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Structural Design Challenges of Shanghai Tower

上海中心大厦的结构设计挑战


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Abstract

This paper discusses the structural challenges and solutions of the 632m tall Shanghai Tower. A unique "Core-Outrigger-Mega Frame" lateral system is used to meet China code requirements. The exterior perimeter Mega frame provides additional stiffness and strength. A foundation with a 6m thick mat and fin walls extending from a central core distributes loads to piles constructed with an end grouting technique to provide high bearing capacity and reduced settlement. The tower crown design incorporates features for construction efficiency while providing multiple load paths. Performance Based Design is used to verify tower performance under different seismic hazard levels through non-linear dynamic time-history analysis.

Keywords: Tall building; Performance-Based Design; Outrigger; Super column; Belt truss, Crown

摘要

本文讨论了632米高的上海中心的结构挑战和解决方案。为满足中国规范的要求，上海中心采用了一个独特的“核心筒-外伸臂桁架-巨型框架”抗侧系统。外围巨型框架为整体结构提供了额外的刚度和强度。基础筏板厚6米，並有肋墙从中心核心筒伸延至桩来分散荷载，桩以桩端注浆技术来建造来提供高承载力及减小沉降。上海中心的塔冠设计综合考虑了施工效率与提供多个负载路径的特点。通过非线性动态时程分析，采用基于性能化的设计来确认塔楼在不同地震灾害等级下的抗震表现。

关键词：高层建筑、基于性能化的设计、外伸臂桁架、巨柱、环形桁架、塔冠

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Project Description

Shanghai Tower in lot Z3-1 is adjacent to Jin Mao Tower, with its pagoda-like gesture to China's past, and Shanghai World Financial Center, representing China's present. Rising as a landmark on the city skyline to represent the future, the 128-story Shanghai Tower will house Class A office space, entertainment venues, retail stores, a conference center, a luxury hotel and cultural amenities. The 5-story deep basement serves retail, MEP and parking spaces (see Figure 1). Occupying a total site area of about 30,370 m^2, the Shanghai Tower has a total gross floor area (GFA) of approximately 573,400 m^2 (6.2 million ft^2).

The tower structure takes the form of nine cylindrical buildings stacked one atop another, including a business zone at the bottom podium levels, five office zones, two hotel/apartment zones, and sightseeing or observation floors at the top. Each zone can be considered an independent city or village with communal space at an amenity level extending to the outer twisting façade (see Figure 2). The tower floor plate diameter varies by zone, from 82.2m at Zone 1 to 46.5m at Zone 8 (see Figure 3). The stacked-zone tower concept within an exterior façade tapering

项目描述

上海中心位于Z3-1地块毗邻金茂大厦和上海环球金融中心，金茂大厦的古塔式姿态代表着中国的“过去”；上海环球金融中心代表中国的“现在”；上海中心则代表着中国的“未来”，将成为上海市天际线中的新地标。128层的上海中心将容纳A级写字楼，娱乐场所，零售商店，会议中心，豪华酒店和文化设施。5层深的地下室，提供零售商铺，机电设备和停车位（见图1）。上海中心总用地面积占地约30370平方米，总楼面面积（GFA）约573400平方米（620万平方英尺）。

塔楼内部由9个圆柱体建筑堆叠而上，包括了一个底部裙房层的商务区，5个办公区，2个酒店/住宅区，和一个在顶部的观景或观光层。每个区域可被视为是一个有公共空间的独立城市或村落。公共空间位于各个分区的配套层，并延伸至建筑外部扭转的幕墙（如图2所示）。每区域的塔楼板平面直径不同，从1区的82.2米一直减小至8区的46.5米（如图3所示）。堆叠区域塔楼外立面随着高度缩进、扭转的概念形成了令人惊叹的建筑设计。

岩土工程条件与塔楼基础

因为由于重力引起的巨大竖向力以及由风荷载与地震荷载引起的巨大倾覆力，使得

Figure 1. Shanghai Tower 3D Rendering View (Source: Gensler)
图1. 上海中心大厦3D渲染视图（来源：Gensler）

and twisting with height creates a spectacular architectural design.

