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Structural Performance Upgrading and Optimization of Supertall Residential Buildings | 超高住宅结构性能提升与优化

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Abstract | 摘要

Due to huge investment amounts, supertall residential buildings are commonly developed as luxury properties whose building performance requirements are high. Typical requirements include large interior spaces, broad vision, expansive balconies, and indoor swimming pools, etc. The structural design for the lateral system of supertall building is commonly controlled by stiffness and human comfort performances under lateral loads for which the aforementioned requirements are disadvantageous. The developers manage the construction costs to increase yield rate. However, these requirements reduce the structural efficiency, and thus increase the construction cost control difficulty. The discrepancies between performance, efficiency and cost have to be resolved by introducing proper performance upgrading and optimization methods. A supertall residential building cluster located in Xiamen, namely Dijingyuan project, is employed to investigate these methods which cover various aspects, such as loads, materials, systems, structural layouts, vibration control devices, optimization algorithm, model parameters, and connection upgrading etc.

Keywords: Human Comfort, Lateral System and Stiffness Performance, Performance Upgrading, Structural Optimization, Super Tall Residential Buildings

由于投资庞大，超高住宅通常定位为豪宅，对建筑性能要求高，典型要求包括高大空间、开阔视野、大悬挑露台、室内泳池等等；超高结构抗侧力系统的设计通常由水平荷载下的刚度和舒适度性能控制。上述建筑性能的要求对结构抗侧力系统的刚度和舒适度性能控制是不利的；从开发单位角度，希望能够对建设成本进行严格控制以获得更高的投资收益。由于这些要求对结构性能的控制不利，显著降低了结构效率，从而增加了成本控制的难度。综上，性能、效率以及成本之间存在矛盾，需要通过合理的性能提升及优化设计方法寻求最佳解决方案。本文通过厦门帝景苑项目案例对超高住宅项目的建筑性能提升和结构性能优化方法进行了研究探讨，研究内容涵盖荷载、材料、体系、结构布置、减振装备、优化算法、模型参数和构件节点等等。

关键词：人体舒适度、抗侧力体系和侧向刚度、性能提升、结构优化、超高住宅

Introduction

Following the high growth of the economy and fast improvement of the urbanization level, there will be several hundred million rural immigrants pouring into cities. A large amount of residential buildings need to be provided to meet the need of housing. Compared with the horizontal extension of low-rise buildings, the vertical extension of supertall residential buildings makes a high density living mode possible, which is more suitable for the shortage of land resources in China. Accompanied by the increasing requirement of dwelling environment, a growing number of super high-rise residences are emerging in first and second tier cities. In comparison to common residences, the vertically spreading space within supertall residential buildings can bring a refreshed and open-minded mood to the residents. The characteristics of low humidity, excellent ventilation, more sunlight and good air quality make it pretty suitable for living. As the

引言

随着中国经济的不断发展和城市化进程的加快，城市需要给不断涌入的人口提供大量住宅。相比水平方向的不断延伸，超高住宅的密度聚居方式更适合中国有限的土地资源现状。物质与社会文明的进步，使人们对于居住环境的要求越来越高，越来越多的高档超高住宅在中国的一、二线城市中涌现出来。

相比于普通住宅，超高住宅的竖向高度更易给住户带来舒畅、豁达的居住心理，湿度小、通风好、日照好、空气质量优良等特点也体现了超高住宅的宜居性。高档超高住宅更加注重用户的居住体验，在建筑性能上通常有更高的要求，如高大空间、开阔视野、大悬挑露台、室内泳池等等。一方面，超高结构抗侧力系统的设计通常由水平荷载下的刚度和舒适度性能控制，上述建筑性能的要求对结构抗侧力系统的刚度和舒适度性能控制是不利的，显著降低了结构效率；另一方面，开发商希望能够对建设成本进行严格控制以获得更高的

advanced supertall residential buildings lay more stress on the residential experience, the requirements for architectural performance are usually higher, such as large interior spaces, broad vision, large cantilever balconies and indoor swimming pools.

On the one hand, the lateral system design of supertall structures is generally controlled by indicators of stiffness and human comfort under lateral force. And the aforementioned architectural performance is unfavorable for these indicators and will remarkably reduce the efficiency of structures. On the other hand, the developers expect that the construction cost can be controlled, strictly aiming to a higher investment yield. Hence a huge contradiction is generated among performance, efficiency and cost, the solution of which can be sought in performance upgrading and optimization methods.

In this paper, the architectural and structural performance requirements of supertall residential buildings are discussed, and a performance based optimal design method is introduced. The case of the Dijingyuan project in Xiamen is chosen for the research of architectural performance improvements and structural performance optimization, which includes loads, materials, structural systems, structural layout, vibration absorbers, optimization algorithms, model parameters and member joints.

Theoretical Basis

Performance Requirements

Architectural Performance Requirements

For supertall residential buildings, not only vertical transport, fire safety and evacuation should be satisfied, but space beautification also needs to be pursued further to create a peasant residential mentality. The typical requirements are listed below.

- *Large interior spaces and broad vision*
  A space of small area, low height and closure will make people inside feel depressed. On the contrary, a space of large area, great height and broad vision can bring a comfortable and pleasant residential mentality. To achieve that effect, large interior space areas, great net ceiling heights and unobscured sights are required. The advantage of super vertical height renders the inhabitants a panoramic view of the urban scene outside. However large interior spaces and broad vision will lead to flat beams and demolishing columns, which reduce the structural efficiency and increase the construction cost.
- *Large cantilever balconies and indoor swimming pools*
  With the courtyard space regressing and evolving in modern architecture, it gradually draws more attention in the design of supertall residences. For instance, staggered floor balconies as a set or part of a volume are excavated to acquire a full height of two floors; plane dimension is amplified to gain a larger activity space. The existence of large cantilever balconies and indoor swimming pools can help construct a livable atmosphere and draw closer to the natural environment. But the large cantilever and huge load will doubtlessly consume a mass of material and raise the construction cost.

