Title: **High-Performance Floor System Design**

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High-Performance Floor System Design
高性能楼盖体系设计

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The floor system is important part of a supertall building structure. It not only supports the vertical load, but also connects the lateral-load resisting system as a whole. In this chapter, the key points of the design and optimization of high-performance floor systems of supertall buildings are summarized in four aspects, and the influence of the floor system on the cost of supertall buildings is analyzed as well. Finally, the ideas for floor-system optimization of supertall buildings are illustrated through three case studies.

楼盖体系是超高层建筑重要的组成部分，其不仅承担着支撑竖向荷载的作用，更将抗侧力构件连接成一整体使之共同工作。本文从四个方面总结了超高层建筑楼盖体系设计与优化要点，并分析了楼盖体系对超高层建筑成本的影响，最后通过三个案例分析了超高层建筑楼盖体系优化的思路。

Overview

The floor system is an important part of the gravity system of supertall building structures. Floor systems sustain the floor loads by bending and shearing, transmitting the loads to the vertical supporting members. Meanwhile, the floor structure also connects all vertical members into a whole and serves as the lateral support of the vertical structural system. It is important to stabilize the lateral load-resisting system and optimize its performance (Shen, 2003).

The reinforced-concrete floor system and steel-beam composite floor system are common types of tall-building floor systems. The slab of the composite floor system, specifically, can be divided into three forms, namely, the open-trough profiled deck system, the flat-profiled deck system, and the steel-bar truss deck system.

The cost of the floor system accounts for 20%-30% of the total construction cost in supertall buildings, and the self-weight of floor system accounts for 20%-50% of the total weight of the buildings in reinforced-concrete tall buildings. Thus it is of great importance to reduce the cost and self-weight of the floor system. On the other hand, floor thickness affects the structural performance of sound insulation and fire protection directly. Floor-system design plays an important role in assuring the structural flexural capacity, stiffness, durability as well as the wind-resistant and seismic performance. Therefore, design and optimization of floor system is of great importance due to its significant economic and social benefits.

High-Performance Design

Horizontal Framing Layout

The overturning moment of supertall building is very large under lateral loads. Therefore, the weight of the floor should be transmitted to the outmost members, so that the tension caused by overturning moment can be offset by the pressure produced by the weight of the structure. That is to say, the long-span floor system should be chosen to span as far as possible and facilitate the removal of inner columns (Lin & Stotesbury, 1999).

概述

楼盖是水平承重结构体系，是超高层建筑的重要组成部分。楼盖结构通过抗弯和抗剪起着支承楼面荷载的作用，并将楼面荷载传递给竖向承重结构，与此同时，楼盖结构也将各竖向承重构件连接成一个整体，成为竖向承重结构的水平支撑，从而增加了竖向承重结构的稳定性，使之更好地发挥作用(沈蒲生，2003)。

超高层建筑的楼盖体系一般可分为钢筋混凝土楼盖和钢梁组合楼盖两种形式。钢梁组合楼盖体系又根据楼承板形式的不同主要分为开口型压型钢板、闭口型压型钢板和钢筋桁架组合楼盖。

超高层建筑中，楼盖约占土建总造价的20%～30%; 在钢筋混凝土高层建筑中，楼盖的自重约占总自重的20~50%，因而降低楼盖的造价和自重对整个建筑物至关重要。此外，楼板厚度对于建筑隔声和防火有直接影响。楼盖的合理设计对于保证建筑物的承载力、刚度、耐久性，以及提高抗风、抗震性能也有重要的作用。因此，正确、合理地设计和优化楼盖体系，不仅是必要的而且是重要的，它会带来明显的经济效益和社会效益。

As for the floor beams, the layout principle is as follows: 1) Arrange orthogonally or radially to the extent possible, to make the load transfer directly; 2) Control the depth of the beams to meet the requirement of clear height; 3) Arrange to ease equipment and pipeline crossings; 4) Set the spacing of beams to be equal to the extent possible. The spacing of steel beams is determined by the unsupported construction span of the steel deck, while the spacing of concrete beams is determined by the span of the floor slabs.

