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Unique Structural Design Aspects

独特的结构设计

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This chapter discusses the unique structural solutions for the 632m tall Shanghai Tower. An innovative "Core-Outrigger-Mega Frame" lateral system is adopted to meet China's conservative code requirements for lateral stiffness and member capacities to realize the iconic architectural profile effectively. The 6m thick CIP pile supported-mat foundation, enhanced by the concrete fin walls at basement levels, help distributes loads more evenly to the soft supporting soil underneath. End grouting is provided at the tip of the pile to increase pile capacity and reduce settlement. Optimization of the tower lateral system is a continuous process through all design phases: a 20% wind load reduction is achieved by fine tuning the tower profile; 13,000 tons of steel saving is achieved through extensive optimization of outrigger trusses and structural steels encased in super columns. Advanced Performance Based Design (PBD) is used to verify tower performance under different seismic hazard levels through non-linear dynamic time-history analysis.

本文讨论了632米高的上海中心大厦所采用的独特结构方案。该结构创新性地使用了"核心筒-外伸臂-巨型框架"抗侧力体系，在满足中国规范对侧向刚度和构件承载力严格要求的同时，有效地体现了建筑轮廓的标志性。厚度达6米并且在基础部分由混凝土翼墙加强的现浇桩筏基础帮助荷载更加均匀地传递到下方软支撑土。在桩顶采用了桩端注浆方法以提高单桩承载力，减少沉降。结构侧向体系的优化过程贯穿了所有的设计阶段: 通过塔楼轮廓的微调减少了20%的风荷载; 通过对外伸臂桁架及巨柱中结构配筋进行深度优化，节省了13000吨的钢材。采用非线性动力时程分析的高级性能设计 (PBD)，用于验证在不同地震等级下的塔楼性能。

Project Description

Shanghai Tower has a unique twisting skin, but inside it takes the form of nine cylindrical buildings stacked one atop another, including a business zone, five office zones, two hotel/apartment zones, and one top zone with observation floors. Each zone can be considered an independent city or village with communal space at an amenity level where the slab extends to reach the outer twisting façade (see Figure 3.1). The regular tower floor plate at each zone is a circular shape with diameters that vary from 82.2m at bottom to 46.5m at top (see Figure 3.2). The stacked-zone tower concept within a tapering and twisting exterior façade creates a spectacular architectural design. Shanghai Center was topped-out on August, 2013 (see Figure 3.3) and will be the tallest building in China when completed in 2015.

Site Conditions and Foundation Design

Like other supertall buildings, the foundation mat design of Shanghai Tower was a big challenge due to large gravitational forces and large overturning forces from wind and seismic loads. Soft soil conditions at the site reinforced that challenge. With nine layers of sands and soft clays alternating to at least 120m below grade, bedrock is considered beyond reach for practical construction purposes. Because the top 15m is very soft clay, the site for seismic design is considered as Type IV— the most unfavorable class according to the Chinese code and roughly comparable to Site Class "F" under the International Building Code (IBC) (see Table 3.1).

The foundation system of Shanghai Tower is a reinforced mat foundation supported on 947 1m diameter cast-in-place (CIP) concrete piles. Testing piles were constructed to determine the pile capacity. The production piles are effectively 52m to 56m long and bear at layer 9-2-1. The end grouting is provided at the pile's tip to increase pile capacity and reduce settlement. A staggered pattern pile layout is used to fit more piles under the core and super columns. The mat construction set a record of pouring 61,000 cubic meters of concrete continuously in 60 hours. See Figure 3.4 for construction photo of pouring mat.

项目介绍

上海中心大厦有一个独特的扭曲表面，但它的内部采用的是九个圆柱体堆叠的建筑形式，其中包括一个商务区，五个办公区，两个酒店/公寓区，以及顶层观光区域。每个区域都可被当作一个拥有公共空间的独立的城市或村落，公共空间位于由楼板延伸到外扭曲的玻璃幕墙所形成的舒适层 (见图3.1) 。每个区域的常规塔楼是圆形的，直径从底部的82.2米到顶部的46.5米递变 (见图3.2) 。外墙立面逐渐变细同时随高度扭曲的堆叠塔式概念造就了一个壮观的建筑设计方案。上海中心大厦于2013年8月封顶 (见图3.3) ，在2014年竣工时将成为中国最高的建筑。

