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From "O" to "L" Design Challenges, Gazprom Tower

从"O"到"L"设计的挑战，俄罗斯天然气工业公司大楼

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Peyman A. Nejad is International Design Principal. Peyman has dedicated himself to structural innovation throughout his prestigious career. His renowned contribution is the invention of the "Hexagrid" structural system for the tall buildings. While broadly known for his work on supertall buildings; he has had a notable career in the analysis and design of concrete and steel structures and is an acknowledged expert in the design of supertall buildings. During his experience worldwide, he has been involved in designing of many tall building, which the most recent is Lakhta Tower (Gazprom), Russia.

Peyman A. Nejad是国际设计总监。在他的职业生涯中, PEYMAN 主要投身于结构创新。他的著名的贡献是发明了高层建筑中的"六边形单元网格"和" Hexagrid "结构系统。他不仅仅在超高层建筑设计方面的工作为人所周知;他还从事于混凝土和钢结构的分析及设计，是超高层建筑设计领域的公认的专家。凭借他在世界范围内的相关经验，他曾参与许多高层建筑的设计，最近参与的是俄罗斯Lakhta 大楼 (俄罗斯天然气工业公司) 的设计。

Abstract

Each supertall building project has its own design challenges and difficulties. The experience with Okhta "O" center which became Lakhta "L" center complex project in Saint Petersburg, Russia, has proven to have its own unique challenges. While the design is contextual to the city, it also represents an evolution and a refinement of an architectural continuum of skyscraper design. It is very unique structurally, taking advantage of new and innovative thinking about technology, building materials, life-cycle considerations and energy conservation. As this building creates unique challenges, it requires an open mind in search of the optimal solution for every challenge, even if it means going beyond the proven and accepted methods, processes, or technologies.

Keywords: Design Challenges; Evolution; Structural Innovation; Optimal Solution; Energy Conservation

摘要

每个超高层建筑项目都有自己的设计挑战和困难，我们在Okhta"O中心"和俄罗斯圣彼得堡的Lakhta" L中心"综合体项目的经验，都体现了各自独特的挑战性。设计不仅与城市背景相协调，它也代表了摩天大楼设计的建筑连续的演变和细化。由于有了技术、建造材料、生命周期的考虑和节能方面的创新思维的优势，它们在结构方面非常的独特。设计这样一个标志性的高层建筑是前所未有的挑战，它需要一个开放的心态中寻找每一个挑战的最优解，即使这意味着要超越的证明和公认的方法，过程或技术。

关键词: 设计挑战;进化;结构创新;最佳的解决方案; 能源节能

The Lakhta ("L") Center is planned to include the first supertall skyscraper in the city, a scientific and educational complex, sports and leisure facilities, and an outdoor amphitheater. The 463-meter main tower of Lakhta Center, upon its planned completion in 2018, is expected to be the tallest building in Russia and Europe.

The design of the main tower of Lakhta ("L") Center project inherited the design of the main tower of the project Okhta ("O") Center, which was succeeded by the project Lakhta Center upon the decision of Gazprom and the city of Saint Petersburg, to relocate the project of Gazprom's new headquarters in December 2010, from Okhta region to Lakhta region, next to the gulf of Finland.

Lakhta Center is a Large Scale Project in Primorsky District – Saint Petersburg. Implemented as a pilot project of an integrated development of the area and the construction of a mini city inside Saint Petersburg: A sustainable district for life and work (see Figure 1).

Lakhta中心 ("L") 的规划包括了该城市第一个超高层摩天大楼、一个科学和教育综合体、体育和休闲设施、以及一个室外圆形剧场。预期在2018年完成的Lakhta中心462米的主大楼将会成为俄罗斯和欧洲最高的建筑。

Lakhta ("L") 中心项目的主大楼的设计继承了Okhta ("O") 中心项目的经验，这是Lakhta中心项目团队在俄罗斯天然气工业公司和圣彼得堡市共同决策的成功。在2010年12月，将俄罗斯天然气工业公司的新总部项目的主大楼的从Okhta 地区移到了Lakhta地区，毗邻芬兰湾。

Lakhta *拉开塔中心是一个位于圣彼得堡滨海区的大型项目。实施区域是一个圣彼得堡市内部的一个迷你城市综合开发试点项目。一个可持续发展的集居住及工作为一体的区域。 (见图1) 。

Lakhta 中心大厦概述

Lakhta 中心大厦是一个位于圣彼得堡市的建设中的多功能综合项目，由两栋塔楼、基座区域 (地下空间) 、拱门 (大楼入口) 和园林绿化组成，占地面积为13.9公顷。

大楼的形态是一个独特的形状，通过连续的动作: 挤压、扭转、经锥状收缩与弯曲使

Lakhta Center Tower Overview

The Lakhta Center Tower is part of an under Construction Multifunctional Complex Located in St. Petersburg, Russia, including two other Buildings, stylobate areas (underground), Arch (Tower Entrance) and a Landscape area on a site area of 13.9 Ha.