Structural Performance Requirements

The lateral load applied on the supertall structure is relatively greater. The overturning moment caused by the lateral load and the axial force in the vertical members caused by the overturning moment are in proportion to the square of the structure height. Therefore, the lateral load becomes the controlling factor in the design of supertall residences. The requirements of seismic and wind-resistant performance are listed below.

- *Seismic performance requirements*
  According to the goals of seismic performance requirements, a series of indicators should be satisfied by the structures including global, assembly and component aspects (Figure 1) (Dong, 2015).

Seismic Performance 抗震性能	Design Requirements 设计要求	Component Requirements 构件要求	Assembly Requirements 组件要求	Global Requirements 整体要求
Component strength | 构件强度	Strength | 强度	√		
Component stability | 构件稳定	Stability of structural members 构件稳定性	√		
Component ductility | 构件延性	Compressive axial ratio of columns and walls 墙、柱轴压比	√		
Component stiffness | 构件刚度	Shear deformation | 剪切变形	√		
Multiple guard lines | 多道防线	Proportion of frame shear to story shear 外框承担剪力比		√	
Overall stiffness | 整体刚度	Story drift | 层间位移角			√
Overall strength | 整体强度	Shear-weight ratio | 剪重比			√
Overall regularity | 整体规则性	Torsion displacement ratio 扭转位移比			√
Overall regularity | 整体规则性	Lateral stiffness ratio | 楼层侧向刚度比			√
Overall regularity | 整体规则性	Shear capacity ratio | 楼层承载力比			√

Figure 1. Seismic performance requirements (Source: Yaomin Dong)
图1. 抗震性能要求（来源：Yaomin Dong）

投资收益。性能、效率以及成本之间存在矛盾，需要通过合理的性能提升和优化设计方法寻求解决方案。

本文对超高住宅的建筑性能要求和结构性能要求进行了探讨，并引入了基于性能优化设计方法。通过厦门帝景苑项目案例对超高住宅的建筑性能提升和结构性能优化方法进行了研究探讨，研究内容涵盖荷载、材料、体系、结构布置、减振装置、优化算法、模型参数和构件节点等等。

基本理论

性能要求

建筑性能要求

超高住宅除了要满足垂直交通、消防和疏散等建筑性能要求外，还要进一步追求美化空间，为住户创造良好的居住心理。典型的要求有：

- 高大空间、开阔视野
  面积小、高度低且较封闭的空间，容易产生压抑感。相反，面积大、高度高、视野开阔的空间，会为住户创造舒适、愉悦的居住心理。这就要求室内空间面积较大、楼层净高较高、视线不易被遮挡。加之超高住宅的竖向高度高，从室内就可将室外城市的景色尽收眼底，住户视野相当广阔，有利于住户心情的舒畅豁达。但高大空间、开阔视野的要求会使建筑设计出现扁梁、拔柱的情况，影响结构效率，增加建造成本。
- 大悬挑阳台、室内泳池
  随着院落空间在现代建筑中的回归和再演绎，超高住宅的设计也逐渐重视院落空间的设计，如设置错层阳台或通过体量的挖减获得两层通高的院

- *Wind-resistant performance requirements*
  According to the goals of wind-resistant performance requirements, a series of indicators should be satisfied by the structures including global, assembly and component aspects (Figure 2) (Dong, 2015).

Performance Based Optimal Design

On the basis of the initial design, the optimal design team uses experience based structural optimization, sensitivity analysis based optimal design, numerical structural optimization, and integrated optimization method to get a more optimized design. The whole process can be named as optimal design. The main difference between traditional design and optimal design is that the former mainly focuses on the feasibility of the design, while the latter mainly focuses on the optimization of the design on the premise of the feasibility of the design (Zhao & Liu, 2015).

Experience Based Optimal Design

According to the performance requirements, the designer proposes a design scheme with reference to similar engineering design firstly. Then the designer modifies the design scheme and checks strength, stiffness and stability performances repeatedly to get a more optimized design. The optimization results and efficiency are mainly up to the experiences and understanding of the structure of the designer.

Sensitivity Analysis Based Optimal Design

Sensitivity coefficient is taken as a reference index for structural member optimization in sensitivity analysis based optimal design. According to the sensitivity coefficient of members, the designer can adjust the material distribution directly to reduce the structural economic costs on the premise of meeting all the performance requirements. Compared with experience based optimal design, the sensitivity analysis based optimal design is easier to be mastered by engineers and more efficient, providing a clearer optimization direction (Choi & Kim, 2006).

Numerical Optimal Design

The core of numerical optimal design is establishing the mathematical relationships between optimization variables, design constraints and optimization objective (Zou, 2002). Once the mathematical relationships have been established, numerical optimization algorithms such as optimality criteria method and sequential quadratic programming method can be used to optimize the structural member size. Based on rigorous mathematical and mechanical theory, numerical optimal design is more efficient and easier to get an optimal solution than the first two optimal design methods.