场地条件和基础设计

与其他超高层建筑一样，因为有极大的重力及由风荷载和地震荷载所产生的倾覆力，上海中心大厦的基础筏板设计是一个很大的挑战。所处地点的软土条件使得情况变得更加严峻。有九个砂与软粘土的交替相间的土层达到至少120米以下级，该岩床被认为是不可能进行实际施工的。因为表层15米是很软的粉质粘土，该场地的抗震设计类别为IV型——该类别为中国规范中的最不利情况，大致相当于国际建筑规范 (IBC) 中的"F"类。 (见表3.1)

Figure 3.1. With the outer skin removed, the regular circular floor plates are revealed. (Source: Gensler)
图3.1. 将外层表皮剥离后，可以看到每层平面都呈现规则的圆形。（来源：Gensler）

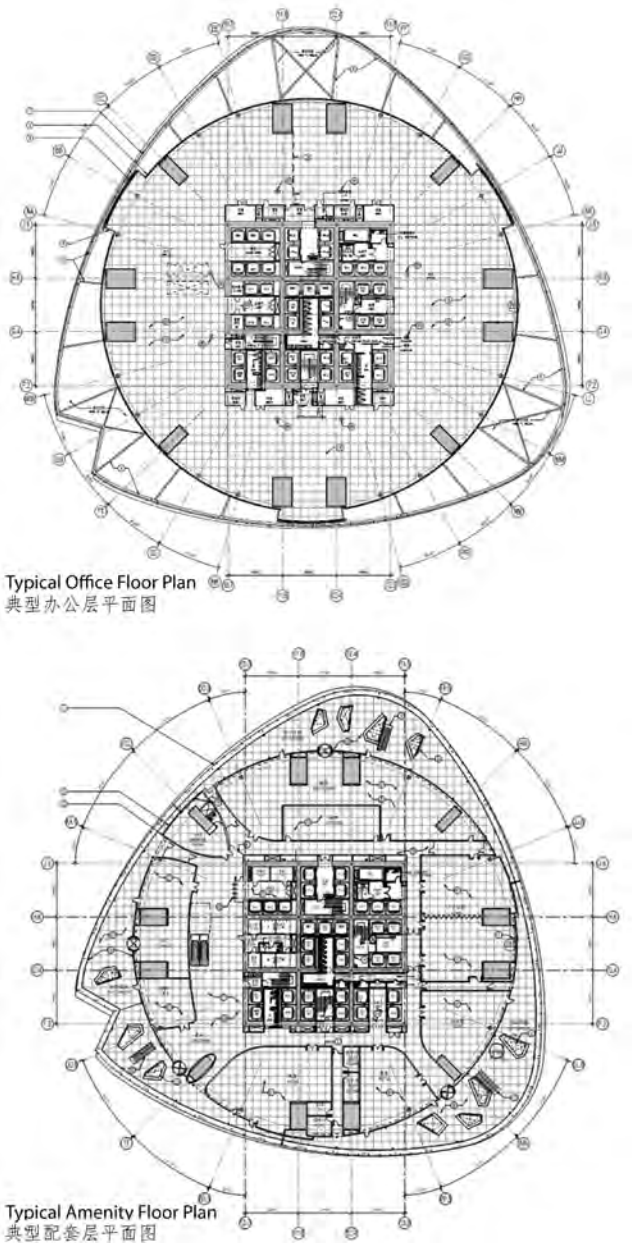


Figure 3.2. Shanghai Tower Typical Floor Plans (Source: Gensler)
图3.2.上海中心大厦标准层平面图 (来源: Gensler)

A 6-meter mat was not sufficient to provide reasonably uniform settlement. To distribute the tower load more uniformly and to reduce the differential settlement as well as overall settlement, eight 5-story tall fin walls with embedded steel plates were provided at the basement levels to engage both core and super columns. About 20%-30% of the predicted differential settlement was greatly reduced. Figure 3.5 shows the settlement contours with and without fin walls, including the estimated peak tower settlement of 100mm to 120mm after 5 years.

Another challenge for foundation design is the differential settlement between the tower and the surrounding podium. The water table is 0.5m below grade and the top elevation of the mat is -25.4m. Therefore, the

上海中心大厦采用了一个由947根现浇混凝土桩支撑的强化筏板基础，每根桩直径为1米。通过建造测试桩以确定单桩承载力。成品桩被支撑在9-2-1层上，其有效长度为52到56米。在桩顶采用了桩端注浆方法以提高单桩承载力，减少沉降。桩的布局采用了交错模式以便核心筒和巨柱下有更多的桩。该项目在筏板施工过程中创下了连续60个小时浇注61000立方米混凝土的记录。浇注筏板的施工照片见图3.4。