The Tower figure follows a unique shape through the subsequent movements: extrusion, twisting, cone and bending. The higher the floor, smaller is the footprint. All structural and façade elements follows the equivalent concept and technically custom-made to the concept. The Total Height of the Tower is 465.7 m BSL (Baltic Sea level).

The Tower Building is projected to have 86 Floor Levels above ground (floor to floor height 4.20 m) and 03 Levels below ground. Within its outer limits will hold functions such as Technical Areas, Office Spaces, Dining Areas, Lobbies (including Sky Lobbies), Conference Areas and Archives. It is designed to be Green Certified (USA) Building, especially due to the energy savings. And others such as;

- Natural Ventilation at summer time;
- Trench Heaters at Winter Time;
- Maximize daylight and control solar gain;
- Maximize daylight and control solar gain;
- Reduce the mechanical intervention under both heating and cooling modes

The Tower has an inner and outer façade creating between them an area which is called Buffer Zone, planned to give a greater thermal performance in winter and summer time improving the comfort within Office Areas.

The building will be equipped with the latest technology in terms of vertical circulation located in the central core of the tower. High speed lifts will serve the Tower in a smart way.

Structurally it has a box foundation (with stiffened extra walls) seating on a massive reinforced concrete raft foundation supported by reinforced concrete piles for the substructure. Underground part of the Tower Sub-Structure form the pile box-foundation consisting of a bottom slab with the thickness of 3.6 m (Raft Foundation), a top plate with the thickness of 2.0 m (Transfer Slab), a core and 10 diaphragms of rigidness (Fin-Walls). The pile box-foundation carries out a function of a uniform load distribution from the Tower core onto the pile foundation. For the superstructure it has a reinforced concrete core, composite slabs, steel columns and outriggers (see Figure 2).

Tower Façade

The Tower Outer Façade is a Unitized System assembled by panels units having a height of 4.20 m. The total Glass Area in each panel is about 11 m^2. It comprises Double and Single Stories. The double story receives an extra steel reinforcement from floor to floor vertically at every mullion position. In order to track the twisted shape of the Building the glass uses the cold bending technology. Profiles are in aluminium, with Stainless steel as final finishing. The Façade comprises Areas with triple, double and non glazed part at the top (where a stainless steel mesh will take place).

The façade corners are vertical and continuous from bottom to top made by stainless steel sheets as finish surface (It is intended to include operable openings for Natural Ventilation, heating cables, aviation

Figure 1. Lakhta center (Source: Client, JSC “Okhta Center”)
图1 Lakhta中心 (资料来源: 客户，“Okhta中心”股份公司)

Figure 2. Lakhta Center complex facilities. (Source: Client, JSC “Okhta Center”)
图2 Lakhta 中心。 (资料来源: 客户，“Okhta中心”股份公司)

该塔楼高区的楼面小于底部。所有的结构和幕墙构件遵循相同的概念并且在技术上与概念相符合。大楼的总高度是465.7米 (波罗的海平面为基准) 。

大楼在地面以上共有86层 (楼面间距高为4.20米) 及三层地下室。在其内部包含以下功能，如: 设备区域、办公空间、餐饮区、大堂 (包括换乘厅) 、会议中心和档案馆。该建筑物是按照 (美国) 绿色认证的建筑的要求进行设计，特别侧重于能源的节约。以及其他，如:

- 夏季自然通风;
- 冬季地台取暖;
- 最大化采光与控制太阳能增益;
- 自然光最大化;及
- 减少加热和冷却模式下的机械干预

大楼设有内外两层幕墙体系，在两层幕墙之间形成的空腔，这就是我们常说的所谓的缓冲区，它将在冬季和夏季的时间提供更好的热工性能并提高办公区域的舒适性。

lighting, architectural lighting, lightening system integration, BMU rails, etc. on the corners).

Calculations are expressed on the Design enhancing the thermal characteristics of the façade, especially the condensation possibilities of occurrence on the internal surface of the outer façade.