Geotechnical Conditions And Tower Foundation

Foundation design is always challenging for tall buildings due to large vertical forces from gravity and large overturning forces from wind and seismic loading. Site conditions at Shanghai Tower add to the challenge. Nine layers of sand and clay area alternating to at least 120m below grade. Bedrock is considered beyond reach for practical construction purposes. Because the top 15m is very soft silty clay the site for seismic design is considered as Type IV, the most unfavorable class according to the China code and roughly comparable to Site Class 'F' under the International Building Code (IBC) (see Table 1).

Under the tower footprint a 6m thick mat foundation is supported by 947 piles with one meter in diameter. The cast-in-place (CIP) concrete piles have end grouting to increase their capacity and reduce settlement. Under the core and super columns load is concentrated so a staggered pattern pile layout is used to fit more piles than where using a simple grid arrangement. The 1000-metric ton capacity piles are effectively 52 to 56 m long and bear at layer 92-1, a thick silty sand layer.

Modest soil stiffness offers little ability to distribute gravity loads. Concentrating piles under the core and super columns is not sufficient by itself to provide reasonably uniform settlement; pile group effects also play a role. To distribute the tower load more uniformly and thus reduce the overall settlement and differential settlement, concrete fin walls five stories tall are provided at the basement levels to engage both core walls and super columns. To handle the large forces being redistributed the walls include embedded steel plates. These fin walls reduce the maximum predicted settlement by 20 - 30% and greatly reduce differential settlement. Figure 4 shows the settlement contours with and without fin walls. Tower peak settlement after 5 years is estimated to be 100 to 120mm.

Differential behavior between the tower and surrounding podium also poses structural challenges. The water table is just 0.5m under grade, while the mat top elevation is at -25.4m. Under the tower footprint self-weight is sufficient to more than offset buoyancy, but the surrounding podium will have to resist net uplift forces due to high buoyancy forces. The difference in net foundation loads and the soft subgrade conditions will cause differential settlement between

高层建筑的基础设计总是具有挑战性。上海中心的场地条件增加了挑战的难度。9层的粉沙和粘土层交替延伸至地平面以下120米。按实际工程目的，岩床认为是无法触及的，因为土层顶部15米是非常软的粉质粘土，地震设计的场地类别是第IV类，这是中国规范中最不利的类别，大约相当于国际建筑规范（IBC）中的场地类别F（见表1）。

在塔楼覆盖范围之下为6米厚的筏板基础，以947根桩支撑，每根直径为1米。现浇（CIP）的混凝土桩以端部灌浆来提高桩的承载力、减小沉降。在核心筒和巨型柱下荷载较集中，因此采用了交错排列的桩位布置，相比方形网格排列可以布置更多的桩。桩基承载力为1000吨，有效长度为52至56米，端承在较厚的粉质砂土

Figure 2. Shanghai Tower Stacking (Source: Gensler)
图2. 上海中心大厦分层（来源：Gensler）

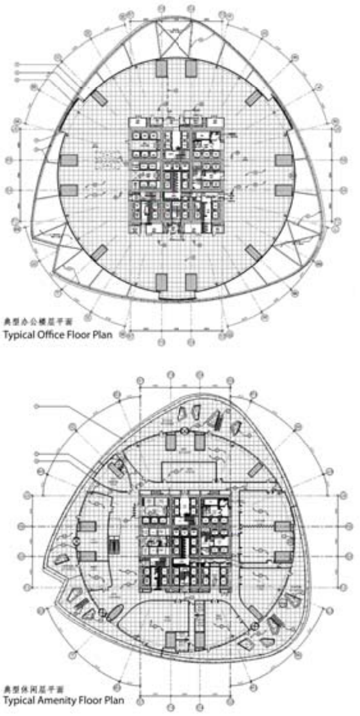

Figure 3. Shanghai Tower Typical Floor Plans (Source: Gensler)
图3.上海中心大厦标准层平面图（来源：Gensler）