Floor Slab Design

In mainland China, a reinforced-concrete floor system is usually used in tall buildings with a height below 250 meters, while a composite floor system is adopted in tall buildings with heights above 250 meters, in consideration of construction duration and building costs. Based on the form of the deck, the floor slab of the composite floor system can be divided into an open-trough profiled deck floor system (see Figure 3.12a), flat-profiled deck floor system (see Figure 3.12b) and steel-bar truss deck-floor system (see Figure 3.12c) typically.

The open-trough profiled deck system has feature of light weight, low cost and easy construction, and is proven to be mature

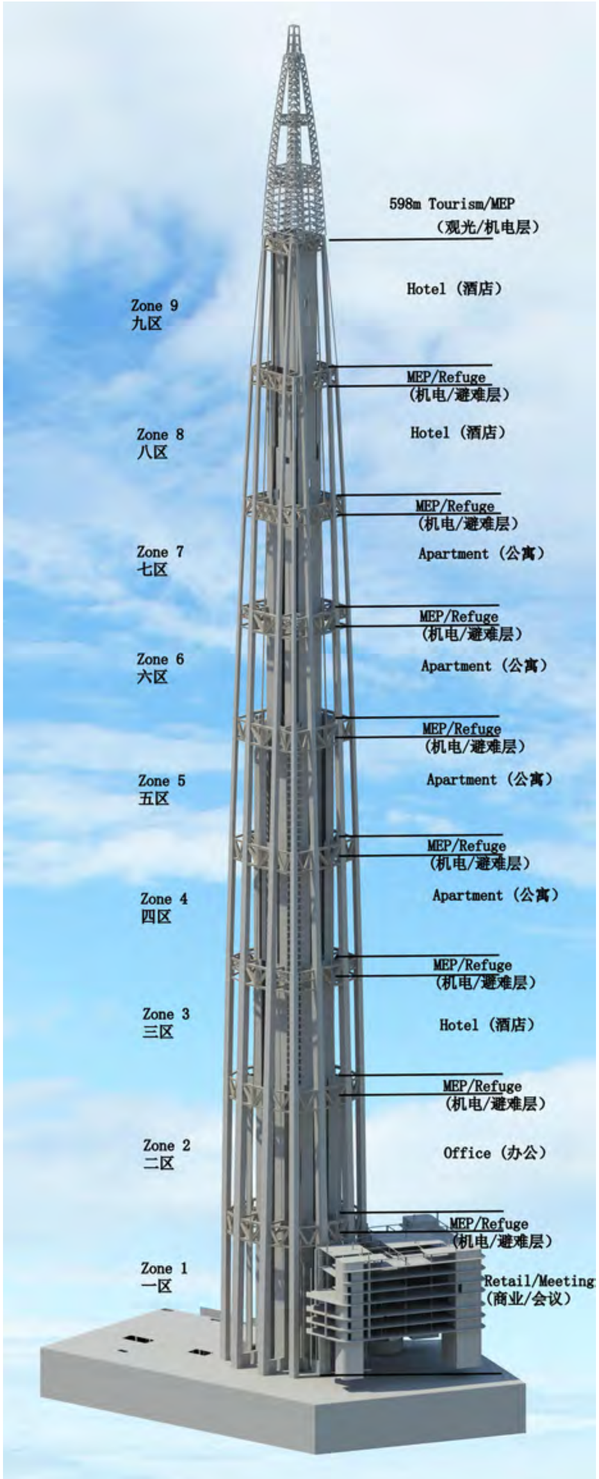

Figure 3.47. Tower Main Lateral System (Source: Thornton Tomasetti)
图3.47. 塔楼主体抗侧力体系 (来源: 宋腾添玛沙帝)

超高层建筑结构高性能楼盖体系设计

楼盖体系布置

超高层建筑中，在水平荷载作用下结构的倾覆力矩是非常大的。因此，在设计时，应尽可能的把楼盖上的重量传到最外面的抵抗倾覆力矩的构件上，由结构自重产生的预压力平衡倾覆力矩产生的拉力，即要尽可能采用大跨度的楼盖体系，取消内柱(林同炎，S.D.斯多台斯伯利，1999)。

