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Plot 17-18 Project: Tall Building Design in "Moscow City"

17–18地块项目："莫斯科城"的高层建筑设计

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Emre Ekici has been providing structural services for high-rise and special-use structures throughout the world for the past 8 years.

Since joining Renaissance Construction four years ago, Ekici has gained structural engineering experience in a variety of projects, which includes residential, office, hotel and retail facilities. His responsibilities include direct involvement and management of design and construction phase services in connection with these projects.

He graduated from İstanbul Technical University with a Bachelor of Science degree in Civil Engineering and a Master of Science degree in Structural Engineering.

EmreEkici 过去八年里一直在世界范围内提供高层建筑和特种建筑的结构工程服务。

4年前加入Renaissance Construction公司之后，Emre Ekici参与了多个项目的结构工程，包括居家、办公、宾馆和零售设施。他的职责范围包括直接项目相关设计及施工阶段服务的参与和管理。

他毕业于伊斯坦布尔技术大学，并获得了土木工程学士学位和结构工程理学硕士学位。

Abstract | 摘要

Renaissance Construction is one of the common development companies in Russia, planning to build a mixed-use project within Moscow City, a new development area along the Moscow River 5.5 km from the Kremlin. The Plot 17-18 project consists of office and residential towers to be arranged on a triangular site, with a parking and retail podium at ground and below – for a 357,000 m2 total project area.

This paper studies the use of the outrigger and belt wall system for the Residential Tower subjected to wind loads and progressive collapse scenarios. For the three dimensional 77–story model, 70% maximum displacement reduction can be achieved by providing the first outrigger at the 29th level and the second outrigger at the 49th level of the structure. Additionally, the outrigger and belt walls create structural redundancy, which is beneficial in progressive collapse scenarios.

Keywords: Moscow City, Outriggers, Progressive Collapse, Structural Engineering, Tall Building, Wind Loads

Renaissance Construction公司是俄罗斯的一家开发公司，计划在距克林姆林宫5.5公里的莫斯科河沿岸上的新开发区，即莫斯科城内建造一个多用途项目。17–18号地块由呈三角形分布的办公楼和居住楼构成，地上地下还有停车场和零售裙楼——项目总面积为357,000平方米。

本文研究了336.9米高的居住塔配套悬臂梁和带状墙体在风载和连续倒塌条件下的表现。在77层楼的三维模型上，通过在第29层设置第一道悬臂梁、在第49层设置第二道悬臂梁可最大减少70%的位移。此外，悬臂梁和带状墙体实现了结构冗余，有利于抵抗连续倒塌情况。

关键词：莫斯科城、悬臂梁、连续倒塌、结构工程、高层建筑、风荷载

Moscow City

Moscow International Business Center, also referred to as "Moscow City," is a commercial district in central Moscow, Russia. Moscow City is currently under development, and is expected to become the first zone in Russia to combine business activity, living space and entertainment in a single development (Figure 1).

The Moscow government first conceived the project in 1992. An estimated 250,000–300,000 people will be working in, living in, or visiting the complex at any given time. The project occupies an area of 60 hectares; the territory chosen is the only area in central Moscow that can accommodate such a project. Before construction began, the area had been an old stone quarry where most of the buildings were old factories and industrial complexes that had been closed or abandoned. The total cost of the project is estimated at $12 billion.

莫斯科城

莫斯科国际商务中心又名"莫斯科城"，是俄罗斯莫斯科中心城区的商业区域。莫斯科城目前仍在开发中，预期将成为俄罗斯境内首个融合商业活动、生活空间和娱乐设施的开发项目（图1）。

莫斯科政府1992年首次提出这个项目。预计这个综合设施可同时容纳250,000–300,000人在其中工作、生活或参观。项目占地60公顷，选择在莫斯科唯一的中心建立该项目，因为仅仅只有这里适合。施工开始前，该区域是一处老旧的采石场，大多数建筑都是已经倒闭或废弃的老旧工厂和工业中心。项目总成本估值为120亿美元。欧洲最高的建筑联邦大楼在莫斯科IBC。该中心也包括欧洲高度排名第二、第三、第五、第六和第七的建筑。

项目信息和结构体系选定

Renaissance莫斯科大楼位于距克林姆林宫5.5公里莫斯科中心城内的莫斯科城一是

Figure 1. Moscow International Business Center 2016 (Source: Renaissance Construction)
图1. 莫斯科国际商务中心2016（来源：Renaissance Construction）

Europe's tallest building, the Federation Tower, is in the Moscow IBC. The complex also includes the second, third, fifth, sixth, and seventh-tallest buildings in Europe.

Project Information and Structural System Determination

Renaissance Moscow Towers are located in the center of Moscow, 5.5 km away from Kremlin, in Moscow City – the finance, business and entertainment center of Russia and new CBD of Moscow. The Project's location combines living space, business activity and entertainment together. One of the strongest characteristic of the Project is its over 8,000 sq. m of green area, which provides residents with a green garden, including walking, entertainment and leisure zones. The natural setting of this green space serves as a relaxation area for its residents.

The project comprises a 289 m 61-strory office tower, a 336 m 77-story residential tower and a four-story podium building of mostly parking accommodation and retail (Figure 2).