Soil Stratum Succession 土层次序	Soil Stratum Name 土层名称	Average Soil Stratum Thickness(m) 平均土层厚度(m)	Average Distance to the bottom of stratum (m) 平均底层埋深(m)	Saturated undrained Shear Strength C_u (KPa) 饱和不排水抗剪强度 C_u(kPa)	Shear Wave velocity (m/s) 剪切波速(m/s)
1	Fill 填土	2.2	2.2	-	-
2	Silty clay 粉质粘土	1.6	3.8	-	-
3	Very soft silty clay 非常软的粉质粘土	5.2	9.0	30	125
4	Mucky clay 淤泥质粘土	7.9	16.9	51	147
51a	Clay 粘土	3.7	20.6	70	178
51b	Silty clay 粉质粘土	4.2	24.8	96	215
6	Silty clay 粉质粘土	4.2	29.0	115	271
71	Sandy silt + silty sand 砂质粉土+粉砂	8.0	37.0	-	263
72	Silty sand 粉砂	27.4	64.4	-	333
73	Silty sand 粉砂	4.8	69.2	-	377
91	Sandy silt 砂质粉土	9.0	78.2	-	399
92-1	Silty sand 粉砂	11.2	89.4	-	421
92-2	Silty sand 粉砂	9.6	99.0	-	457

Table 1. Soil Profile
表1. 土层概况

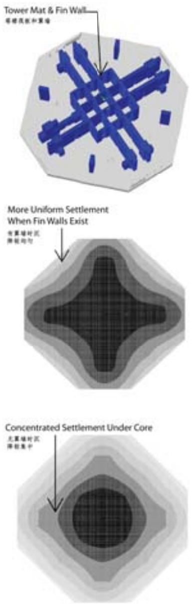

Figure 4. Settlement Contours With and Without Fin Walls (Source: Thornton Tomasetti)
图4. 有无肋墙的沉降等高线（来源：Thornton Tomasetti）

podium and tower. To reduce the effects of differential settlement, a delayed-pour strip is provided. The mat reinforcement design must consider loads and deformations occurring during different construction stages, before and after the delayed-pour strip are closed for independent and combined cases, and include additional reinforcement locally at the interface of tower and podium as needed. The bottom reinforcement at the transition zone is governed by the independent cases; while the top reinforcement is governed by the combined cases.

Tower Lateral System

The Shanghai Tower lateral system is a "Core-Outriggers-Mega Frame" and it consists of three parts: Concrete Composite Core, Exterior Mega Frame (Super Columns, Diagonal Column and Double Belt Trusses), and Outrigger Trusses (see Figure 5). The Exterior Mega Frame with the sloping Super Columns and Diagonal Columns resist around 55% of the base shear and 75% of the overturning moment at the base level under wind and seismic load.

层--92-1层。

适度的土壤刚度提供了较小的能力来分散重力荷载。在核心筒和巨柱下的集中布桩还不足以单独地提供一个合理的均匀沉降；群桩效应也发挥了作用。为了将塔楼的荷载传递更均匀，同时减低整体沉降以及不均匀沉降，在地下层设有5层高的混凝土肋墙将核心筒墙与巨柱两者连结。肋墙内的嵌入钢板来对付被重新分配在墙内的巨力。这些肋墙将降低塔楼最大预测的沉降值达20%-30%，同时大大减小了不均匀沉降。图4显示了在有无肋墙情况下基础的沉降等高线。5年后塔楼的沉降最大值预计为100毫米至120毫米。

塔楼和周边裙房之间的差别刁性也是对结构设计的一大挑战。水位仅在地面下0.5米处，然而筏板顶部标高在地下24.5米处。在塔楼覆盖范围下的自重足以抵消浮力，但是周围的裙房因高浮力需抵抗净上举力。不同的净基础荷载和较软的基床条件将导致裙房与塔楼之间的不均匀沉降。为了降低不均匀沉降的影响，在塔楼和裙房之间布置了后浇带。在不同施工阶段，于独立与合并的案例中后浇带闭合前后，筏板钢筋设计必须考虑相关所产生的荷载与变形，并按需要在塔楼和裙房的界面局部地设置额外的钢筋。在交界区域的底部钢筋是受独立案例支配，而顶部钢筋是受合并的案例支配。

塔楼抗侧系统

上海中心的抗侧力系统是一个“核心筒-外伸臂桁架-巨型框架”，它由以下三部分组成：混凝土复合核心筒，外部巨型框架（巨柱，对角柱和双层环形桁架），和外伸臂桁架（如图5所示）。倾斜的巨柱和对角柱的外部巨型框架在风荷载和地震荷载作用下能抵抗大约55%的底部剪力和在底层75%的底部倾覆弯距。

