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Wuhan Greenland Center Main Tower: Seamlessly Integrating Structure and Architecture

武汉绿地中心主塔：结构设计与建筑设计的完美结合

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Abstract

Wuhan Greenland Center Main Tower is a 125-story, 600+ meter mega-tower in China. The tower structural system has been developed to harmonize with the architecture as an integrated whole to maximize efficiency and enhance safety. The distinctive floor "slots" help reduce the vortex shedding effect. Slot locations were coordinated to avoid causing structural discontinuities. Above the roof, steel trussed tripod legs rise from tower plan wing tips to seamlessly complete the building form with a dramatic crown. Design challenges include evaluating building performance under seismic events through PBD and performing Progressive Collapse Analyses to evaluate structural redundancy. Parametric modeling tools were used to reduce cladding costs by maximizing the use of field-warped, flat-glazed panels rather than costly curved glass panels.

Keywords: PBD, Performance Based Design, Parametric Modeling, Outrigger, Belt Truss

摘要

武汉绿地中心主楼共125层，总高度600米以上。主楼的结构设计追求建筑和结构的完美结合、结构效率的最大化以及安全性的提升。 独特的“风槽”的设计有效降低了风旋涡脱落效应。在塔楼顶部，三脚钢桁架沿楼面边缘向上呈汇聚式延伸，在顶部实现无缝对接，形成了一个造型别致的塔冠结构。 如何通过基于性能的设计评估建筑抗震性能、如何通过抗连续倒塌分析来评估结构冗余度是本项目结构设计的主要挑战。通过对参数化模型的运用，（建筑幕墙设计者）对平板玻璃现场冷弯的使用达到了最大化，尽可能地避免采用造价昂贵的曲面玻璃，从而减小外幕墙的建造成本。

关键词：PBD、基于性能的设计、参数模型、桁架、带状桁架

Introduction

The wave of Mega-Tall building construction in China started with cities along the east coast and is now moving inland. Located in Wuhan, an inland city adjacent to the Yangtze River, the Wuhan Greenland Center Main Tower is a 125-story, 600+ meter mega-tower on track to be the 7th tallest building in the world, a mixed-use skyscraper with offices up through the 69th floor, apartments at the 70th to 89th floors, a hotel from the 91st floor to the top floor and a five (5)-story deep basement housing the mechanical spaces plus parking. Located at the tower top, a unique 61m-tall tower crown and a 35m-tall tower dome highlight the tower's distinctive personality. (see Figure 1).

The major structural system of Wuhan Greenland Center Main Tower consisting of robust composite walls, giant slightly sloping composite SRC columns and curved belt trusses, is adopted to resist the lateral loads (wind or seismic) effectively. The locations and geometry of structural components have been carefully optimized to not only provide enough strengths and stiffness but integrate with the architecture seamlessly.

引言

中国对超高层建筑的追求浪潮始于东面沿岸城市，并逐渐向内地发展。武汉绿地中心主塔将坐落于毗邻长江的内陆城市武汉。塔楼共125层，总高度达600米以上，是一个多功用的超高层建筑，建成后将成为世界第七高楼。主楼底层到69楼用于办公室、70至89层为公寓、91层到顶楼为酒店、另有5层地下室作停车和容纳机电设备之功用。一个高61米的独特塔冠和高35米的穹拱位于塔楼顶部，凸显塔楼独特的建筑风格 （参见图1）。

为了有效地承担侧向力(风荷载和地震荷载)，武汉绿地中心主楼的主要结构体系包括强大的组合剪力墙、微倾的巨型SRC组合柱和曲线型的环带桁架。结构构件的位置和几何形状都经过了精心地优化以满足强度和刚度的要求， 同时与建筑设计达到完美的结合。

减少塔群风荷载

如同其它的超高层建筑，侧向荷载（含风荷载和地震荷载）在武汉绿地中心主楼的结构设计中起至关重要的作用。根据中国《建筑抗震规范》(GB50011-2010)，武汉位于抗震设防烈度6度区，设计基本地震

Tower Massing to Reduce the Wind Load

Like other super tall buildings, the lateral loads, wind and seismic, play the most important role in the structural design of Wuhan Greenland Center Main Tower. According to China "Code for Seismic Design of Buildings " (GB 50011-2010), Wuhan is located in the Seismic Fortification Zone #6, with design ground acceleration specified as 0.05g under moderate earthquake, which is defined as a earthquake with "10% Exceedance Probability in 50-year" or an earthquake with 475-year return period. RWDI performed wind tunnel tests to determine the structural wind loads for tower strength and stiffness design. For the strength designs of the tower structure, the 100-year wind load and seismic load under frequent earthquake, which is defined as "63% Exceedance Probability in 50-year" or an earthquake with 50-year return period, shall be combined with gravity load. Unlike most building codes , in which the seismic load case never combines with the wind load case, the frequent earthquake load for this tower needs to be combined with 100-year wind load as per "Technical Specification for Concrete Structures of Tall Building "(JGJ 3-2010). The Table 1 lists the 100-year wind load and code-base frequent earthquake load. From Table 1, the base shear and overturning moment under a 100-year wind load is much larger than the values under the frequent earthquake load.