Integrated Optimal Design

Compared with the initial design, the design with passive energy dissipation system is called performance upgrading design. The performance has been promoted and the loss cost caused by disaster is smaller than the initial design; nevertheless, passive energy dissipation systems are expensive. Thus, for the entire lifecycle of the structure, a performance upgrading design may increase the total cost. The structural responses under wind load and seismic action can be reduced due to additional damping generated by installation of a passive energy dissipation system, and sectional dimensions of structural components can be optimized. The method to optimize the main structure based on the performance upgrading design is integrated optimal design (Zhao & Zhang, 2014). The integrated optimal design not only enhances structural performance, but also can save overall structural costs for the entire lifecycle.

Case Study

Case Introduction

The Dijingyuan project, sitting on the first-line lake view of Yuandang Lake, is the first supertall and ecological housing group that is of steel structure and with a height of almost 250 m in China. The project is composed of five 244.75 m high residential buildings and two commercial buildings. The

Wind-Resistant Performance 抗风性能	Design Requirements 设计要求	Component Requirements 构件要求	Assembly Requirements 组件要求	Global Requirements 整体要求
Component strength | 构件强度	Strength | 强度	√		
Component stability | 构件稳定	Stability of structural members 构件稳定性	√		
Component stiffness | 构件刚度	Shear deformation |剪切变形	√		
Overall stiffness | 整体刚度	Story drift |层间位移角			√
Overall human comfort | 整体舒适度	Peak acceleration | 顶点加速度			√

Figure 2. Wind-resistant performance requirements (Source: Yaomin Dong)
图2. 抗风性能要求（来源：Yaomin Dong）

落空间，增大平面尺度获得较大活动空间。大悬挑露台、室内泳池的设计营造出富于浓郁生活气氛的环境，使住户感受到亲切的自然气息，但大悬挑、大荷载必将导致结构材料的大量消耗，建造成本的增加。

结构性能要求

超高结构水平荷载大，且水平荷载对结构产生的倾覆力矩，以及由此在竖向构件中所引起的轴力，与结构高度的两次方成正比，水平荷载成为超高住宅结构设计中的控制因素。抗震性能要求和抗风性能要求如下：

- 抗震性能要求
  根据结构抗震性能目标，结构应满足一系列整体、组件、构件层面的性能要求，如图1所示（图1）（Dong，2015）。
- 抗风性能要求
  根据结构抗风性能目标，结构应满足一系列整体、组件、构件层面的性能要求，如图2所示（图2）（Dong，2015）。

基于性能优化设计方法

基于性能优化设计是指优化设计团队在初始设计基础上，采用经验优化、基于约束敏感性优化、数值优化和集成优化方法得到的更为优化的设计成果。传统设计仅满足于设计结果的可行性，而优化设计则重点关注设计结果的最优化，这是传统设计与结构优化设计的根本区别，也是结构优化设计的精髓所在（Zhao & Liu，2015)。

经验优化设计方法

设计者根据性能要求，参考类似的工程项目设计出一个初始方案，检查结构的强度、刚度、稳定性，反复调整设计方案以获得更优的设计。优化设计的好坏和结构效率的高低很大程度上取决于设计者的经验和对结构设计的理解。

基于约束敏感性优化设计方法

在基于约束敏感性优化设计方法中，敏感性系数是构件优化的参考指标。依据构件的敏感性系数，对构件进行有方向的材料重分布，使结构在满足性能要求的前提下，显著地减少经济成本。基于约束敏感性优化设计相比经验优化设计具有更加明确的优化方向，更易于工程师的简单运用，可提高结构效率，增加结构的经济性（Choi & Kim，2006）。

数值优化设计方法

数值优化设计的关键在于建立优化变量、约束条件和优化目标的数学关系 （Zou，2002）。一旦建立了数学关系，应用最优准则法、序列二次规划算法等数值优化算法就可优化结构构件的尺寸。基于数值方法和力学理论，数值优化设计方法较前两种优化设计方法更易得到最优设计结果。

planning area is 54,287 m^2, and the building area is 550,065 m^2.

The total plane layout of the project adopts a mode of staggering and single rows to achieve unobscured sight and broad vision in residences of every building. For the housing programming, the height of the standard floor is 3.6 m, and the area of penthouses range from 400 to 600 m^2. Every dwelling size of the penthouse is north–south transparent and both ventilation and day lighting are good. Staggered floor balconies and large cantilevered indoor swimming pools are set to acquire a courtyard space of two floors height.

Each of the five residence towers has 62 stories above ground and three stories underground, and adopts the steel frame-supporting system with strengthened stories. Among the system, frame columns are rectangular SRC (steel tube concrete) columns, and lateral force-resisting members are composed of steel braces and steel plate shear walls.

For the tower buildings, the 2nd, 3rd, 22nd, 43rd and 60th floors are set as strengthened stories to improve the whole rigidity of structures. The 1st floor underground is chosen as partial fixing. The gravity load is supported by the steel-concrete composite floor system and is transferred to the frame columns through floor beams, floors labs and braces. Only the 1st, 2nd and 3rd buildings are discussed in this paper, as the 4th and 5th buildings are same as the 2nd one.

Approaches to Optimal Design

Due to the high requirements of architectural performance, the flat beams, demolishing columns, and large cantilevers and lack support, which is extremely unfavorable for the stiffness and human comfort control, and will reduce the structure efficiency. The construction cost will inevitably be high if the structure is designed as per traditional methods. This research provides a solution by introducing proper performance upgrading and optimization methods. The approaches of structure optimization are shown in Figure 3.

Calculation Parameter Optimization

Calculation parameter optimization is one of the experience based optimal design methods. The margin of structure optimization can be improved by adjusting the calculation parameters reasonably. It is divided into two approaches, including weight reduction and stiffness increases.