6米厚的筏板不足以保证均匀的沉降。为了使塔楼荷载分布更均匀并且减少不均匀沉降和总体沉降，在基础部分放置了8片5层楼高的嵌入钢板的翼墙以连接核心筒和巨柱。这使得不均匀沉降比预期大幅减少了约20%-30%。图3.5显示了有翼墙和没有翼墙两种情况下的沉降图，5年之后最大沉降量的估计值约为100到120毫米。

基础设计的另一大挑战是塔楼与周边裙楼的不均匀沉降。该项目的地下水位为0.5米以下级，筏板顶部的标高为-25.4米。因此，裙楼的沉降量很小而塔楼的沉降量却很大。为了减小塔楼和裙楼之间的不均匀沉降，采用了在两者相接处设立后浇带的方法。

塔楼侧向系统

上海中心大厦的"核心筒-外伸臂-巨型框架"系统由三部分组成: 组合混凝土核心筒，外部巨型框架 (有箱型环带桁架的巨柱) 和外伸臂桁架 (见图3.6) 。

核心筒在区域1到4中部采用长宽均为30米的九单元布置; 该核心筒的4个边角在区域5和

Figure 3.3. Shanghai Tower Topped-out structurally in August, 2013 (Source: Thornton Tomasetti)
图3.3.上海中心大厦于2013年8月封顶 (来源: 宋腾添玛沙帝)

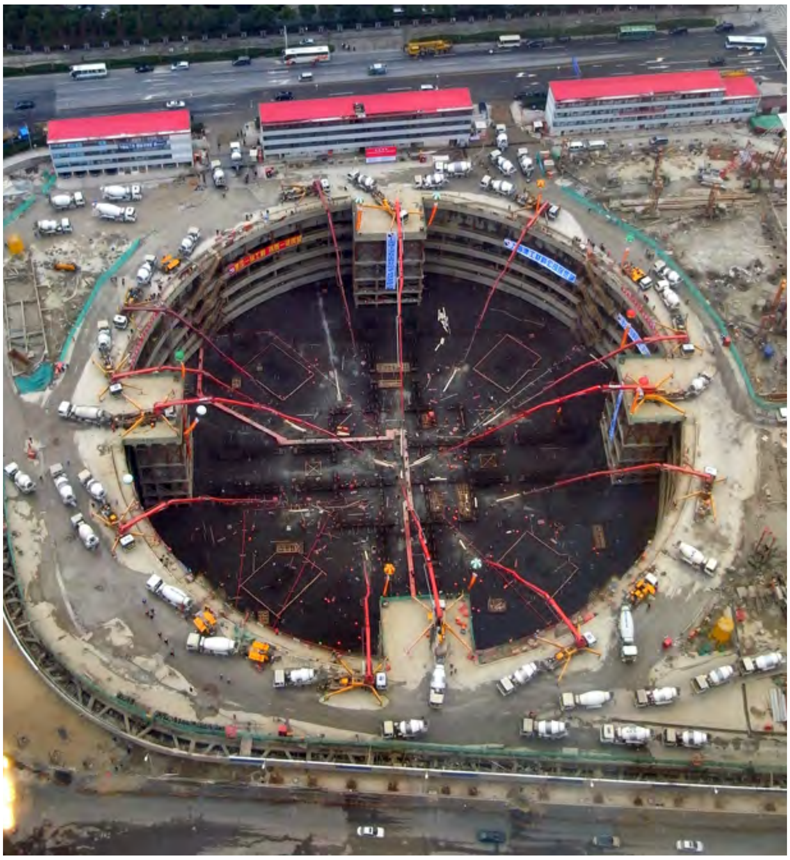


Figure 3.4. Construction Photo of Pouring Mat (Source: Thornton Tomasetti)
图3.4.筏板浇筑的施工照片 (来源: 宋腾添玛沙帝)

podium experiences very little settlement while the tower experiences greater settlement. To compensate the differential settlement between the tower and podium, delayed pour strips were provided in between.

Tower Lateral System

The "Core-Outriggers-Mega Frame" system of Shanghai Tower consists of three parts: Composite Concrete Core, Exterior Mega Frame (Super Columns with Box Belt Trusses), and Outrigger Trusses (see Figure 3.6).

A nine-cell 30m square core is placed in the center of the plan from Zones 1 through 4; the four core corners are cut back at Zones 5 and 6; and the core becomes a cruciform plan at Zone 7 and 8. The flange (outermost) wall thickness varies from 1.2 m to 0.5 m, while the interior web wall thickness varies from 0.9 m to 0.5 m. Embedded steel columns are provided at the boundary zones: wall corners and wall intersections. The steel plates are placed in the core walls at the bottom two zones to increase the shear capacity. The core wall resists most of lateral shear and serves as the fundamental line of defense to prevent building collapse under severe seismic events.