Architectural massing of the Wuhan Greenland Center Main Tower was developed to optimize both the structural and programmatic performance of the building. Four primary design solutions were implemented to deal with both of these issues: a tapered profile, a dome top, triangular floor plans with rounded soft corners and the vent slots (see Figure 2). Since all of these elements help to minimize the negative effects of wind acting on Supertall buildings, they allowed the quantity of structural materials to be reduced and significantly decreased the construction cost.

From a structural perspective, every Supertall building is a cantilever beam in vertical direction, with lateral loads (wind or seismic) and construction costs increasing dramatically as the building height increases. A tapered profile has been proved effective in reducing overall tower lateral loads and has been adopted for many Supertall buildings around the world. Architecturally, the tapering shape also helps to resolve different floor plate size requirements for varied program elements without using a traditional step profile for the building massing.

Programmatically, Supertall buildings are usually developed as mixed-use projects. Multiple entrances at Ground Level distinguish each type of user and control access. Floor plates typically reduce in size and lease span as the building rises into the sky. The Wuhan Greenland Center Main Tower provides spaces for three distinctive functions: office, apartment and hotel. While some mixed-use towers separate users by levels, the triangular floor plan of this building allows for the tenants or visitors to have separate entrances all at Ground Level. Soft corners and a round tower top not only help create unique public

Figure 1. Wuhan Greenland Center Main Tower Rendering (Source: ASGG)
图1. 武汉绿地中心主塔效果图（来源：ASGG）

加速度值为0.05g，其中设计基本地震定义为50年超越概率为10%的地震或回归期为475年的地震。RWDI进行风洞试验以确定用于塔楼结构强度设计和刚度设计的风荷载。对于塔楼结构构件的强度设计，100年风荷载和常遇地震荷载需要与重力荷载组合，其中常遇地震被定义为50年超越概率为63%的地震或回归期为50年的地震。在海外的设计规范中，地震荷载不要求与风荷载进行组合。与其它海外的设计规范不同，《高层建筑混凝土结构技术规程》(JGJ 3-2010)要求地震荷载与100年风荷载进行组合。表1列出了100年风荷载和根据规范计算的常遇地震荷载数值并进行了比较。根据表1，100年风荷载下的基底剪力和倾覆力矩均远大于常遇地震下的数值。

为了获得最佳的建筑功能和结构性能，武汉中心主楼的建筑体量在设计过程中进行了不断地优化，主要采取了以下四项措施：（沿竖向）逐渐缩进的体型、穹拱式的塔冠、带圆角的三角形楼层平面和散落在不同高度的风槽（参见图2）。由于这些措施能够有效减小作用于超高层建筑的不利风荷载效应，所以结构材料的用量可以得到节省，建造成本也会大幅降低。

从结构的角度上看，每一幢超高层建筑均可视为沿竖向的悬臂梁。侧向荷载（风或地震）以及建造成本均会随建筑高度的增加而急剧增加。逐渐缩进的建筑体型已经被证明可以有效地减小作用于塔楼的整体侧向荷载，故被世界上许多超高层建筑所采用。从建筑的角度上看，逐渐缩进的建筑体型有利于解决不同建筑体量对楼层面积的不同需求，避免传统的呈阶梯状的楼层平面突变。

超高层建筑项目通常具备多种建筑功能。在首层要对各类用户及其通行加以区分。通常情况下，沿建筑高度方向楼层面积和出租

Load Case	100-Year Wind 100年风荷载		Frequent Earthquake Load 常遇地震下荷载		Wind / Seismic (风荷载)/(地震荷载)比值	
Direction 方向	Base Shear 总剪力V (kN)	Overturning Moment (OTM) 总倾覆力矩 (kN-m)	Base Shear :V 总剪力V (kN)	Overturning Moment (OTM) 总倾覆力矩 (kN-m)	Shear 剪力比	Overturning Moment (OTM) 倾覆力矩比
X-direction X- 方向	64,956	21,645,051	44,729	12,123,867	1.45	1.79
Y-direction Y - 方向	62,183	21,528,803	44,775	12,147,109	1.39	1.77

Table 1. Lateral Load Comparison. Based on wind load data from RWDI, February 2012.
表1. 侧向力比较. 风荷载数值基于RWDI于2012年2月提供的风荷载

Figure 2. Architectural Building Massing Concept (Source: ASGG)
图2. 建筑体量概念图（来源：ASGG）

spaces that attract visitors to the building, but help reduce the tower wind load. To further reduce the wind loads on the tower, openings have been provided though the building in locations optimized through wind tunnel testing. Three massing options, as shown in Figure 3, were tested in a wind tunnel by RWDI. All three options had tapered profiles. Option 1 featured a solid surface and served as the baseline option. Option 2 featured an opening between the crown and dome plus slotted floors at multiple elevations. Option 3 featured wing walls and vertical slots. The overall tower wind loads for three options from the wind tunnel test are listed in Table 2.

From Table 2, Option 2 reduced the overall wind load by 15% and 6.6% along "X" and "Y" respectively, while Option 3 did not show a significant wind load reduction. The wind tunnel consultant considered that, the opening at the tower top made a great contribution to wind load reduction. Architecturally, an opening at the tower top would separate the whole tower top into an upper crown and a lower dome. So, in addition to reducing the wind load at tower top, the opening at tower top would give the tower a unique architectural feature. Therefore, it was incorporated in the final design. In addition, a building maintenance unit or window cleaning machine is concealed in the crown to clean the dome surface.