Several variations on the tower's structural concept were studied such as "outrigger systems" and "wing walls system." The goal of

俄罗斯的金融、商业和娱乐中心，也是莫斯科的中央商务区。项目位置将住宅空间、商业活动和娱乐设施结合在一起。项目的最大特点是超过8000平方米的绿化区域，为居民提供了一个可以散步、娱乐和休闲的绿色花园。这片绿色空间的自然环境可以为居民提供一个放松区域。

项目包含一栋289米、61层的办公大楼，一栋336米、77层的住宅大楼和一栋主要用于泊车和商业的四层裙房（图2）。

对于大楼结构概念变化进行了研究，例如“伸臂系统”和“翼墙系统”。研究目的是在提升单元布置灵活性的同时，实现施工成本最小化，并且在完成施工后实现二者的融合。伸臂系统在高层建筑的结构设计中非常普遍，因为它可以有效增强结构刚度，从而增强抗侧力体系的结构宽度。通过将建筑核心筒与周边柱子相连可以抵抗倾覆力，伸臂则可以通过与周边柱子分担荷载降低倾覆应力，与此同时，需避免连续的墙垛或连接核心筒与所有周边柱子的支撑与建筑发生冲突。

大楼结构在概念设计阶段是基于设计，以及施工团队对多方案的成本、施工能力、施工速度、可靠性、稳定性方面的评估。结构概念选择了以核心筒墙体结构和柱子承担重力荷载及侧向荷载。这一系统也可以将结构对于可租赁楼层的影响降到最低。两栋大楼的结构概念大体相同——两座大楼均在核心筒结构周围采用了钢筋混凝土墙以及后张混凝土楼面框架。办公大楼和住宅大楼均设置了伸臂，极大地降低了核心筒的力，从而可使用更细长和更有效的核心筒结构，并使总体用材最小化。

今日，全世界尤其是欧洲境内的恐怖袭击增多。因此，连续倒塌现象也成为了高层建筑设计中一个至关重要的问题。伸臂和环带墙系统对于连续倒塌计算（支持可能在爆炸及类似冲击后出现关键结构缺失后

Figure 2. 3D view from conceptual design studies (Source: Speech Architectural Design Office)
图2. 概念设计研究中的3D视图（来源：Speech建筑设计室）

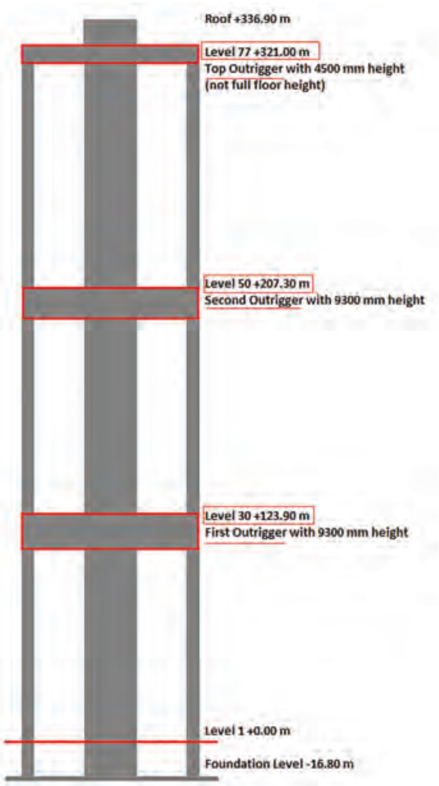

Figure 3. System diagram of the residential tower. Concrete core walls are linked to the perimeter columns at mechanical floors. Outrigger elements (red) are typically reinforced concrete walls (Source: Renaissance Construction)
图3. 住宅大楼的系统分析图。混凝土核心墙体与设备层的周边支柱相连。悬臂梁结构（红色）通常为钢筋混凝土墙体（来源：Renaissance Construction）

the studies was to minimize construction cost while allowing more flexibility in laying out units and combining them after construction. Outrigger systems are prevalent in the structural design of tall buildings because they efficiently increase structural stiffness and thereby increase the structural width of lateral system. By linking building cores with perimeter columns to resist overturning forces, the outriggers relieve overturning stresses in a building's core by sharing the loads with the perimeter columns, all while avoiding the architectural disruption of having continuous fin walls or diagonal bracing linking the core to the perimeter columns throughout the height of the building.

The tower structures are also based on the design and construction team's assessment of the cost, constructability, speed of construction, reliability and robustness of a number of alternatives during the concept design phase. A structural concept was selected with central core wall structure and columns supporting both gravity and lateral loads. This system also minimizes the structure's impact on leasable floor areas. The structural concepts for the two towers are generally similar – both towers utilize reinforced concrete walls around the core elements with reinforced and post-tensioned concrete floor framing. For both the office tower and the residential tower, providing the outriggers greatly relieves forces on the core wall, allows the core to be more slender and more efficient within the floor plate, and minimizes total material usage.

In recent days, there are increased terrorist attacks throughout the world and especially in Europe. Therefore, progressive collapse scenarios have become a very critical issue in tall building design. The outrigger and belt wall systems are very effective for progressive collapse calculations, helping the rest of structural elements after the critical elements are potentially lost due to blasting effects, or similar effects to blasting, as they provide a mechanism for large scale load transfer through the building.

The outrigger and belt wall systems of the residential tower are located in mechanical floors to adopt architectural and mechanical design. The first outrigger system is between L29 and L30 at +123.9 m and the second one is between L49 and L50 at +207.3 m (Figure 3). The top one is not full height of the storey in order to provide a leasable residential floor at the top of the tower. The top outrigger system is designed for not only lateral stiffness, but also has very critical role in progressive collapse scenarios.

Wind Tunnel Test Studies and TsNIISK (The V.A. Kucherenko Central Scientific Research Institute for Building Structures)

Rowan Williams Davies & Irwin Inc. (RWDI) was retained by Halvorson and Partners, P.C. to study the wind loading on the proposed Residential and Office Tower of the Renaissance Mixed-Use Development on Plot 17-18 in Moscow, Russia. RWDI provided both structural loads and a cladding wind load study of these two towers in October, 2014. A 1:400 scale model of the proposed development was constructed using the architectural drawings provided by Renaissance Construction. The model was instrumented with pressure taps and was tested in the presence of all surroundings within a full-scale radius of 460 m, in the RWDI's 2.4 m x 2.0 m boundary layer wind tunnel facility in Guelph, Ontario (Figure 4). The HFFB procedure was used to compute the global static wind loads acting on the tower while the HFPI procedure was used to compute the local wind pressure acting on the cladding of the building. The taps are located every five floors with 33 sensors for each floor, so that the total number of sensors is about 1,060 in the model.

