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Core Structural Design and Optimization
核心筒布置选型与优化

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Due to its excellent lateral stiffness and space flexibility, the megaframe-core wall structure is widely applied in supertall buildings. The efficiency of the central service core is critical for the optimal design of the megaframe-core structure. This chapter addresses the optimal layout arrangement of the central service core for efficient megaframe-core structural design. The typical layouts in the current supertall building service core design practices will be introduced first. The design criteria to be considered for the optimal structural design of central service core are then discussed. The Suzhou Zhongnan Center will be employed as an example to show the process on the optimal structural design of the service core. Five service core layouts will be analyzed, and the pros and cons of the five service core layouts will be compared and discussed.

由于其良好的抗侧刚度和建筑效果，框架¬核心筒结构广泛应用于超高层建筑。核心筒的抗侧刚度和效率是框架-核心筒结构设计的关键点。如何有效地、经济地布置核心筒值得结构工程师研究。本文针对核心筒布置选型对框架-核心筒结构设计的影响进行探讨。首先对中国现有超高层建筑核心筒形式进行回顾，其次对核心筒设计需要考虑的设计标准进行讨论，然后以中南中心大厦模型为例提出了5个典型的核心筒方案并建立模型进行计算分析。最后，对各方案进行比选分析。

Introduction

With the rapid development of urban areas in recent decades, supertall buildings have become an important symbol of economic prosperity, social development and urbanization in mainland China. Such buildings are mainly distributed in the Pearl River delta and Yangtze River delta regions and in other megacities.

The megaframe-core wall structure is widely adapted in structural design of supertall buildings. The efficiency of the central service core is one of the key aspects for the optimal design of megaframe-core wall structure. The efficient core structural design has to consider the core layout, structural cost and structural weight.

The typical layouts of central service cores are the 9-grid square layout, the 16-grid square layout and the triangular layout. The 632-meter Shanghai Tower has a 9-grid square core layout (see Figure 3.19). Ding, Chao et. al. (1996) addressed critical issues of structural analysis for the Shanghai Tower project, and introduced the main design criteria of the central core. The central service core of the Shanghai Tower is 30 meters by 30 meters, and is made of concrete. The corners of the service core were cut off above zone 5 due to accommodate the shrinkage of floor plane. The perimeter walls of the service core were further removed, and only central cross walls were left for the high zones. Ping An International Financial Center also has a 9-grid square layout service core. Huang and He (2014) introduced the main design criteria of the core and the typical core layout of Ping An International Financial Center (see Figure 3.21). Dalian Greenland Center is 606-meter megatall building, and its service core layout is triangle-shaped (see Figure 3.20). The 96-story-tall CTF Tianjin Tower's service core has a 16-grid layout in a square shape (see Figure 3.22).

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. The core structure contributes significantly to the overall building structure. The central core is one of the critical components of the main lateral load resisting system, and takes a large percentage of the gravity loads, base shear and overturning moment of the tower.

引言

随着中国超高层建筑近几年的迅猛发展，超高层建筑已经成为中国大陆地区的经济社会发展和城市化进程的重要标志之一。目前，超高层建筑主要分布在珠三角和长三角地区等一线城市。

框架-核心筒结构在我们超高层建筑中得到了广泛的应用。而核心筒的抗侧刚度和效率是框架-核心筒结构设计的关键点。核心筒设计必须考虑布置选型、结构造价以及结构质量等问题。

核心筒平面有九宫格、回字形、矩形及三角形等方案。上海中心建筑总高度为632m，采用九宫格形式，如图3.19。丁洁民、巢斯等人 (2010) 研究了上海中心大厦的关键结构设计问题，并引出了核心筒设计的主要设计指标。上海中心中央核心筒底部为30m×30m方形混凝土筒体。从第五区开始，核心筒四角被削掉，逐渐变化为十字形，直至顶部。深圳平安国际金融中心也采用九宫格形式布置核心筒，见图3.21。黄用军和何远明等人 (2014) 阐述了核心筒设计的主要设计标准以及深圳平安国际金融中心的核心筒典型平面布置。如图3.20所示，大连绿地中心是一座高606米的超高层建筑，其核心筒形式为三角形。图3.22为高96层的天津周大福大厦，其核心筒布置形式为16宫格。