Tower Lateral System

The structural system of Greenland Center Main Tower has been carefully developed to harmonize with the architecture as an integrated whole, to maximize efficiency and to enhance safety. The central "Y" plan concrete core extends 31.3m in plan from the tower center to its far ends at lower zones, and sets back twice at Levels 70 and 91. The core was organized to provide multiple benefits across

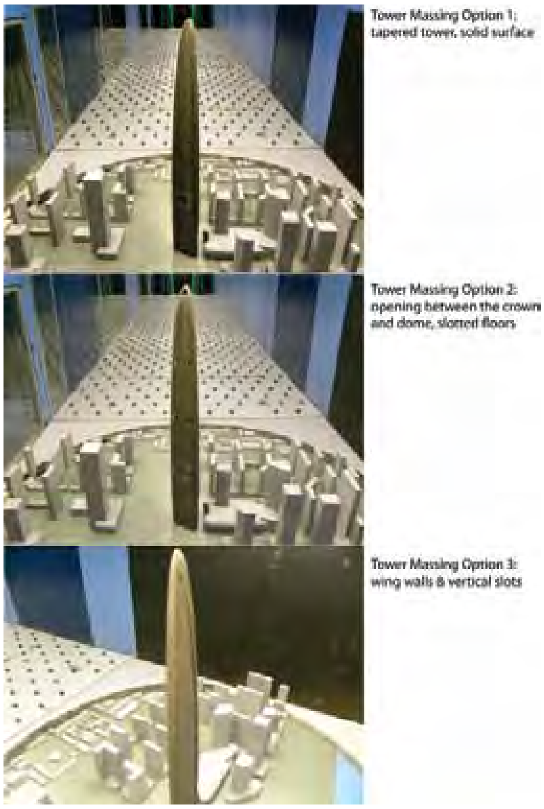

Figure 3. Tower Massing Options (Source: RWDI)
图3. 不同的塔楼（建筑）体量方案（来源：RWDI）

楼面的跨度大小均逐渐减小。武汉绿地中心塔楼拥有三个功能分区：办公、公寓和酒店。虽然一些超高层建筑通过楼层位置来区分租户和访客，本项目独特的三角形平面允许租户和访客在首层拥有其独立的入口。采用圆弧曲线加以修饰的（三角形平面的）角部以及位于塔顶的圆形拱顶创造出独特的功用空间，它不仅吸引更多的游客，更有助于减小风荷载。为了进一步减小塔楼风荷载，以风洞试验结果为指导，在塔楼某些部分开洞。（风洞试验顾问）RWDI在风洞中测试了三个建筑体量布置方案（参见图3）。三个方案均拥有逐渐收缩的体型。方案1在建筑立面没有开洞。以方案1作为方案比较的基础，方案2的特点是塔冠和穹拱之间存在空隙，并在建筑立面上存在局部开洞。方案3的特点是建筑立面上存在翼墙和竖向开槽。 表2列出了由风洞试验获得的（三种方案下的）塔楼整体风荷载。

由表2可以看出，（与方案1相比）方案2中“X”向和“Y”向的风荷载分别减小15%和6.6%，而方案3中的风荷载没有明显的减小。从建筑上看，（方案2中）塔楼顶部处的开口把塔顶分成上部塔冠和下部穹拱两个部分，此举不仅减小了风荷载，而且赋予塔楼一个独特的建筑特征。另外，用于清洗穹拱的塔冠围护设备或擦窗机也可以隐藏于塔冠之中。最终方案2被采用。

Option 方案	Wind Load : 'X' Direction 'X' 方向风荷载			Wind Load : 'Y' Direction 'Y' 方向风荷载		
	Force 水平力 (kN)	Overturning Moment (OTM) 倾覆弯矩 (kN-m)	Relative Value 相对值	Force 水平力 (kN)	Overturning Moment (OTM) 倾覆弯矩 (kN-m)	Relative Value 相对值
1	8.24E+04	2.62E+07	100.00%	6.95E+04	2.32E+07	100.00%
2	7.01E+04	2.32E+07	85.10%	6.49E+04	2.17E+07	93.40%
3	7.58E+04	2.52E+07	92.00%	7.06E+04	2.37E+07	101.60%

Table 1. Tower Wind Load Comparison for Different Massing Options. Based on wind load data from RWDI, February 2011.
表1. 三种建筑竖向布置方案下的塔楼风荷载比较. 基于2011年2月RWDI风洞试验结果汇总

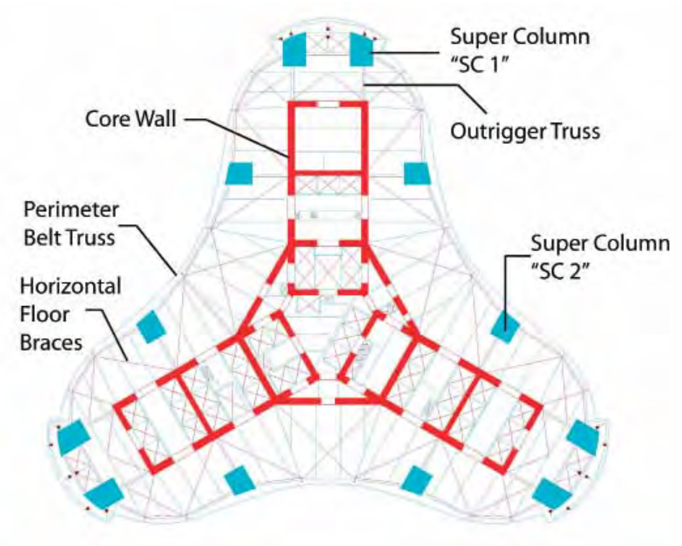

Figure 4. Wuhan Greenland Center Main Tower Structural System (Source: Thornton Tomasetti)
图4. 武汉绿地中心主楼结构系统（来源：宋腾添玛沙帝 Thornton Tomasetti）

different disciplines: separating office, hotel and apartment operational functions, providing significant structural stiffness and strength for the tower to resist lateral and gravity loads, and accommodating the mechanical system floor and riser space requirements.

