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Performance-Based Design and Optimization
基于性能的设计与优化

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Performance-based structural design often includes performance requirements for safety (structural safety, fire safety, earth quake resistance and so on), health, serviceability, energy efficiency and environmental impact. Building performance is an indicator of how well a structure supports the defined needs of its users. To satisfy the requirements for performance-based structural design, the engineers should choose suitable technical solutions. With the increasing development of supertall buildings, performance-based design optimization techniques for supertall buildings are in high demand, as it can not only decrease cost and construction period, but also improve the performance of structures. A systematic performance-based design framework, critical optimization measures, and an assessment of the effectiveness and applicability of those measures for the Suzhou Zhongnan Center are chronicled in this chapter.

基于性能的结构设计通常需要考虑安全性 (结构安全，消防安全，抗震性能等)，舒适性，经济性和环境影响。建筑结构性能是评价其满足用户需求程度的重要指标。为了满足基于性能的结构设计要求，工程师应采取合理高效的技术方案。随着超高层建筑的日益发展，基于性能的超高层建筑优化设计技术存在巨大的社会需求。这类技术不仅会降低结构成本，减少施工周期，同时也将改善结构的性能。本文提出了一系列针对超高层建筑结构基于性能优化设计的措施和建议，并通过一座超过729m的超高层建筑项目苏州中南中心作为工程案例，验证了超高层建筑结构性能优化技术的经济性和实用性。

Introduction

The concept of performance-based structural design was gradually accepted by designers and researchers in Europe, America and other developed countries after World War II. The performance-based design approach is not proposed as an immediate substitute for design to traditional codes. Rather, it can be viewed as an opportunity to enhance and tailor the design to match the objectives of the community's stakeholders. It is an approach that focuses on the objective of a building asset, in order to prescribe desired results, as opposed to dictating a method to get things done. In a performance-based approach the focus of all decisions is on demand requirements and on required performance in use. As seen in the case of the Suzhou Zhongnan Center, it represents the development direction of structural design in the future (see Figure 3.12).

In performance-based design, any measure and tool can be used to achieve multiple performance requirements, providing a chance for new materials, architecture, and design methods to be applied in structural designs. The structural optimization design is consistent with the performance-based structural design, which can decrease the cost and construction period of structures without changing the structural performance.

The performance-based optimization design method has drawn attention in engineering practices. Huang et al. (2012) developed a novel computer-based optimization technique for wind-induced serviceability design of large-scale tall buildings, and the optimization technique has been used in a tall building project in Hong Kong. Zou et al. (2002) developed a systematic and comprehensive design optimization technique, which could minimize the construction cost or life-cycle cost during the lifetime of building structures, subject to deterministic and non-deterministic seismic design constraints, while simultaneously satisfying multiple levels of practical seismic performance requirements.

Liu et al. (2003) presented a multi-objective optimization procedure to solve a performance-based structural optimization problem that involved objectives related to initial construction expense (material weight), the number of different steel sections used in the design (diversity), and future seismic risk associated with story drift resulting from both frequent and infrequent ground motions. Zhao et al. (2011) developed a sensitivity vectors algorithm (SVA)

概述

基于性能的结构设计理念在第二次世界大战以后逐步为欧美等发达国家的设计人员、研究人员所接受，它是一种科学合理的生命周期设计方法。基于性能的设计方法不会直接替代规范设计方法，相反，它可以改善传统设计方式，更多考虑利益相关者的需求。 基于性能的设计主要关注用户需求和结构使用性能要求。正如苏州中南中心一样，它代表了未来结构设计的方向 (见图3.12) 。

任何设计策略和工具都可以用于结构性能化设计中，它为新的材料和新的设计方法提供了应用的机会。结构优化设计是性能化设计的一部分，它能在不降低甚至提升结构性能的基础上，减少结构的成本及施工周期。

基于性能的优化设计已引起了工程界的广泛关注。黄铭枫等 (2012) 研发了一种基于风振性能的高层建筑抗风设计优化方法，该技术已用于香港某高层建筑结构项目中。周晓康等 (2002) 开发了一套系统而全面的优化技术，它可以在确定性和非确定性抗震设计约束条件下，减少结构在使用寿命期间的建造成本或生命周期费用，同时满足多种实用抗震性能要求。