This chapter mainly addresses the core structural design and optimization of supertall and megatall buildings. The design criteria for core structures will be firstly discussed for supertall buildings generally. The megatall Zhongnan Center project will then be used as an example to show the influences of different core layouts on structural design. In total, five layouts will be considered, and the pros and cons of each layout will be compared and discussed.

Design Criteria

The core structural design has to consider the controlling factors for tall buildings, such as story drift, vibration period, and minimum seismic shear ratio.

The story drift limit for supertall buildings is set by satisfying the deformation requirements of non-structural components and making the structure remain elastic under moderate wind loading and frequent earthquake action. The story drift limit is commonly set to 1/500 for supertall building designs in China.

For supertall buildings, the vibration period is commonly quite long, and the long period response components have to be carefully considered. Due to the lack of long-period ground motion records, there are many uncertainties in the understanding of long-period response components for engineering projects. In current supertall building design practices in China, the first vibration period of supertall buildings is commonly controlled to be less than 9.5 seconds. Adjustment can be made for the minimum seismic shear ratio of structures with long periods (T > 5 s). Considering that the base shear derived from The China Quality Certification Center (CQC) guidelines is larger than that derived from the simplified equivalent base-shear method, the minimum shear-to-weight ratio can be multiplied by a reduction factor of 0.85 (Wang 2013).

The strength and axial compression ratio requirements should also be satisfied for core shear wall members. For supertall

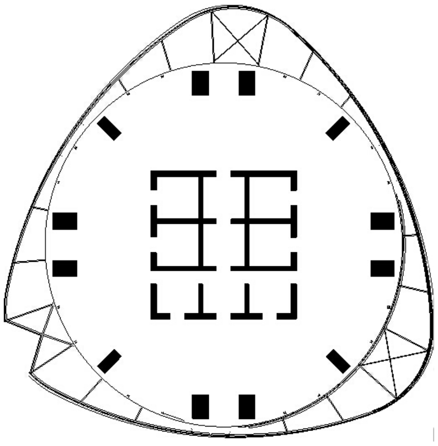

Figure 3.19. Typical layout plan of Shanghai Tower (Source: Guangjing Sha)
图3.19. 上海中心典型层平面图（出自: 沙广璟）

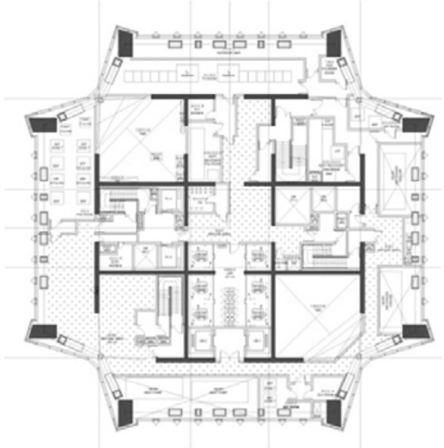

Figure 3.21. Typical layout plan of Ping an International Financial Center (Source: Guangjing Sha)
图3.21. 平安国际金融中心典型层平面图（出自: 沙广璟）

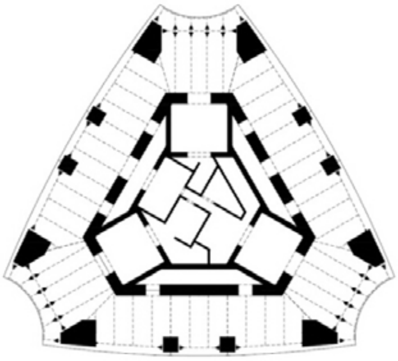

Figure 3.20. Typical layout plan of Dalian Greenland Center (Source: Guangjing Sha)
图3.20. 大连绿地典型层平面图（出自: 沙广璟）