To maximize the structural stiffness given by a "Y" shape plan, a pair of massive super columns (SC1) is located at the tip of each tower wing. Two additional super columns (SC2) are spaced at approximately one-third points along each face and serve to reduce the spans of perimeter structural members. The super columns are Steel Reinforced Concrete (SRC) columns, with welded built-up steel column shapes embedded within large concrete columns up to 3.3m X 4.6m in plan dimension. Steel outrigger trusses two and three stories tall connect the super columns to the core walls at Levels 36 to 39, 67 to 70 and 101 to 103, in addition to cap trusses at Levels 121 to 123. Ten sets of steel belt trusses following the building perimeter are distributed along the tower height. Distributed almost uniformly along the tower to maximize structural efficiency, all outrigger trusses and belt trusses are located either at mechanical floors or refuge floors to avoid impact on the leasable floors. Segmented belt trusses curved in plan tend to twist under vertical loads. To restrain the twist of the segmented belt trusses a horizontal floor bracing system, consisting of double angles and steel floor beams, is provided at the top and bottom chord levels of each belt truss. The tower structural system is shown in Figure 4.

Optimization of Slotted Floor Location

Wuhan Greenland Center Main Tower's unique architectural shape evolved from a classic tapered tower with "Y" plan shape into an elegant curvilinear figure. By locally omitting portions of floors and perimeter framing at different elevations, "slots" are created in the building envelope to provide a distinctive architectural personality while reducing wind loads on the structure from vortex shedding. (see Figure 5).

Slot locations were carefully coordinated to avoid causing structural discontinuities. Originally, the slots are located at mechanical levels. A Vierendeel truss system would seem to be a natural structural solution at slotted floors, since the lack of diagonals would allow the most air flow. However, Vierendeel truss systems have two major drawbacks. First, structural efficiency is much less than for traditional truss systems

塔楼抗侧力体系

经过（设计者）精心地优化，绿地中心主楼的结构体系与建筑融为一体，以便最大限度地提高结构效率和增强安全性。平面上呈“Y”型的混凝土核心筒（从其底区）从塔楼中心点到其最外边的距离达31.3米。（这种对）核心筒的布置不仅有利于区分办公、旅馆和公寓的功能，也为塔楼结构提供巨大的结构刚度和承载力以承担侧向力和重力荷载，同时增大了容纳机电设备的空间和管井空间。

为了最大限度地发挥“Y”形平面的结构刚度，在（Y形平面的）各肢最外端位置分别布置一对巨柱（SC1）。为了减小外周结构构件的跨度，在塔楼周围每边约在每个Y形平面的三分之一的位置 各布置2根巨柱（SC2）。巨柱的最大截面尺寸达3.3 m×4.6m左右并加入由钢板焊接而成的组合钢柱。两至三层高的钢外伸臂桁架把巨柱与核心筒相连。外伸臂桁架布置在第36层至39层、第67层至70层以及第101层至103层之间，另外在第121层至123层之间布置帽桁架。在塔楼高度方向沿建筑周边布置十道钢环带桁架。外伸臂桁架和环带桁架沿建筑高度方向接近均匀分布以最大限度地发挥结构效率，同时所有桁架均布置于机电层或避难层以避免对出租面积的影响。平面上呈折线形的（环带）桁架在重力荷载作用下有扭转的倾向，故在（环带）桁架上下弦杆平面布置水平支撑体系以约束桁架的受扭。楼面水平支撑体系由楼面钢梁和双角钢斜撑组成。塔楼的结构体系如图4所示。

风槽楼层位置的优化

武汉绿地中心主楼的建筑外形在经典的“Y”形平面基础上逐步演化，最终成为具有优雅曲线的独特外形。在不同的建筑标高位置，通过去掉局部楼面及位于建筑外周的部分结构构件形成建筑立面上的(开口)“风槽”。这些“风槽”既赋予建筑物与众不同的个性，又减小了由风旋涡脱落引起的结构风荷载（参见图5）。

“风槽”的位置经过了精心地选择以避免结构的不连续性。在设计初期，这些风槽布置于机电层。由于空腹桁架没有斜腹杆，便于更多气流通过，所以位于风槽层（即机电层）的环带桁架采用空腹桁架的形式似乎是合理的选择。然而空腹桁架有两个主要缺点。首先，空腹桁架的结构效率远不如带斜腹杆的传统桁架体系。其次，环带桁架作为转换桁架支承位于相邻两个环带桁架层

Figure 5. Slotted Floor: Exterior View (Source: Thornton Tomasetti)
图5. 风槽楼层—外视图（来源：宋腾添玛沙帝 Thornton Tomasetti）

with diagonal members. Second, as they serve as transfer trusses supporting perimeter columns in one zone bounded by adjacent belt truss levels, the trusses are critical to prevent progressive collapse by carrying additional load from columns acting as hangers in the event of failure of a perimeter column below (see Figure 6). After discussions between the architect and structural engineer, the slotted floors were located below the belt truss floors; and the continuous perimeter belt trusses are of conventional design, reducing construction costs compared to Vierendeels. Secondary steel columns are also interrupted by the wind slots. In the progressive collapse analysis, floor beams can span loads normally carried by those columns if the discontinuous perimeter steel column below the floor slots fails. Those loads would then be redirected to adjacent columns.