刘敏等 (2003) 开发了一种多目标优化的程序，以解决基于性能优化设计中有关初

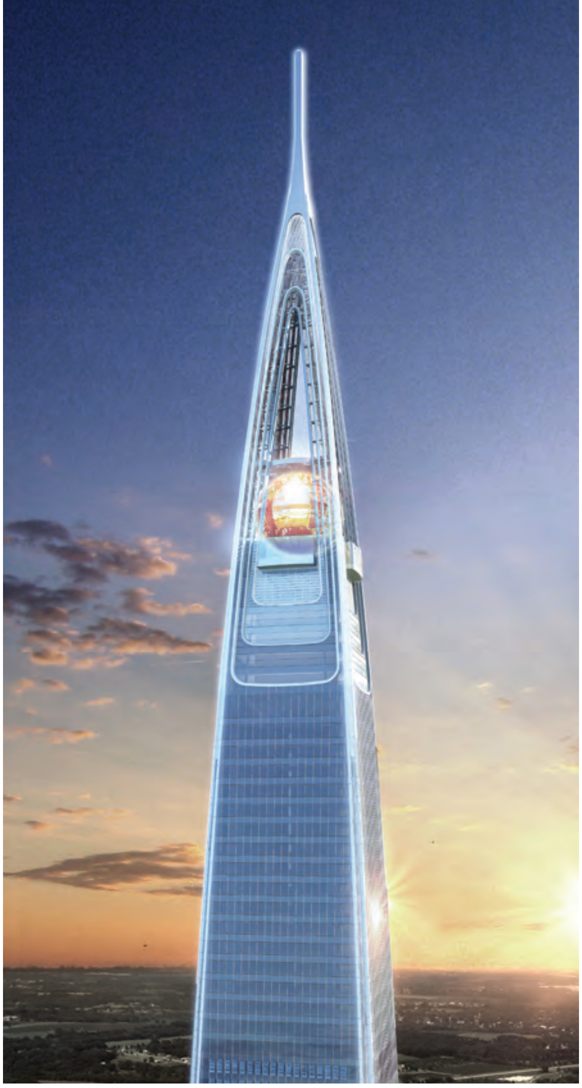

Figure 3.12. Top of the Suzhou Zhongnan Center (Source: Gensler)
图3.12. 苏州中南中心顶部 (来源: Gensler)

to figure out the optimal quantities and placements of outriggers subjected to the story drift constraint under wind loads. Based on the engineering practice, this chapter presents a short review of the performance-based wind-induced and seismic designs and some critical optimal member-design measures are proposed.

Performance Based Design

Performance-based wind design should take into consideration the design requirements in both construction and operation phases, such as human comfort, building deflection, member strength and structural stability. The three levels of the performance-based wind-induced design are defined as follows:

The first level: Basic wind pressure with a return period of one to five years. Evaluate the human comfort performance of structures by checking the wind-induced responses of structures, and check the comfort performance criteria defined.

The second level: Basic wind pressure with a return period of 10 years. Control the peak vibration acceleration and avoid the damage of nonstructural members. The second level

期建设费用 (材料的重量)、型钢截面数量 (多样性) 和地震作用下层间位移角约束的问题。赵昕等 (2011) 提出了一种灵敏度算法，当结构层间位移角为约束条件时，通过该算法可获得超高层建筑伸臂桁架的最优数量和布置位置。基于工程经验，本文对抗风和抗震性能化设计进行了简介并提出了一系列超高层建筑结构设计中关键构件优化的策略。

基于性能的设计

基于性能的抗风设计应该考虑建筑结构设计、施工和维护的各个阶段的设计需求，如人体舒适度、结构变形、构件强度和结构耐久性等。基于性能的抗风设计的三水准可按如下定义。

第一水准: 重现期为1~5年常遇设计风速确定相应风荷载。通过验算结构风致加速度响应，并与事先确定的舒适度标准比较来评估建筑物舒适度使用性能。

第二水准: 重现期为10年的偶遇设计风速，通过控制风振峰值合成加速度并且避免非结构构件破坏。第二水准主要用于限制高层在偶遇台风下的振动烈度，防止过大的振动效应造成局部维护构件的破坏。

第三水准: 重现期为50年或100年基本风压。确保结构的位移、强度和稳定性满足要求。基于性能抗震设计的主要理念: 即结构在其设计使用期间，应有明确的抗震性能设防目标，并且使得结构在整个使用周期中总造价最小。

我国规范对高层建筑结构划分为四个性能目标，性能目标按小震、中震和大震的地震三水准确定。每个性能目标分别包含结构在小震、中震和大震下的性能状态和损伤程度。超高层建筑中抗震性能设计从整体层间及构件层面两部分出发。整体层面主要关注结构层间位移角，剪重比等刚度和强度指标; 从构件层面考察，首先需要理清构件在整体结构扮演的角色明确不同重要程度构件需要满足的性能状态，以内力和抗力为衡量参数。关键构件应考虑其对结构安全的重要性而提高其抗震性能目标。一般要求其在设防地震时满足保持弹性状态，普通竖向构件及耗能构件可适当降低抗震性能目标。

超高层建筑结构需满足不同回归期风荷载和地震荷载作用下的性能要求。在施工阶段，

Return period of the wind / year 风荷载回归期 / 年	Construction Phase 施工阶段			Operation Phase 使用阶段			
	Deformation 变形	Strength 强度	Stability 稳定	Comfort 舒适度	Deformation 变形	Strength 强度	Stability 稳定
5				X			
10	X	X	X	X			
50					X		
100						X	X
1700							X

