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Case Study: Shanghai ifc

案例研究：上海国际金融中心

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Abstract

Shanghai ifc, a landmark mixed-use development located in the heart of Lujiazui, Shanghai includes a 250-meter multi-function tower (South Tower), a 260-meter office tower (North Tower), a 100-meter hotel block, retail podium and 4-levels basement. The design of the South Tower adopted a new structural system of mega columns in low zone, required to accommodate the high-end office layout requirement, and an exterior frame tube to the high zone that coincided with the hotel room layout. The combination of these two solutions, together with a high level transfer structure, makes this building a unique design case delivered within an active seismic zone. A performance-based design approach was adopted to address the determination of performance objectives with consideration of risk of casualties, occupancy interruption, and the economic loss that may occur as a result of earthquakes. This paper describes the design approaches to meeting the challenges of this landmark project.

Keywords: Seismic, Performance-Based Design, Shanghai ifc

摘要

上海国际金融中心是上海陆家嘴中心的地标，项目发展包括了一幢250米高的多功能塔楼（南塔）、一幢260米高的办公楼（北塔）、一幢100米高的酒店公寓、裙楼和四层地下室。南座塔楼的设计采用了一种新的结构体系，塔楼在低层采用巨型柱来满足高档办公楼布局要求，而在高层采用与酒店房间布置相符的外围框架。这两个方案的组合再加上转换层结构的设计，使这建筑在地震活跃带成为一个独特的设计案例。本项目采用性能化设计方法，通过考虑由地震引起的伤亡、使用中断和经济损失等风险，以设定及实现所要求之性能目标。本文介绍了应对这一这地标建筑的挑战所采用的设计方法。

关键词：地震、性能化设计、上海国际金融中心

Introduction

Shanghai ifc is bounded by Century Avenue, Middle Yin Cheng Road and Hua Yuan Shi Qiao Road. The entire Shanghai ifc development will have four million square feet of floor area, including two Grade "A" office buildings, a high-end shopping mall to attract a variety of major international retailers, a five-star Ritz-Carlton Hotel and serviced apartments. This combination provides a unique environment for work, leisure and living for business people and the residents in Shanghai.

The site is well located within Shanghai, connected to the city through direct access from the mall basement LG2 to Lujiazui station of the Shanghai Metro Line 2. The future Metro Line 14 Station is integrated within the basement of the development. The site, which gives easy access to the upcoming Line 14, also provides 1,800 parking spaces.

The two Grade "A" office spaces comprise 200,000 square meters of gross floor area fitted with advanced information technology facilities. Panoramic views out overlook the Huangpu River, Oriental Pearl TV Tower, Lujiazui Central Park and The Green. The Ritz-Carlton Hotel, within the 18 highest levels of the South Tower, features 285 rooms designed

简介

上海国际金融中心位于世纪大道、银城中路和花园石桥路交界处。整个上海国际金融中心的发展将有四百万平方尺的楼面面积，包括两幢甲级办公楼，一所吸引各种大型国际零售商的高端购物商场，五星级丽思卡尔顿酒店和服务式公寓。这种组合为上海的商务人士和居民提供了一个独特的工作、休闲、生活环境。

项目地块位于上海市中心，从购物商场地下二层可以直达上海地铁二号线陆家嘴站。地铁十四号线也将在这项目的地下室设有地铁站。项目还提供了1800个停车位。

两幢甲级办公楼，包括配置了先进信息技术设施的20万平方米总楼面面积。全景可以俯瞰黄浦江、东方明珠电视塔、陆家嘴中央公园和绿地。位于南塔最高18层的丽思卡尔顿酒店，有285间当代风格设计、突出装饰艺术的房间。所有房间和餐厅都可以看到外滩的景色。上海国际金融中心是第一个在能源和环境设计上获得美国绿色建筑协会（LEED）黄金级别预认证的上海商业开发项目。

大量的国际顶级商店和美食餐厅位于上海国际金融中心商场内。商场根据零售行业急速变化的需求而设计，大跨度天窗屋顶

to a contemporary style, with an emphasis on the decorative arts. All of the rooms and restaurants offer views of the Bund. IFC is the first commercial development in Shanghai to have achieved Leadership in Energy and Environmental Design (LEED) Gold pre-certification from the U.S. Green Building Council.

A wide range of international top-level shops and gourmet restaurants are located within the IFC shopping mall. The mall was designed with the needs of the fast-moving retail industry in mind, with large span skylight roof to the atrium, a structural frame that allows for different types of internal layout, building services, and equipment arrangement.

Site Constraints and the Ground Condition

The entrances to Lujiazui Metro Line 2 on Century Avenue and Yanan Road Cross River Tunnel are adjacent to the north boundary of the site, while the Yin Cheng Road Interchange is near the east boundary. A 35-KV transform plant building and the Podong water treatment plant abutting the west boundary (see Figure 1).

The site investigation found thick weak clay soil between the levels 0 mPD to -35 mPD. Sandy soil was found between the levels -35 mPD and 63 mPD, with coarse gravel found underneath the sandy soil. The ground water table lies from approximately 0 mPD to -1 mPD. Confined water at sandy soil stratum induces 3 to 11 meters water head at that level.

At the initial stage of the project, the appropriate planning considerations for the site constraints were taken into account.