Approach 措施	Calculation Parameter Optimization 计算参数优化	Increasing Stiffness of High Zones 提高高区刚度	Sensitivity Analysis Based Optimization 基于约束敏感性优化	Viscous Damper Integrated Optimization 黏滞阻尼系统集成优化
Optimization Objective 优化目标	Increase the margin of structure optimization 提高结构优化余量	Decrease story drift of control region, in crease the comfort performance, and increase margin of structure optimization. 减小控制区域层间位移角，提高结构舒适度，增加结构优化余量	Reduce the steel consumption 降低结构用钢量	Make stiffness and human comfort meet the code 使结构刚度和舒适度更易满足规范需求
Optimization Variables 优化对象	Select rational calculation hypothesis and parameters to reduce the structure self-weight and increase the stiffness 选用合理的计算假定和参数，以降低结构自重，增加结构刚度	Increase lateral stiffness of high zone 提高高区抗侧刚度	Optimize the member section size 优化构件截面尺寸	Utilize additional damping provided by viscous dampers to reduce the structure response under wind load and seismic action 利用黏滞阻尼器提供的附加阻尼比降低风荷载和地震作用
Specific Approach 具体措施	Deduct the region of slabs overlapping walls and columns; build the model of steel plate and concrete shear-wall elements per to overall elastic modulus method; consider the nodal rigid zones; build the model of structure above the partial fixing. 扣除墙柱与楼板的重叠区域；钢板混凝土剪力墙单元按等效弹模方式建模；考虑梁柱节点刚域作用；仅建嵌固端以上结构	Cast concrete into steel pipe column of high zone; seal living room's top of the double deck housing in 2nd building and add frame beams in the structure corners. 高区钢管柱灌混凝土；2号楼楼中楼户型客厅上空封闭，结构角部增加框架梁	On the basis of integral sensitivity analysis results, use different methods to optimize members aiming at controlling design constraint redundancy and deficiency. 以整体约束敏感性分析结果为基础，分别针对控制性设计条件约束冗余和约束不足的情况下，采取不同方式进行构件优化	Redesign the damper scheme and use the layout form of displacement amplification to improve working efficiency. 重新设计阻尼器方案，采用位移放大的布置方式，提高工作效率

Figure 3. Approaches of structure optimization (Source: Jiemin Ding)
图3. 结构优化设计的措施（来源：丁洁明）

集成优化设计方法

在原有结构上增加消能减震系统的设计方法被称为性能提升设计。结构的性能得到了提升，在自然灾害发生时结构的失效损失费用较原设计小，但消能减震技术产品费用较高，因此在生命周期总成本中，性能提升设计可能会造成结构的总体费用上升。由于消能减震技术能够提高结构的阻尼，使结构主体部分在地震、风等作用下响应降低，主体结构的构件尺寸存在优化空间。因此本研究将基于性能提升设计后再对主体结构进行优化的设计称为集成优化设计（Zhao & Zhang, 2014）。集成优化设计不仅能够保证结构的性能提升，而且还能够节省结构整个生命周期的总体费用。

工程案例

案例介绍

厦门帝景苑项目坐拥Yuandang 湖一线湖景，是250米中国首个钢结构超高层生态住宅群。帝景苑由5幢建筑高度为244.75m的超高住宅楼，2幢商业建筑组成。规划占地面积54287m2；总建筑面积550065m2。

项目建筑总平面布局采用错开方式、单排布置，实现前后无遮挡，每一栋建筑的住户都拥有宽广的视野。住宅部分标准层高3.6米，大平层户型从400m2到600m2，每个户型都是南北通透，采光、通风佳。错层设置大悬挑阳光房或大悬挑泳池获得两层通高的院落空间。

在社区绿化方面，从地下停车库、地面、架空层、空中花园全方位引进休闲绿化设计，提高居民接触机会，增加邻里交往，从不同空间形式多层次体现生态、人性化住宅设计。

5幢住宅均为地下3层，地上 62 层。均采用带加强层的钢框架–支承结构（剪力墙板）体系。其中框架柱采用矩形钢管混凝土柱，抗侧力构件采用钢支撑和钢板剪力墙。塔楼部分在结构层首层之上两个加强层、22 层、43 层和 60 层设置加强层用来提高结构的整体刚度。塔楼的嵌固端取在地下负一层。重力荷载由钢–混凝土组合楼面体系承担，并通过楼面梁、楼板、支撑传递到框架柱。由于4、5号楼原设计与2号楼一样，故本文只针对1–3号楼进行论述。

优化设计措施

由于建筑性能要求高，出现了拔柱、扁梁、大悬挑、少支撑等现象，对结构的刚度和舒适度控制极为不利，降低了结构效率。按照常规的设计方法设计结构必然带来高额的建设成本，本研究通过合理的性能提升和优化设计方法寻求解决方案。结构优化设计的措施如图3所示（图3）。

计算参数优化

计算参数优化是一种经验优化设计方法，通过合理的调整计算参数，提高结构优化余量。分为减重优化措施和刚度提升优化措施：

- 减重优化措施
  扣除墙柱与楼板的重叠区域，

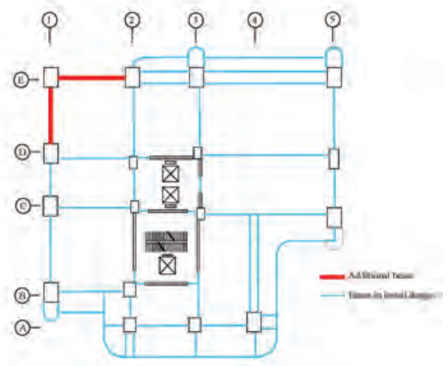

Figure 4. Frame beams added in corners above 30th floor in 2nd building (Source: Jiemin Ding)
图4. 2号楼30层以上角部隔层增设框架梁（来源：丁洁明）