Table 3.3. Performance matrix of structures under wind loads
表3.3. 风荷载作用下结构性能矩阵

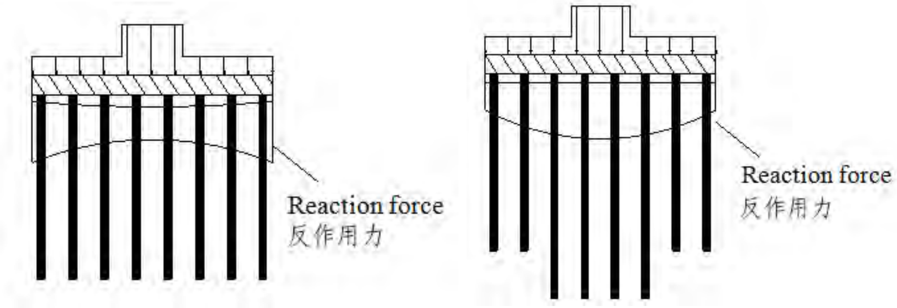

Figure 3.13(a). Uniform pile arrangement (b). Variable stiffness pile arrangement (Source: Jiemin Ding)
图3.13 (a). 均匀布桩 (b). 变刚度布桩 (来源: 丁洁民)

is mainly used for limiting the vibration severity under the occasional typhoon, preventing damage of local maintenance members caused by violent vibration.

The third level: Basic wind pressure with a return period of 50 or 100 years. Ensure that the displacement, strength and stability of structures satisfy the requirements.

The idea of performance-based seismic design is that the structure should have specific performance levels under given seismic loads during the period of service and that it has a minimal cost for the whole life cycle.

Four performance objectives are specified for the seismic design of supertall buildings in Chinese codes. They are determined by three seismic performance levels under frequent, moderate and rare earthquakes. Performance states and levels of expected damage are specified for each seismic performance level. In general, performance-based seismic design for supertall buildings contains the overall structural design and component design. The overall structural design mainly concerns structural strength and stiffness criteria such as story drift and shear-to-weight ratio. As for component design, the role components perform in the seismic design should be measured by the internal force and load capacity. The crucial members need to be improved in the performance objectives due to structural safety. They are required to be elastic in the moderate earthquake, while common vertical components and dissipative components can be designed based on appropriate secondary seismic performance objectives.

Supertall buildings are supposed to meet the appropriate performance requirements under wind loads and earthquakes with various return periods. In the construction phase, the structures are time-dependent and should meet the requirements of deformation, strength and stability. In the operation phase, structures should meet the performance requirements of human comfort, deformation, strength and stability. The performance requirements under different levels of wind loadings and earthquake actions are shown in Tables 3.3 and 3.4.

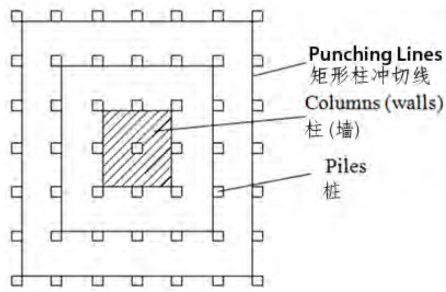

Figure 3.14. Punching lines of rectangular columns (Source: Jiemin Ding)
图3.14. 矩形柱冲切线 (来源: 丁洁民)

结构具有时变性，需要满足变形、强度和耐久性方面的性能要求。在使用阶段，结构需满足舒适度、变形、强度和耐久性方面的性能要求。不同回归期风荷载和地震荷载作用下的结构性能要求见表3.3和表3.4。

优化设计要点

桩基

桩基设计时宜采用变刚度调平设计方法。对于超高层建筑的桩筏基础，传统设计重视承载力和沉降，忽略上部结构、承台、桩、土相互作用，采用等桩长，结果导致基础沉降呈锅形分布，反力呈马鞍形，基础弯矩增加。而变刚度调平设计则是通过调整地基、承台和基桩的刚度分布，使反力与荷载分布相协调，使沉降变形趋向均匀，从而使基础所受弯矩、冲切力和剪力减至较小状态的方法。调平的方法主要有:根据荷载差异改变桩长、根据基础变形差异改变桩的分布和改变桩径 (见图3.13) 。

单桩可通过改变桩长和桩径来确定较优方案。对于单桩承载力特征值 (侧摩擦力+端承力) 大于桩身强度承载力的桩，可以通过提高混凝土强度、减少桩身配筋进行优化。对于桩身配筋，桩身可以采用两种不同直径的纵筋，在桩身下部截断钢筋时优先截断大直径钢筋以节约造价。