Foundation Design

With a vast amount of data available for Shanghai, the design parameters including soil friction and end bearing resistance in each layer of soil had been well published and even included in the Shanghai Foundation Code. In order to obtain more accurate site specific data, we conducted a detail soil investigation, together with in-situ and laboratory testing on different soil layers, and thus verified and improved in the design parameters. We also carried out trial piles testing to verify the design approach and justified the highest possible pile load carrying capacity, achieving design optimization in foundation.

With good rock strata set at over 120 to 150 meters deep, pile foundations usually take the form of friction piles, with the more common pile types cast in place concrete piles with diameters varying between 600 to 1,000 mm. For a high-rise design, the pile foundation will usually be designed to found on Layer 7 soil or below with length usually over 60 to 70 meters.

Recent developments in small diameter cast in place design pointed to a base grouting technique that was initially designed to compensate the possible inability to achieve maximum design end-bearing resistance, due to tricky workmanship essential to thoroughly clean and concrete the pile tip. Such base grouting technique not only ensured the end bearing resistance, but could also enhance the pile's load carrying capacity.

The mechanism of grouting relied on stiff soil bulb formed with grout, sediment and soil at founding level which could effectively transfer and spread the loading. Voids between the soil particles were filled by the grout, meaning that the bearing capacity and modulus for the soil at founding level were enhanced.

的中庭采用了结构框架，使其能配合不同类型的室内布置、建筑系统和机电设备要求。

场地限制和地质条件

位于世纪大道和延安路越江隧道的地铁二号线陆家嘴地铁站入口，在场地北部边界附近；银成路的交汇处位于东部边界；而35-KV变压厂房和浦东污水处理厂则位于场地西部边界。(见图1)

场地勘测结果显示弱粘土标高介于0mPD至-35mPD。沙土位于-35mPD至63mPD，粗砾石处于砂土下层。地下水位大约从0mPD至-1mPD。砂土地层的承压水产生了3至11米的水头。

在项目的初始阶段，对各类场地的限制条件已作了合理规划考虑。

基础设计

上海基础规范已经提供了许多设计参数，包括各个土层的土壤摩擦和端轴承压力。但为了获得更准确的场地数据，进行了详细的土壤勘测，对不同土层进行现场和实验室测试，从而验证和优化设计参数。我们还进行了试桩来验证设计方法和最大的合理桩基承载力，从而优化基础设计。

由于良好岩层位于超过120至150米的深度，桩基础通常采用摩擦桩，并会采用600至1000 mm直径较常见的混凝土现浇桩。对于高层建筑的设计，通常需采用超过60-70米的桩基础并达7层土层或以下。

就最近发展的小直径现浇设计，带出了一种基础灌浆技术，由于小直径现浇需要严格的工艺，尤其是需要彻底清洁桩孔和桩端浇筑混凝土，初期灌浆技术被视为对桩端承载力可能无法达到最大设计标准的补偿。实际这种基础灌浆技术不仅确保端轴承阻力，而且也提高了桩的承载力。

这种灌浆技术靠水泥、沉淀物和土壤形成硬土，使有效地转移和扩散荷载。土壤颗粒之间的空隙充满灌浆，这意味着作为基础的土壤承载力和模量都提高了。

通过桩测试仪来验证桩端灌浆对现浇钻孔灌注桩的影响，连同电脑记录的应变计来测试桩身承载力和桩端承载力。该试验在上海率先采用实为创新做法。

灌浆前后的试验数据显示（见图2），桩的荷载和沉降关系呈现更弹性特质，灌浆后桩的端阻力增加了。桩的沉降减少50%，侧摩阻力提高，最大摩阻力增加了20%。

这种基础特性能够大幅度增加承载力、减少沉降、减少混凝土使用量和适合可持续设计和施工。

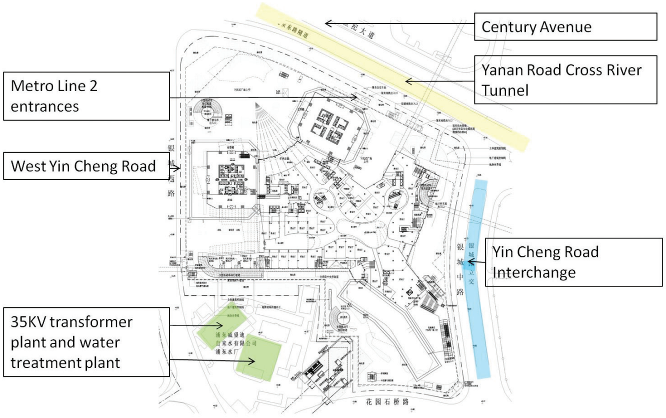


Figure 1: Site Plan (Source: Project Information)
图1： 场地平面图（来源：项目资料 ）

Instrumented pile testing was performed to utilize and to verify the effect of toe grouting to the in-situ bored piles. As the vanguard in Shanghai, strain-gauges together with computerized recording were used for the assessment of shaft and end bearing performance and thus the pile capacity.

Based on test data before and after post-grouting on pile (see Figure 2), the load/displacement relationship of the piles showed more elastic characteristics, and the pile tip resistance increased after the grouting. The settlement of pile decreased by 50% and lateral friction resistance improved, the maximum friction resistance increased by 20%.

The performance of the foundation shows substantial increase of capacity, reduction of settlement and reduction of concrete used, and provides for sustainable design and construction.

The significant increase in pile load carrying capacity and the reduction in settlement not only resulted in a cost saving, but also addressed the rather difficult local ground conditions, in particular for the challenge of the design of a tall building. This, beyond code advancement, also set the stage for other local developments, and also alleviated concern of the impact of the building settlement to the adjacent Metro underground station.

