，因此地震作用最小化的方法没有唯一解。

1. Structural seismic action reduction can be achieved through modification of mass, stiffness and damping.
2. Outrigger configuration has impact on structural seismic action. Study on outrigger configuration is suggested to reduce seismic force.
3. Adding dampers onto a structure can reduce seismic force. A damper manufacture consultant shall be engaged early in the project to explore different options, and potential benefit of using damper device.
4. More study on seismic action reduction is recommended, especially in considering elasto- plastic analysis for a supertall building in seismic design.

结论与建议

本文结合一个高地震烈度区的超高层办公楼工程案例，对超高层工程初步设计阶段，采用建立在分析模型基础上的结构实用分析方法，对如何减小结构地震作用进行了研究，初步结论和建议如下:

1. 通过对质量、刚度和阻尼的调整，可以减小结构上的地震作用。
2. 结构加强层数量和布置对结构地震作用有一定的影响。建议对其进行敏感性分析，以减小结构上的地震力。
3. 设置外部阻尼器对减小地震作用效果明显。设计初期应与阻尼器生产商尽早接触，共同探讨不同方案和给项目带来的利益。
4. 建议今后加强对超高层结构减小地震力的研究，特别是结构抗震弹塑性分析阶段减小地震作用的研究。

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