从1区至4区的核心筒平面由9个30米方形单元组成。核心筒的4个角部在区域5区和6区被削除，区域7和8的核心筒变为十字形。凸缘（最外层）墙的厚度，从1.2米分5步逐渐减小至0.5米。内部腹壁厚从0.9米到0.5米。在核心筒边缘部位以及核心筒的墙角和端部，设有嵌入的宽翼缘钢柱，以增强核心筒的强度，并对从外伸臂桁架传到核心筒的力提供了清晰的荷载路线。在底部两个区域的核心筒墙体内置钢板用来提高核心筒的延性，并允许剪力墙厚度的减少。

8根巨柱一直延伸至第8区，而4根对角柱延伸至第5区。设置在低区的对角柱提高了外部巨型框架的刚度，同时通过减小巨柱之间的跨度来减小巨型框架的变形。巨柱和对角柱中嵌入了钢柱，其

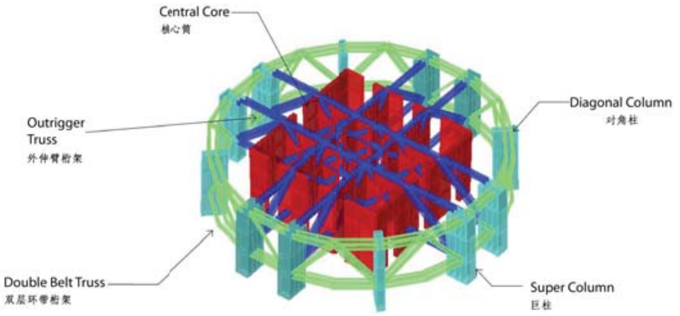

Figure 5. Lateral System Components (Source: Thornton Tomasetti)
图5. 抗侧系统组成（来源：Thornton Tomasetti）

The core forms a nine-cell 30m square shape in 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 in five steps from 1.2 m to 0.5 m. Interior web wall thickness varies from 0.9 m to 0.5 m. Embedded wide flange steel columns are provided at the boundary zones, or stressed core wall corners and ends to both strengthen the core and to provide a clear load path from outrigger forces into the core. Embedded steel plates are placed in the core walls at the bottom two zones to enhance wall ductility and permit a reduced wall thickness.

There are eight Super Columns up to Zone 8, and four Diagonal Columns up to Zone 5. Diagonal Columns are added at bottom zones to increase the Exterior Mega Frame stiffness and reduce deflection by cutting the span between Super Columns. Steel columns embedded in the super columns and diagonal columns have a steel ratio range from 4% to approximately 6%. The Super Columns and Diagonal Columns 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 per China Code requirement of structural system having multiple seismic defense line. Outer and inner belt trusses are laced together to form a boxed space truss for redundancy and torsional stiffness. Belts also serve to transfer secondary column gravity loads to the Super Columns.

Six sets of two-story high steel Outrigger Trusses are placed at the MEP floors (see Figure 6). The location and number of outrigger trusses was extensively studied and optimized. The outriggers at low zones are effective in reducing the building fundamental period, while upper outriggers contribute more to control of story drifts at upper zones.

The fundamental period of the tower is shown in Table 2 with the first 3 modes representing X-direction Translation, Y-direction Translation and Torsion, respectively.

The Outrigger Trusses and Belt Trusses help the structural system to be stiff enough to meet the stringent story drift limit of 1/500 required by China Code. The max story drift of Shanghai Tower is h/505 under resultant wind and h/623 under frequent seismic load (see Figure 7).

Tower Gravity System

Typical office floors use a 155 mm thick composite slab (80 mm concrete above 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 above 75 mm metal deck). Steel perimeter gravity columns have their gravity loads transferred through the belt trusses into the super columns.

中含钢率约为4%至6%。巨柱和角柱与8道2层高的双层环形桁架一起形成了“外部巨型框架”。巨型框架作为塔楼结构体系的第二道防线，以满足中国规范规定的结构系统应具有多道抗震防线的要求。外圈和内圈环形桁架相连结以形成了箱型空间桁架，提供了结构冗余度和扭转刚度。环形桁架同时也有助将次结构柱中的重力转换至巨型柱上。

在塔楼机电层布置了6道2层高的外伸臂桁架（如图6所示）。对外伸臂桁架的位置和数量进行了深入的研究和优化。低区的外伸臂桁架有效的减小了建筑的基本周期，而高区的外伸臂桁架主要用于控制高区的层间位移。