筏板

筏板优化主要针对厚度和配筋。筏板的厚度主要由抗冲切控制。冲切线选取时，需

Return period of the earth-quake/ year 地震作用回归期 / 年	Construction Phase 施工阶段			Operation Phase 使用阶段		
	Deformation 变形	Strength 强度	Stability 稳定	Deformation 变形	Strength 强度	Stability 稳定
10	X	X	X			
50				X	X	X
475				X	X	
2000				X	X	

Table 3.4. Performance matrix of structures under earthquake
表3.4. 地震作用下结构性能矩阵

Critical Optimal Design Points

Pile Foundation

The variable rigidity design method for settlement adjustment is appropriate for pile foundation design. For supertall buildings, the settlement and capacity of pile foundations are emphasized in conventional design, while the interaction among superstructure, pile caps and soil is ignored. If the piles are of uniform length, the settlements of foundation and reaction forces are dome-shaped and saddle-shaped, respectively. Based on the variable rigidity design method, the stiffness of the foundation, pile caps and foundation piles is modified to coordinate with the distribution and reaction of loads. Therefore, the settlements become uniform, with optimized moments, punching force and shear force. The optimization method modifies the length and distribution of piles according to the loads and foundation deformations (Figure 3.13).

The length and dimension of piles can be adjusted to suit the optimal scheme. When the modified value of a single pile's load-carrying capacity (side friction plus end-bearing capacity) is larger than the load-carrying capacity, it can be optimized via increasing the pile's concrete strength and reducing the amount of rebar. Rebar with two different diameters can be utilized to reduce the steel consumption. Large-dimension rebar will be truncated in the lower part of piles.

Rafts

In an optimization exercise, the thickness and rebar can be optimized for the optimal design of raft. The thickness of raft is controlled by the punching capacity. All the lines connected with the boundary of the piles in the first row, and piles in the 45° direction of rafts should be checked for the punching calculation. The detrimental position derived by the punching lines can be obtained as shown in Figure 3.14. The punching loads for columns (walls) should deduct the reaction force and water buoyancy of pile-soil in the broken cones. However, the interaction between the piles, the water buoyancy and weight of rafts are commonly not considered in practice; only the reaction force in the broken cones is deducted. The reaction force is the actual force of piles and can be calculated roughly as 80%-90% of modified pile load-bearing capacity. The amount of rebar is determined by the bending moments of rafts.

Core

The typical layouts of central service cores are the nine-grid square layout, 16-grid square layout and triangular layout. The shear walls should be arranged along the main axis of the structure. The optimal design of the core structure has to consider comprehensively different requirements, such as vertical transportation, planning organization, fire evacuation, MEP pipeline arrangements and MEP facility rooms. In general, the 16-grid square layout is better than the other layouts for buildings with apparent plane shrinkage along the building height.

In general, the shear walls of the low zones are controlled by the axial compression ratio, while shear walls of high zones are controlled by the stiffness or shear-strength requirements under rare earthquakes. For calculating the axial compression ratio of shear walls, connected shear walls could be treated as a whole to reduce the axial compression ratio. The intersections of

要分别计算柱 (墙) 边第一排桩边缘至45°斜边线范围内桩边缘不同的连线，即从多道冲切线中得到最不利冲切位置 (见图3.14)。冲切验算时，柱 (墙) 的冲切力应扣除冲切破坏椎体内桩土的反力及水浮力。但桩的相互作用，一般忽略桩间土的反力和水浮力及筏板自重，只扣除冲切破坏椎体内桩的反力，而该反力应为桩的实际受力，可按单桩承载力特征值的80%~90%粗略计算。筏板受力钢筋应根据筏板的弯矩配置。

核心筒

核心筒平面布置形式有九宫格、回字形及三角形等方案，剪力墙应沿建筑平面的主要轴线布置，宜上下连续贯通。核心筒的优化布置方案应综合考虑各种要求，如垂直运输、消防疏散、功能布局、机电管线布置和设备用房设置等。一般情况下，回字形核心筒对于平面收进较为明显的建筑来说经济性较好。

低区核心筒剪力墙一般由轴压比控制，高区剪力墙由刚度控制或大震下抗剪截面控制。对剪力墙进行轴压比验算时，可将相连剪力墙墙肢进行整体验算，以提高轴压比验算的通过率，节约工程造价。在核心筒角部埋置型钢，可提高核心筒的延性并降低墙体在中震、大震下的拉应力。同时约束边缘构件的钢筋，也提高了剪力墙的抗拉承载力。

巨柱

超高层建筑的巨柱按材料一般分为钢柱、钢筋混凝土柱和组合柱。在组合材料的发展背景下，组合柱特别是巨型组合柱在超高层建筑中的应用越来越广泛，两种材料的结合达到取长补短的效应，这是建筑材料创新的必然结果，也是超高层走向更高的突破点。