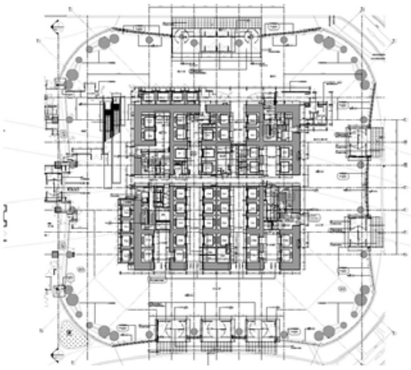

Figure 3.22. Typical layout plan of CTF Tianjin Tower (Source: Guangjing Sha)
图3.22. 天津周大福中心典型层平面图（出自: 沙广璟）

核心筒结构优化设计必须全面考虑不同的设计要求，例如垂直交通、火灾疏散、设备层管道布置、加强层设备房间布置等。核心筒对整体结构有着显著的作用。核心筒是结构主要抗侧力体系构件之一，承担了结构大部分的重力荷载，基底剪力和倾覆力矩。

本文主要研究了超高层建筑核心筒设计以及优化。首先探讨了核心筒结构的设计指标。并以中南中心大厦为例研究了5种不同核心筒布置对于结构的影响，并对各方案进行比选分析。

设计参数

核心筒结构设计必须考虑超高层结构的一些控制因素，例如层间位移角、自振周期以及最小剪重比。

超高层结构层间位移角限值必须满足非结构构件的变形要求以及使结构在风荷载以及小震下依旧保持弹性状态。在中国高层规范中位移角限值经常被设置为1/500。

对于超高层建筑，结构的自振周期通常都较长，故结构长周期响应必须在结构设计中考虑。由于缺少长周期地震动记录，所以在实际工程中对于长周期响应仍然存在不确定的因素。在目前中国超高层结构设计中，超高层结构第一自振周期通常被控制在9.5s以内。根据王亚勇的研究 (2013)，考虑到运用振型分解CQC组合的基底剪力比简化的底部剪力法得到的基底剪力小，最小剪重比限值可以乘以折减系数0.85”。

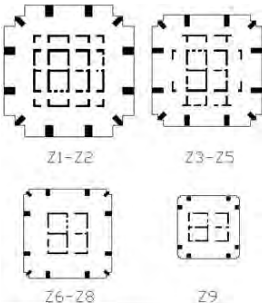

Figure 3.23. Typical layout plan for Scheme 1 (Source: Guangjing Sha)
图3.23. 方案1典型层平面图（出自: 沙广璟）

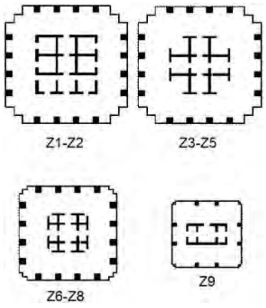

Figure 3.24. Typical layout plan for Scheme 2 (Source: Guangjing Sha)
图3.24. 方案2典型层平面图（出自: 沙广璟）

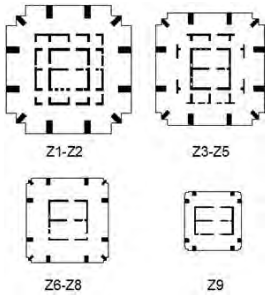

Figure 3.26. Typical layout plan for Scheme 4 (Source: Guangjing Sha)
图3.26. 方案4典型层平面图（出自: 沙广璟）

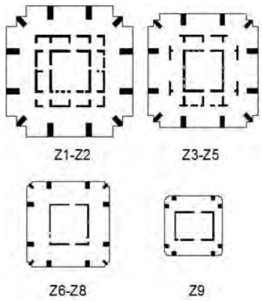

Figure 3.25. Typical layout plan for Scheme 3 (Source: Guangjing Sha)
图3.25. 方案3典型层平面图（出自: 沙广璟）