的剩余结构部件）非常有效，后者可在整栋楼内实现一个大型的荷载转移机制。

住宅大楼的伸臂和环带墙系统位于设备层以适应建筑和机械设计。第一套伸臂系统位于+123.9米的L29与L30之间，第二套位于207.3米的L49与L50之间（图3）。为了在大楼顶层留出租赁空间，顶部伸臂系统未按大楼完整高度进行设计。顶部伸臂系统设计不仅考虑侧向刚度，在连续倒塌场景中也有着至关重要的作用。

风洞试验研究TsNISK（V.A.Kuncherenko中央建筑结构科学研究院）

Rowan Williams Davies& Irwin公司（RWDI）受Halvorson and Partners, P.C.委托，对位于俄罗斯莫斯科17-18号地块的Renaissance综合开发项目拟建的住宅和办公大楼的风荷载进行了研究。RWDI于2014年十月提供了针对两栋大楼的结构风荷载和幕墙风荷载研究。根据Renaissance Construction公司提供的建筑图纸，制作了拟建项目的1:400缩尺模型。该模型设置了测压孔，并在RWDI位于安大略圭尔夫的2.4m x 2.0 m边界层风洞设施中，包括了全尺度下460m半径内所有周边环境（图4）。采用了HFFB方法计算了作用于大楼的全局静态风荷载，采用了HFPI方法计算了建筑幕墙的局部风压。每五层设置一个测压孔，每层配置33个传感器，模型中总共配置约1060个传感器。

为了预测以重现期为函数的、作用于建筑的全尺度风压，风洞数据结合了当地风气候统计模型。风气候模型以在Mikhelson观测站、Vnukovo机场和Sheremetyevo机场测量的当地地面风数据为依据。

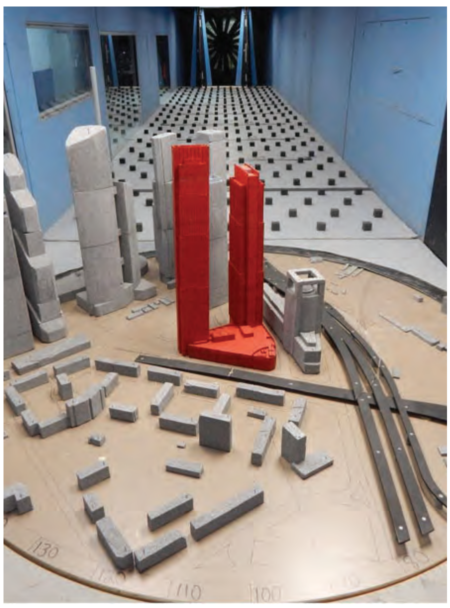

Figure 4. Wind tunnel study model (Source: RWDI)
图4. 风洞研究模型（来源：RWDI）

In order to predict the full-scale wind pressures acting on the building as a function of return period, the wind tunnel data were combined with a statistical model of the local wind climate. The wind climate model was based on the local surface wind measurements taken at Mikhelson Observatory, Vnukovo Airport, and Sheremetyevo Airport.

Figure 5 shows a comparison of the strength and directionality of the extra-tropical wind climates for Moscow. These plots are illustrative only and are not to be used directly for predictions of wind loads (Figure 5). The two plots show the directionality of common and extreme winds. It can be seen that for the extreme events, the Mikhelson Observatory shows the winds from the northwest and southeast are the strongest.

The design wind speed for Moscow, as specified in the Russian Wind Loading Code (SNIP) is a 5-year return period, 10 minute mean reference wind pressure of 0.23 kPa (19.4 m/s) at a height of 10 m in an open terrain. This is multiplied by a factor of 1.5, on pressure, as required for Moscow (Standards of Building Construction in Moscow 4.04-94) to obtain a 50-year return period, 10-minute mean wind speed of 23.8m/s. This wind speed is also shown in Figure 5, along with the estimated 1- and 5-year return period wind speeds. For the wind loading predictions in this study, the wind climate model was scaled to match the code wind speed at the 50-year return period.

The V.A. Kucherenko Central Scientific Research Institute for Building Structures, also referred to as "TSNIISK," is the main organization of Russian construction science. All large-scale construction projects in Russia require TSNIISK's recommendations and consulting. They have adopted RWDI wind tunnel test studies to Russian norms according to the requirements of SP 20.13330.2011. After their studies, TSNIISK has decided the worst case of wind loading with α = 250° angle for the office tower and α = 10° angle for the residential tower (Figure 6).