There are eight super columns up to Zone 8 and four diagonal columns up to Zone 5 which are reinforced with built up steel plates of approximately 4% to 6% of column cross area. All of them work together with eight sets of two-story-high double belt trusses to form the "Exterior Mega Frame" which serves as a second line of defense required by China's Code.

Six sets of two-story high steel outrigger trusses are placed at the MEP floors. When connected to the core through outriggers, the super columns provide large bending stiffness for the tower structure.

The outrigger trusses and belt trusses help the structural system to be stiff enough to meet the stringent story drift ratio limit required by China's Code. The max story drift is h/505 under 50-year wind load and h/623 under frequent seismic load (a 50-year seismic event). One-story-high radial trusses cantilever at the upper MEP level to support slab areas beyond the super columns. Those radial trusses also support the exterior façade system.

6处缩短; 核心筒在区域7和8处采用十字形布置。外墙厚度自上而下变化范围为1.2米至0.5米，内墙厚度自上而下变化范围为0.9米至0.5米 。在边界区域放置嵌入式钢柱: 墙角和墙面相交处。钢板被放置在底部两个区域的核心筒壁，以增加剪切承载力。核心筒壁承受大部分横向剪切，并且作为严重地震时起到防止建筑倒塌的主要防护系统。

巨柱和斜柱中配有约占柱截面面积4%到6%的预制钢板，8根巨柱由地面到区域8，4根斜柱由地面到区域5。这些柱与8组两层楼高的双环带桁架一起组成"外部巨型框架"系统，该系统为中国规范要求中的次要防护系统。

机电层布置有6组两层楼高的外伸臂钢桁架。当巨柱通过外伸臂与核心筒连接时，巨柱为整个塔楼结构提供了很大的抗弯刚度。

外伸臂桁架与环带桁架给予了结构体系足够的刚度，满足了中国规范严格的层间位移限值的要求。该结构50年风荷载作用下的最大层间位移角为1/505，频发地震 (50年一次) 荷载作用下的最大层间位移角为1/623。在上部机电层悬挑出单层圆环桁架以支撑超出巨柱范围的楼板。圆环桁架同时也支撑外部幕墙体系。

上海中心大厦塔冠是建筑幕墙系统的一个重要部分，拥有多种用途。L125层中央核

Soil Stratum Succession 土层演替编号	**Soil Stratum Name** 土层名称	**Average Soil Stratum Thickness** 平均土层厚度 **(m)**	**Average Distance to the bottom of stratum (m)** 距土层底端的平均距离	**Saturated undrained** 饱和不排水强度	**Shear Wave velocity (m/s)** 剪切波速
1	Fill	2.2	2.2	-	-
2	Silty clay	1.6	3.8	-	-
3	Very soft silty clay	5.2	9	30	125
4	Mucky clay	7.9	16.9	51	147
51a	Clay	3.7	20.6	70	178
51b	Silty clay	4.2	24.8	96	215
6	Silty clay	4.2	29	115	271
71	Sandy silt + silty sand	8	37	-	263
72	Silty sand	27.4	64.4	-	333
73	Silty sand	4.8	69.2	-	377
91	Sandy silt	9	78.2	-	399
92-1	Silty sand	11.2	89.4	-	421
92-2	Silty sand	9.6	99	-	457

Table 3.1. Soil Profile (Source: Thornton Tomasetti)
表3.1.土壤构成 (来源: 宋腾添玛沙帝)

Figure 3.5. Settlement Contours With or Without Fin Walls(Source: Thornton Tomasetti)
图3.5.有翼墙 / 无翼墙的沉降图谱 (来源: 宋腾添玛沙帝)

The Shanghai Tower crown is an important part of the building façade system and serves multiple functions. It houses a 1,100-ton tuned mass damper (TMD) on top of the central core at L125, a series of wind turbines at the perimeter of L122~L124, cooling towers at L128 surrounding the TMD, and window washing machine tracks along the crown's top surface.

The design of curtain wall support system (CWSS) at the roof went through a few rounds of revisions. To ease the construction difficulty, engineers used a more conventional scheme for tower crown structural system and its support for the crown cladding system.