对于楼面梁，其布置原则如下: 1) 尽量正交或放射状布置，这样传力直接、受力均匀; 2) 控制梁高，满足建筑净高需求; 3) 易于设备管线穿越; 4) 楼面梁布置间距受楼板类型影响，钢梁布置间距一般根据压型钢板楼承板无支撑施工跨度决定，混凝土梁间距一般根据板跨确定。

and reliable. The maximum unsupported construction span of the open-trough profiled deck floor system is about 3.0 to 3.3 meters. The thickness of a composite floor, however, is about 30 to 40 mm larger than that of a flat-profiled deck floor system or a steel-bar truss deck floor system, though it has superior fire-resistance capability. The flat-profiled deck floor system is thinner and has better fire-resistance performance and aesthetics. The cost of installing equipment and pipelines can be reduced due to the unique suspension system. However, the maximum unsupported construction span of a flat-profiled deck floor is generally no larger than 3 meters. The steel-bar truss deck composite floor system has better mechanical performance, and is often used in areas with complex stresses, such as in mechanical floors. The maximum unsupported construction span of a steel-bar truss deck composite floor system can be as long as 3.6 meters. But its construction is more complicated and its cost is higher.

Floor Structure Design

Floor structure design includes composite beam design and composite slab design. The steel beams in composite floor systems should be designed with consideration of the combination action of steel beams and slabs, and thus be designed 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. Over-pre-cambering should be avoided; 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.

The composite slabs should be designed according to the flexural capacity limit state and the serviceability limit state in both the construction stage and the service stage. The decks of the open-trough profile and flat-profile systems bear the self-weight of concrete and the construction loads as temporary forms during 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 resist the 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 tall buildings commonly need to meet the fire-resistance requirements of Class 1 – a heat insulation limit of at least 1.5 hours. In this situation, the concrete thickness beyond the rib of open-trough profiled decks 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.

Human-Induced Vibration

The issue of vibrations in floor systems has gotten more and more attention in recent years. Because of the low vertical vibration frequency, human activities can induce the vertical vibration of long-span slabs or cantilevered slabs in tall buildings, making people uncomfortable. In the design of the floor system, the vertical vibration frequency of slabs should be controlled to be not less than 3 Hz. Alternately, the peak ground acceleration (PGA) of slabs' vertical vibration can be controlled in the proper range through time-history analysis or simplified calculation. As for residences and offices, the PGA is to be limited to not more than 5 Gal (Lu, et al. 2012).

Floor Systems and Building Cost

Because there are many floors in supertall buildings, a slight change in floor systems has a significant impact on the structure's height, floor weight and floor cost.

Taking a 60-story building as an example, each floor height increase of 30 cm will make the structural height increase 18 meters, and the wind load and earthquake action will increase

楼板结构选型

在中国大陆地区，从成本角度考虑，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钢梁组合楼盖体系，其根据楼承板形式的不同主要分为开口型压型钢板 (图3.12a) 、闭口型压型钢板 (图3.12b) 和钢筋桁架组合楼盖体系 (图3.12c) 。

开口型压型钢板组合楼板自重轻、经济性好、施工方便、成熟可靠，其施工无支撑跨度约为3~3.3m，但是其楼板总厚度比闭口型和钢筋桁架楼板增加30~40mm。闭口型压型钢板板厚较小，板底平整，具有更好的美观性和更好的抗火性能，其独特的悬挂系统可节约机电管道的安装成本，其施工无支撑跨度一般不大于3m。钢筋桁架组合楼板的受力性能最好，常应用于受力复杂的区域，如加强层，其施工无支撑跨度可达3.6m以上，但其施工较为复杂，自身成本较高。图3.12a—3.12c对比了三种不同的楼盖体系。