Determination of the Tower Scheme

The multi-functional design of the tower has to accommodate both office and hotel usages. While the office floors called for a mega column arrangement providing the best open view and columnless floor configuration, the hotel floors allowed for smaller intermittent columns aligning with the room layout.

Different structural schemes were examined. The chosen scheme was based on better seismic performance, lighter weight, economy and meeting the functional requirements (see Table 1).

The chosen scheme has a mega-column arrangement at the lower floors with columns spacing at 21 and 24 meters. The upper portion of the tower, the hotel floors, has columns aligning the 4.8 meter room module, with a transition through a transfer truss structural system. This high level transfer is critical in seismic design. Structural implications of change in stiffness, the drift and rotational effect, structural continuity and joint stress performance all needed special attention.

An advancement and breakthrough in structural arrangement was required. The design considered a balance of functional, architectural, interior design and constructional requirement and constraint.

Application of Performance-based Seismic Design

As the towers exceed the China Tall Building Code allowance in several aspects, a performance-based seismic design approach was adopted for the project. This approach designs the building with an understanding of the risk of casualties, occupancy interruption, and economic loss that may occur as a result of earthquakes. It addresses the specific project characteristics and performance requirements. It includes the determination of performance objectives, the identification of critical elements, the design approach of the building structure and the study of elastic and elasto-plastic performances to satisfy the various levels of seismic protection implied in the code. With the consideration of the above and after detail discussion with the expert review panel, performance objectives for each tower were established.

桩承载力的显著增加和沉降的减少不仅节约了成本，而且还解决了当地非常棘手的地质条件问题，尤其是对高层建筑设计的挑战。这不仅为当地其他发展做准备，也减轻了建筑沉降对临近地铁地下车站的影响。

塔楼方案的选定

塔楼采用多功能设计来同时满足办公楼和酒店的用途。办公楼层需要采用巨型柱、少柱的布置来提供最开阔的视野，而酒店楼层允许根据房间的布局布置较小的柱子。

比较不同结构方案后，基于更好的抗震性能、较轻的重量、更经济、同时满足功能要求的原则，确定了最终的方案。（见表1）

所选择的方案在较低楼层采用间距21米和24米的巨型柱布置。塔楼上部为酒店所在楼层，通过转换桁架的结构体系转换，变成柱子沿着4.8米的房间布置。这种高层转换结构是抗震设计的关键。对于刚度变化、扭转位移、结构连续性和节点应力对结构性能的影响等，都需要特别注意。

综合考虑了这个设计的使用功能、建筑布置、室内设计、施工要求和限制，需要采用一个先进和突破性的结构布置方案。

基于性能的抗震设计应用

由于塔楼在几个方面超过了中国高层建筑规范的限值，所以需要针对该项目采用基于性能的抗震设计。这种方法，基于对地震

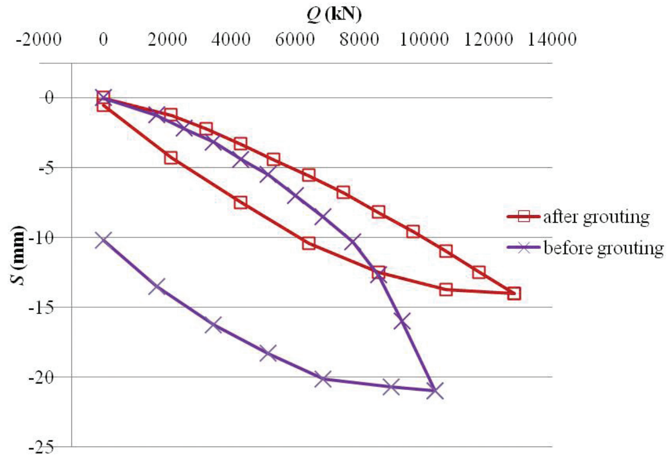


Figure 2: Settlement Curve before and after grouting (Source: AECOM)
图2：注浆前后沉降曲线（来源：AECOM）

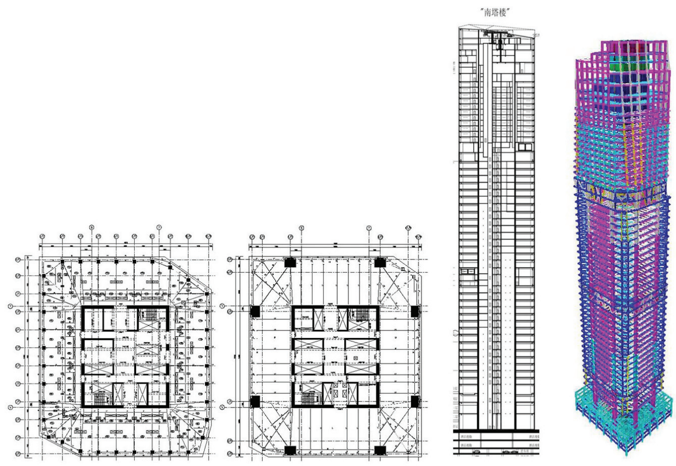


Figure 3: Shanghai ifc South Tower (Source: Project Information)
图3： 上海IFC南塔（来源：项目资料）

Shanghai ifc - South Tower: (see Figure 3)

Tower height: 250 meters
Number of stories: 53
Structural system: RC core wall–composite frame structure
Key characteristics:

- Mega-columns arrangement at 24 meters space for low zone (office zone) and columns at 4.8 meters space for high zone (hotel zone)
- Transfer truss structure at high-level to accommodate the different usage requirement.
- Two layers of outrigger trusses and belt trusses act as a bracing structure.