The façade will include a Building Maintenance Unit (BMU) from level +369.60 m down to the bottom through platforms and above this level to the very top by personnel.

All façades will be controlled by an automated environmental control system being part of the so called "Intelligent Building". Customized computerized automation system required of unprecedented complexity. Initial engineering, construction, commissioning and operation require highly specialized firms.

The inner façade is a Double Glazed Façade with a spandrel panels between floors with modules of 1.5 m width. It is located between Office Spaces and Buffer Zones. At the Bottom of the Tower there will be a skylight glazed surface.

Tower Crown on the Top

The panoramic restaurant and the observation deck are located at 83rd floor and 86th floor.

The two levels of the observation deck are functionally connected with each other by the panoramic elevator, as well as by the ramp encircling the core of the Tower.

Tower Substructure & Superstructure

Tower Pile Foundation

A significant amount of site and laboratory work has been carried out to allow the foundation design to be developed. This has included an extensive site investigation comprising boreholes to a depth of 150 m, laboratory analysis (triaxial, odometer and shear box testing), In-situ tests e.g., cone penetration test (CPT). pressure meter, hydrogeology, geophysics and preliminary load testing of three full scale foundation elements.

Developed pile foundation for the Tower consists of piles of length 55 ... 65 m, located with variable spacing. Outside of the central core, the tower load is transmitted to foundation only by the distribution through reinforced concrete fin- walls, which explains the application of 55 m long piles in that area. Application of 65 m long piles in a relatively more loaded areas of the foundation would result in excessive rigidity, reduction of settlements at the edges of the foundation and an increase rigidity in the central part. The scheme of pile foundation is characterized by a variable pile spacing, mean value of which is 4...6 m or 2...3-diameters, due to the hexagonal shape of foundation and high loads concentration within the central core of the tower.

In the central zone of the foundation, immediately below the stiffness core, piles arranged at a 5 m spacing (2.5 diameter). Outside of the pile field center, in the area of concentration of the load from the central core, 3 rows of piles are placed at the minimum step 3 ... 4 m (1.5 ... 2 diameters). These piles are the most loaded, which is caused by the transfer of a significant load from the core, and from the fin- walls as well. Pile spacing increases to 5 m (2.5 diameter) as the distance from the center increase. Foundation loads have been divided into two zones. Zone 1 is the zone under the core and zone 2 is the zone under the columns.

大楼将在位于大楼的中间核心筒区域配备最新技术的垂直交通体系。高速电梯将为大楼提供智能化的垂直交通体系。

结构采用一个箱形基础 (设有附加刚性隔墙) 由一个庞大的钢筋混凝土桩筏基础来支承。塔的地下部分结构形成桩-箱基础，包括一个3.6米 (筏基础) 厚的底板 、2.0米厚的 (转板) 顶板、一个核心和10个刚性隔板 (翼墙) 。桩-箱基础将从塔楼核心筒传来的荷载均匀地分布到桩基础的。上部结构采用钢筋混凝土核心、组合楼板、钢结构柱和伸臂桁架体系。（见图2）。

塔楼幕墙

大厦外幕墙采用单元系统，单元由4.20米高的面板单元组装。每个单元的总玻璃面积大约11平方米。它包括双层和单层层高的单元。双层高的幕墙将会设有一个附加的、位于每个竖框的位置的、从楼面到楼面的垂直钢构件。为了满足大厦的扭曲形状的玻璃采用了冷弯技术。采用铝合金来找形，以不锈钢作为最后的装饰收边。该幕墙由三层玻璃，双层玻璃和在顶部的非玻璃部分组成 (顶层采用不锈钢丝网) 。

幕墙采用垂直角，并从底部到顶部由不锈钢板作为完成面 (这个角部包括了可操作的自然通风开口，加热电缆、航空照明、建筑照明、减轻系统集成、擦窗机导轨等) 。

计算体现在了幕墙的热工特性的设计增强，尤其是针对可能发生在外幕墙内表面的冷凝的可能性。

从高度369.60米到地面，幕墙的维护及清洁将通过建筑维护系统的平台来实现，建筑物顶部的清洁将采用人工来完成。

所有的外墙将通过自动环境控制系统即所谓的"智能建筑"进行控制。前所未有的复杂性要求定制电脑自动化系统。最初的工程设计，施工，调试和运行需要高度专业化的公司。

内外墙是双层玻璃幕墙与1.5米宽度的模块层之间的窗间墙。它位于办公空间和缓冲区之间。在大楼的底部都会有一个天窗釉面。

塔楼顶冠

全景餐厅和观景台位于第83楼及第86楼。

这两层的观景层由全景电梯相连，以及环绕大楼核心筒的斜坡连接。

塔楼的地下和上部结构

大楼桩基础

一个大量的现场和实验室工作已经开展来进行基础设计工作。这包括了广泛的实地勘探调查，包括150米深的钻孔，实验室分析 (三轴，固结仪和剪切盒测试) ，原位测试 (耐压仪，水文地质和地球物理学) 和三全量程的基础初步负载测试元素， 例如，静力触探 (CPT) 。压力仪表，水文地质，地球物理和三个桩基的荷载测试。