楼盖结构设计

楼盖体系的设计主要包括组合梁和组合楼板的设计。对于组合楼盖体系中的钢梁，应考虑钢梁和楼板的组合作用，按照组合梁进行设计，需进行强度和挠度计算以及抗剪连接件的计算。如果钢梁的计算挠度过大可采用预起拱的方式解决，但预起拱值也不宜太大或相邻跨间有较大差异，以免施工困难或完成后出现明显的楼板不平整现象。通常预起拱值比重小于跨度的1/1000，并且小于2cm。

组合楼板应对其施工及使用两个阶段分别按承载能力极限状态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，而在使用阶段可部分替代或全部替代板底钢筋，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不应小于80mm，而闭口型和钢筋桁架组合楼板的总厚度不应小于110mm。

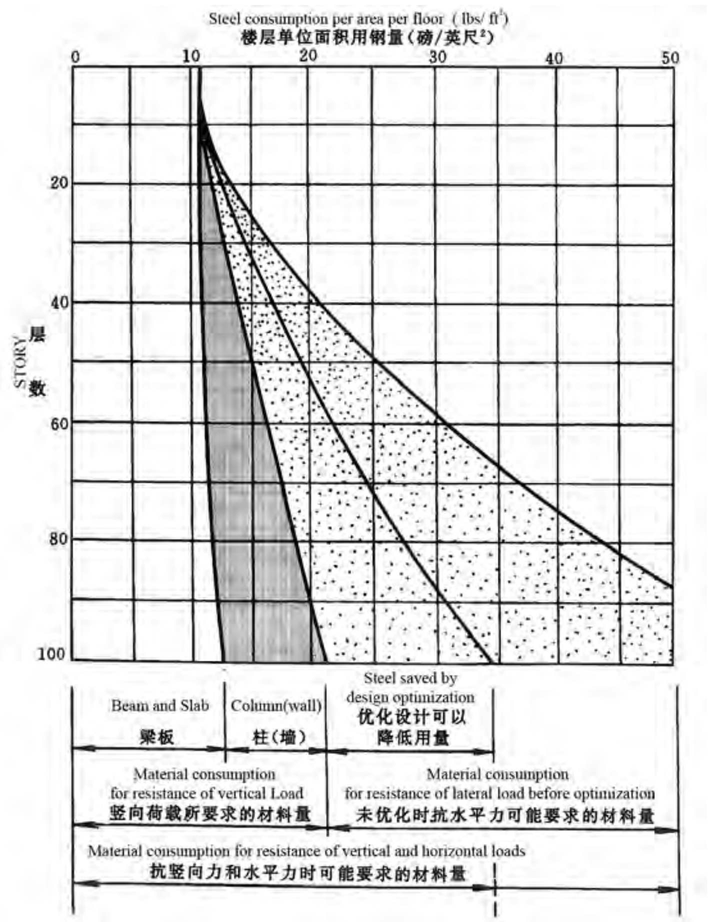

Figure 3.48. The change of structural cost with structural height (Source: Lin T.Y. &Stotesbury, S.D.)
图3.48. 结构成本随结构高度的变化 (来源: 林同炎 & Stotesbury, S.D.)

significantly. In addition, the cost of elevators, wall decorations and other mechanical and electrical facilities will also increase accordingly.

For supertall buildings in a seismic region, the weight of the floor system should be decreased in order to reduce the seismic action of the structure, so that the rebar consumption of the lateral load-resisting members can be reduced. There are lots of methods to decrease floor weight, such as using steel-composite floor systems, using lightweight concrete floors, using rational building surfaces and lightweight partition walls, and so on. In addition, the reduction of floor weight is beneficial for controlling the vertical component size and the foundation cost. In the soft-soil ground area, the cost of underground structures (including foundations) accounts for about 30% of the total structural cost. Therefore, reducing the weight of floor systems is significant for saving construction costs.

In mainland China, reinforced-concrete floor systems are commonly used in tall buildings with heights less than 250 meters, from the perspective of structural cost control. On the contrary, steel composite floor systems are used in tall buildings of more than 250 meters' height, for reducing the structural weight and easing construction. With the increase of structural height, the cost of floor systems basically remains unchanged, while the cost of lateral load-resisting members increases quickly, so the proportion of the floor system cost relative to the total cost gradually decreases (see Figure 3.48).