- *Weight reduction*
  Deducting the region of slabs overlapping walls and columns can reduce 5% of structure weight. Compared with equivalent thickness methods, the model of steel plate and concrete shear-wall elements per overall elastic modulus methods can reduce self-weight effectively and appears more reasonable.
- *Stiffness increasing*
  Due to the big size of columns and strong action of joints, node rigid zones should be considered when analyzing. This project is positioned as luxury properties in which the dwelling size is large and there are less partition walls, so the period time deduction factor can be adjusted from 0.85 to 0.9. Only the structure above the partial fixing is taken into consideration in the analysis of the whole structure response.

Increase Stiffness of the Upper Zone

Increasing stiffness of the upper zone is another experience based optimal design method. It is accomplished by determining the reasonable stiffness distribution through the conceptual design principle and then readjusting the stiffness. As no concrete is cast into the steel pipe columns of upper zones (45–62nd floors) in the 1st, 2nd and 3rd buildings, the maximum story drifts occur in these zones. So, casting concrete into the steel pipe columns of these upper zones can improve stiffness.

In addition, the east and west sides of the 2nd building feature double-deck housing, whose living rooms occupy the two floors. There are no frame beams connecting in the structure corners. Now the owner adds the floor slabs above the 30th floor, and frame beams should be added in the corresponding floor corners (Figure 4).

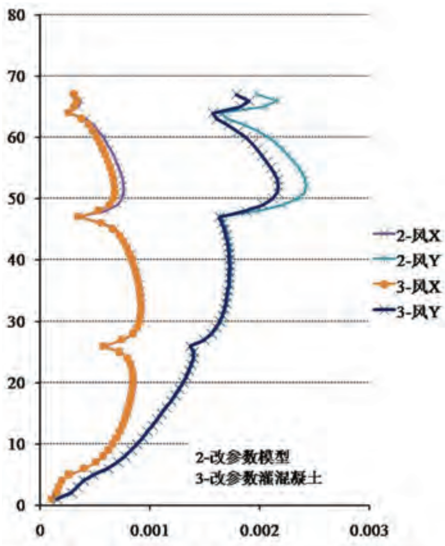

Figure 5. The variation of story drift under wind load after increasing stiffness of upper zones in 1st building (Source: Jiemin Ding)
图5. 1号楼高区刚度提升后风荷载下层间位移角的变化（来源：丁洁明）

After casting concrete into steel pipe columns of these upper zones, the self-weight increases as every single building is less than 5%, and there is a significant addition of stiffness and an obvious decrease of story drift and peak acceleration. Take the 1st building as an example; the variation of story drift under wind load is shown in Figure 5, and the variation of story drift and peak acceleration is shown in Figure 6.

It should be noted that the structural peak acceleration is related to the structural natural vibration period and structural vibration mode shape. In this case, after casting concrete into steel pipe columns of these upper zones, the lateral stiffness of high zones increase and the

约5%；钢板混凝土剪力墙单元按等效弹模方式建模，而非等效厚度建模，有效减少自重且更合理。

- 刚度提升优化措施
  由于柱尺寸较大、节点作用强，分析时考虑梁柱节点刚域；本项目为豪宅，户型大、隔墙少，周期折减系数从0.85调整为0.9；结构整体响应分析建模仅考虑嵌固端以上结构。

提高高区刚度

提高高区刚度是一种经验优化设计方法，通过概念设计原理判断结构合理的刚度分布，再对结构刚度进行调整。1–3号楼原设计高区钢管混凝土柱（45–62层）内未灌混凝土，由于结构最大位移角发生在高区，因此在1–3号楼45–62层的钢管混凝土柱内灌注混凝土，提高结构高区的刚度。此外，原2号楼东西侧为楼中楼户型，客厅为两层挑空，结构角部无框架梁连接，现业主在30层以上增加楼板，相应在楼面角部增加框架梁（图4）。

高区灌混凝土后，各楼结构自重增加的比例均不超过5%。而灌混凝土后，高区结构刚度有较大的增加，结构层间位移角、顶点加速度明显降低。以1号楼为例，风荷载下结构层间位移角的变化见图5（图5），风荷载下结构层间位移角、顶点加速度的变化见图6（图6）。

需要说明的是，结构加速度与周期、振型相关。在本案例中，高区灌混凝土后，结构高区刚度增大，从而结构顶点的振型分量减小。虽然高区灌混凝土后，结构自重增加，周期变长，但周期增大的幅度小于结构顶点振型分量减小的幅度，因此最终结构顶点加速度降低。