Performance objectives were chosen with the following key requirements:

- Core wall at strengthen zone designed to be elastic at basic seismic case
- Transfer truss designed to be elastic at basic seismic case
- Outrigger trusses designed to be un-yielded at basic seismic case
- Belt truss designed to be un-yielded at basic seismic case
- Under rare seismic case, the allowable design capacity of the concrete section for the core wall should be larger than the design shear force.

Shanghai ifc - North Tower: (see Figure 4)

Tower height: 260 meter
Number of stories: 58
Structural system: RC core wall–composite frame structure
Key characteristics:

- Megacolumns arrangement at 24 meters space for the whole tower
- Two layers of outrigger trusses and belt trusses act as a bracing structure.

Performance objectives were chosen with the following key requirements:

- Core wall at strengthen zone designed to be elastic at basic seismic case

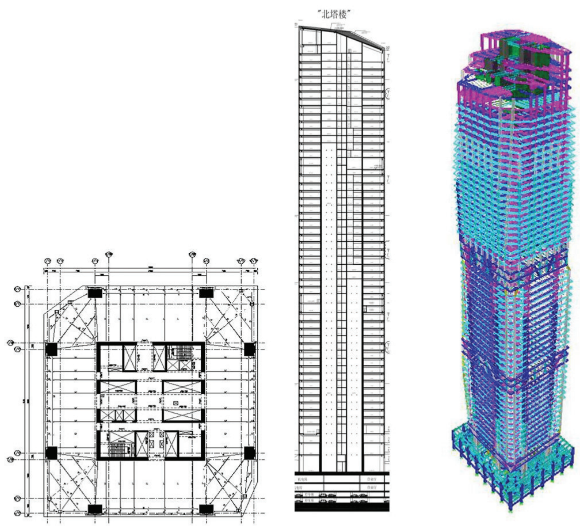


Figure 4: Shanghai ifc North Tower (Source: Project Information)
图4： 上海IFC北塔（来源：项目资料）

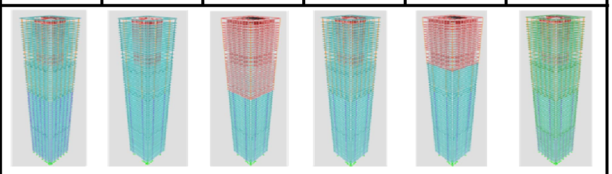
Scheme Comparison方案比较						
	Scheme 1 -9 m c/c Perimeter Columns方案1——周长9m c/c的柱子	Scheme 2 -Mega Columns方案二——巨型柱	Scheme 3 –Mega Columns for Office, Shear Wall for SA and Hotel 方案三——在办公空间使用矩形柱，在SA和酒店使用剪力墙	Scheme 4 –Mega Columns for Office, 9/m Perimeter Column for SA and Hotel 方案四——办公空间使用巨型柱，在SA和酒店使用周长9/m的柱子	Scheme 5 -Mega Columns for Office and SA, Shear Wall for Hotel 方案五——办公空间使用巨型柱，在SA和酒店使用剪力墙	Scheme 6 –Mega Columns for Upper Office Zone, 9m Perimeter Column for Lower Office zone, SA and Hotel 方案六——上层办公区域使用巨型柱，在下层办公区域、SA和酒店使用周长9/m的柱子
						
PROS 优点	• Flexible for Architectural Planning for Hotel对于酒店的建筑规划较灵活 • No Structural Transfer无结构转换	• More Usable Floor Space for Office办公室的可用楼层空间更多 • No Structural Transfer无结构转换	• More Usable Floor Space for Office办公室的可用楼层空间更多 • Better Control of Period using Shear Wall Structure通过剪力墙结构能更好控制周期	• More usable Floor Space for Office办公室的可用楼层空间更多 • Flexible for Architectural Planning for Hotel对于酒店的建筑规划较灵活 • Mass is the least体块质量最小	• More Usable Floor Space for Office办公室的可用楼层空间更多 • Better Control of Period using Shear Wall Structure通过剪力墙结构能更好控制周期	• More Usable Floor Space for Office办公室的可用楼层空间更多 • Flexible for Architectural Planning for Hotel对于酒店的建筑规划较灵活
CONS缺点	• Less Usable Floor Space for Office办公室可用楼层空间更少	• Less Flexible for Planning especially for Hotel and SA对于酒店和SA建筑规划的不够灵活	• Mass is Relatively Large体块相对较大 • Abrupt Stiffness Change 刚度陡变 • Weak Story楼层不够牢固	• Gradually Change of Stiffness and Shear Resistance Compared with Schemes 3, 5 and 6 相较方案3、5和6，刚度和抗剪承载力逐渐变化	• Mass is Relatively Large体块质量相对较大 • Weak Story楼层不够牢固	• Two transfer Levels 两个转换层 • Less Usable Space for G/F Lobby G/F大厅可用空间更少 • Uneven Load Distribution for the Transfer Structure at Low Level低层转换结构的负载分布不均匀

Table 1: Scheme Comparison (Source: AECOM)
表1：方案比较（来源：AECOM）

引起的伤亡风险、使用中断和经济损失的研究，来作建筑结构设计。它涉及具体项目的特点和性能要求。它包括性能目标的确定、关键因素的识别、建筑结构的设计方法和弹性/弹塑性性能的研究，以满足规范中各级抗震设防。基于上述考虑以及与审查小组的详细讨论，确立了每幢塔楼的性能目标。