Unlike the suspension system for the façade in a typical zone, the major component of the façade supporting system for the crown are the vertical trusses, which are located behind the crowns outer face and transfer gravity load directly to L118 below. The lateral wind loads are delivered to core framing through radial struts. Simpler kicker trusses support the crown's inner face and laterally brace the outer trusses above the tower roof level at L129. Vertically braced bays at three triangle corners work with a horizontal floor truss at every other floor to aid the crown system in resisting torsion.

The clean structural supporting scheme adopted allows for conventional fabrication and erection (Figure 3.7).

心筒顶部设有一个1100吨的调谐质量阻尼器 (TMD) ; L122层至L124层周边设有一系列的风力涡轮机; L128层调谐质量阻尼器 (TMD) 的周围设有多座冷却塔; 洗窗机轨道安置在冠顶表面上。

塔楼屋顶的幕墙支撑系统设计经过了数次的修改。为了降低施工难度，工程师采用了对于塔冠结构系统及其支撑冠覆层系统的常规方案。

不同于典型区域的幕墙悬挂系统，外墙体系中支撑冠顶的主要部分是位于冠顶外表面的垂直桁架，将重力荷载直接传递至L118下方。横向风荷载是通过径向支撑传递到核心框架。简单起脚桁架支撑冠顶内面并横向固定塔顶层 (L129层) 以上的外桁架。在三个三角形转折处竖向加固的结构

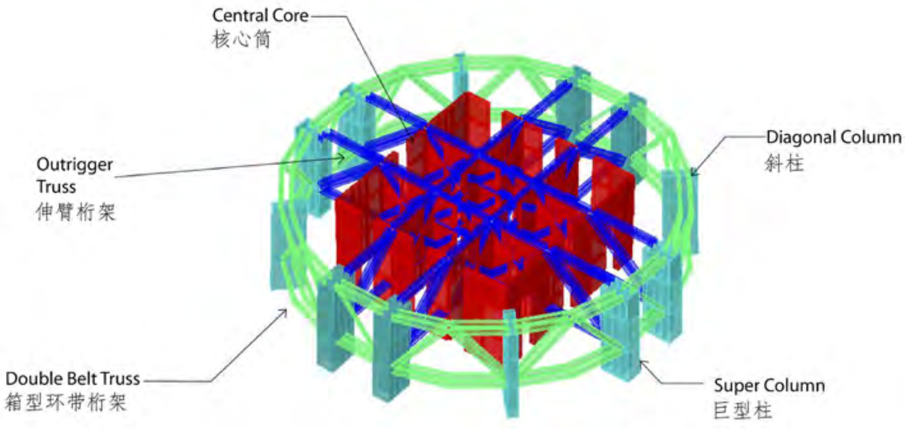


Figure 3.6. Lateral System Components (Source: Thornton Tomasetti)
图3.6.横向系统构件 (来源: 宋腾添玛沙帝)

Optimization of the Lateral System

The success of a supertall building design relies on the selection of an efficient lateral load resisting system.

The cost of lateral systems accounts for a large portion of construction cost, so several structural options, including Tube-in-Tube, Mega Frames, a few hybrid systems, and Core Outrigger Mega Frame scheme, were developed at the beginning of project for the owner, the architect, and the cost estimator to evaluate.

The Core-Outrigger Mega Frame scheme proved to be the optimal system for the Shanghai Tower. After the structural option was selected, engineers made continuous efforts to optimize the structure through all phases of the project.

The goal was to find the most economical system using the least quantity of building material without compromising architectural functions. At the beginning of the design stage, outriggers were placed at every MEP floor (Figure 3.8) in order to maximize the structural lateral stiffness to meet the strict story drift requirement in China's code.

The outrigger locations along the building's height were extensively studied and optimized. Engineers found that the outriggers at low zones are effective in reducing the building fundamental period, while upper outriggers contribute more to controlling the story drifts at upper zones. The first and third outriggers were removed and saved 3,500 tons of steel.

The structural steel encased in the super columns accounted for almost 35% of the

与每两层的水平楼面桁架一起帮助冠顶系统抵抗扭转。

该项目所采用的结构支撑方案清晰明了，使制作和安装变得简单易行 (见图3.7) 。

侧向系统的优化

超高层建筑设计的成功取决于有效的侧向力支撑系统的选择。

侧向系统的成本占了总建设成本的很大一部分，所以在项目开始阶段，数个结构方案被提出以便甲方、建筑师和成本估价师进行评估，这些方案包括筒中筒体系，巨型框架体系，混合结构体系和核心筒—外伸臂—巨型框架体系。