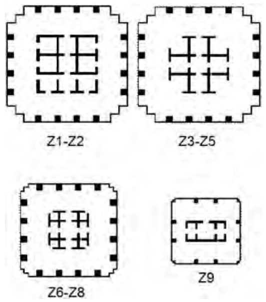

Figure 3.27. Typical layout plan for Scheme 5 (Source: Guangjing Sha)
图3.27. 方案5典型层平面图（出自: 沙广璟）

buildings, the axial compression ratio limit for the core shear walls is commonly 0.5, according to Chinese code. The size of the shear walls in the low zones is usually controlled by the axial compression ratio. The size of the shear walls in the high zones is controlled by the requirement of lateral stiffness, and sometimes by the shear capacity requirements under a rare earthquake.

Considering the effective usable area and the building function requirements, the area of the service core is about 25 percent to 35 percent of the plane area. Thus, the core structure makes significant contributions to the overall structural lateral stiffness. The core shear walls should line up with the main plane axes and continuously extend to upper and lower floors to avoid potential transferring requirements. To increase the usable area, the web shear walls in the high stories can be omitted, or parts of the fin shear walls can be replaced by gravity columns.

Case Study

The frame-core wall structure of the Suzhou Zhongnan Center is composed of megacolumns, a central service core, belt trusses, and outrigger trusses.

By considering the relationship between megacolumns, corner columns, the central service core and outriggers, in total five plane layouts were investigated for the Zhongnan Center project:

1. Core scheme 1: 16-grid core layout, eight widely spaced megacolumns, four corner columns (see Figure 3.23)
2. Core scheme 2: 9-grid core layout, eight closely spaced megacolumns, four corner columns (see Figure 3.24)
3. Core scheme 3: 16-grid core layout, eight widely spaced megacolumns, four corner columns, without interior web walls in both direction (see Figure 3.25)

核心筒剪力墙需要满足强度以及轴压比的要求。根据中国混凝土规范，对于超高层建筑，剪力墙轴压比限值通常为0.5。低区剪力墙的尺寸通常是由轴压比控制。而高区剪力墙的尺寸通常是由侧向刚度要求和罕遇地震下的抗剪承载力要求。

考虑到有效使用面积以及建筑使用功能的要求，核心筒面积比一般控制在25%到35%之间。核心筒对结构整体刚度有着显著的贡献。剪力墙应沿建筑平面的主要轴线布置，宜上下连续贯通。为提高建筑平面使用效率，可以在高区取消中间部分腹墙，亦可在高区将外侧部分核心筒剪力墙变为重力柱。

案例分析

结构采用框架-核心筒结构体系，在设计中采用巨柱、核心筒、环带桁架、伸臂桁架组成。

在考虑巨柱、角柱、核心筒以及伸臂桁架之间的相互关系，最后筛选了5个核心筒优化布置方案进行分析:

1. 核心筒方案1: 16宫格布置，8根长间隔巨柱，4根角柱，如图3.23所示。
2. 核心筒方案2: 9宫格布置，8根长间隔巨柱，4根角柱，如图3.24所示。
3. 核心筒方案3: 16宫格布置，8根长间隔巨柱,4根角柱，取消X、Y向内腹墙，如图3.25所示。
4. 核心筒方案4: 16宫格布置，8根长间隔巨柱，4根角柱，取消Y向内腹墙，如图3.26所示。
5. 核心筒方案5: 9宫格布置，16根短间隔巨柱，无角柱，如图3.27所示。