上海国际金融中心（上海IFC），南塔楼：（见图3）

楼高： 250米
层数： 53
结构体系： 钢筋混凝土核心筒组合框架结构
关键特征：

- 低层（办公楼层）以24米间距布置巨型柱；高层（酒店层）以4.8米间距布置柱子
- 在高层处采用转换桁架来协调不同使用功能的要求
- 伸臂桁架和带式桁架作为支撑结构

基于以下关键要求确定性能目标：

- 中震情况下，核心筒在加强区被设计成弹性
- 中震情况下，转换桁架被设计成弹性
- 中震情况下，伸臂桁架被设计成不屈服
- 中震情况下，带式桁架被设计成不屈服

- Outrigger trusses designed to be un-yielded at basic seismic case
- Belt trusses designed to be un-yielded at basic seismic case
- Under rare seismic case, the allowable design capacity of the concrete section for the core wall should be larger than the design shear force.

Overall seismic performance of the towers

- The core wall at strengthen zone is designed to be elastic at basic seismic case. With consideration of the load factor, this vertical element will be nearly elastic under un-factored load at rare seismic case.
- The transfer truss is designed to be elastic at basic seismic case. With consideration of the load factor, this transfer element, which is controlled by the gravity load, will be nearly elastic under un-factored load at rare seismic case.
- Outrigger trusses are designed to be un-yielded at basic seismic case. With consideration of strength, this bracing element, which is controlled by seismic load, will be partial yield or yield under un-factored load at rare seismic case. However, no sudden failure will happen. This means that the deformation may increase, but the overall integrity and stability will remain.
- The belt truss is designed to be un-yielded at basic seismic case. With consideration of strength, this bracing element, which is controlled by seismic load, will be partial yield or yield under un-factored load at rare seismic case. However, no sudden failure will happen. This means that deformation may increase but overall integrity and stability will remain.
- Under rare seismic case, the allowable design capacity of the concrete section for the core wall should be larger than the design shear force. This clearly indicated that no brittle failure mode will happen at this critical element.

With the Performance Base Design approach, the more critical structural elements would need to be identified and considered to be designed for higher seismic loads. These elements include core wall and columns which are main skeleton of the structure to resist seismic force, outrigger and belt-truss which are major seismic fortification measures, transfer truss which are related to the overall stability of the high zone. For example, at the lower zone (strengthen zone) of the towers, the vertical elements are designed for additional load factor of 20% to 30% higher than that at the high zone.

As shear failure is one of the most unfavorable failure modes in the structure under seismic force. The shear capacity for the core wall has to be increased to the value which is sufficient to resist the rare seismic case. The design has to address the formation of plastic hinges and allow dissipation of energy during high intensity earthquake.

Shaking Table Test and Joint Tests (see Figures 5 and 6)

In order to ensure the seismic safety and reliability of the high-rise structure, in addition to the analysis and design measures, it was necessary to perform shaking table tests for the irregular structural system. The purposes of a shaking table test are the measurement of natural periods, mode shapes and damping. The test simulates the structure under frequent, basic and rare seismic cases. Displacement, acceleration and extent of damages are measured under different seismic conditions. By visual examination of the seismic performance, a deeper understand of the behaviors of the structure was provided. The

- 罕遇地震情况下，核心筒的混凝土允许设计强度应大于设计剪切力

上海国际金融中心（上海IFC），北塔楼：（见图4）

楼高：　　　　　260米
层数：　　　　　58
结构体系：　钢筋混凝土核心筒组合框架结构
关键特征 ：

- 整座塔楼以24米间距布置巨型柱
- 伸臂桁架和带式桁架作为支撑结构

基于以下关键要求确定性能目标：

- 中震情况下，核心筒在加强区被设计成弹性
- 中震情况下，伸臂桁架被设计成不屈服
- 中震情况下，带式桁架被设计成不屈服
- 罕遇地震情况下，核心筒的混凝土允许设计强度应大于设计剪切力

塔楼的整体抗震性能

- 中震情况下，核心筒在加强区被设计成弹性。参考荷载系数值，竖向构件在罕遇地震不考虑附加系数的荷载下接近弹性。
- 中震情况下，转换桁架被设计成弹性。参考荷载系数值，主要受重力控制的转换构件，在罕遇地震不考虑附加系数的荷载作用下接近弹性。
- 中震情况下，伸臂桁架被设计成不屈服。考虑实际强度，这种受地震力控制的支撑构件，在罕遇地震不考虑附加系数的荷载作用下将部分屈服或屈服。但是，不会发生突然破坏。这意味变形会增加，但将保持整体的完整性和稳定性。
- 中震情况下，带式桁架被设计成不屈服。考虑实际强度，这种受地震力控制的支撑构件，在罕遇地震不考虑附加系数的荷载作用下将部分屈服或屈服。但是，不会发生突然破坏。这意味变形会增加，但是将保持整体的完整性和稳定性。
- 罕遇地震情况下，核心筒的混凝土允许设计强度应大于设计剪切力。这明确表明，关键构件不会发生脆性破坏。

Figure 5: Scale 1 in 30 model on shaking table (Source: AECOM)
图5： 振动台1：30模型（来源：AECOM）

Figure 6: Joint test (Source: AECOM)
图6： 节点试验（来源：AECOM）

analytical results were compared with the findings from the tests.