大楼桩基长度由55... 65 米长度，采用不同的桩距。中央核心之外，大楼负荷通过钢筋混凝土肋片墙和长55米的桩传递到基础。在重载区采用65米长的桩基来增加刚度和减小基础边缘的沉降量。桩基础的方案的特点是采用可变的桩间距，平均值为4 ... 6米或2 ... 3倍直径，在塔的中部核心内的基础和高负荷区采用梅花形布桩。

Piles

The designed pile substructure of the Tower consists of piles 55 to 65 m long spaced irregularly (two types). Total piles: 264 units (including test piles), (see Figure 3).

Box-Shaped Foundation

The tower has unique sub-structure foundation. The whole basement has been designed as one rigid structural element. The central reinforced-concrete core is the basic load-bearing structural element of the building in box foundation. The core bears vertical and horizontal loads, including the constant torsion which is caused by the form of building, having twisted and tapered columns at each level, and it transfers them to the foundation. The collaboration work of the bottom and top slabs of the box-shaped foundation is provided by 10 diaphragm plates, which is called Fine-Walls, diverging from the building core in the radial direction (see Figure 4).

Shoring System

According to the project, the construction of underground part of Tower structure is planned to perform from the 18 m deep excavation pit, for which 1200 mm Diaphragm Wall with the depth of 30 m construction is planned by the contour of the underground part of the complex. The Diaphragm Wall method is one of the most progressive and flexible technologies used for shoring system at the intricate sites where the pit excavation has to be done. In accordance with the results of geological investigations, the bottom of the Diaphragm Wall will be embedded in the layer of hard clay of Vendian horizon for more than 9 m.

A shoring system called "Compression Ring", consisting of 4 reinforced-concrete discs, it is proposed to support the diaphragm wall during pit excavation of top down construction works of the Tower Building. Reinforced-concrete discs act as compression rings which are supported by steel dowels embedded into the D-wall at one side, horizontally, and by the system of plunge columns at another side, vertically. The Plunge columns are necessary to provide transitional support of the reinforcement disks in top down construction, and they are only temporary used which they are installed into the bored piles during the casting the piles work prior to shoring discs installation and excavation of the pentagonal pit.

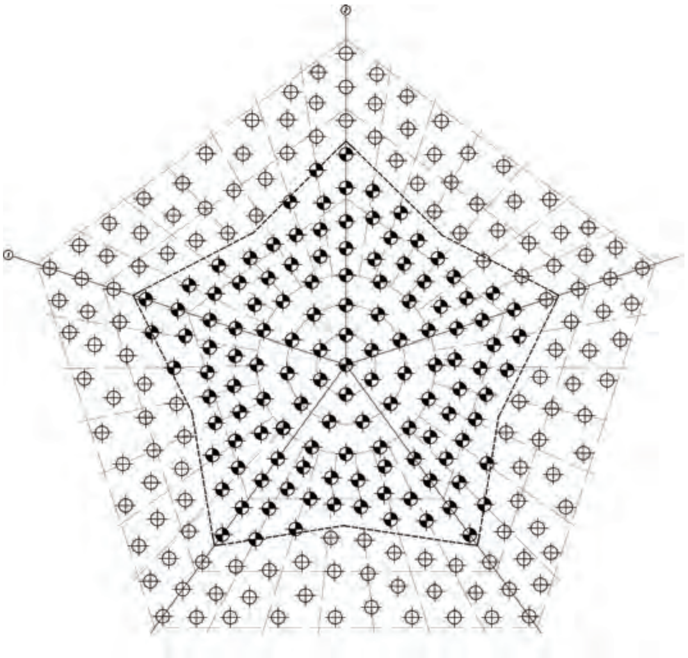

Figure 3. Tower Piles. (Source: Peyman Askarinejad.)
图3 大楼桩。（资料来源: Peyman Askarinejad）