方案1核心筒为16宫格形式。在1、2区为正方形，在3区至5区外翼墙切角，6区外翼墙消去。核心筒内翼墙最大厚度在一区底层为1.2米，沿高度方向逐渐减至0.5米。墙厚详细尺寸见表3.5。方案1在正方形四边分别布置一对 (共八根) 巨型钢骨混凝土巨柱，尺寸由底层3.80m×4.90m随着高度方向逐渐减小至1.90m×1.90m。相邻巨柱之间的典型距离达到19.5米，在建筑角部共布置四根角柱。角柱尺寸由底层3.60m×3.60m逐渐缩至1.50m×1.50m，在9区底部终止。

The Number of Walls 墙数	Zone 区域	Story 层数	The Thickness of Shear Walls 剪力墙厚度
W1	Zone 3	27~42	750
W1	Zone 5	60~75	450
W2	Zone 5	60~75	750
W2	Zone 6	76~90	750
W2	Zone 7	91~104	600
W2	Zone 8	105~120	550
W2	Zone 9	121~138	500
W3	Zone 5	60~75	650
W3	Zone 6	76~90	650
W3	Zone 7	91~104	550
W3	Zone 8	105~120	450
W3	Zone 9	121~138	400

Table 3.5. The thickness of shear walls (Source: Guangjing Sha)
表3.5 剪力墙厚度 (出自: 沙广璟)

Location 位置	The Thickness of Abdominal Wall in the Y Direction 腹壁在Y方向上的厚度	
	Scheme 1 阶段1	Scheme 4 阶段4
Z1	1200	1400
Z2	1100	1300
Z3	1000	1200
Z7	600	750
Z8	550	750
Z9	500	700

Table 3.6. The thickness of web wall in the Y direction (Source: Guangjing Sha)
表3.6. Y方向腹墙厚度 (出自: 沙广璟)

4. Core scheme 4: 16-grid core layout, eight widely spaced mega columns, four corner columns, without interior web walls in the Y direction (see Figure 3.26)
5. Core scheme 5: 9-grid core layout, 16 closely spaced mega columns, no corner columns (see Figure 3.27)

The service core of scheme 1 is a 16-grid square layout. The shape of the core is square in zones 1 and 2. The corners of fin walls are cut off from zone 3 to 5. The exterior fin walls are fully removed from zone 6 upwards. The maximum thickness of the exterior fin wall is 1.2 meters at the bottom, and gradually reduces to 0.5 meters at the top. Table 3.5 shows the dimensions of the shear walls. Eight megacolumns are arranged on four sides of the core square, and four corner columns are arranged on the four corners of the plane. The megacolumn size reduces from 3.8 m by 4.9 m at the bottom to 1.9 m by 1.9 m on the top. The corner column size reduces from 3.6 m by 3.6 m at the bottom to 1.5 m by 1.5 m on the top. The space of the two megacolumns in the same side is 19.5 meters.

Scheme 2 also has twelve megacolumns and the square central service core. Because the megacolumns and outriggers should be aligned with the web walls, the two megacolumns of Scheme 2 are closer to each other. Based on Scheme 1, Scheme 3 removed the web walls both in X and Y directions. Because the lateral stiffness in the Y direction is bigger than the one in the X direction, Scheme 4 removes the web walls in the Y direction and increases the thickness of the web walls in the X direction. Table 3.6 shows the thickness of web walls. Core layout of Scheme 5 is the same as Scheme 2, but the area of the megacolumns increases to 16.

The results of the analysis are shown in Table 3.7. The first– and second– order mode shape of each schemes are translational, and the first order mode shape translates to X direction, the second order mode shape translates to Y direction, the third order mode shape is torsional. As the table shows, except in scheme 2, the first period of all schemes is less than 9.5 seconds, and all the schemes satisfy specification limits that the ratio of the first torsion period of structure and the first translation period is less than 0.85. This demonstrates that the plane layout of each scheme has appropriate torsional capacity.

Under the lateral loads, the story drift for each floor is calculated. The interstory drift of each scheme under wind loads is shown in Figures 3.28 and 3.29.