Vortex shedding is defined as an unsteady flow that occurs at building corners due to the formation and detachment of alternating low –pressure vortices or wind whirlpools on the leeward side of the edge of an object. Cyclic formation and shedding of vortices applies cyclic wind loads to a building that can generate large crosswind movements if not suppressed. Floor slots let some wind pass through building corners to the leeward side, inhibiting the formation of vortices and reducing the effects of vortex shedding. Although the total downwind load (drag) on the tower will not be reduced much by the relatively small slots at limited locations, the slots do help reduce vortex shedding locally.

While the slots were welcomed by the structural engineer as a way to achieve an efficient structure through optimized floor slot locations, the Architect took advantage of the slot voids and created fantastic view opportunities at the unique spaces.

Performance of Core Wall Under Severe Earthquake

For a building taller than 600 meters, a nonlinear structural analysis to check building performance under a severe earthquake, defined as "2% Exceedance Probability in 50 years" or a 2475-year earthquake, is mandatory in China per the Technical Specification for Concrete Structures of Tall Building (JGJ 3-2010). Following the principles of Performance-Based Design and using the material constitutive relationship curves specified in China codes to define material nonlinearity, the structural engineer created a mathematical model using analysis software ABACUS and performed nonlinear time-history analyses under seven sets of acceleration time-histories records. In initial analyses, the core walls at top levels were found to experience excessive nonlinear demand and failed to achieve targeted performance levels. The extent of upper level wall damage resulted in an extremely long analysis time to reach the converge point, nearly one week for each time-history record. The damage was apparently related to core property changes from a major core wall setback at Level 91 (see Figure 7). As a way to alleviate predicted wall damage, the Architect and structural engineer jointly decided to reduce the change in core properties by having smaller wall setbacks, simply extending some core wall portions to Level 123 that were originally stopping at Level 91 (see Figure 8). Extending those wall segments increased tower core strength and stiffness, reduced predicted wall damage under the severe earthquake case and helped the core structure achieve performance level goals. Reduced wall nonlinear behavior was also reflected in analysis run times as each analysis converged much faster, and the run time to finish one time-history record reduced to just two days. The Architect adjusted the stair layout to accommodate the added walls and reduced the number of guest room types, which was welcomed by the hotel operator.

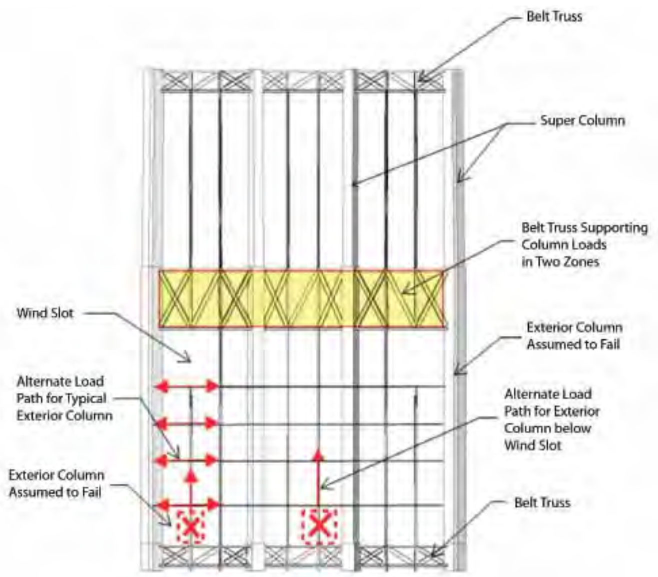

Figure 6. Progressive Collapse Analysis of Exterior Frame (Source: Thornton Tomasetti)
图6. 外部框架抗连续性倒塌分析（来源：宋腾添玛沙帝 Thornton Tomasetti）

之间的外周重力柱，当环带桁架下方某一楼层的外周重力柱失效时，（失效楼层以上的）重力柱作为吊杆把楼层荷载传至（上方）环带桁架，因此环带桁架在抗连续倒塌体系中有至关重要的作用（参见图6）。经过建筑师和结构工程的协调配合，风槽层被布置于环带桁架层之下，这样环带桁架层可采用传统的（带斜腹杆的）桁架形式；与空腹桁架相比可节省建造成本。风槽层也造成了某些次要周边柱（在竖向）的不连续。在抗连续倒塌分析中，当位于风槽层下方楼层的非连续重力柱失效时，这些楼层的楼面梁（被设计为）可以承担原先由失效重力柱承担的楼面荷载并把这些楼面荷载传至相邻柱子。