Destruction mode was analyzed for some of the major stress components including core wall, mega columns, belt truss, and high levels transfer structures, enabling tests exploring whether the whole structure can meet the seismic fortification requirements. The comprehensive analysis of test results can inform adaptions for improvement, validation and optimization of structural design.

Test load conditions were performed in accordance with the intensity of frequent case, basic case and rare case in a Grade7 seismic zone and a Grade 8 seismic zone, including seismic wave input at different levels before and after the white noise sweep on the model, measuring of natural vibration frequency, vibration mode and damping ratio. During the seismic tests, El Centro wave, Pasadena wave and SHW2 wave were applied. Seismic wave duration, on a similar relationship for the in situ shock wave compression of 1/11.79, entered into a two-way or one-way direction of the level of input. The shaking table input acceleration peak simulates different earthquake levels.

The shaking table test data analysis demonstrated that the overall structure met current seismic code Grade 7 security requirements. However, taking into account the rare seismic in Grade 8 zone, certain parts of structure could experience serious damage. The detailing of closed spaced column and high zone and the transfer truss were thus adjusted to improve the ductility. The shaking table and joint test in this project not only to verify building performance but also facilitate design to extremity without unnecessary reserves.

Wind Tunnel Test (see Figure 7)

In addition to the code defined wind load requirement, the results from the wind tunnel test, which was based on historical climatological data, which take into account not only the strength but also the wind directions, were considered in the analysis of the tower.

The wind tunnel test was conducted at the Boundary Layer Wind Tunnel Laboratory (BLWTL). It included

- Site Proximity Wind Analysis
- Force Balance Test for structural loading
- Peak Pressure Measurement on the external surface for use in the design of windows and cladding
- Predications of Wind Environment in pedestrian areas around the site

The 260 meter tower, the 250 meter tower and the Low Block were all tested, with all three of the towers present (configuration 1) (see Figure 8). In order to simulate the phased completion, the 250 meter tower was also tested without the 260 meter tower present (configuration 2) (see Figure 9).

Winds in Shanghai with two basic types of weather systems: non-typhoon and typhoon winds. For non-typhoon winds, a design probability distribution of gradient wind speed and direction had been previously developed for the area on the basis of full scale meteorological records from the Longhua and Minhang weather stations in Shanghai. For typhoon winds, a simulation technique is used, involving thousands of simulated hurricanes matching the characteristics of actual recorded typhoons that happened within a 500-kilometer radius of Shanghai.

The Shanghai combined non-typhoon and typhoon wind model predicts 10-year, 50-year and 100-year return hourly mean wind speeds

Figure 7: Wind Tunnel Test Model (Source: BLWTL)
图7： 风洞试验模型（来源：BLWTL）

基于性能的设计方法中，相对关键的结构构件需要确定并考虑更高的地震设计荷载。这些构件包括结构主要抵抗地震力的骨架，如核心墙和柱子，主要地震设防措施，如伸臂桁架和带状桁架，高层部分整体稳定性的构件，如转换桁架。例如，在塔楼的低层区（加强区），竖向构件设计时比高层区多考虑20%至30%的负荷率。

由于剪切破坏是地震力下结构最不利的破坏模式之一，所以核心筒的抗剪切能力需要增加到足以抵抗罕见地震。设计需要解决塑性铰的形成，并允许在高强度地震中能量耗散。

振动台试验和节点测试（见图5、图6）

为了确保高层结构的抗震安全性和可靠性，除了分析和设计措施，对不规则的结构系统进行振动台试验是必须的。振动台试验的目的是测量自振周期、振型和阻尼。试验模拟结构在常遇、基本和罕遇地震情况下的振动。测量不同地震情况下结构的位移、加速度和破坏程度。通过对抗震性能的检查，能够更深入地了解结构在地震下的形态。从测试结果比较分析结果。

针对一些主要应力构件，包括核心墙、巨型柱、带状桁架和高层转换结构，进行破坏模式分析。试验探究整体结构是否可以满足地震设防要求。试验结果的综合分析可以提高、验证和优化结构设计。

荷载试验的条件是根据7级和8级地震的常遇情况，基本情况和罕遇情况进行设定，具体来说，这包括过程中输入这三种情况的地震波参数（包括白噪音过滤前和过滤后），以及对结构的自然震

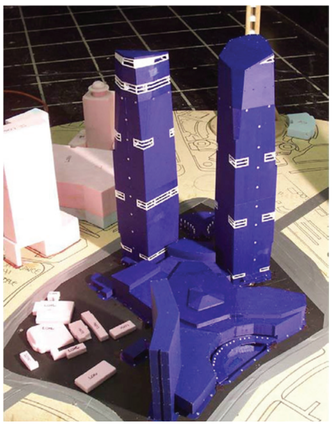


Figure 8: Wind Tunnel Configuration 1 (Source: BLWTL)
图8： 风洞试验装置1（来源：BLWTL）

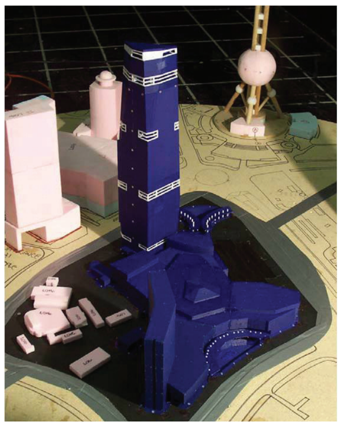


Figure 9: Wind Tunnel Configuration 2 (Source: BLWTL)
图9： 风洞试验装置2（来源：BLWTL）

of about 36 m/s, 44 m/s and 48 m/s respectively at a height of 500 mm above ground. The corresponding hourly mean wind speeds at a 10-meter height are about 23 m/s, 28 m/s and 31 m/s for the 10-year, 50-year and 100-year return periods respectively.