基于约束敏感性优化

敏感性分析对于整体约束控制设计的情况提供了有效的手段，可以判断不同构件对整体约束的贡献程度，通过把结构材料从低效区域（对整体约束贡献小的构件）转

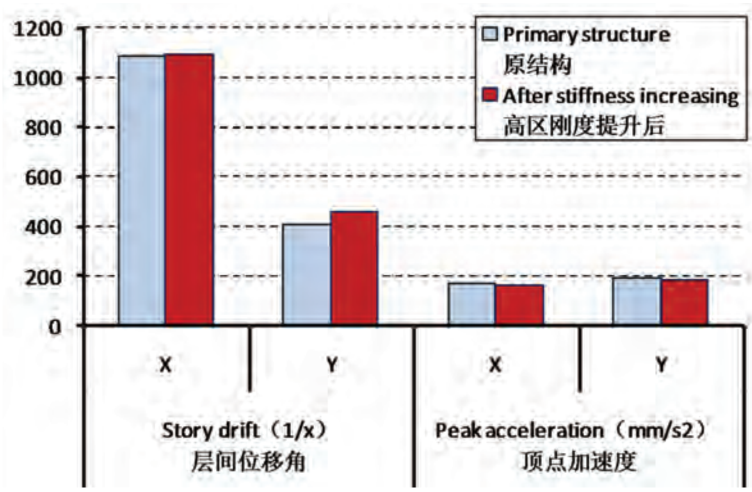

Figure 6. Comparison of structure response under wind load before and after increasing stiffness of upper zones in 1st building (Source: Jiemin Ding)
图6. 高区刚度提升后风荷载下结构响应的变化（来源：丁洁明）

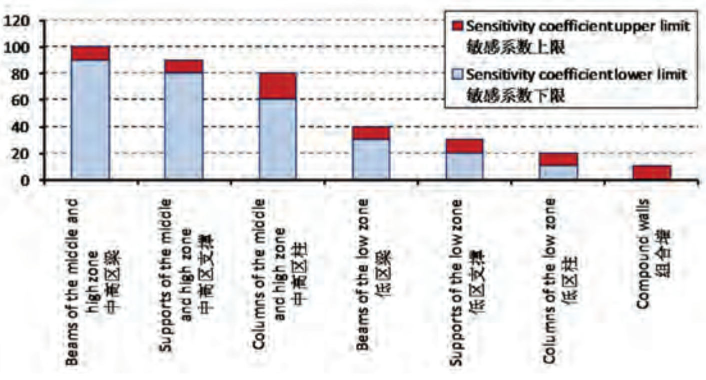

Figure 7. Result of member sensitivity analysis in 1st and 2nd buildings (Source: Jiemin Ding)
图7. 1–2号楼构件敏感性分析结果（来源：丁洁明）

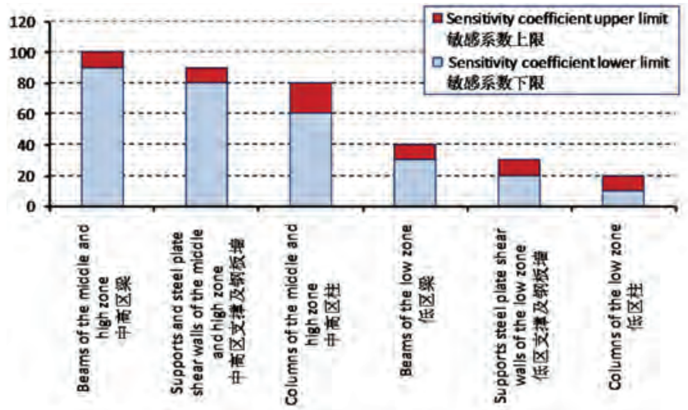

Figure 8. Result of member sensitivity analysis in 3rd building (Source: Jiemin Ding)
图8. 3号楼构件敏感性分析结果（来源：丁洁明）

structural vibration mode shape component of top floors decreases. Although after casting concrete into steel pipe columns of these upper zones, both the structural self-weight and the structural natural vibration period increases; the increase of structural natural vibration period is less than the decrease of structural vibration mode shape component for the top floors. Therefore, the structural peak acceleration is reduced.

Sensitivity Analysis Based Optimization

Sensitivity analysis provides an effective way to understand the integral constraints controlling design. Through this method, the designers can determine the contribution of members to the integral constraints. The overall structure efficiency can be effectively improved by transferring the material from inefficient regions (the members whose contribution is small to the integral constraints) to the high efficiency regions (the members whose contribution is large to the integral constraints).

Through the sensitivity analysis on constraint condition of story drift of then 1st, 2nd and 3rd buildings, the relative value of sensitivity coefficient can be obtained (Figures 7 & 8). As the sensitivity coefficient of support and beams is relatively large, the size of partial beams can be enlarged. During the optimization progress, the size of beams and supports should remain unchanged as much as possible. The optimization object should be concentrated on the shear walls of middle and upper zones and columns of middle and upper zones. The optimization progress should be conducted, combining with the constraint condition redundancy and sensitivity coefficient of related members.

Viscous Damper Integrated Optimization

- *Former damper design*
  The former structure design intends to add viscous dampers to control the wind-induced vibrating comfort. For floors 45–60 in the 1st building, 8 dampers are set in Y-direction at every story, and there are a total of 128 dampers. For floors 45–60 in the 2nd building, 8 dampers are set in both X-direction and Y-direction at every story, and there are a total of 256 dampers. In a structure stiffness analysis of these 3 buildings, additional damping is not taken into consideration. The location of the former damper design is shown in Figure 9, and the layout is horizontal.
- *Viscous damper optimization*
  The horizontal layout of the former damper, of which, the seismic reduction efficiency is low and quantity is large, occupies a residential story and can exert unfavorable influence on the residents. By adopting devices of displacement amplification, the efficiency of energy dissipation can be increased to 2–4 times as before under the same deformation of structural elements. This way, the number of dampers can be reduced and the additional damping will not decrease (Taylor & Tonawanda, 1999). In this case, the main advantages of the device of displacement

移至高效区域（对整体约束贡献大的构件），可以有效提升结构的总体效率。

对1–3号楼进行以层间位移角为约束条件的敏感性分析，得出各构件的敏感性系数相对值（图7、8）。由于支撑和梁敏感系数较大，可结合建筑功能对部分梁尺寸适当增加，优化过程中尽量保持梁和支撑截面尺寸不变，优化对象首先针对中高区剪力墙，其次是中高区柱。优化过程结合约束条件冗余及相关构件的敏感性系数进行。