目前常用两种形式: 1) SRC型钢混凝土柱，如上海中心、深圳平安中心 (见图3.15(a)) 、上海环球金融中心等; 2) CFT钢管混凝土柱，如天津117、台北101 (见图3.15(b)) 、深圳京基100等。对于大尺度巨型构件，从吊装和安装角度，型钢混凝土柱较有优势。

伸臂桁架

对于300m以上的超高层结构，若层间位移角不满足规范要求，可结合设备层或避难层设置伸臂桁架。伸臂桁架将框架柱与

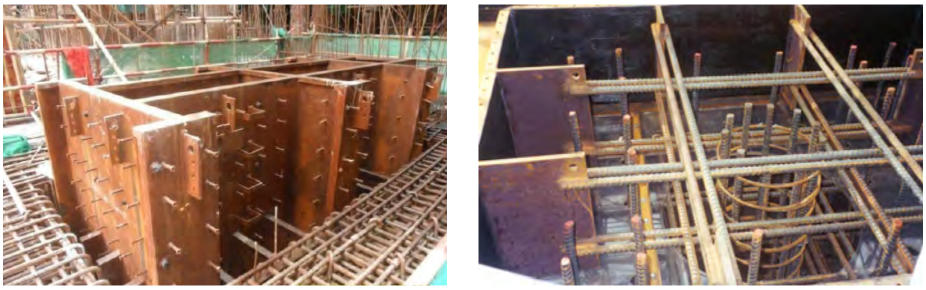

Figure 3.15(a). SRC columns (b). CFT columns (Source: Jiemin Ding)
图3.15 (a). 型钢混凝土柱 (b). 钢管混凝土柱 (来源: 丁洁民)

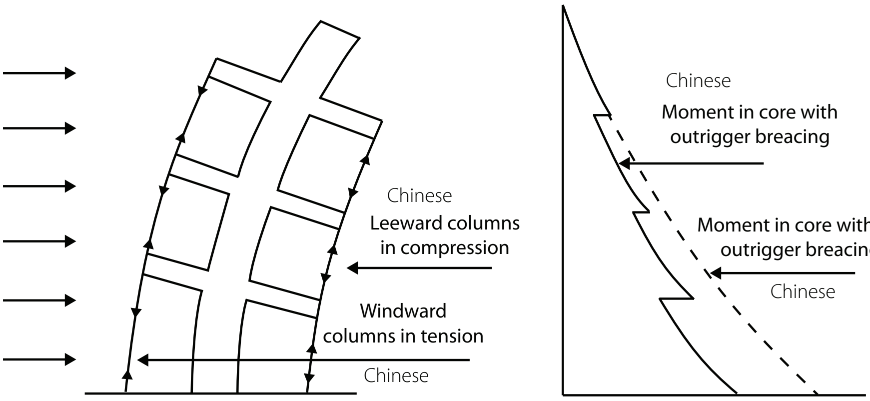

Figure 3.16. Interaction of core and outriggers (Source: Jiemin Ding)
图3.16. 核心筒与伸臂桁架相互作用 (来源: 丁洁民)

core shear walls are embedded with steel in order to increase ductility and reduce the potential shear-wall tension stress under moderate and rare earthquakes. The main reinforcements in the boundary columns of the core shear walls also contribute to the tensile bearing capacity.

Megacolumn

With the development of composite materials, composite columns, especially composite megacolumns, have been widely used in supertall buildings. The two materials – steel and concrete – in the composite columns complement each other and exhibit a good mechanical performance.

Two types of commonly used megacolumns are listed as follows: 1) Steel-reinforced-concrete (SRC) columns, which are used in Shanghai Tower, Ping An Finance Center (Figure 3.15(a)), Shanghai World Financial Center and so on; 2) and Concrete-Filled Tube (CFT) columns, which are used in Goldin Finance 117, Taipei 101 (Figure 3.15(b)), KK100 and so on. For large-scale megacolumns, the SRC columns have an advantage compared to CFT columns, from the perspective of lifting and installation.

Outrigger Truss

The outrigger trusses are commonly installed in mechanical floors to reduce the story drift for supertall buildings (taller than 300 meters). Outrigger trusses connect frame columns and core tubes effectively to reduce the maximum story drift of the tower. Outrigger systems are very efficient and cost-effective solutions to reduce the overall structural deformation and story drifts. The working principle is shown in Figure 3.16. The arrangement of outrigger trusses along the structural height will have different effects on the structure. For example, the outrigger trusses set on the upper zones are effective for reducing the story drift but may increase the structural period. It is desirable to optimize the quantities, placements and structural form during the optimization design of outrigger trusses. Furthermore, considering the economy and construction period of the project, the number of outrigger trusses can be reduced.