核心筒—外伸臂—巨型框架体系为上海中心大厦的最佳结构体系。结构方案确定后，工程师们在项目的所有阶段不断努力对结构进行优化。

我们的目标是在不影响建筑功能的前提下找到消耗材料最少、最经济的结构体系。在设计阶段初期，外伸臂被布置在每个机电层 (见图3.8) ，保证结构侧向刚度的最大化，以满足中国规范中严格的层间位移角要求。

我们对沿建筑物高度分布的外伸臂进行了进一步研究和优化。工程师们发现下部区域的外伸臂在减小建筑基本周期上十分有效，而上部区域的外伸臂则对控制上部区域的层间位移贡献很大。第一和第三外伸臂被移除，这一举措的实施节省了3500吨的钢材。

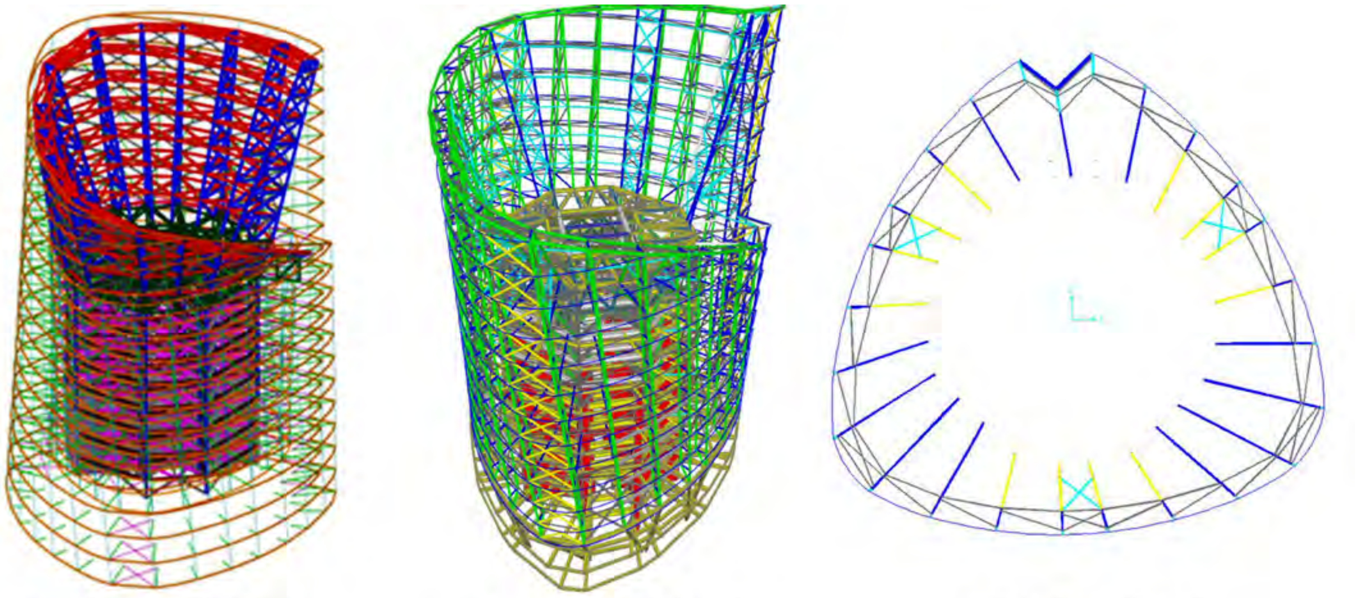
嵌入在巨柱的结构钢占了总用钢量的35%。尽管更多的嵌入钢有益于增加柱的延性，但所之而来的建造成本的极大增加以及工期的显著延长不容忽视。因此，对巨柱的嵌入钢配筋率进行了优化，以达到建筑性能与建造经济性的平衡。通过优化后节约了约13000吨钢材。

风力工程研究与空气动力学优化

作用在高层建筑上的风荷载是结构设计中最重要的一个考虑方面之一。风工程顾问RWDI进行了高频压力积分测试 (HFPI) 来确定结构所受的曳力风荷载和横向风荷载。然而，HFPI测试不能直接测试出风振响应，也不能模拟全尺寸的雷诺数。因此，随后通过使用气动弹性模型和高雷诺数测试两种方法来确认HFPI所得到的结果。一个比例为1:500的模型被用来研究建筑外表面扭转角的影响。结果显示与100度的扭转角相比，120度的扭转角减小了25%的风荷载。用1:85的模型在NRCC实验室的9米 x 9米的风洞中进行高雷诺数测试，能够估计静态曳力和动态升力的值。雷诺数测试结果与HFPI测试结果略有不同。