塔楼的基本周期如表2所示，前三个模式分别代表了了X方向平动，Y方向平动和扭转。

外伸臂桁架和环形桁架使得结构系统具有足够的刚度来满足中国规范中层间位移限值为1/500的严格要求。上海中心最大层间位移在合成的风荷载情况下为h/505，在多遇地震荷载下为h/623（如图7所示）。

塔楼的重力系统

典型的办公楼层所用的楼板为155毫米厚的复合楼板（80毫米的混凝土在75毫米厚的压型金属甲板上），根据实验测试结果，它能满足2小时的防火要求。典型的机械设备楼层和配套层所用的楼板为200毫米到250毫米厚的复合楼板（125到175毫米的混凝土在75毫米厚的压型金属甲板上）。外围的型钢重力柱将其重力荷载通过环形桁架传至巨柱。

在机械设备层上的一层高的径向桁架用于支撑巨柱外悬挑的楼板区。这些径向桁架也为外立面系统提供了支撑，详见之后进一步的论述。

塔冠的重新设计

上海中心的塔冠是建筑外立面系统中一个重要部分，同时塔冠也提供了多重功能。它容纳了一个位于中心核心筒，在第125层上的1100吨调谐质量阻尼器，位于第122层至124层周边有一系列风力涡轮机，以及布置在第128层调谐质量阻尼器周边的冷却塔，和一个沿塔冠顶部设置的擦窗机轨道（如图8所示）。

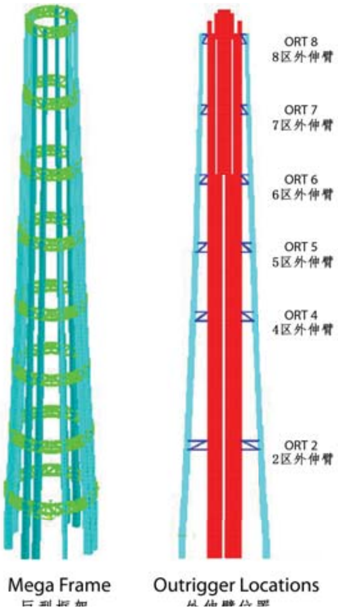

Figure 6. Exterior Mega Frame and Outriggers (Source: Thornton Tomasetti)
图6. 巨型框架和外伸臂桁架（来源：Thornton Tomasetti）

	ETABS
T1	9.05
T2	8.96
T3	5.59
T4	3.31
T5	3.20
T6	2.62

Table 2. Building fundamental Period
表2. 建筑基本周期

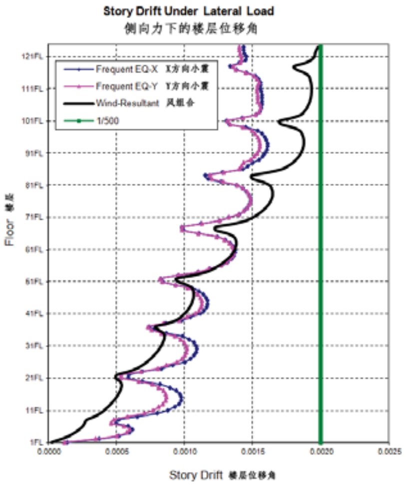

Figure 7. Tower Story Drift under Lateral Load (Source: Thornton Tomasetti)
图7. 楼在侧向荷载下的层间位移（来源：Thornton Tomasetti）

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 facade system, as discussed below.

Redesign Of Tower Crown

The Shanghai Tower crown is an important part of the building façade system and serves multiple functions. It houses an 1,100-ton tuned mass damper on top of the central core at L125, a series wind turbines at the perimeter of L122~L124, cooling towers at L128 surrounding the TMD, and a window washing machine track along the crown top surface (see Figure 8).

The original design was based on a pretensioned vertical cable net for the outer crown surface to satisfy architectural criteria. The crown inner surface was carried on radial, outward-sloping cantilevered 'fin' trusses that also supported the cable net upper end loads. The fin trusses stood on criss-crossed two-way trusses to transfer load to the core below.

Resisting lateral loads, particularly torsion, required circumferential horizontal trusses to tie the fin trusses to braced bays. While a perimeter building skin carried on tension rods hanging from the crown top would have minimal visual interface behind the glass, such a hung system would be costly and slow to build (see Figure 9 Original Tower Crown 3D view).