Belt Truss

Belt trusses have two functions in megastructure. One function is to act as the transferring members for all the secondary floor systems, and the other function is to engage all the

核心筒有效地联系起来，约束核心筒的弯曲变形，减小结构总体变形及层间位移，其工作原理见图3.16。若必须布置多道伸臂，不同位置伸臂会对结构产生不同效果，如: 为了控制层间位移角可考虑在上部布置伸臂，但可能会增大结构的自振周期。伸臂的数量、位置和结构形式应合理选择，应注意寻找最优布置方案。考虑对施工工期的影响，应尽可能减少伸臂桁架的数量。

环带桁架

环带桁架在巨型结构中具有两个功能。首先，它可以传递次级楼盖系统的重力作用。其次，它可以有效连接外围柱以抵抗横向荷载。环带桁架支撑所有的重力柱，并将楼板上的荷载传递到巨柱，从而减小风荷载和地震作用下巨柱的拉力 (图3.17)。

目前，在实际工程中主要采用四种类型的环带桁架，分别为普通单层环带桁架、L型单层环带桁架、U性环带桁架和双层环带桁架。环带桁架的性能主要取决于它的刚度。因此，为了使超高层建筑具有更好的性能水平，针对环带桁架的形式和构件尺寸的优化时需要格外仔细斟酌。

楼盖体系

从经济性和施工角度考虑，250m以下高层建筑结构一般采用钢筋混凝土楼盖体系; 250m以上高层建筑结构常选用组合楼盖体系，其主要包括开口型、闭口型和钢筋桁架组合楼盖体系。开口型组合楼板经济性最好、施工方便，但板厚较大，相对闭口型和钢筋桁架组合楼板，开口板最小防火厚度约增加30～40mm。开口型组合楼板的最大无支撑跨度为3～3.3米。

组合楼盖在施工和使用阶段应根据承载能力和正常使用极限状态进行设计。

开口型和闭口型组合楼板中的压型钢板在

perimeter columns in the resistance to lateral loads. The belt trusses support all the gravity columns and transfer the load in the floor from the belt trusses to the megacolumns, thus decreasing the pulling forces in the megacolumn due to wind load or earthquake. (Figure 3.17).

There are four belt-truss types in engineering practice, namely, ordinary single truss, L-type single truss, U-type single truss and double truss. The performance of the belt truss depends greatly on its stiffness. Thus the belt truss stiffness has to be carefully optimized for better megastructural performance.

Floor System

Considering structural cost and ease of construction, a reinforced concrete floor system is commonly used in tall buildings with a height of less than 250 meters, while composite floor systems are typically applied in tall buildings of more than 250 meters. Composite floor systems mainly include three types: the open-trough profiled deck floor, the flat-profiled deck floor, and the steel-bar truss deck floor systems. The open-trough profiled deck is most cost-effective and easy to construct; however, it is about 30-40 mm larger than that of flat-profiled deck floor systems and steel-bar truss deck floor systems, considering the fire-resistance performance. The maximum unsupported construction span of the open-trough profiled deck floor system is about 3.0 – 3.3 meters.

The composite slabs should be designed according to the bearing capacity limit state and serviceability limit state in both the construction and service stages.

Open-trough profile and flat-profile decks bear the self-weight of concrete and construction loads as temporary forms in the construction stage. In the service stage, the deck bears the working loads, partly or fully replacing the steel bars. The deck of the steel-bar truss composite floor system only serves as a supporting form in the construction stage and will not bear loads in the service stage. As long as the thickness of the floor slab meets the minimum requirements, the composite slabs can meet the fire-resistance performance requirements without fire protection. The slabs of the tall buildings commonly need to meet Class 1 fire-resistance requirements, for a heat insulation limit of at least 1.5 hours. In this situation, the concrete thickness beyond the rib of the open-trough profiled deck should be no less than 80 mm, while the total thickness of flat-profiled slabs and steel-bar truss composite slabs should be no less than 110 mm.

The design of steel beams in composite floor systems should consider the combination action of steel beams and slabs that act as composite beams. The strength, deflection and shear connections need to be checked. Pre-cambering can be used to reduce the large deflection of steel beams. It is not appropriate to pre-camber too much; otherwise, the slabs will be uneven after construction. Commonly, the pre-cambering amount is below 1/1000 of the span and less than 2 cm.

Case Study

The structural optimization measures and results of Suzhou Zhongnan Center are briefly introduced in this part.

Piles and Rafts

This chapter describes the optimization of the pile and raft of Suzhou Zhongnan Center. Optimization has been made by making a comparison of pile length, pile diameter and strength. The longitudinal reinforcement, stirrup and post-grouting of piles have also been optimized. The thickness of the raft is 6.3 meters after optimization, while the original design thickness was 7 meters.