在桩基的中部区域，刚度核心的正下方，采用5米桩距 (2.5米直径) 。在中部区域以外，核心区域之外的荷载集中区域中，3排桩以最小间距布置即3—4米 (1.5—2米直径) 。这些桩是负载最大的，这是由于由中心和翼墙传来的巨大压力所导致的。随着与中心距离的增加，桩距增大到5米 (2.5米直径) 。基础负荷被分为两个区。第 1区是核心区，第2区域是柱下的区域。

桩

塔楼的桩基设计采用55~65米长桩按不等距来进行布置 (两种类型) 。总桩数：264根 (包括试桩) ，（见图3）。

箱形基础

该大楼具有独特的地下室结构基础。整个地下室已经被设计为一个刚性结构单元。中央钢筋混凝土核心是建筑在箱形基础的基本承重结构元素。核心承载的垂直和水平载荷，包括因建筑物的形式不断扭转引起的扭矩，由每个楼层的扭曲的锥形柱将它们传递到基础。箱型基础的底部和顶部板的协作工作是由10片隔墙，这些翼墙，将荷载从建筑物的核心在径向方向进行传递。(见图4) 。

支撑系统

据该项目，大楼结构的地下部分的建设计划从18米深的基坑进行，为此，30米深的1200毫米地下连续墙根据复杂的地下部分的轮廓进行布置。地下连续墙的方法，用在复杂的工地上，是支撑基坑开挖系统的最先进和灵活的技术之一。根据地质勘探结果，地下连续墙的底部将被嵌入硬质粘土层内大于9米。

一个名为"压缩环"支撑系统，包括4个钢筋混凝土环，在大楼大厦的逆作法施工中采用这些钢筋混凝土环来支撑地下连续墙。钢筋混凝土环作为受压环在水平向由一些钢销钉与地下连续墙相连，在竖向由立柱桩来支撑。立柱桩需要承受逆作法施工工艺中混凝土受压环的临时荷载，它们是在钻孔灌注桩施工时安装到灌注桩中的。

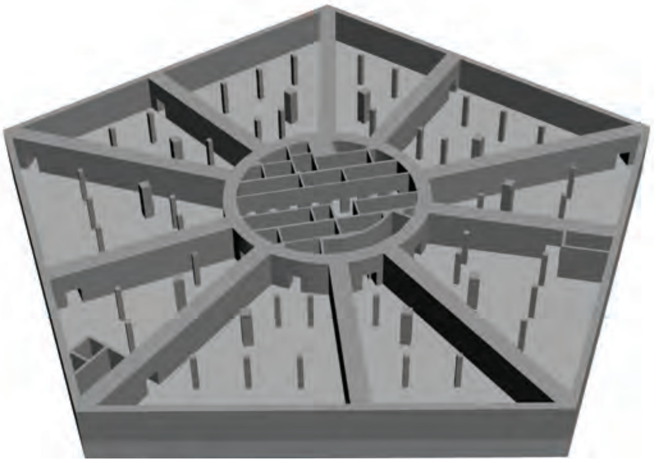

Figure 4 Box-Shaped Foundation 3D (Source: Peyman Askarinejad)
图4 箱形基础的3D（资料来源: Peyman Askarinejad）

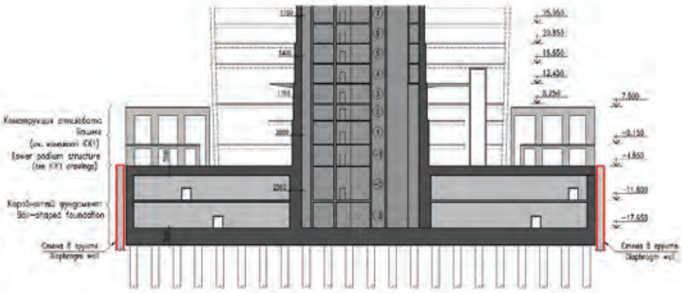

Figure 5. Box Foundation Section. (Source: Peyman Askarinejad)
图5 箱形基础部分。（资料来源: Peyman Askarinejad）

Raft Foundation

The sub-structure consists of three underground levels. Underground levels form in plan equilateral pentagon with each side of 57.5 m. Underground levels, in whole, act as a box foundation, which consists of 3.6 m thick raft, 2.0 m thick top slab, core and 10 walls acting as stiffening diaphragms. Box foundation equally redistributes loading from the Building's core to the pile foundation (see Figure 5).