粘滞阻尼系统集成优化

- 原设计阻尼器
  结构原设计考虑了增加粘滞阻尼器进行风振舒适度控制，其中1号楼在45–60层每层Y向布置8个阻尼器，一共128个阻尼器，2号楼在45–60层每层X、Y向各布置8个阻尼器，一共256个阻尼器，3号楼未布置粘滞阻尼器，且在进行结构刚度分析时均未考虑附加阻尼比作用。原结构阻尼器的布置位置如图9所示（图9），布置形式为水平布置。
- 粘滞阻尼系统优化
  原阻尼器采用水平布置方式，减振效率低，布置数量多，且占用住宅使用楼层，对住户有较大影响。而采用位

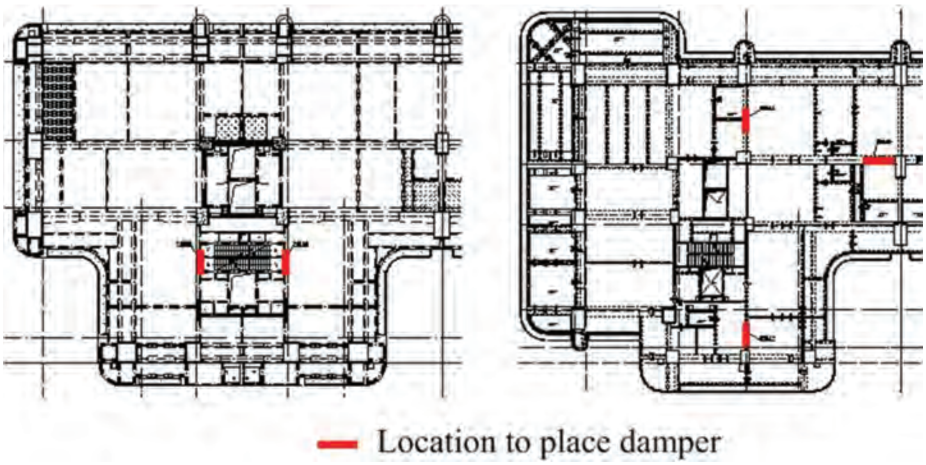

Figure 9. The location of the former damper design (Source: Jiemin Ding)
图9. 原结构阻尼器的布置位置（来源：丁洁明）

amplification are: the deformation of the damper amplified to 2–4 times and efficiency improved; quantity of dampers reduced under the same additional damping; dampers set centrally on service levels and influence avoided; and convenient for overhauling and maintenance. The form of displacement amplification device in this case is toggled, and the space below can be set aside for a door opening as shown in Figure 10. Through optimization of geometrical parameter, quantity and location, 24 displacement amplification devices are adopted in the 1st and 2nd buildings and 28 in the 3rd. The damper quantity is shown in Figure 11, and the unit price of the damper is calculated as 150,000 yuan.

- *Main structure integrated optimization*
  The member size of the main structure is mainly controlled by stiffness. For the main structure, taking the additional damping provided by viscous dampers into consideration, not only can this solve the problem of comfort at top floor, but it can also reduce the dynamic response under wind load and seismic action. Thus, a margin is provided to the global stiffness index and further main structure optimization can be conducted.

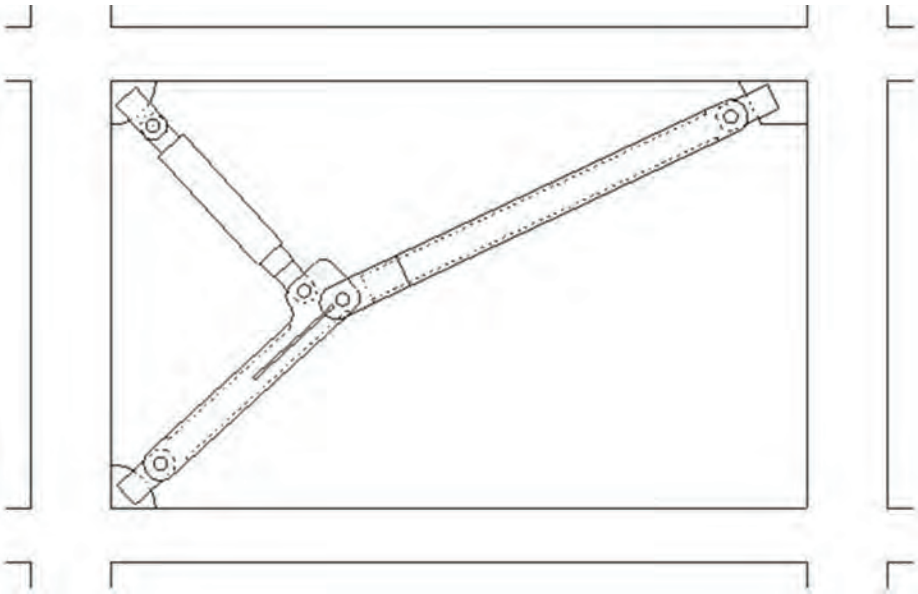

Figure 10. Displacement amplification device in toggle type (Source: Jiemin Ding)
图10. 肘节式位移放大装置（来源：丁洁明）

Optimization Result

The optimization result of every building is shown in Figure 12. In total, the steel, damper