The structural design of all high rise buildings located in Moscow City has to be completed with TSNIISK recommendations of wind tunnel test studies. Applying the TSNIISK recommendations is also one of the main steps of design approval by Russian authorities. The expertise of tall buildings from Russian Government, always requests to see that all recommendations of TSNIISK have been applied on the wind load design of the structure. As a result, TSNIISK is the first step in tall building design in a non-seismic active

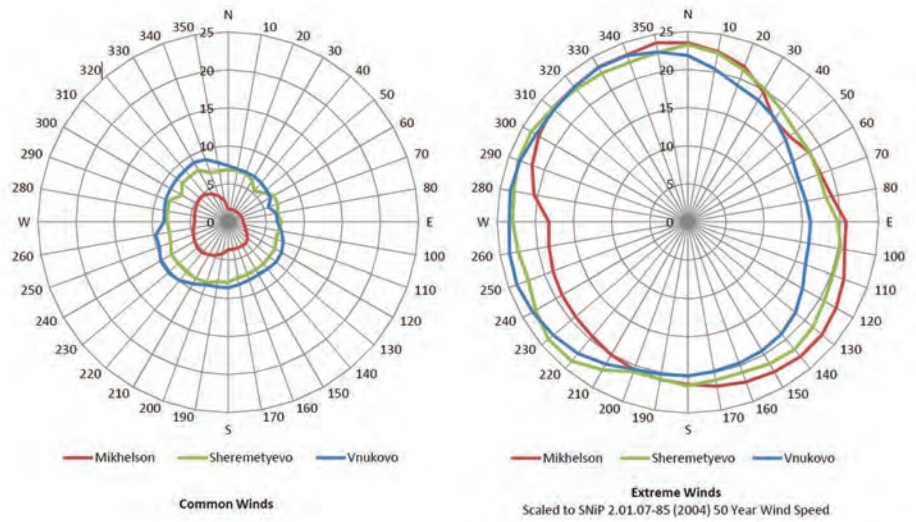

Figure 5. Directional distribution of local wind speeds (Source: RWDI)
图5. 局部风速的方向分布（来源：RWDI）

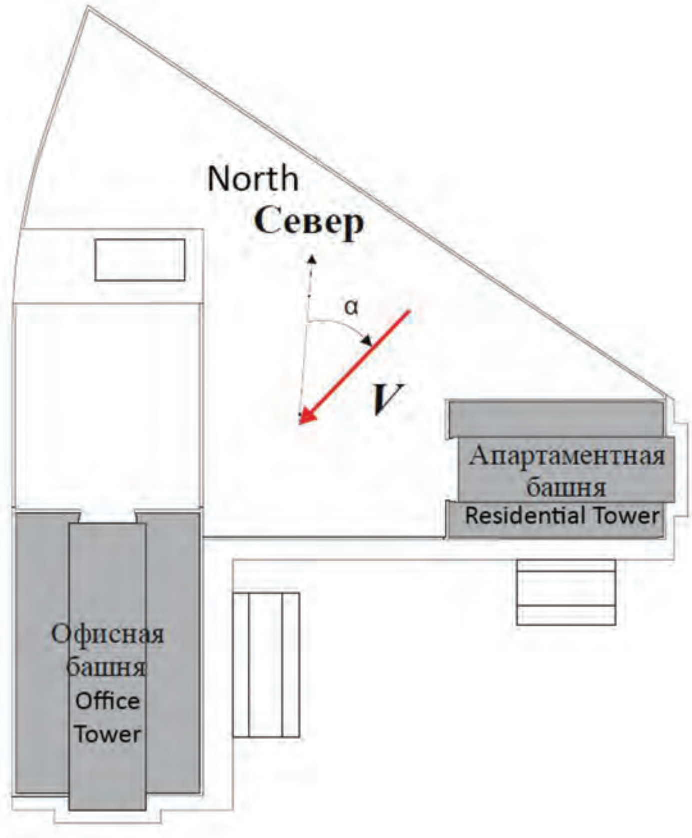

Figure 6. Wind loading case on the plan view (Source: TsNIISK)
图6. 风荷载平面图（来源：TsNIISK）

图5显示的是莫斯科热带外风气候强度和方向的对比 （图5）。这些图片仅作为说明材料，不得直接用于风荷载预测。两张图显示的是常遇风和极端风的风向。可以看出，在极端条件下，Mikhelson观测站处发现西北和东北方向的风力是最强的。

俄罗斯风荷载规范（SNIP）规定的莫斯科设计风速为5年重现期内，开阔场地10米高度的10分钟平均参考风压为0.23kPa（19.4m/s）。这一标准按莫斯科规定（莫斯科建筑施工标准4.04–94）对压力乘以1.5的系数即得到50年重现期10分钟平均风速为23.8m/s。这一风速数据在图5中与1年及5年重现期风速预计值一同列出。关于本研究中的风荷载预测，对风气候模型进行了调整以符合50年重现期的规范风速。

V.A. Kucherenko中央建筑结构科学研究院，亦称作“TSNIISK”，是俄罗斯主要的建筑科学机构。所有俄罗斯境内的大型施工项目都需要TSNIISK提供建议和咨询。他们根据SP20.1330.2011的规定，在俄罗斯的规范中采用了RWDI的风洞试验研究结果。在他们的研究之后，TSNIISK已经确认办公楼最不利风荷载为α = 250°角，住宅楼最不利风荷载为α = 10°角（图6）。

莫斯科城内这一高层建筑的结构设计必须得到TSNIISK出具的风洞试验研究建议

zone or a wind load dominant region such as "Moscow City" of Russian Federation.

The Structural Design Stages of Residential Tower with Consulting of "Halvorson and Partners"

Halvorson and Partners has completed the schematic design and structural optimizations in further stages of the project. Several options such as outrigger and belt walls, beam/column frame with wing walls, perimeter beam/column frame with lighter outriggers and wing walls systems were studied when deciding on the main structural system of the towers. After all of the studies were reviewed, the outrigger and belt wall option was decided to offer minimal cost, more constructability, higher speed of construction and more leasable area – a key architectural demand.

Analysis and calculations of the main lateral structural system have been done in ETABS structural analysis software by Halvorson and Partners. Russian structural norms have been used for loads, foundation design, reinforced concrete design, structural steel design and fire resistance while consulting with American building codes. The Special Technical Conditions document prepared by "TsNIISK" for the Plot 17-18 project was also considered in all steps of the structural design and limitations.