Case Studies

150-Meter-High Supertall Building

In a 150-meter-high supertall building, the original design scheme arranged two rows of columns for the frame-tube system. The internal columns were ineffective because they were too close to the core wall. The optimization design scheme cancels the internal columns and adopts a ribbed-beam floor system that transmits vertical loads to the external columns and balances the tension created by horizontal load efficiently (see Figure 3.49). This optimization proposal saves about 3,700 cubic meters of concrete, 300 metric tons of rebar, and provides an additional 560 square meters of usable floor area.

人致振动问题

超高层建筑的楼盖振动问题越来越引起人们的关注。对于超高层建筑中的大跨度楼盖和悬挑楼盖，由于楼板自振频率较低，当人正常行走时容易引起楼盖的竖向振动，从而引起人的不舒适感。在楼盖设计中，一般控制楼板的振动频率不小于3Hz;也可通过输入人的步行荷载曲线进行时程分析或进行简化计算，控制楼盖的竖向振动峰值加速度在一个合理的范围内，对于住宅和办公一般控制振动峰值加速度不大于5 gal (吕西林等，2012) 。

楼盖体系与建筑成本

由于超高层建筑的楼盖有很多层，因此楼盖体系的一点改变对整个结构都有很显著的影响。楼盖体系对超高层建筑成本的影响主要体现在结构高度、楼盖重量及自身造价。

以60层建筑为例，楼盖高度每增加30cm，结构总高度则增加18m，风荷载和地震作用将显著增大。此外，电梯、墙饰面以及其他机电设施的造价也要相应增加。

对于地震区的超高层结构，应注意减轻楼盖体系的自重以减小结构的地震作用，从而减少抗侧力构件的配筋，如: 采用钢梁组合楼盖体系、采用轻质混凝土楼板、采用合理的建筑面层和轻质隔墙等。另一方面，楼盖自重的减轻有利于控制竖向构件尺寸和基础的造价。在软土地基地区，地下结构 (含基础) 造价约占结构总造价的30%。因此，减轻楼盖体系自重对于提高结构经济性具有重要意义。

从控制结构成本的角度，中国大陆地区250m以下的超高层建筑通常选用钢筋混凝土楼盖体系，但是当结构高度超高250m时，为减轻结构自重一般选用钢梁组合楼盖体系。因为，随着结构高度的增加，楼盖体系的成本基本保持不变，而抗侧力构件的成本呈非线性增长，楼盖系统成本占总造价的比例逐渐降低，如图3.48所示。