风旋涡脱落被定义为发生在建筑物角部的紊流。它发生于物体的下风向边缘处，由低压涡流（或风旋涡）的交替产生和脱离造成。如果不加以控制，周期性的旋涡生成和脱离造成施加于建筑物上的周期性风荷载，即横向风荷载。风槽层能让风直接穿过建筑物角部到达下风向一侧，故可以抑制旋涡脱落的形成，从而减小旋涡脱落的影响。虽然作用在塔楼上的总体顺风向荷载（拖力）不会因为局部存在的小风槽的影响而减小太多，但是这些风槽肯定对减小局部的风旋涡脱落有帮助。

由于可以利用风槽位置的优化达到提高结构效率的目的，风槽得到了结构工程师的欢迎，而建筑师则利用风槽创造出独特的空间和奇妙的景观。

核心筒在罕遇地震下的性能

依据《高层建筑混凝土结构技术规程》（JGJ3-2010），对于600米以上的超高层建筑需要进行罕遇地震下的弹塑性结构分析以评估建筑物在地震中的性能。罕遇地震定义为50年内超越概率为2%或2475年一遇的强震。遵循性能化设计原则和使用中国规范定义的材料非线性本构关系曲线，结构工程师利用分析软件ABACUS创建数学模型，并输入7套地震波进行非线性时程分析。初步计算表明塔楼顶部楼层核心筒墙体单元进入塑性的程度比较高，未能达到预期的性能水准。对上部墙体损坏程度的运算需要很长的时间才能达到收敛，每条地震波下的结构分析需要运算长达近一个星期。计算结果表明该部分墙体性能的减弱明显与91层的主核心筒的缩进有关。这一缩进显著改变了核心筒的力学性能（参见图7）。为了减小这一影响，建筑师和结构师相互协作，将原方案到91层就停止的部分核心筒墙体延伸到123 层，从而以最简洁的方式保持了核心筒的力学性能（参见图8）。延伸的墙体增加了塔楼核心筒的强度和刚度，降低了上部墙体在罕遇地震下的破

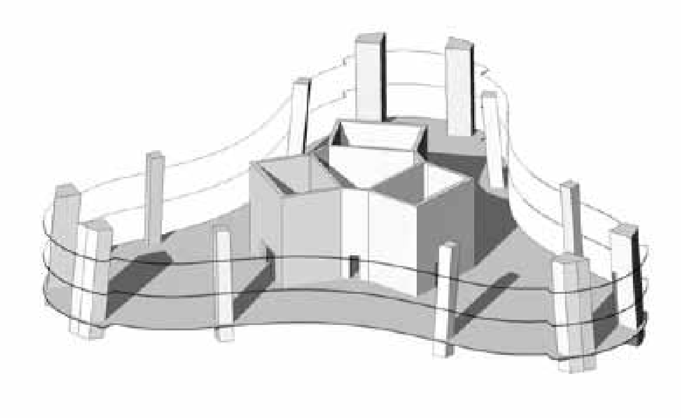

Figure 7. Original Scheme: Larger Core Wall Setback at Level 91 (Source: Thornton Tomasetti)
图7. 原定方案：91层尺寸较大的核心筒缩进（来源：宋腾添玛沙帝 Thornton Tomasetti）

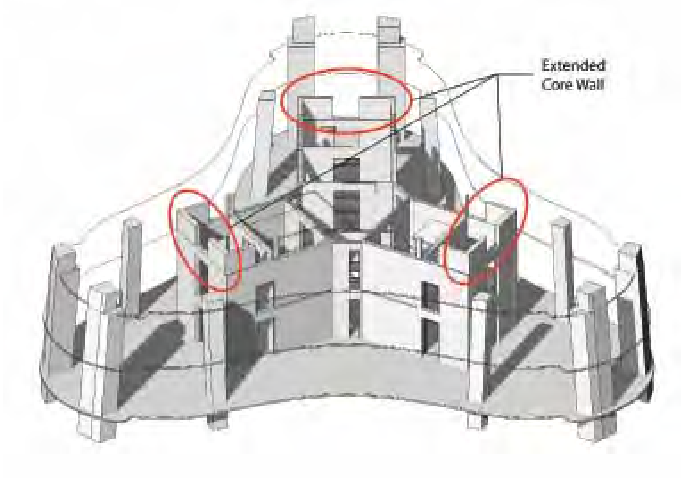

Figure 8. Current Scheme: Less Core Wall Setback at Level 91 (Source: Thornton Tomasetti)
图8. 现行方案：91层尺寸较小的核心筒缩进 （来源：宋腾添玛沙帝 Thornton Tomasetti

Tower Crown Structure

The top of the Wuhan Greenland Center Main Tower is an expression of the project design philosophy. As the tower reaches into the sky, the cladding splits at the line between two architectural components known as the body and the shield. This separation was created to help alleviate tower top wind forces and thus significantly improve building behavior. This simple but powerful statement about the effectiveness of coordinating architecture and structure in Supertall building design has become the building's most iconic feature and is certain to create a landmark on the city skyline.