For the foundation system of the residential tower, the piles and raft foundation were proposed by Halvorson and Partners for sharing of load between the piles and the rock substrata. The diameter of the piles is 1500 mm with 18 m length; 135 piles were applied in the 2 000 sq. m raft foundation of the77-story residential tower.

The residential tower consists of four architectural zones: low-rise zone up to L29, mid-rise zone up to L49, high-rise up to L66 and top-rise zone up to the roof of the building. The large part of lateral stiffness is gained by vertical elements in the low-rise zone and the rest of lateral stiffness is provided by vertical elements in the mid-rise zone of the building. The structural design scheme uses smaller vertical elements in the high-rise and the top-rise zones of the building to provide less mass, reducing peak accelerations. Total peak accelerations are the main limitations in the lateral structural design because the slenderness ratio of the core is about 336/20 = 33.6:1, which is extremely slender. RWDI has provided peak acceleration limits according to ISO criteria, and TsNIISK has confirmed acceleration limitations based on SP 20.133330.2011.

The low-rise zone is the most important part of the structural system in lateral stiffness and peak acceleration limitations. By considering this issue, the vertical elements are heavier than the structural elements of the upper zones (Figure 7).

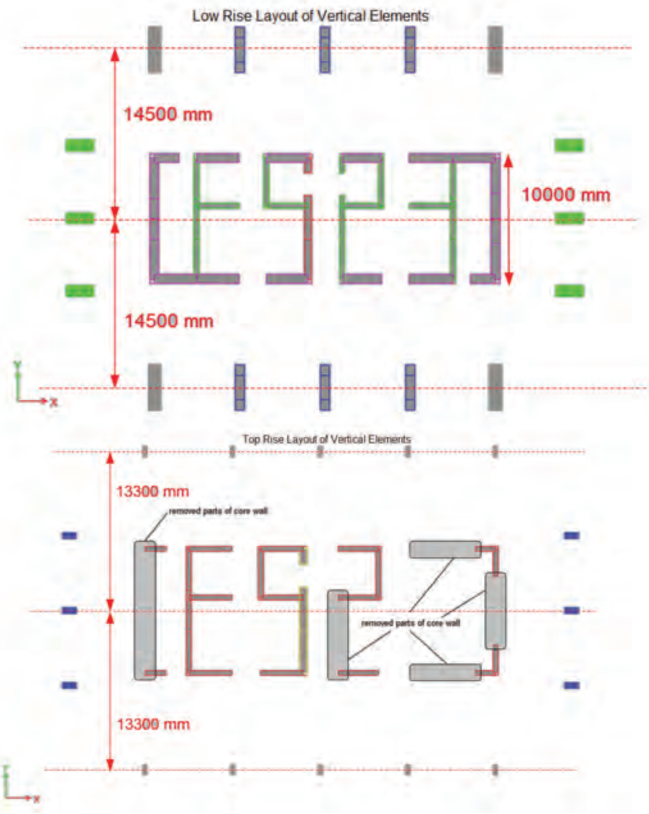

Figure 7. The layout of vertical elements in low-rise and top-rise zones (Source: Renaissance Construction)
图7. 低层区和顶层区垂直结构分布（来源：Renaissance Construction）

才能完成。申请TSNIISK的建议也是俄罗斯权威部门设计审核的主要步骤之一。俄罗斯政府的高层建筑专家通常会要求TSNIISK关于结构风荷载设计的所有建议均已执行。因此，TSNIISK是非地震活跃区或类似于俄罗斯联邦“莫斯科城”这类风荷载控制区域的高层建筑设计的第一步。

“Halvorson and Partners”顾问的住宅大楼结构设计阶段

Halvorson and Partners已经完成了方案设计和该项目后续阶段中的结构优化。对于伸臂和环带墙、带翼墙的梁/柱框架、带有较轻型伸臂和翼墙的梁/柱周边框架等几个方案的研究均已完成，并确定了大楼的主要结构体系。在完成所有研究的审核后，选定伸臂和环带墙，实现了最小施工成本、更强施工性、更快施工速度和更大租赁面积——满足一项关键的建筑需求。

Halvorson and Partners采用ETABS结构分析软件完成了所有主要横向结构体系的分析和计算。荷载、基础设计、钢筋混凝土设计、钢结构设计和防火设计遵循俄罗斯结构规范，并参考了美国建筑规范。所有结构设计和限制条件中同样考虑了“TsNIISk”为17–18号地块项目编写的特殊技术条件文件。

住宅大楼的基础系统方面，Halvorson and Partners考虑到桩与岩石地层之间的荷载分担而选定了桩筏基础结构。桩直径1500毫米，长18米；77层住宅大楼的2000平方米地基内共设置135根桩。

住宅大楼包括四个建筑分区：L29以下的低层区，至L49的中层区，至L66的高层区和包括建筑屋顶在内的顶层区。侧向刚度主要通过低层区的竖向构件实现，剩余侧向刚度则由中层区的竖向构件实现。结构方案中在高层区和顶层区采用了较小的竖向构件，以减少质量、降低最大加速度。最大加速度峰值即为抗侧力结构设计的主要限制条件，因为核心筒部分的长细比为336/20=33.6:1，非常细长。RWDI提供了ISO标准的最大加速度限值，TsNIISK根据SP20.133330.2011确定了加速度限值。

低层区是结构体系在横向刚度和最大加速度限值方面最重要的部分。考虑到这一问题，竖向构件的重量大于上层结构的结构部件（图7）。

住宅大楼核心筒墙体从地基至建筑地面标高处厚1100毫米。住宅大楼零标高以上至第一道伸臂所在楼层——L30核心筒墙体的厚度为750毫米，至第二套伸臂所在楼层——L50的核心筒墙体厚度为600毫米，至构造屋顶的厚度为400毫米。住宅大楼边柱至L29低层区的尺寸为