Design Verification and Optimization

The design process has gone through various design verification to ensure that it satisfied the established performance criteria. Results of the wind tunnel test and the seismic shaking table test together with the joint tests provided design parameters and data. Numerical analysis including elastic and elasto-plastic analysis have been performed for different seismic levels. An optimization process has been included in the design process to fine tune the structural design to achieve cost effectiveness and the required safety standard.

Design and Construction of Key Steel Elements

The structural performance of the towers hinged on the design and construction of the mega columns, outrigger trusses, and transfer trusses (see Figure 10).

Various design options were studied and compared for the design of the mega columns, including steel composite (H or crucifix form), concrete fill tube (CFT), reinforced concrete and steel. The choice of composite steel for this project proved to be most cost effective. While providing a saving in sizes, it is also more flexible in adjusting size along the height of the building. The design also takes into consideration the hoisting capability of tower cranes with a balance between it and the steel section percentage.

The outrigger trusses are critical to couple the mega columns and the building's core. The use of a cross bracing arrangement, together with connected top and bottom chord within the wall of the core wall provided an effective arrangement to mobilize the mega columns in lateral stability. The outriggers are rigidly connected in stages to alleviate stress build-up due to differential shortening.

The transfer trusses transfer gravity load while providing additional rotational stiffness to the building. The connection to the mega columns below and the upper smaller columns required a continuous section approach to achieve the same higher design level that of the transfer trusses.

The differential shortening between the core wall and the exterior composite columns during construction was one of the key issues needed to be considered in the design. For this complex behavior, detail analysis to predict the creep, shrinkage and temperature effects was done to calculate the elastic and long term deformation for the core wall and the exterior columns.

In order to achieve the tight program, close relationship coordination with the contractor was required. The construction sequence of the core wall of the tower was constructed at around 4 floors ahead of the structural frame. The core wall and the structural steel construction is followed by the composite deck placement, the floor slab concreting, the MEP installation and finally the exterior cladding system installation.

Construction Sequence

To achieve fast track construction and an earlier delivery of the South Tower, the construction was divided into three major areas (see Figure

动周期、震动模式和阻尼比的测量。在抗震试验中，采用了EI Centro波、Pasadena波和SHW2波。地震波持续时间，为在原位1/11.79冲击波压缩的类似关系，以双向或者单向输入。振动台输入加速度峰值模拟不同的地震级别。

振动试验台数据分析表明，整体结构满足现行抗震规范7级的安全要求，但是，考虑到在8级罕遇地震下，结构的某些部分会有较严重破坏。因此，间隔较密的高层柱子和转换桁架的节点大样需要调整以提高延展性。这个项目中的振动台试验和节点测试不仅验证了建筑的性能表现，也减省了设计中的一些不必要的储备。

风洞试验（见图7）

除了规范中定义的风荷载要求，塔楼分析考虑了风洞试验的结果，基于过去的气候数据，在分析受力时不仅考虑了强度，也考虑了风向。

在边界层风洞实验室（BLWTL）进行风洞试验。它包括

- 实地近似风分析，
- 结构力天平测试，
- 窗户和外墙设计中使用的外表面峰值压力测量，
- 在场地附近的行人专用区域进行风环境预测。

260米的塔楼、250米的塔楼和底座都按照装置一进行测试（见图8）。为了模拟分阶段施工，按照装置二测试了没有260米塔楼时250米塔楼的情况（见图9）。

在上海，风的天气系统有两个基本类型：非台风和台风。对于非台风的风设计，梯度风速和风向的概率分布设计已基于之前在上海龙华和闵行气象站的气象记录完成。对于台风的风设计，考虑数千个匹配上海500公里半径范围内发生的实际台风特点的模拟技术，被用来模拟飓风。

综合上海非台风和台风模型来预测10年、50年和100年的重现周期，在地面500 mm以上平均风速约为36米/秒、44米/秒和48米/秒。相应在10米高度，10年、50年和100年重现周期的平均风速分别为每小时约23米/秒、28米/秒、31米/秒。

设计验证和优化

设计过程已经通过各种设计验证，以确保它满足既定的性能目标。风洞试验和地震振动台试验以及节点测试的结果提供设计参数和数据。针对不同等级地震进行了许多分析，包括弹性和弹塑性分析。在设计过程中已包含结构优化设计，以实现成本效益和所需的安全标准。

主要钢构件的设计与施工

塔楼结构性能取决于巨型柱、伸臂桁架和转换桁架（见图10）。

为了设计巨型柱，我们进行了多种设计方案的研究和比较，包括钢复合材料（H或十字形式），混凝土填充管（CFT），钢筋混凝土和钢结构。对于这个项目，复合钢结构被证明是最具成本效益的形式。在节省材料的同时，沿建筑高度调整大小尺寸也比较灵活。设计还考虑到塔式起重机的起重能力和型钢截面百分比之间的平衡。

伸臂桁架对于连接巨型柱和核心墙是至为重要的。交叉支撑的布置，以及在内部核心墙连接的顶部和底部弦杆，可以非常有效地利用巨型柱增加结构横向稳定性。伸臂架采用的刚性连接减轻差异压缩引起的应力集中。

转换层桁架可以传递重力，同时提供额外的扭转刚度。下方巨型

11). The South Tower area (Zone 2) was the first to be excavated and constructed. The smaller area enabled the period for excavation be controlled and shortened. The W Hotel area (Zone 1) was the second to be excavated. This area also contained the future Metro L14 Station. The station structure was integrated into the basement structure, with the track level requiring a pit in pit excavation. With the physical separation between Zone 1 and Zone 2, the excavation was carried out with an overlapping program. Zone 3, consisting of the North Tower and the retail podium, was excavated with an overlapping sequence with both Zone 2 and particularly Zone 1. The intermediate temporary dividing wall had to be assessed with different scenarios and excavation.