案例分析

150m超高层

某150m超高层建筑，原设计方案采用内外两排框架柱-核心筒结构体系，内排柱因过于靠近核心筒，无法充分发挥作用，效率

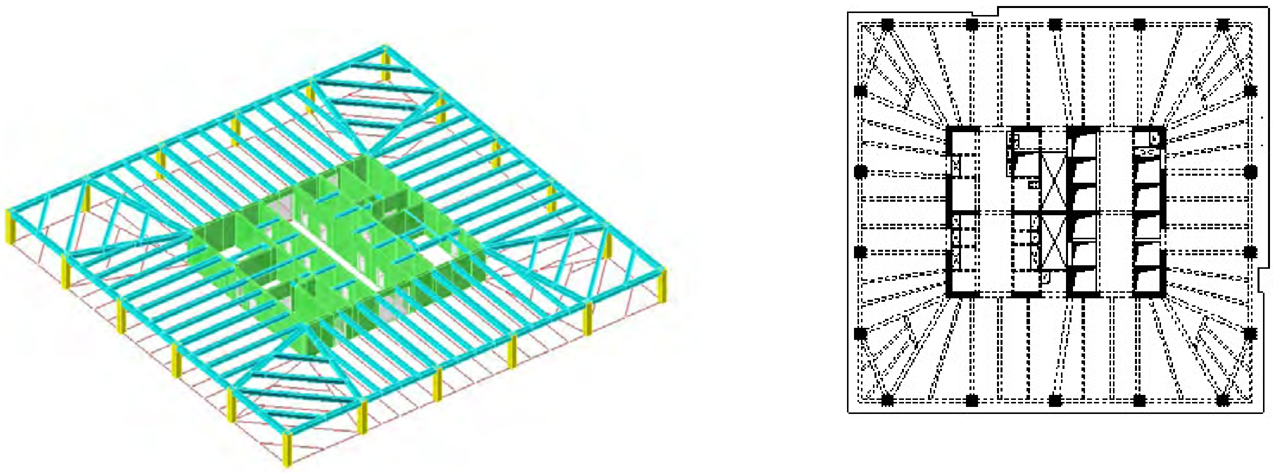

Figure 3.49. Floor systems layout optimization – Optimization design scheme (Source: Xin Zhao)
图3.49. 楼盖体系布置优化案例 – 优化设计方案 (来源: 赵昕)

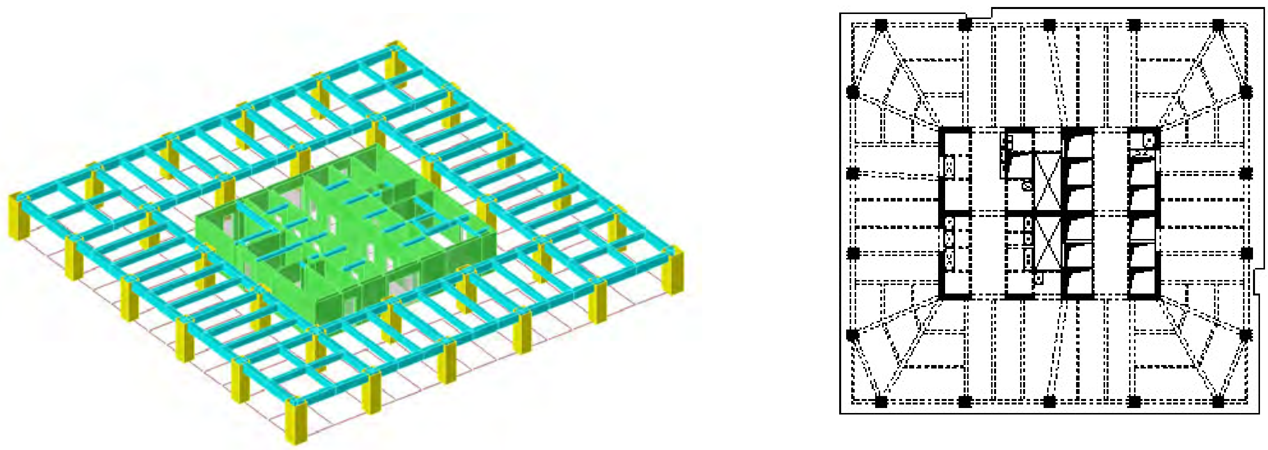

Figure 3.50. Floor systems layout optimization – Original design scheme (Source: Xin Zhao)
图3.50. 楼盖体系布置优化案例 – 原设计方案 (来源: 赵昕)

220m High Supertall Building

In a 220-meter-high supertall building, the original structural system was designed as a frame-core lateral load resisting system and reinforced-concrete floor system. The secondary beam and the main beams cross in the corner of the structure, while the indirect force transmission leads to the large section of the main beams and corner columns. After the optimization, the thickness of cantilever slab was reduced to 110 mm from 200 mm, and the section of the corner beams and columns and steel ratios of corner columns were all reduced, compared to the original scheme (see Figure 3.50).

Suzhou Zhongnan Center

Different types of composite floors were comparatively studied for the Suzhou Zhongnan Center. The total cost and weight of the open-trough profiled deck composite slabs, flat-profiled deck composite slabs and steel-bar truss deck composite slabs were compared (see Table 3.29 and Table 3.30). As a result, the total cost of the open-trough profiled deck composition slabs was 7% less than the others, and the weight of the open-trough profiled-deck composite slabs was 3% less than the others.

On account of the floor thickness, complex forces and high performance requirements, the steel-bar truss deck composition slabs are the most appropriate for use in mechanical stories.