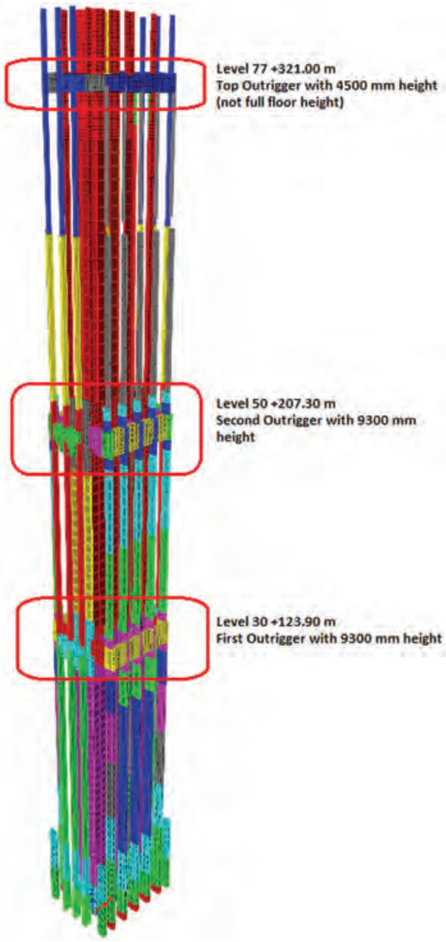

Figure 8. 3d view of vertical elements from ETABS analysis model of residential tower (Source: Renaissance Construction)
图8. 住宅大厦ETABS分析模型垂直结构3D视图（来源：Renaissance Construction）

The thickness of the core wall of the residential tower starts with 1100 mm from the foundation to the ground level of the building. Above the zero level, the core walls of the residential tower are 750 mm thick up to the 1st outrigger level – L30, 600 mm thick up to the 2nd outrigger level – L50 and 400 mm thick up to the roof level of the structure. The dimensions of the perimeter columns of the residential tower are 800 mm x 3900 mm in the low-rise up to L29 and 600 mm x 3000 mm in the mid-rise up to L49. The dimensions decrease down to 400 mm x 900 mm in the top-rise to provide more leasable area in the upper floors.

The outrigger and belt wall systems are located at Level 30 (+123.9 m) and Level 50 (+207.3 m) (Figure 8). The top outrigger and belt walls are designed for progressive collapse scenarios rather than lateral stiffness of the structure. The effectiveness of outrigger and belt walls systems can be seen in the displacement diagram of story diaphragms (Figure 9).

Structural Design Adaption to Russian Authorities and Progressive Collapse Provisions

For tall building design in Moscow City, all foundation and substructure design is completed and approved by one of Russia's government organizations – "NIIOSP." The Gersevanov Research Institute of Bases and Underground Structures (NIIOSP) is a world-wide known Institute specializing in the field of foundations and substructures, which is dealing with the entire range of geotechnical matters inclusive of surveying activities, scientific research, design and construction of foundations and substructures for buildings of various functions without limitation to the severe soil environment and climate-relevant conditions. NIIOSP has completed all pile calculations, foundation settlements and slurry wall interaction with the structure in PLAXIS analysis software (Figure 10). NIIOSP has also provided all documentation to Renaissance Construction during the expertise submission of Russian government authorities.

800 mm x 3900 mm，至L49的中层区为600 mm x 3000 mm。为在上层楼层实现更大的租赁面积，顶层区的尺寸降至400 mm x 900 mm。

伸臂和环带墙系统位于Level 30 –(+123.9 m)和Level 50 – (+207.3 m)，（图8）。顶部伸臂和环带墙采用了针对连续倒塌，而不是结构侧向刚度的设计方案。伸臂和环带墙的效果见楼层位移图（图9）。

适应俄罗斯官方和连续倒塌规定的结构设计

莫斯科城内的高层建筑设计，所有基础和地下结构设计需由俄罗斯政府机构——“NIIOSP”完成和审核。Gersevanov基础和地下结构研究院（NIIOSP）是俄罗斯最大，也是世界知名的基础和地下结构领域专业组织，从事多种功能的建筑基础及地下结构的勘测活动、科学研究、设计和施工等各类岩土问题，不限于恶劣土壤环境和气候相关条件。NIIOSP已经在PLAXIS分析软件中完成了全部桩计算、地基沉降及地下连续墙与结构相互作用等

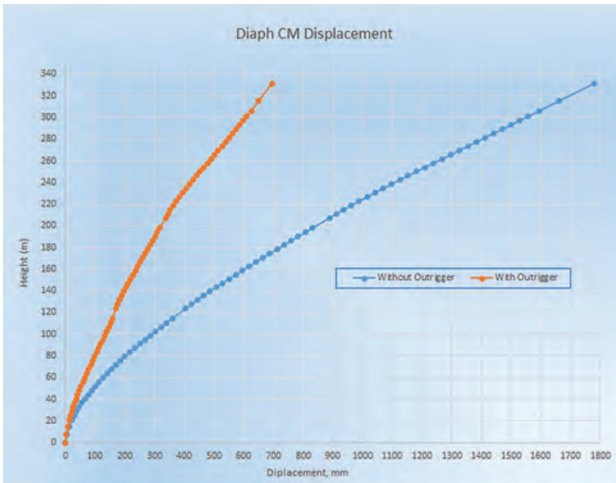

Figure 9. The displacement diagram of story diaphragms in wind loading (Source: Renaissance Construction)
图9. 风荷载模拟示意图中的位移示意图（来源：Renaissance Construction）