The analysis results of the interstory drift are shown in Table 3.8 and Figures 3.28 and 3.29. Schemes 1, 4 and 5 meet the drift limit 1/500. The maximum interstory drift of scheme 5 is the minimum by a small margin. While scheme 2 and scheme 3 apparently do not meet the drift requirements, the interstory drift is far less than 1/500 due to excessive stiffness loss.

The final minimum seismic shear ratio limit is taken to be 1.11%. The calculation results are shown in Table 3.9. The minimum seismic shear ratios occur at the bottom. All of the schemes satisfy the limit except for Scheme 3. The minimum seismic shear ratio in direction X reaches 1.13%, and the minimum seismic shear ratio in direction Y reaches 1.14%, which is superior to the other schemes.

方案2采用十二根柱以及九宫格形式核心筒。因巨柱、伸臂桁架等构件一般与核心筒内腹墙对齐，故巨柱相对于方案1，向中心轴线靠近，与腹墙对齐。方案3在方案一的基础上去除核心筒X、Y向腹墙，形成类似十六宫格核心筒。因为Y向的侧向刚度大于X向的侧向刚度，所以方案4在方案1的基础上去除核心筒Y向腹墙，并增大了X向腹墙的厚度。腹墙的厚度变化如表3.6所示。方案5与方案2的核心筒布置相同，同样采用九宫格形式的核心筒，并在此基础上将巨柱改为16根柱。

结构自振周期计算分析的结果如表3.7所示。各方案第一、二阶振型皆为平动，第一阶振型为X向平动，第二阶振型为Y向平动，第三阶振型为扭转。如表所示，除方案2以外，各方案第一阶周期皆小于9.5s，且满足结构第一扭转周期与第一平动周期的比值小于0.85的规范限制，体现了各方案的平面布置是较合理的。

在侧向荷载下，对结构进行层间位移角计算，各方案风荷载作用下层间位移角见图3.28、3.29。

各方案层间位移角计算结果如表3.8以及图3.28、图3.29所示，方案1、4、5都满足规范限制1/500，方案5最大层间位移角最小，但都相差不大。而方案2以及方案3显然不满足规范要求，刚度较弱，远低于1/500。

本结构最小剪重比取为1.11%。计算结果如表3.9。经过计算结构最小剪重比皆出现在底层，且除方案3以外都满足1.11%的限制。方案1剪重比最大，X向达到1.13%，Y向剪重比达到1.14%，优于其他各方案。

比较各方案，方案2巨柱间距较近，对于抗侧刚度效率较低，且核心筒在5~6区间收进形成斜墙，而5~6区对位移角敏感，对结构整体刚度不利，造成结构最大层间位

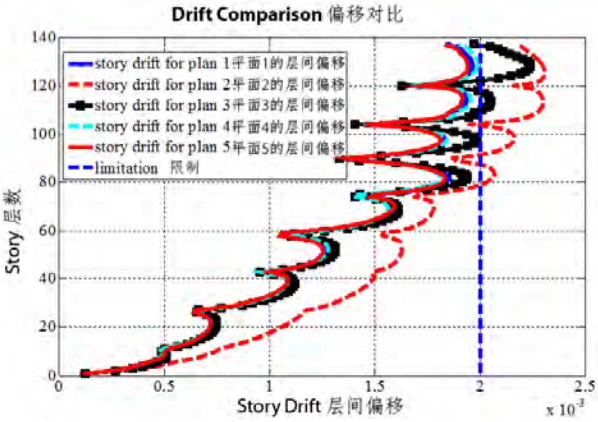

Figure 3.28. Story drift under wind load in the X direction (Source: Guangjing Sha)
图3.28. 风荷载下x方向层间位移角（出自: 沙广璟)