塔楼重力系统

办公室标准层采用155毫米厚组合楼板 (80毫米钢筋混凝土楼板浇筑在75毫米厚金属楼板上) ，该组合楼板通过实验室测试，有2个小时的防火性能。机电标准层和配套设施楼层


Original Tower Crown 3D View
原塔冠三维视图

Current Tower Crown 3D View
现塔冠三维视图

Current Struct Level Floor Plan
现结构层平面图

Figure 3.7. Tower Crown 3D view (Source: Thornton Tomasetti)
图3.7.塔冠三维视图 (来源: 宋腾添玛沙帝)

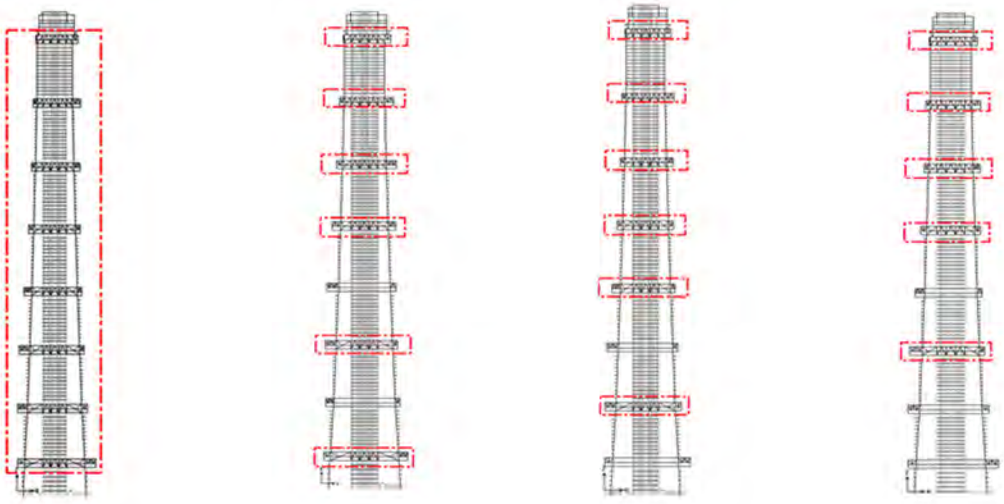


Figure 3.8. Optimization of Outriggers (Source: Thornton Tomasetti)
图3.8.外伸臂的优化 (来源: 宋腾添玛沙帝)

total steel. Although more embedded steel increases column durability, the tremendous increase in construction cost and construction time could not be neglected. So optimization on the embedded steel ratio of the super column was performed to find the balance between building performance and construction economy. About a 13,000 ton steel reduction has been achieved after the optimization.

Wind Engineering Study and Aerodynamic Optimization

Wind load acting on high-rise buildings is one of the most important aspects in structural

采用200毫米—250毫米厚的组合楼板 (125毫米—175毫米钢筋混凝土楼板浇筑在75毫米金属楼板上) 。承载楼层重力的边缘重力钢柱通过环带桁架把荷载传到巨型柱上。

性能设计

性能设计 (PBD) 明确地考虑了结构构件的非线性和延展性，可以用来评估在不同程度的地震条件下结构整体行为和构件行为。广泛应用于非线性分析的ABAQUS和Perform 3D软件被用来进行数学模型的开发和分析。

根据中国规范中提供的混凝土和钢筋本构关系曲线，对结构部件的非线性负载变形特性进行了建模。从世界范围内现有的相匹配的泥土成分中挑选出了7组地面加速度的时程，并对这些时程进行缩放以反应预期的现场地震烈度。每一组时程包含了以1: 0.85 : 0.65的比例同时发生的两个正交水平分量和一个垂直分量。

扩展性性能设计的总结如下:

- 关于最大层间位移角，X方向平均值为1/131，Y方向平均值为1/144 (见图3.9) 。
- 核心筒受压需求低于极限承载力，在个别局部点除外。

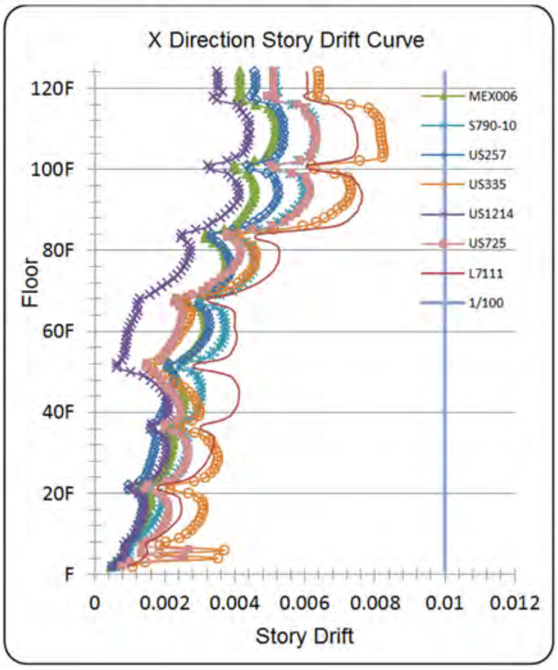


Figure 3.9. Maximum story drifts under different time-histories (Source: Thornton Tomasetti)
图3.9.不同的时程下的最大层间位移 (来源: 宋腾添玛沙帝)

design. A high frequency pressure integration (HFPI) test was performed by RWDI, the wind engineering consultant, to establish drag and cross wind loads for the structure. However, a HFPI test cannot measure the wind-induced response directly or simulate full size of Reynolds number. Therefore both an aeroelastic model and a high Reynolds number test were performed to confirm the results from HFPI. A 1:500 scale model was used to study the effects of the façade's twisting angle. The results show that the 120 degree twist angle reduced the wind loads by 25% when compared to a 100 degree twist. A high Reynolds number test was able to estimate static drag force and dynamic lift force by using 1:85 scale model tested in 9mX9m tunnel in NRCC lab. The Reynolds number test results slightly differed from the HFPI test.

Tower Gravity System

Typical office floors use a specific 155 mm thick composite slab (steel rebar reinforced 80 mm concrete slab cast on a 75 mm deep profile metal deck) that provides a two-hour fire rating according to laboratory tests. Typical MEP levels and Amenity levels use 200 to 250 mm thick composite slabs (125 to 175mm concrete above 75 mm metal deck). Steel perimeter gravity columns, picking up the floor gravity loads, transfer the loads into the super columns through the belt trusses.

Performance Based Design (PBD)

PBD explicitly considers the nonlinearity and ductility of structural members and can be used to evaluate the structure's overall behavior and member behaviors under different levels of seismic events. Abaqus and Perform 3D computer programs, widely used for nonlinear analysis, were used to develop and analyze the mathematical models.

The nonlinear load-deformation characteristics of structural components were modeled according to the constitutive relation curves of concrete and steel provided in China's code. Seven sets of ground acceleration time histories were selected from among available worldwide records to match the soil profile and were scaled to reflect expected earthquake intensity at the site. Each set included two orthogonal horizontal components plus one vertical component acting simultaneously at a ratio of 1: 0.85: 0.65.

A summary from extensive PBD analyses includes the following findings:

- For maximum story drift ratios, average values are 1/131(X) and 1/144(Y) (see Figure 3.9).
- Core compressive demand is below ultimate capacity except at a few local points.
- Most link beams exhibit plastic deformations within the "Life Safety" limit.
- Most outrigger trusses and belt trusses members are still in the elastic range.

- 大部分连梁展现出在"生命安全性"限值内的塑形变形。
- 大部分外伸臂桁架和环带桁架仍在弹性范围内。
- 嵌入巨柱的钢单元和核心筒壁在弹性范围内。
- 总体而言，塔楼达到了所要求的"生命安全性"性能等级。

结论

通过使用外部巨型框架系统增加了侧向刚度与强度和使用性能设计这样的先进分析工具等这些创造性的结构解决方法，最终得到了一个既创新又经济的结构设计方案。

上海中心大厦的结构设计克服了一系列的挑战:

- 在软性土上采用了基础体系来支撑高层塔楼荷载;
- 通过结构优化，减少了施工成本。通过分离独特的扭外立面结构支撑系统和主要建筑系统实现了一个简单而直接的主要结构体系;
- 利用了PBD评估不同等级地震烈度下的结构性能。

- Embedded steel elements in super columns and core walls are in the elastic range.
- Overall, the tower achieves the requested "Life Safety" performance level.

Conclusion

Creative structural solutions, such as an Exterior Mega Frame system, enhances tower lateral stiffness and strength, and state-of-the-art analysis tools like Performance Based Design result in an innovative and economical structural design.

A series of challenges were overcome in the design of the Shanghai Tower Structural System:

- Adopted a foundation system supporting high tower loads on soft soils
- Reduced construction cost through structural optimizations. Achieved a simple and straightforward main structural system by disengaging the unique twisting exterior façade structural support system from the main building system
- Utilized the PBD to evaluate structural performance under different levels of seismic events

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