Rising from gently tapering tower wing tips, the taper steadily and continuously increases to the point that the tips converge on the tower centerline to form a unique 61m tall crown (see Figure 9). Tapering of other building surfaces defines a 35m tall dome. Cleaning of the dome glass will be performed by equipment suspended from the crown above. Cladding of the outer crown is supported by a special tripod structural system. Because crown tripod leg framing is concealed within opaque cladding, support structural design was based on material efficiency and constructability. Each crown tripod leg, a half-arch in profile, is trapezoidal in cross-section or plan. The four faces of each leg are trusses following simple surfaces, with the upper/outer and side trusses triangulated for shear stiffness and the lower/inner truss a Vierendeel without diagonals. Pipes up to 500 mm diameter are used for truss chords and smaller diameter pipes are used for web members and braces. The inner truss Vierendeel configuration and the hollow tripod leg design without internal diaphragms were both selected to work with the window washing machine within. The side trusses taper nearly to a point at the crown base, landing on the super columns at wing tips and connecting directly to the embedded steel columns in the super column for secure load transfer.

The tower dome structure posed different design challenges. Dome cladding is transparent but substantial cladding support framing is required at long spans and high wind pressures. Viewing up through the peak of the dome is desired. Dome structural framing will be visible to visitors so a dramatic sculptural appearance is desired.

Multiple structural schemes were proposed by the structural engineer for consideration by the architect. Systems included support framing distributed along all faces, framing concentrated at discrete locations, horizontal spanning schemes and vertically spanning schemes. For each scheme the relative hierarchy of framing sizes and functions

坏，使核心筒达到了预期的性能水准。这一措施也降低了上部墙体进入塑性的程度，使得每条地震波的运算时间大大减少，完成一条地震波的运算缩减到两天。建筑师通过调整楼梯布局以适应增加的墙体，并且相应减少了客房类型，这样的建筑调整也受到了酒店运营商的欢迎。

塔楼冠层结构

武汉绿地中心主塔楼顶部集中表现了整座建筑的设计理念。随着塔楼向上延伸，建筑表面逐渐分化为两个建筑部分：主体和外壳。这种分离设计有利于减轻塔顶的风荷载，从而显著提高了建筑的性能。这一简洁有力的设计证明了建筑和结构在超高层设计互相协调的有效性，（该塔冠）为塔楼增添了最具标志性的特征，无疑将使之成为武汉市天际线上的地标。

随着塔楼高度增加，塔楼翼缘逐渐锥化收缩，直到与塔楼中轴线在顶部汇聚为一点，形成一个61米高的塔冠（参见图9）。而建筑表面另一角度的锥化收缩形成了35米高的穹顶。穹顶玻璃幕墙的清洗将由悬挂在塔冠上的擦窗机完成。塔冠建筑外幕墙采用一个独特的三脚架结构体系支承。由于塔冠三脚架的桁架隐藏在不透明的幕墙内，因此支承结构的设计要尽量考虑节省材料并有利于施工。塔冠三脚架的每一个脚在竖向剖面上都呈半个拱形，横截面为梯形。（三脚架的）每条支腿形成4个侧面，每一侧依建筑的表面形状布置桁架。上/内侧和两边的三角形桁架提供了结构的抗剪刚度，底/外侧则布置无斜杆的空腹式桁架。桁架支承弦杆采用最大直径500mm的钢管，而桁架腹杆和斜杆选用小尺寸的钢管。内侧桁架斜杆的形式和三脚架支架中空的布置保证了内部擦窗机的正常工作。两侧边桁架逐渐收缩，在塔冠底部交汇为一点，支承在翼缘端部的巨柱上，并直接与巨柱内的型钢相连接，以保证荷载完全的传递到巨柱。

塔顶穹拱结构是设计上的另外一个挑战。穹拱幕墙是透明的，而且支承构件有较大的跨度，承受较高的风荷载。此外，建筑上还要求透过拱顶能够仰视景观。由于穹拱结构在观光层是可见的，因此穹拱的结构设计需具有很强的空间雕塑美感。

结构工程师提出多个结构方案供建筑师选择。方案包含全穹拱均匀分布式结构体系、局部集中布置式结构体系、水平支承式结构体系和竖向支承式结构体系。无论每一种结构方案都综合考虑到了构件尺度对层次感与建筑美学的影响，结构效率和施工可行性。为减小水平环梁的直径，采用钢吊杆悬挂的方式来降低重力方向上的跨度。由三弦杆桁架构成的外露的三脚架支承来自环梁的风荷载和吊杆的重力荷载。三脚架的内侧弦杆逐渐向外侧弦杆

was considered for aesthetic intent, structural efficiency and constructability. The selected system has horizontal curved pipe girts to support the tower skin. To minimize girt pipe diameter, gravity load spans are reduced by suspending the girts from steel hangar rods. Exposed tripod legs framed as tri-chord trusses resist wind load from the girts and gravity loads from the hangers. The inner chord of each truss vanishes at the lowest truss panel so the tripod structure lands on the tower wing tip columns and visually merges with the crown tripod above and outside, while being separate for fabrication and erection (see Figure 10). While one might expect the tripod legs to merge at a peak through a solid compression hub, a different approach was required to maintain views up through the dome. The legs stop before the peak, and plane trusses are added at leg truss top panels to tie the three Tripod legs together. The result is a space frame structure with enhanced lateral stiffness of the dome.

The tower crown and dome structures were integrated with the architectural design to provide a seamless envelope transition from walls to crown and dome cladding while providing a column free space for visitors. The clad crown trusses are visually solid objects for reading clearly on the skyline. The exposed dome trusses read as sculpture to visitors within the transparent dome, with minimal visual obstruction by girts. All loads from the tower crown and dome flow directly onto the super columns, providing short load paths and secure connections.