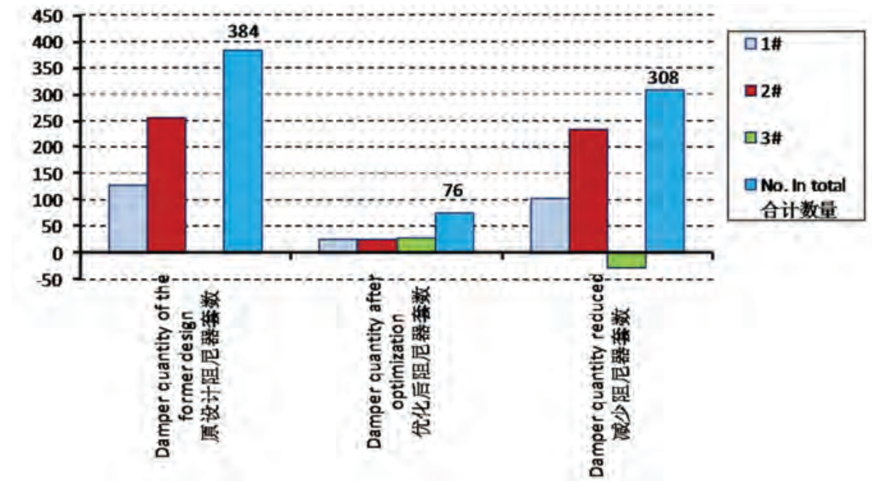

Figure 11. The optimization result of viscous dampers (Source: Jiemin Ding)
图11. 粘滞阻尼装备套数优化结果（来源：丁洁明）

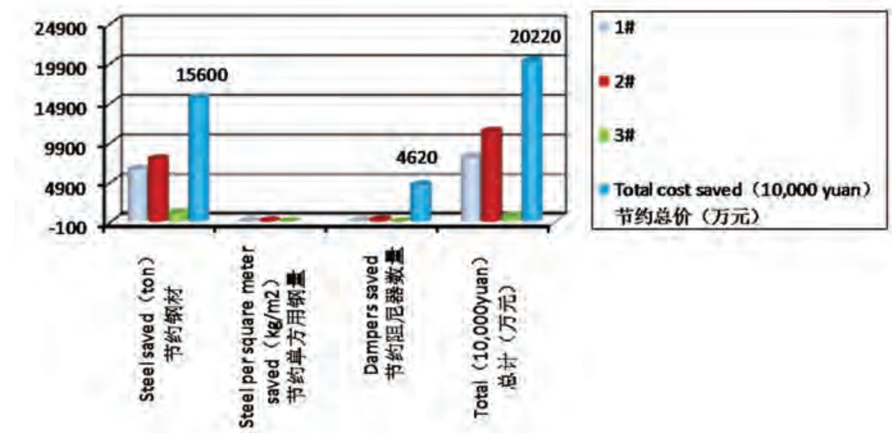

Figure 12. The optimization result of the 1st , 2nd and 3rd buildings (Source: Jiemin Ding)
图12. 1–3号楼优化成果统计（来源：丁洁明）

移放大装置，在同样的结构区格变形下，提高耗能效率达到2~4倍，从而达到在提供同样的附加阻尼比情况下，减少粘滞阻尼装备数量的效果（Taylor & Tonawanda, 1999）。对于本案例，粘滞阻尼系统采用变形放大装置的优点主要有：放大阻尼器变形2~4倍，提高效率；同样的附加阻尼比需求，可减少阻尼器数量；可集中布置在设备层，避免对住户的影响；便于后期检修和维护。本案例采用肘节式位移放大装置，如图10所示(图10)，下部空间可预留门洞。对位移放大型装置进行几何参数、数量、布置位置的优化。最终，1号和2号楼采用了24套位移放大型装置，3号楼采用了28套位移放大型装置，比原设计节约的阻尼器数量和造价估计见图11（图11），阻尼器单价按15万/套计算。

- 主体结构集成优化
  主体结构的构件尺寸主要由刚度控制，通过在主体结构中考虑粘滞阻尼系统提供的附加阻尼比，一方面解决了顶部舒适度的问题，另一方面又减少了风荷载和地震作用下结构的动力响应，从而为整体刚度指标提供了余量，可进一步实施主体结构优化。

优化成果

各楼的优化结果见图12所示，总计节约钢材15600吨，节约阻尼器308个，合计节约造价约2.02亿元人民币（图12）。

结论

- 超高住宅的建筑性能要求高，对结构抗侧力系统的刚度和舒适度性能控制不利，显著降低了结构效率，增加了结构成本。

quantity, and cost saved are respectively 15,600 tons, 308 and 202 hundred million (Figure 12).

Conclusions

- Architecture performance requirements for supertall residential buildings are high and disadvantageous for stiffness and human comfort performances under lateral stiffness. The requirements will reduce the structural efficiency, and thus increase the construction cost.
- To manage the construction costs and increase yield rate, performance upgrading and optimization methods can be introduced. The performance based optimal design methods include experience based optimal design, sensitivity analysis based optimal design, numerical optimal design and integrated optimal design.
- This paper has discussed the optimization design of the Dijingyuan project. The performance based optimal design can improve the structure performance and control the construction cost. The results obtained from this study provide references for similar projects.

- 为严格控制建设成本以获得更高的投资收益，可采用性能提升和优化设计方法进行设计。基于性能的优化设计方法有：经验优化设计方法、基于约束敏感性优化设计方法、数值优化设计方法、集成优化设计方法。
- 本文对厦门帝景苑项目案例的优化设计进行了探讨，基于性能的优化设计方法能提高结构性能、控制建造成本。研究成果可供类似项目参考。

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