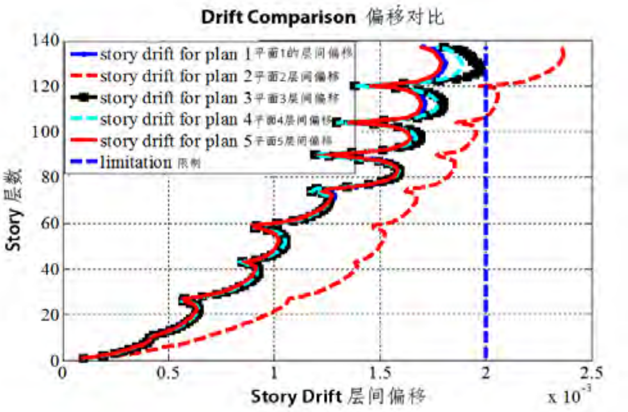

Figure 3.29. Story drift under wind load in the Y direction (Source: Guangjing Sha)
图3.29. 风荷载下Y方向层间位移角（出自: 沙广璟)

Compared with other schemes, the space between megacolumns is closer in Scheme 2. The lateral stiffness efficiency is lower, and the core forms inclined walls in Zone 5 and 6. Furthermore, Zones 5 and 6 are sensitive to interstory drift, which is adverse to the overall stiffness of structure. Thus the maximum interstory drift of structure does not meet the requirements and the first period is too long. The inclined walls also have great influence on the function of apartments and complicate the arrangement of elevators in Zone 5 and 6.

Scheme 3 removes web walls of the core, both in the X direction and the Y direction. Although the flexibility of the building layout is increased, it has a greater influence on the lateral stiffness of structure. The maximum interstory drift does not meet the requirements. The whole criterion of Scheme 4 meets the specification requirements, but compared with Scheme 1, the cost increases by about US $2 million. The spacing between megacolumns is small in Scheme 5, and thus the daylight penetration of Scheme 5 is relatively poor. Due to the increase of megacolumns, the cost of the structure increases substantially (see Figure 3.30).

Considering structural lateral stiffness, construction cost, architectural requirements and other factors, Scheme 1 is better than the others. The architectural layout is flexible and the lateral stiffness is suitable. Because the megacolumns and outriggers should be aligned with the web walls, the contribution from the layout of megacolumns of scheme 1 is the best.

Period 周期	Scheme 1 阶段1	Scheme 2 阶段2	Scheme 3 阶段3	Scheme 4 阶段4	Scheme 5 阶段5
T1	9.37	11.39	9.2	9.32	9.2
T2	9.08	11.24	8.88	9.12	8.88
T3	4.05	4.1	4.13	4.12	4.13
T3/T1	43%	36%	45%	44%	45%

Table 3.7. Period Comparing results (Source: Guangjing Sha)
表3.7. 周期对比 (出自: 沙广璟)

Inter-story drift 层间偏移		Scheme 1 阶段1	Scheme 2 阶段2	Scheme 3 阶段3	Scheme 4 阶段4	Scheme 5 阶段5
Wind load with return period of 50 years 风荷载回归周期50年	X	1/509	1/423	1/456	1/502	1/514
	Y	1/545	1/433	1/495	1/530	1/550
Frequent earthquake 多遇地震	X	1/558	1/470	1/508	1/556	1/568
	Y	1/529	1/407	1/472	1/509	1/539

Table 3.8. Story drift comparing results (Source: Guangjing Sha)
表3.8. 层间位移角对比 (出自: 沙广璟)

移角不满足要求，第一阶周期过长。斜墙位于5~6区间，对两区公寓建筑功能影响较大，电梯排布困难。

方案3去除了核心筒X向、Y向腹墙，虽增加了建筑布置的灵活性，但是对结构侧向刚度影响较大，最大层间位移角不满足规范要求。方案4各项整体指标都满足规范要求，但是相对于方案1，在造价方面增加了约200万，经济性较差。方案5巨柱布置间距过密，影响采光。且因为巨柱数量的增多，造成结构成本的增加，不够经济。(见图3.30)