较低。优化方案取消了内排柱，采用密肋梁楼盖体系，把竖向荷载传递到外围框架柱上，有效地平衡了水平荷载在框架柱产生的拉力，如图3.49所示。本次优化共节约混凝土用量约3700方，节约钢筋约300吨，节约材料成本约260万元，另外增加了使用面积约560平米。

220m超高层

某220m超高层办公楼，采用框架-核心筒结构体系，钢筋混凝土楼盖体系。原设计方案结构角部的楼面次梁与主梁相交，传力不够直接，导致主梁截面和角柱尺寸偏大。优化后角部楼面梁的布置如图3.50所示，这样悬挑板厚由200mm降低为110mm，角部主梁截面减小，角柱尺寸和含钢率均比原方案有所减小。

中南中心

针对中南中心项目，对组合楼板的选型进行了对比研究，开口型压型钢板、闭口型压型钢板和钢筋桁架三种楼承板的综合造价以及组合楼板的自重对比见表3.29和表3.30。结果表明，开口型压型钢板的综合造价比闭口型压型钢板和钢筋桁架低7%左

Type 类型	Open Trough Profiled Deck 开槽异形板	Flat Profiled Deck 平的异形板	Steel-bars Truss Deck 钢筋桁架板
Deck unit cost 单元板成本	80	98	110
Additional rebar fees 额外钢筋花费	35	32	16
Seal plate and stirrup 密封板和箍筋	10	5	0
Transportation costs 运费	6	6	12
Total cost 总花费	131	141	138

Table 3.29. Different composition slabs cost comparison (Unit: RMB/m²) (Source: Xin Zhao)
表3.29. 三种楼承板综合造价对比 (单位: 元/平米) (来源: 赵昕)

Type 类型	Open Trough Profiled Deck 开槽异形板	Flat Profiled Deck 平的异形板	Steel-bars Truss Deck 钢筋桁架板
Thickness of deck 板厚	1.0 mm	0.9 mm	0.5 mm
Total thickness of slab 楼板总厚度	155 mm	120 mm	120 mm
Weight of composite floor 合成楼板重量	304 kg/m²	314 kg/m²	–
Additional rebars weight 额外钢筋重量	8 kg/m²	8 kg/m²	–
Total weight 总重	312 kg/m²	322 kg/m²	320 kg/m²

Table 3.30. Different composition slabs weight comparison (Source: Xin Zhao)
表3.30. 三种组合楼板重量对比 (来源: 赵昕)

Conclusion

The design and optimization of supertall building floor systems is a comprehensive subject that directly influences the construction cost and building weight. In order to select the optimized floor system, comparison of multiple design schemes is needed, based on mechanics, cost, use and function, construction management and other factors. Several conclusions can be drawn:

1. Due to the large number of building floors, the floor system will significantly contribute to the cost and weight of supertall buildings.
2. High-performance design of floor systems can be arrived at by considering the horizontal framing layout, floor slab design, floor structure design and human induced vibration.
3. Considering structural cost and ease of construction, reinforced concrete floor system is commonly used in the tall buildings with building height of less than 250 meters, while composite floor systems will be applied in tall buildings with building heights of more than 250 meters in mainland China.

右，开口型压型钢板组合楼板的重量相比其他两种减少3%左右。

考虑到设备层由于楼板较厚、受力复杂、性能要求高，因此建议采用整体性更好、可双向受力的钢筋桁架组合楼板。

结论

超高层楼盖体系的设计和优化是一门直接影响工程项目经济效益的综合性科学，受多种因素的影响和制约。必须从力学、造价、使用功能和施工管理等多方面因素出发，综合分析、权衡利弊、因地制宜，优选出最佳的超高层楼盖体系。本文可得出结论如下:

1. 由于超高层建筑的楼层数量较多，楼盖体系对结构成本和结构自重有较大的影响;
2. 高性能楼盖体系的设计需考虑楼盖体系布置、楼板结构选型、楼盖结构设计和人致振动等问题;
3. 考虑到结构成本和施工便利性，在中国大陆地区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。

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