Fin Wall

The rigidity of the bottom and top slabs of the box-shaped foundation is provided by 10 diaphragm plates in thickness of 2500 mm diverging from the building core in the radial direction see Figure 6).

Tower Super Structure

Tower Rotation

As described in the documents, the tower geometry consists of 5 wings placed about a central circular core. The setting out of the wings varies with the height of the building according to 3 variables. The "cone" and "bend" variables have a quadratic relationship with height, while the "twist" variable has a linear relationship with height (see Figure 7).

Steel Columns

The building columns are situated along its perimeter and are bounded in the groups' three pieces in each petal, creating the curve shape of the Tower. The columns follow the geometry of the wings of the building and are rectangular shapes following the planning grid on each floor.

For increasing the horizontal stiffness of the building ten columns (on two columns in each petal) are connected to the building core by mean the outrigger beams, are situated on four levels of the building height. Thus, the columns actively are put into operation on the bearing of lateral loads to the building (see Figure 8).

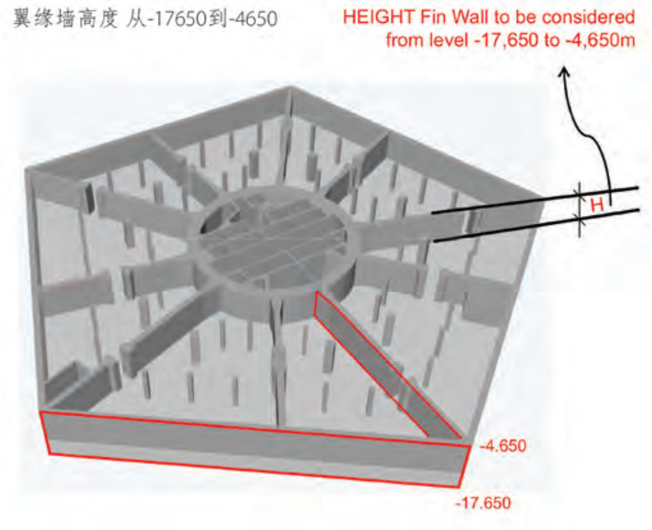

Figure 6. Fin-Walls 3D. (Source: Peyman Askarinejad)
图6 翼墙3D图 。（资料来源: Peyman Askarinejad）

筏板基础

地下结构由三层地下层组成。地下平面为等边五边形，边长为57.5米。地下结构整体上为一个箱形基础，它由3.6米厚筏板， 2.0米厚顶板，核心和10片刚性翼墙组成。箱形基础从建筑的核心筒将荷载均匀地传递到桩基础。（见图5)

翼墙

箱形基础的底部和顶部板的刚性是由10片2500毫米厚的由核心筒沿径向方向向外发散的翼墙来提供的。（见图6）。

塔楼上部结构。

大楼旋转 (见图7)

根据上文的描述，大楼的几何形状由5个翼围绕中央的圆形核心筒组成。5个翼的定位随建筑物的高度根据3个变量而有所不同。由此可见，"圆锥"和"弯曲"的变量具有与高度呈二次关系，而"扭

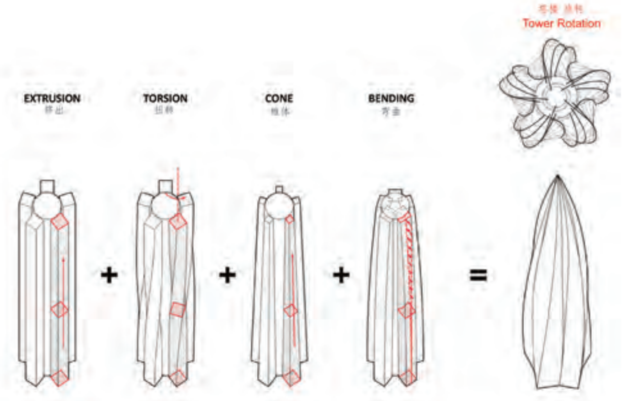

Figure 7. Tower rotation (Source: Peyman Askarinejad)
图7 塔楼旋转 (资料来源: Peyman Askarinejad)

Figure 8. Tower Steel Columns. (Source: Peyman Askarinejad)
图8 塔楼钢结构柱。（资料来源: Peyman Askarinejad)

Floor Slabs

The structural floor system is normal weight concrete slab on metal decking supported by symmetrical steel I-beams fabricated from flat plate. Conventional shear studs are shown in each trough in the deck, and these will give composite bending action between the slab and the beams. Main beams, designed along the floor contour on odd floors carry façade loads and are to reduce their deformation, which influences on façade structural solutions.