The current scheme follows a more conventional approach to cladding support and the structural system. Instead of suspended pretensioned rods, vertical trusses behind the crown outer face support the façade and deliver its gravity load directly to L118 below. Lateral loads from wind pressure are delivered directly to core framing through radial struts. Instead of cantilevered fin trusses, simpler kicker trusses support the crown inner face while laterally bracing the outer trusses above the tower roof level at L129. Simple vertically braced bays at three triangle

原设计是采用预应力竖直拉索作为外层塔冠表面来满足建筑的要求。塔冠内表面继续径向、向外倾斜的悬臂鳍状桁架，同时也为拉索网顶端荷载提供了支撑。鳍状桁架通过交错布置的双向桁架上将荷载传递至下面的核心筒。

抵抗侧向荷载，特别是扭转，需要在圆周边的水平桁架连结致鳍状桁架以撑牢开间。建筑的外表面由塔冠顶部悬吊的拉杆所支撑，对玻璃幕墙的可视性影响非常低，但悬吊系统的造价高，施工缓慢（如图9所示，原塔冠3D效果图）。

目前方案沿用了一个更常规的方法作包覆支撑和结构系统。塔冠外表面后的竖直桁架代替了悬挂式预应力拉杆，将其重力荷载直接传到下方的118层。通过径向支撑，由风压引起的侧向荷载直接被传送至核心筒框架。更简单的隅撑桁架代替悬臂鳍状桁架来支撑在塔冠内侧，同时为129层之上的竖向外侧桁架提供了侧向支撑。简单垂直支撑的开间在三角形的三个转角处与隔层布置的垂直支撑一起共同帮助塔冠系统抵抗扭转。通过提供直接的荷载传导路径，及更常规的制造和安装方式，和更可靠的多重传导荷载路径使系统效率更高（如图9所示，现塔冠3D效果图和现支撑水平平面图）。

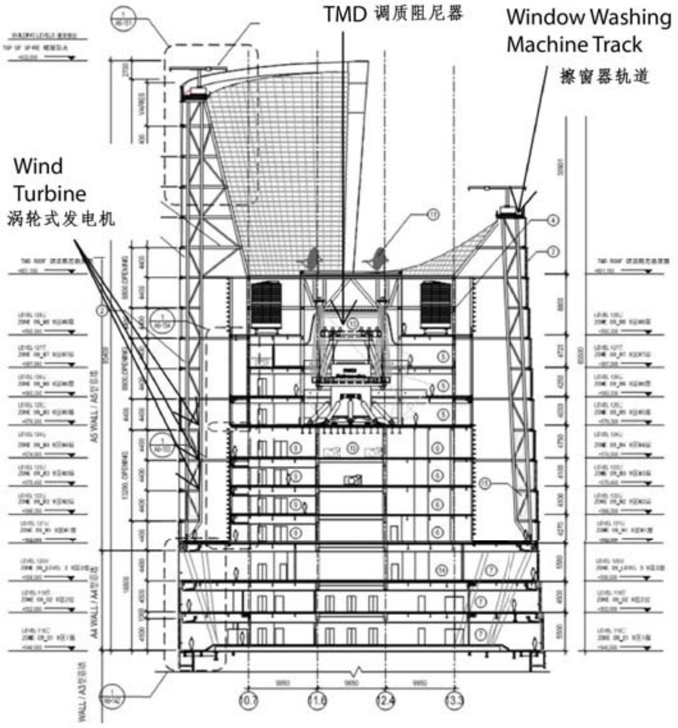

Figure 8. Tower Crown Section (Source: Gensler)
图8. 塔冠剖面（来源：Gensler）

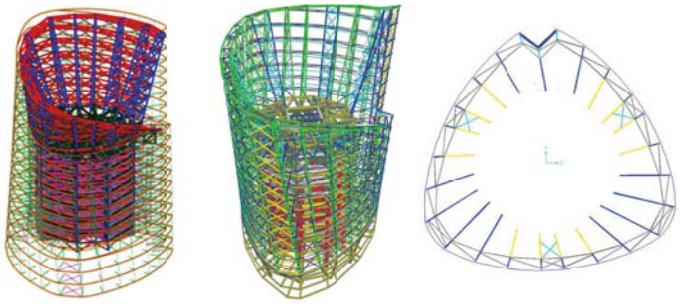
Original Tower Crown 3D View
初始塔冠结构三维视图
Current Tower Crown 3D View
当前塔冠结构三维视图
Current Struct Level Floor Plan
当前楼层结构平面图