结合结构侧向刚度、经济性以及建筑要求等各项因素，方案1较好。十六宫格的核心筒布置方式，对于建筑布置较灵活，且侧向刚度较大，且因为巨柱一般需对齐核心筒内翼墙，方案1的巨柱布置对整体结构侧向刚度的贡献也是最佳的。

结论

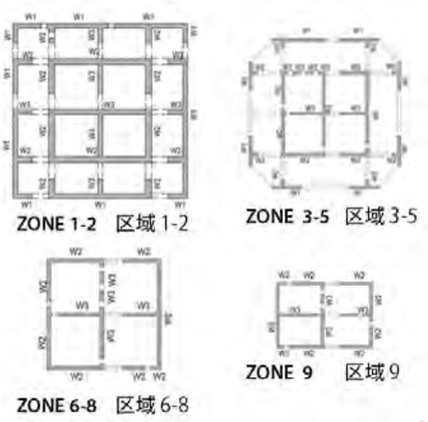

Figure 3.30. Typical layout plan of Dalian Greenland Center (Source: Guangjing Sha)
图3.30. 大连绿地典型层平面图 (出自: 沙广璟)

Limit 限制	**Scheme 1** 阶段1		**Scheme 2** 阶段2		**Scheme 3** 阶段3		**Scheme 4** 阶段4		**Scheme 5** 阶段5	
	X	Y	X	Y	X	Y	X	Y	X	Y
1.11%	1.13%	1.14%	1.12%	1.14%	1.09%	1.09%	1.11%	1.12%	1.12%	1.13%

Table 3.9. Comparing results of minimum shear weight ratio (Source: Guangjing Sha)
表3.9. 最小剪重比对比 (出自: 沙广璟)

	Scheme 1 阶段1	**Scheme 2** 阶段2	**Scheme 3** 阶段3	**Scheme 4** 阶段4	**Scheme 5** 阶段5
Cost 成本	normal 一般	normal 一般	low 低	high 高	high 高

Table 3.10. Structural cost estimation (Source: Guangjing Sha)
表3.10. 结构成本造价 (出自: 沙广璟)

Conclusions

This chapter addressed the core structural design and optimization for supertall buildings. Several design criteria were discussed, and the Suzhou Zhongnan Center project was employed as an example for the comparative studies of the different core layouts. The 9-grid core layout and the 16-grid core layout were combined with different numbers of megacolumns and corner columns to generate different structural systems. Based on the above discussions and comparative study results, we can come to the following conclusions:

1. The optimal design of the core structure can only be achieved by comprehensively considering different design requirements such as vertical transportation, structural efficiency, fire evacuation, etc.
2. For the case of the Suzhou Zhongnan Center, the 16-grid core layout can offer better lateral stiffness and shear capability, and can be properly applied for intense vertical transportation demand;
3. Compared with the 16-megacolumn scheme, the 8 megacolumn / 4 corner-colum schemes have better lateral stiffness and are more conducive to natural lighting;
4. The optimal core layout should be obtained by properly testing the relationship between megacolumns, corner columns, core layouts and outriggers.

本文探讨了超高层建筑核心筒设计及优化，并研究了各项设计控制指标。以中南中心大厦为研究对象对不同核心筒布置方案进行对比分析。各方案以9宫格和16宫格两种核心筒布置方式为基础，并和不同数量的巨柱以及角柱相结合。基于以上的讨论以及对比分析结果，得出以下结论:

1. (1) 核心筒优化设计需要全面考虑不同设计要求，例如垂直交通、结构效率、火灾疏散灯。
2. (2) 对于中南中心案例，16宫格核心筒布置方案可以提供更好的侧向刚度和抗剪承载力，并可以满足垂直交通需求
3. (3) 对比16巨柱方案，9巨柱与4角柱的方案有更好的侧向刚度，并可以提供更好的采光。
4. (4) 核心筒优化需要合理处理巨柱、角柱、核心筒以及伸臂桁架之间的关系。

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