Secondary beams are consist of rolled H-beams and designed from conditions of the joined work with reinforced concrete plate through the flexible supports (studs), fixed by two in a row in each flute of the profile flooring. The beam structural analysis is made in accordance with the directions, given in the "Special Technical Conditions" for designing this building, and small secondary beams are designed from rolled-steel channels (see Figure 9).

Core Wall

The central reinforced-concrete core is the main element which provides the bearing of horizontal loads. However, in the case of the Tower building, in which the relation of the core diameter to the building height makes about 1/17, it was appeared that the rigidity of one core is insufficient for fulfillment the requirements of norms on the horizontal deviation of the building top. Introduction of the out-rigger beams enabled reduction in the horizontal movements of the tower against wind loads and provide lateral resistant to the building (see Figure 10).

Torsion forces on the core result in rotational movement of the floors, increasing up the height of the tower. The image below shows the elastic rotation of the structure due to permanent torsion on the core The rotation will happen incrementally as the building height increases during construction. The construction sequence should take into account the movements and setting out of the structure may have to be adjusted accordingly (see Figure 11).

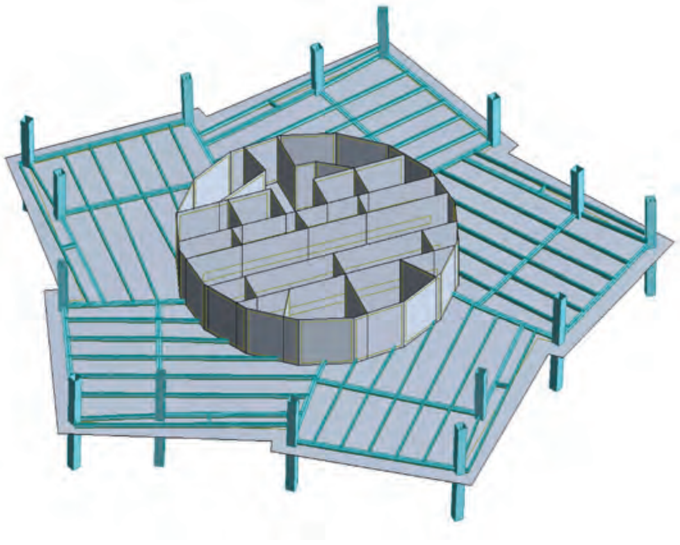

Figure 9. Structure of floor slabs. (Source: Peyman Askarinejad)
图9 结构楼板。（资料来源: Peyman Askarinejad）

曲”变量具有与高度呈线性关系。

钢柱

建筑的柱沿其周边和有界在组三件中的每个花瓣，创造了大楼的曲线形状。柱按照建筑物翼的几何形状，根据每层的轴网采用矩形截面。

为了提高建筑物10柱的水平刚度（在各花瓣两列），沿建筑高度的四个楼层设置与核心筒相连的伸臂桁架。因此，柱成为抗侧体系的一部分来共同承受水平荷载。（如图8所示），（见图8a）

楼板

结构楼板系统是混凝土组合楼板，楼面梁采用焊接对称钢工字钢。传统的剪力栓钉穿透压型钢板，使楼板和钢梁协同工作形成组合梁。主梁，沿楼体轮廓在奇数层设置并设计承担外墙负荷，并减少其变形，从而影响对外墙结构的解决方案。

次梁是根据采用每列设置2个抗剪栓钉的压型钢板混凝土组合梁来进行设计的。梁结构分析是按照“特殊技术条件”的要求来设计这个建筑物，小次梁采用热轧槽钢。（见图9）

核心筒

钢筋混凝土核心筒是提供建筑物抵抗水平力的主要结构。然而，在塔楼体系中，在核心筒直径与建筑物高度的比例关系在大约1/17的情况下，单凭一个核心的刚性不足以达到规范允许的建筑物顶部水平位移要求。因此，我们采用了伸臂梁体系增加建筑物