Figure 9. Tower Crown 3D view (Source: Thornton Tomasetti)
图9. 塔冠3D效果图（来源：Thornton Tomasetti）

Seismic Hazard Level 地震等级		**Frequent Earthquake** 多遇地震	**Moderate Earthquake** 中级地震	**Severe Earthquake** 罕遇地震
Performance level description 性能等级描述		No damage or negligible damage 无破坏或破坏可以忽略	Little Damage, Repairable 轻微破坏，可修复	Serious Damage, No Collapse 破坏严重但不倒塌
Structure Behavior Description 结构性能描述		No damage, structure basically in elastic range 无破坏，结构基本处于弹性状态下	Allow minor damages , structure substantially retains original strength and stiffness 允许轻微的损坏，结构大致保留原有的强度和刚度	Allow serious damage, but no fracture of major connection joint; no shear fracture of super columns and core walls 允许严重损坏，但主要连接构件没有断裂；巨型柱和核心筒没有剪切破裂
Story drift ratio limit 层间位移限值		h/500; h/2000(bottom levels) h/500； h/2000（ 低区）	h/200	h/100
Member performance 构件性能	Core wall 核心筒	Elastic, Strength design per code: - factored seismic load - material design strength 弹性 基于规范的强度： – 设计极限地震荷载 – 材料设计强度	Code-based strength design. At outrigger floors: factored seismic load, material design strength At other floors: unfactored seismic load, material ultimate strength 基于规范的强度设计，在外伸臂桁架楼层：设计极限地震荷载，材料设计强度。 其他楼层：非设计极限地震荷载，材料极限强度	Plastic hinge rotation: θ<IO at at bottom levels, θ<LS at other levels Shear forces<= ultimate shear capacity 塑性铰接转动：θ<IO 底部楼层，θ<LS 其它楼层 剪力<= 极限抗剪能力
	Link beam 连梁		Allow plastic hinge; Code-based strength design 允许塑性铰接；基于规范的强度设计	Plastic hinge rotation: θ<LS and <=0.02 rad 塑性铰转动：θ<LS及<=0.02弧度
	Super column 巨柱		Elastic, Code-based strength design: factored seismic load, material design strength 弹性，基于规范的强度设计：设计极限地震荷载，材料设计强度	Plastic hinge rotation: θ<IO at bottom levels, θ<LS at other levels. Stress in reinf. f > fy but < fu 塑性铰接转动：θ<IO在底部楼层，θ<LS在其它楼层。在钢筋的应力 f > fy 但 < fu
	Belt truss 带状桁架		Elastic: factored seismic load, material design strength 弹性：设计极限地震荷载，材料设计强度	Elastic , steel stress f < fy 弹性，钢材应力f < fy
	Outrigger 外伸臂桁架		Code-based strength design: unfactored seismic load, material ultimate strength 基于规范的强度设计：非设计极限地震荷载，材料极限强度	Plastic deformation: θ<LS and stress f < fu 塑性变形： θ<LS 和应力 f < fu
	Critical Connections 重要节点		Elastic, Strength design per code: factored seismic load, material design strength 弹性、基于规范的强度设计：设计极限地震荷载，材料设计强度	Special FEM analyses are required and stress f<= fy 需要进行特殊的有限元分析和应力 f<= fy

Table 3. Performance Target and Acceptance Criteria
表3. 性能目标与验收标准

corners work with a horizontal floor truss at every other floor to help the crown system resist the torsion. This system is more efficient by providing direct load paths and more conventional fabrication and erection, and more reliable by having multiple load paths (see Figure 9 Current Tower Crown 3D view and Current Strut Level Floor Plan).

Performance Based Design

PBD explicitly considers the nonlinearity and ductility of structural members and can be used to evaluate structure overall behavior and member behaviors under different levels of seismic events. The PBD procedure of Shanghai Center Tower includes:

- Determining performance targets for the overall structure
- A PBD model incorporating the nonlinearity of structural components
- Determining appropriate ground motion time histories
- Performing a nonlinear dynamic time-history analysis
- Comparing member deformations and forces with the acceptance criteria

Performance goals for the overall structural system and structural components are summarized in Table 3.