Core

By considering the relationship between megacolumns, corner columns, the central service core and outriggers, a total of four plane layouts were investigated for the Zhongnan Center

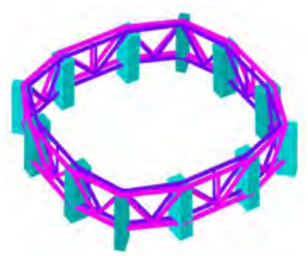

Figure 3.17. Belt truss (Source: Jiemin Ding)
图3.17. 环带桁架 (来源: 丁洁民)

施工阶段作为模板，承受混凝土自重和施工荷载，而在使用阶段可代替一部分或者全部板底钢筋，承受使用阶段荷载。钢筋桁架楼板中的压型钢板仅作为施工阶段的模板使用，而在使用阶段不考虑其受力。只要楼板厚度满足最小厚度要求，无防火保护的组合楼板均可满足耐火性能。超高层结构的楼板一般均为一级防火要求，其隔热极限为1.5小时，此时开口型压型钢板板肋以上混凝土厚度一般不应小于80mm，而闭口型和钢筋桁架组合楼板的总厚度一般不应小于110mm。

组合楼盖中的钢梁应考虑组合作用。在设计时，需对钢梁的强度、变形和剪力键进行校核。钢梁若由挠度控制，可采用预起拱减小构件尺寸，但预起拱值不宜太大。相邻跨预起拱相差不宜过大，以免施工困难或完成后出现明显的楼板不平整现象。通常情况下，钢梁的预起拱值需小于梁跨的1/1000，并小于2cm。

案例研究

本节介绍了中南中心项目结构优化的措施及相关的优化成果。

桩基筏板优化

分别对中南中心塔楼的桩基和筏板进行了优化。桩基部分，分别从单桩变桩长、桩径和桩身强度方面进行对比选型。筏板部分，原设计厚度为7m，优化方案厚度为6.3m，相比原方案减薄了0.7m。

核心筒剪力墙优化

综合考虑了巨柱、角柱和核心筒与伸臂桁架之间的关系，中南中心塔楼对4种核心筒布置形式进行了研究比较 (图3.18) 。从节约材料成本和减少施工周期的角度出发，回字形、九宫格和口字型是较优的核心筒布置形式。本案例中，设计人员对核心筒

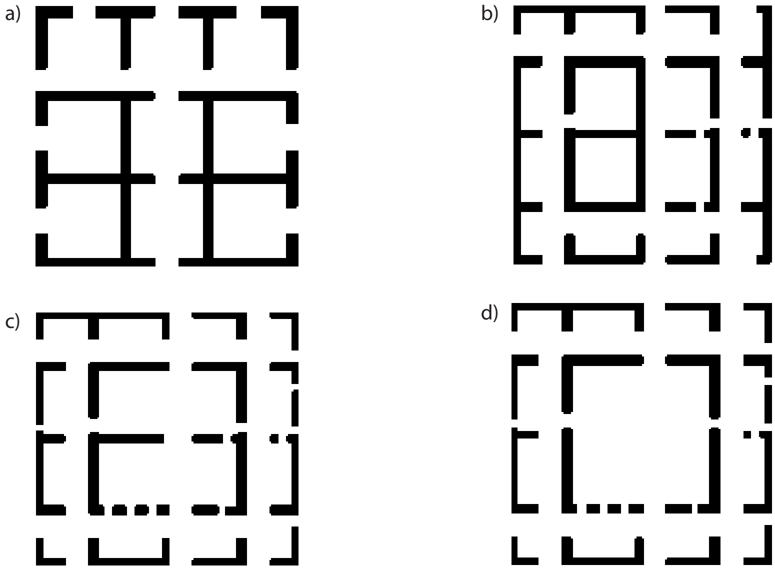

Figure 3.18. Core layouts of Suzhou Zhongnan Center (Source: Jiemin Ding) (a). 9-grid layout (b). 16-grid layout (c). 16-grid layout (without web walls) (d). 16-grid layout (without web walls in the Y direction)
图3.18. 中南中心项目核心筒布置方案 (来源: 丁洁民) (a). 九宫格 (b). 回字形 (c). 回字形 (去掉腹墙) (d). 回字形 (去掉Y向腹墙)

project (see Figure 3.18). The scheme of 16-grid core layout, with eight widely-spaced megacolumns and four corner columns is the best, considering the cost of structural materials, construction period and the need to accommodate building services. The axial compression ratio of the core and the global stabilization of the shear wall are checked. The core shear wall thickness has also been optimized.

Megacolumns
SRC columns with embedded open steel, box steel and rectangular steel tubes are analyzed for the mechanical performance, project cost, fireproof performance, construction performance, joint construction and overall quality. It was found that an SRC column with embedded steel is the most effective. The steel ratio is kept at 4% and the protective thickness of embedded steel meets specification requirements. The steel thickness is effectively decreased after appropriately increasing the flange length and web width.