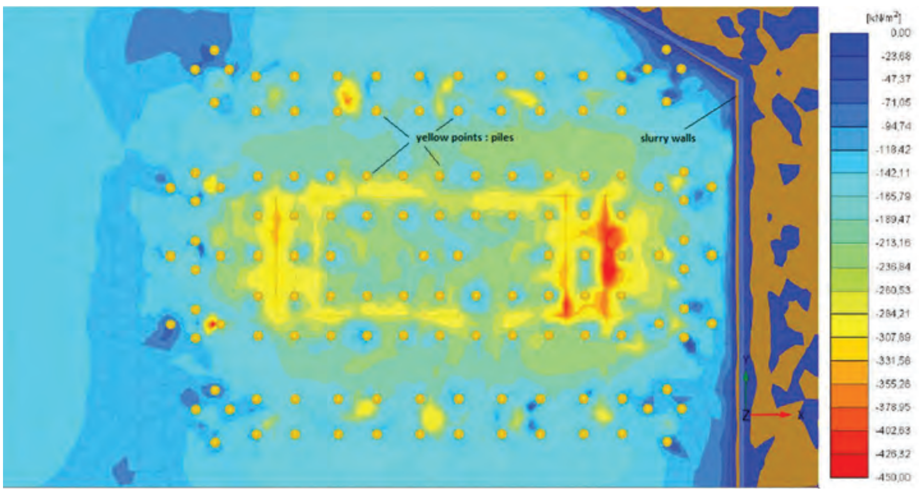

Figure 10. Soil Stress Diagram with interaction of slurry wall and structure (Source: NIIOSP)
图10. 土壤应力示意图，含地下连续壁与构造的互相作用（来源：NIIOSP）

All vertical elements of the tower have 240 minutes' fire resistance (REI240) in accordance with the fire concept document provided by OPB (Russian Fire Consultant). OPB has prepared the technical specification for the fire resistance of all structural and non-structural elements for application in design and construction. These technical specifications are also based on SP and GOST Russian building codes. Also, all controllers in construction site request mesh reinforcement in concrete cover to provide REI240 fire resistance in the vertical elements of the towers.

After finishing the three-dimensional model in ETABS in consultation with Halvorson and Partners, the structures were modeled in another analysis software that has verification and certification in Russian Federation. The first structural analysis model was completed in Ing(+) MicroFE software by the structural design department of Renaissance Construction in Saint Petersburg, Russia. This model includes two towers and the podium structure together with piles in one model (Figure 11). Ing (+) modelling also calculates the peak accelerations according to Russian norms automatically by considering the dynamic pulsation part of wind loads.

The calculations of progressive collapse can also be completed by this software automatically based on the Special Technical Conditions document prepared by "TsNIISK" for the Plot 17-18 project. The scenarios of progressive collapse include removal of one perimeter column, some part of the core wall and 100 sq.m slab area with loss of one tendon in the post-tensioned slab. After removing structural elements, all design loads were taken into account without any load factoring coefficients, and the resistance of structural materials such as concrete and reinforcement are taken as tensile strength for reinforcement and characteristic strength of the concrete in the ultimate design of the structure. The detailing of reinforcement is also prepared by considering progressive provisions for construction drawings. As an example of reinforcement detailing, the main bottom reinforcement of the beams is provided continuously between the perimeter columns to keep the beam above the removed column safe. The outrigger and belt wall systems are very effective to keep the rest of the structural elements safe after removing elements in progressive collapse scenarios (Figure 12). All structural studies must be approved by a Russian consultant for the Moscow City region. Dr. Travush is well-known in dealing with tall building design in Russia. Dr. Travush and his team have completed

（图10）。NIIOSP另外还在俄罗斯政府主管部门的专家意见提交期间向Renaissance Construction公司提供了所有文件。

根据OPB（俄罗斯消防顾问）提供的消防概念文件，大楼的竖向构件全部达到240分钟防火性能（REI240）。OPB编写用于设计和施工的、针对所有结构的和非结构的防火技术规范。这些规范同样以SP和GOST俄罗斯建筑规范为依据。此外，为实现大楼内所有竖向构件REI240的防火性能，所有施工场地的管理人员均要求设置带混凝土保护层的网状钢筋。

Halvorson and Partners在ETABS中完成三维模型后，在另一个经过俄罗斯联邦验证和认证的分析软件中建立了结构模型。第一个结构分析模型由Renaissance Construction公司位于俄罗斯圣彼得堡的结构设计部门在Ing(+) MicroFE软件中完成。这个模型包含两座大楼、裙楼构造以及桩，如图11的模型所示（图11）。Ing (+) modelling在考虑风荷载脉动部分的情况下，根据俄罗斯的规范自动计算了最大加速度。

根据“TsNIISK”针对17–18号地块项目编写的特种技术条件，连续倒塌的计算同样由这个软件自动完成。连续倒塌工况包含移除单个周边立柱，移除核心筒墙体部分以及后张楼板单个钢筋束缺失的100平米楼板区域。移除结构构件后，计算所有设计荷载，但荷载系数不计；在结构极限状态设计中，混凝土和钢筋等结构材料的强度取钢筋抗拉强度和混凝土的特征强度。施工图中的钢筋大样同样考虑了连续倒塌规范。举钢筋大样为例，边柱之间的梁底主筋拉通保证移除柱上梁的安全。伸臂和环带墙体系有效地保证了连续