Abaqus and Perform 3D computer programs, widely used for nonlinear analysis, were used to develop and analyze the mathematical models.

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 Shanghai Center building site. Each set included two orthogonal horizontal components plus one vertical component acting simultaneously at a

基于性能化的设计

基于性能化的设计（PBD）明确地考虑了结构构件的非线性和延性，并可以用于评估结构在不同地震级别情况下的整体性能和构件的性能。上海中心塔的PBD步骤如下：

- 确定整个结构的性能目标
- 包含结构构件非线性响应的PBD模型
- 确定合适的地面活动时程
- 进行非线性动态时程分析
- 将构件的变形和受力与验收准则对比

整个结构系统和结构构件的性能目标总结于表3。

Abaqus和Perform 3D计算机软件被广泛地用于非线性分析，在本工程中，它们被用来发展和分析数学模型。

从世界各地有效记录中选择与本工程土壤信息匹配的7组地面加速时程，並经过缩放反映上海中心建筑场地的预期地震强度。每组包括两个正交的水平分量加一个垂直分量，比例为1：0.85：0.65。

各独立构件的非线性荷载变形特性是根据中国规范提供的钢材和混凝土的基本关系曲线来建模的。

大量的PBD分析总结得到包括以下的发现：

- 最大层间位移比率，平均值为1/131（X）和1/144（Y）（如图10所示）。
- 除了少数局部位置外，核心筒压力需求均小于承载力。
- 大多数连梁的塑性转角满足“生命安全”要求。
- 大多数外伸臂桁架和环形桁架仍处于弹性范围。
- 巨柱和核心筒内埋钢构件处于仍弹性范围。

综上，塔楼达到了“生命安全”的性能水平要求。

ratio of 1: 0.85: 0.65.

The nonlinear load-deformation characteristics of individual components were modeled according to the constitutive relation curves of concrete and steel provided in the China code.

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 10).
- 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.
- 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

The Shanghai Tower design brought structural engineers a series of challenges: supporting a heavy tower on soft soils, resisting huge lateral loads while controlling story drifts, supporting the curtain wall panels of a unique twisting exterior facade disengaged from the main building, and using advanced analysis methods to evaluate structural performance under different levels of seismic events. Creative structural solutions, such as an Exterior Mega Frame to enhance tower lateral stiffness and strength, and state-of-the-art analysis approaches from Performance Based Design were applied to result in an innovative and economical structural design.

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We would like to thank Mr. Leonard Martin Joseph, P.E., S.E., Principal of Thornton Tomasetti, Inc, for enhancing this paper through his thoughtful suggestions.

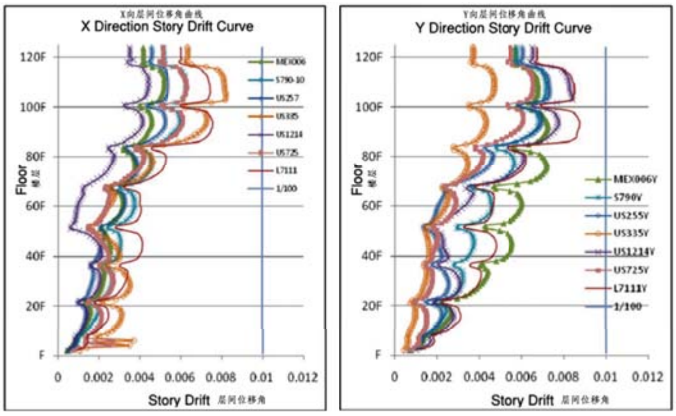

Figure 10. Maximum story drifts under different time-histories (Source: Thornton Tomasetti)

图10. 在不同时程下的最大层间位移（来源：Thornton Tomasetti）

结论

上海中心设计给结构工程师带来了一系列的挑战：在软土地基上支撑一个沉重的塔楼；抵御巨大的侧向荷载的同时控制层间位移；对于主体建筑分离的独特扭曲外立面幕墙板块的支撑；采用先进的分析方法评估结构在不同地震级别情况下的抗震性能。通过创新的结构方案，如以外层巨型框架来加强塔楼的抗侧刚度和强度，以及应用基于性能化设计的顶尖分析方法，产生了一个既具有革新性且相对经济的结构设计。

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