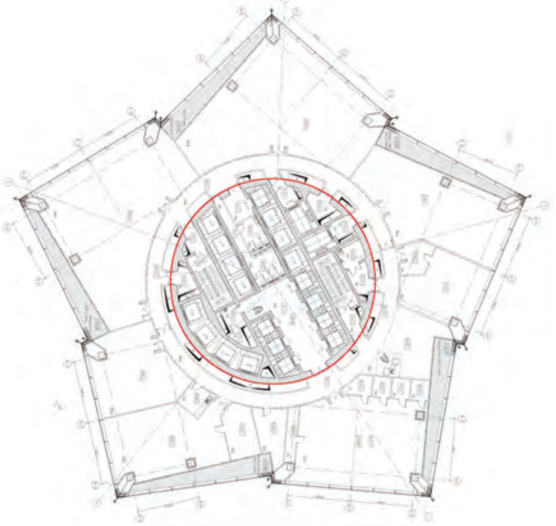

Figure 10. Core wall plan (Source: Peyman Askarinejad)
图10 核心筒（资料来源: Peyman Askarinejad）

Figure 11. Elastic rotation of Tower columns under self weight (Source: Peyman Askarinejad)
图11 自重工况下的大楼弹性旋转（资料来源: Peyman Askarinejad）

Structures of Outriggers

The Outriggers are located in tower at 4 different levels. Each Outrigger level consists of two floors with total height of 8 m. The Outriggers are intended to place opposing shear forces on to a core at upper and lower level of each out-rigger, thus inducing a bending moment in the core. The shear stiffness and strength of a circular section is at its sides in the direction of the load. The placement of radial outriggers requires a system to transfer the shear to the sides of a circular core. It is this transfer of force around the circle that presents the most difficult challenge, due to the rotation of the tower about a constant core plan, the outriggers meet the core wall at a variety of locations which are not controlled by the structural designer. Each position must be checked for local bending.

The stability system of the tower is the concrete core connected to the out perimeter columns through the outrigger trusses, the outriggers covered by the project increase the rigidity of the building on the horizontal forces, and also provide the stability of the building structures located on the outer side of core to the progressive collapse. The outriggers represent the system of radially located in the plan monolithic reinforced-concrete beams that are rigidly restrained in the central reinforced-concrete core of the building and pin-connected to metal columns on the building perimeter (see Figure 12).

Shoring system - Current works. Panorama view (see Figure 13).

的侧向刚度来减少在风载荷下的大楼的水平位移。(见图10)。

随建筑高度而增加的楼层扭转对核心筒产生扭矩。下图显示了由核心筒引起的结构的弹性转动，施工期间随着建筑物高度的增加，旋转将逐步增加。施工顺序应考虑到这个转动，并对结构柱的定位作相应的调整。(见图11)。

伸臂结构

伸臂桁架位于塔的4个不同的层次上。伸臂桁架的目的是把相对的剪切力传到一个核心筒的上下两个楼层，从而也在核心筒上产生弯矩。圆形的剪切刚度和强度是在其侧面中的负载的方向。径向伸臂桁架的放置需要一个系统，以便传递剪力到圆形核心筒。沿着圆形核心筒来传递荷载是极大的挑战。由于塔架沿不变的核心筒进行旋转，伸臂桁架与核心筒的连接位置都不相同，不由结构设计者控制。每个位置必须对局部弯矩进行校核。

大楼的稳定系统是钢筋混凝土核心筒与通过由伸臂桁架连接的核心筒和周边的柱共同来提供的，伸臂桁架增加了建筑物在水平力作用下的刚度，同时还提供建筑结构在核心筒外侧的抗连续倒塌的稳定性。混凝土伸臂桁架与钢筋混凝土核心筒采用刚性连接与建筑物外围钢柱采用铰接。(见图12)

支撑系统-工地现状。全景景象。(见图13)。

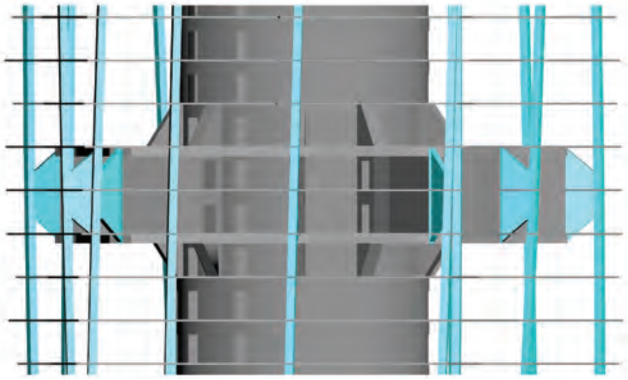

Figure 12. 3D view of outrigger level. (Source: Peyman Askarinejad)
图12 伸臂层的3D视图。(资料来源: Peyman Askarinejad)

Figure 13. Shoring system.- Panorama view of current executed work (Source: Peyman Askarinejad)
图13 支撑系统-当前执行工作的全景景象 (资料来源: Peyman Askarinejad)