Outriggers
A sensitivity vectors algorithm (SVA) was employed to obtain the favorable quantities and placements of outriggers under period and story-drift constraints. The optimization target is to minimize the material consumption. The first vibration period, shear-to-weight ratio and story drift are constraints for the design according to code specifications. The sizes of members are optimized using in-house-developed structural optimization software.

Belt Trusses
Single trusses, double trusses and double composite trusses are compared on the basis of flexural rigidity, torsional stiffness, effective width and torsional efficiency of the joint core area shear interface. Optimization results show that the double composite truss is the most economical and effective scheme. Sizes of belt truss members are optimized by using in-house-developed structural optimization software.

Floor Systems
Open-profile steel sheeting, closed-profile steel sheeting and steel-bar truss floor systems are compared in different aspects such as the cost, weight, construction performance and application. It was found that the flat-profiled deck floor system is suitable for the ordinary floor and the steel-bar truss floor system is suitable for the mechanical floors. The structural framing plane of every typical floor is also optimized.

剪力墙进行了轴压比验算和整体稳定验算，并对核心筒厚度进行了优化。

巨柱优化
针对中南中心项目，首先对巨柱的结构形式进行了选型，从受力性能、工程造价、防火防腐性能、施工性能、质量检测以及节点构造等方面，对比了内埋开口型钢混凝土截面、内埋箱型型钢混凝土截面和矩形钢管混凝土截面的特点，最终建议了内埋箱型型钢混凝土截面。随后又对型钢混凝土柱的内埋钢骨截面进行了优化设计，在保持4%含钢率并确保内埋型钢保护层的厚度满足规范要求的前提下，适当增加了翼缘的宽度和单腹板长度，有效地降低了钢板的厚度。

伸臂桁架优化
针对中南中心项目，采用灵敏度向量算法对伸臂桁架的位置和道数进行了优化，优化设计的约束条件为结构层间位移角和一阶周期，优化目标为结构材料用量最小化。一阶自振周期、剪重比和层间位移角限值根据规范选取。伸臂桁架构件尺寸的优化基于自主研发的结构优化软件平台。

环带桁架优化
针对中南中心项目，对比了单层普通桁架、双层普通桁架和双层混合桁架的抗弯强度、抗扭刚度、节点核心区抗剪截面有效宽度、抗扭效率等结构指标，结果表明双层混合桁架是其中最经济有效的方案。环带桁架构件尺寸的优化基于自主研发的结构优化软件平台。

Conclusions

Performance-based structural design provides a unified approach to designing buildings and fosters predictable and satisfactory performance in case of adverse events.

The advanced optimization measures developed from performance-based design were applied to piles, rafts, core tubes, shear walls, megacolumns, outriggers, belt trusses and floor systems of the megatall Suzhou Zhongnan Center, illustrating the effectiveness of performance-based design framework and optimization measures.

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楼盖体系优化

针对中南中心项目，对楼承板进行了选型，对比了开口型压型钢板、闭口型压型钢板和钢筋桁架楼承板的成本、自重、施工性能及应用广泛性等，建议了普通楼层采用闭口型压型钢板、加强层采用钢筋桁架楼承板的方案。并对每区典型层的楼面梁进行了优化布置。

结论

结构性能设计方法提供了一个设计建筑结构的统一方法，使其在各类荷载和作用下具有可以预测和令人满意的性能。

本文针对超高层建筑桩基、筏板、核心筒剪力墙、巨柱、伸臂桁架、环带桁架以及楼盖体系，提出了先进的基于性能的结构优化措施，并通过苏州中南中心塔楼验证了相关优化措施的有效性。

致谢

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References (参考书目):

Fintel, M., and Ghosh, S.K., and Iyengar, H., (1987) **Column Shortening in Tall Structures-Prediction and Compensation**, Portland Cement Association.

Foley, C.M., (2002) **Optimized Performance-Based Design for Buildings**. Recent Advances in Optimal Structural Design, pp. 169-240.

Huang, M.F., Chan, C.M., and Lou, W.J., (2012) "Optimal Performance-Based Design of Wind Sensitive Tall Buildings Considering Uncertainties," **Computers & Structures**, vol. 98, pp. 7-16.

Liu, M., Burns, S.A., and Wen, Y.K., (2003) "Optimal Seismic Design of Steel Frame Buildings Based on Life Cycle Cost Considerations," **Earthquake Engineering & Structural Dynamics**, vol. 32, no. 9, pp. 1313-1332.

Taranath, B.S., (2009) **Reinforecd Concrete Design of Tall Buildings**, CRC Press.

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, no. 5, pp. 20-23/In Chinese

Zou, X., (2002) **Optimal Seismic Performance-Based Design of Reinforced Concrete Buildings**. Hong Kong University of Science and Technology.