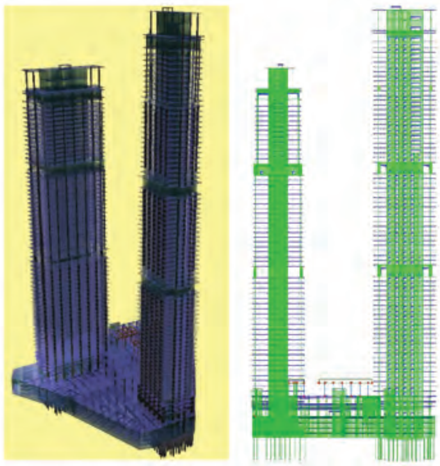

Figure 11. The three dimensional model in Ing(+) MicroFE software (Source: Renaissance Construction)
图11. Ing(+) MicroFE软件中的三维模型（来源：Renaissance Construction）

倒塌工况下构件移除后剩余结构构件的安全（图12）。所有结构研究必须经过莫斯科城区域俄罗斯顾问的批准。Travush博士是俄罗斯高层建筑设计领域的知名人士。Travush博士和他的团队在SCAD中完成了所有结构分析，并根据Renaissance Construction公司在Ing(+)得到的模型结果编写了校核报告。

结论

本研究证实了伸臂和环带墙在非地震活跃区或风荷载控制区域内高层建筑中的应用可以增加刚度，并使得结构形式在侧向荷载中更加高效。77层的三维模型中，通过在构造第29层设置第一道伸臂、在第49层设置第二道伸臂最大可以减少70%的位移。另一方面，混凝土浇筑一个标准层的

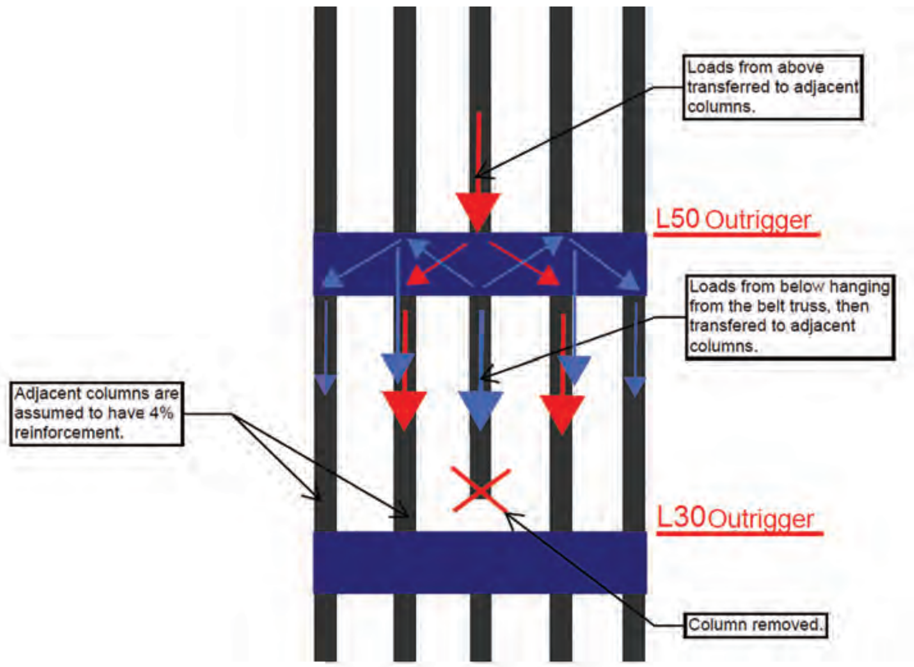

Figure 12. Progressive Collapse Case Study (Source: Halvorson and Partners)
图12. 连续坍塌案例研究（来源：Halvorson and Partners）

all structural analysis in SCAD and prepared a double check report to fit the results of the model prepared in Ing(+) software by Renaissance Construction.

Conclusion

This study demonstrates that the use of the outrigger and belt wall system for tall buildings in a non-seismic zone or a wind load dominant region increases the stiffness and makes the structural form efficient under lateral loads. For the three dimensional 77–story model, 70% maximum displacement reduction can be achieved by providing the first outrigger at the 29th level and the second outrigger at the 49th level of the structure. On the other hand, the concrete pouring cycle is normally 5 days for one typical floor but the construction process is slowing down for 60 days because of the floors including outrigger and belt walls in Plot 17-18 project.

In addition to providing lateral stiffness, the outrigger and belt walls provide an alternate load path for the main structural elements in progressive collapse scenarios. The belt walls are especially effective as they are able to support exterior columns if one is removed in a progressive collapse scenario.

There are many steps related to the Russian authorization for tall building design in Moscow City, Russia. For foundation and substructure design, all design stages and calculations are provided and controlled by NIIOSP. The results of the wind tunnel test cannot be used in design directly because all output of the test should be evaluated and confirmed by TsNIISK. They also prepare the document of the special technical conditions for all tall buildings in Russia. And the approval of full structural design of tall buildings in Moscow City by the expertise of Russian Government can only be possible with a well-known Russian consultant such as Dr. Travush for the Plot 17-18 project.

周期通常为5天，但17–18号地块项目的施工流程由于包含伸臂和环带墙的楼层而延长到了60天。

除了提供侧向刚度，伸臂和环带墙还提供了一个连续坍塌工况下的主体结构构件备用的荷载传递路径。如果连续坍塌中出现外部柱缺失，环带墙由于可以支撑外部柱，效果尤其好。

俄罗斯莫斯科城内的高层建筑设计相关的俄罗斯官方步骤很多。基础和地下结构设计中，所有设计阶段和计算均由NIIOSP提供和控制。因为风洞试验结果需经过TsNIISK评估和确认，风洞试验的结果不得直接用于设计。他们也为俄罗斯内的所有高层建筑编写特殊技术条件。17–18号地块项目中，由俄罗斯政府专家进行的莫斯科城内高层建筑完整结构设计审核全部由Travush博士等知名俄罗斯顾问完成。

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