In order to assess the sophisticated behavior of ground movement, a 3D model of the ELS system was applied to study the interaction of different shoring systems. Since the operation of the Metro Line is very sensitive to any movement, a grout curtain next to the diaphragm wall was carried out to control leaking and movement. During the construction, close monitoring for the movement adjacent to the basement was an essential requirement.

Conclusion

The success of the Shanghai ifc project is a result of strong collaboration with the local design institute (ECADI) and contractor (Shanghai Construction), and the support from Sun Hung Kai Properties Ltd.

The advancement in pile capacity design and verification satisfactorily tackles the difficult local soil condition and with a cost effective result. Using of base grouting to enhance the performance of pile foundation in this project also become a successful example to demonstrate the combination of computer analysis and test verification can allow thorough understanding of individual element performance and the design to extremity.

The design of Shanghai ifc through its detailed design and analysis together with model testing demonstrated the effectiveness of the new hybrid structural system in a seismic sensitive zone. The application of Performance-based Design Approach in the seismic design for the mega column arrangement with a high level transfer has pioneered the acceptability within the concept of the Chinese design codes, and thus provided as reference for other designs.

柱和上部小柱的连接需要连续，并需达至与转换层桁架相同的设计水平。

核心墙和外部组合柱施工期间的压缩差异是需要在设计中考虑的关键问题之一。对于这个复杂的问题，必须详细分析及预测蠕变、收缩和温度的影响，来计算核心墙和外柱的弹性及长期变形。

为了实现紧密的施工计划，必需与施工单位密切协调。塔楼核心墙的施工顺序比结构框架施工领先四层。其后是复合板的放置、楼板混凝土浇筑、机电的安装以及最后的外墙安装。

施工顺序

为了实现快速建设和南塔的早期交付，建设分为三个主要区域（见图11）。南塔楼区（2区）是第一个挖掘和建造的区域。此较小的区域让开挖工期缩短且容易控制。酒店区（1区）是第二个进行挖掘的，这个区域还包括未来的十四号线地铁站。地铁站结构将被纳入地下室结构，轨道需要采用坑中坑开挖方法。1区和2区之间有实质的隔离，故挖掘可采用同期施工方案。第3区包括北塔楼和零售商场，亦会在前两区(尤其是1区)挖掘期间开展。中间的临时分期墙必须根据不同的挖掘工况进行设计评估。

为了评估复杂的地面变形，采用了支护系统的三维模型来研究不同支护系统之间的相互作用。由于地铁线的运行对于任何变形非常敏感，地连墙下的灌浆帷幕将被用来控制透水和地面变形，并且在施工期间，必须要求密切监察邻近地下室的变形。

结语

上海国际金融中心项目的成功是基于与当地设计院（华东院）和施工单位（上海建工）的有效合作，以及业主方新鸿基地产发展有限公司强力支持的结果。

桩承载力提升的设计和验证，圆满地解决了当地困难的地质条件并收获高成本效益。使用桩底灌浆以提高这个项目中的桩基础性能也成为电脑分析和试验验证相结合的成功例子，从而全面理解每一构件的性能并对其进行极限设计。

上海国际金融中心通过其详细分析设计与模型试验，验证新型混合结构体系在地震活跃区的有效性。抗震运用设计中性能化设计方法，应用于巨型柱布置连同高层转换的结构体系，在中国设计规范概念上开创先河，从而也为今后的其他设计提供了参考。

Figure 10 Construction of trusses (Source: AECOM)
图10：桁架施工（来源：AECOM）

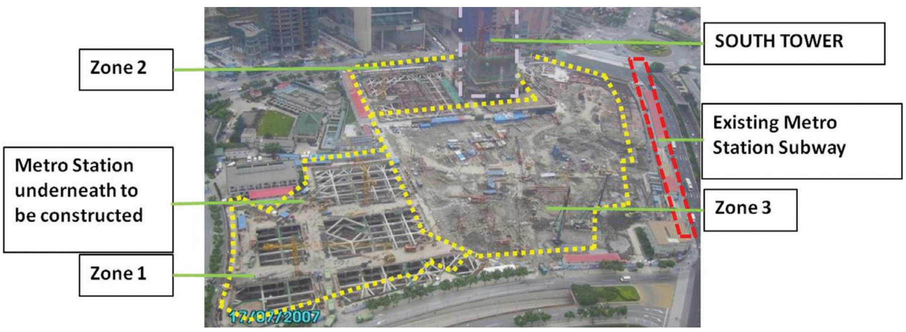


Figure 11: Three major areas of the site (Source: AECOM)
图11： 场地三个主要区域（来源：AECOM）

References（参考书目）:

The Boundary Layer Wind Tunnel Laboratory - **A study of wind effects for Shanghai Lujiazui Finance and Trade Zone Plot X2**