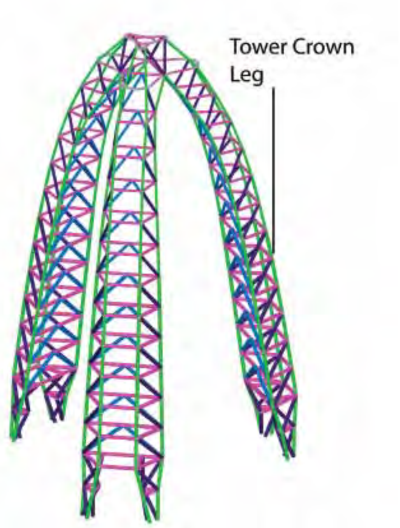

Figure 9. Tower Crown Structure (Source: Thornton Tomasetti)
图9. 塔冠结构（来源：宋腾添玛沙帝 Thornton Tomasetti）

缩进，在穹拱底部与塔冠三脚架交汇于翼端的巨柱，与上部塔冠浑然一体，而施工时，穹拱与塔冠是分别进行吊装并连接在一起的（参见图10）。若穹拱三脚架向上延伸并通过受压节点在顶点交汇，则无法实现透过穹顶仰视景观，需另想办法。因此结构工程师在接近穹顶的位置采用一个平面桁架将三脚架三条腿固定在一起，因而留出顶端的空间。这样便形成了一个具有相当抗侧刚度的空间结构体系。

塔冠和穹拱的结构设计与建筑设计完美结合，实现了流畅的建筑外立面效果，巧妙解决了核心筒墙体、塔冠和穹拱之间的过渡关系，同时实现了顶层的无柱大空间，利于游客观光。从整体上看，塔冠实化，清晰可见，重点突出，而穹拱虚化，与塔冠相呼应。穹拱内部三脚架具有较好的尺度空间感，加上小尺寸的环梁支承玻璃幕墙，最大限度的实现了穹拱的通透效果。塔冠和穹拱上的全部荷载都传递到了巨柱上，传力路径简洁明确，连接可靠性高。

Parametric Modeling Study to Simplify the Curtainwall

Modern graphical design tools offer architects great flexibility in shape creation. Reaching a visually and functionally satisfactory shape should not be the end of the design process. Often seemingly minor, aesthetically and functionally acceptable adjustments to building shapes can provide major benefits for building constructability. This was the case for the Wuhan Greenland Center Main Tower project.

The initial architectural design resulted in a unique exterior surface geometry. The overall surface was very organic, based on numerous curved splines determined and evaluated by visual observation. However, it was clear to the architectural team that the form required further evaluation and adjustments to permit developing appropriate technical details, improve cladding economy and ensure constructability.

Thornton Tomasetti's Building Skin practice was engaged by AS+GG to assist with this process. First the architect's exterior surface model was evaluated at non-planar surfaces for 'warpage' using Rhinoceros software together with Grasshopper. In this case the focus was the amount of surface warpage which might occur, relative to a series of optional glazing patterns. This study allowed the team to identify and quantify those portions of the facade which were warped beyond the constructability limits associated with cold-bending of insulated glass units (IGU's) by applying force to a panel corner (see Figure 11). The team quickly determined that cold-bending of the glass was not an adequate solution for most of the tower using the initial geometry, considering the significant areas of acute warpage that would be required. To enclose the building with reasonable economy, while retaining the original organic tower shape, would likely require that the facade be re-modeled as shingled elements or that other three-dimensionally stepped forms be used.

A small group of detailing strategies were quickly developed and presented to the architect for stepped forms suitable to meet the

（运用）参数化建模简化幕墙设计

现代图形设计工具为建筑师在外形设计上提供了极大的便利。达到视觉和功能都满意的外形不应是设计过程的结束。从美学和功能角度对建筑外形作微小的调整，通常可以提高建筑施工的可行性。武汉绿地中心主塔楼项目就是这样一个实例。

在最初的建筑中（塔楼）拥有一个独特的几何外形。（塔楼的）整个外表面注重视觉效果，由大量的样条曲线组成，所以整体视觉效果非常自然流畅。然而建筑设计团队知道：为了改善幕墙建造的经济性和施工的可行性，在技术细节方面需要作进一步的调整。

Thornton Tomasetti（宋腾添玛沙帝）的幕墙设计团队辅助AS+GG来完成对建筑外表的调整。首先，通过Grasshopper 和Rhinoceros设计软件对建筑师的几何模型进行翘曲参数分析。这一过程的主要目的是分析在几种备选幕墙方案下的曲面翘曲程度。这个分析能让设计团队找出并量化那些翘曲程度超过施工允许范围的幕墙部分。幕墙板块翘曲的允许范围与中空玻璃板块的冷弯能力有关。中空玻璃板块的冷弯是通过在板块的角部施加外力而实现的（参见图11）。设计团队很快发现：塔楼幕墙存在大量剧烈翘曲的部位，所以冷弯玻璃方案在许多区域无法达到原方案的几何形状。为了达到保持原设计中自然的塔楼外表几何形状，且兼顾建造的经济性，幕墙需要采用片状单元形式或其他在三维空间内逐渐缩进的形式。

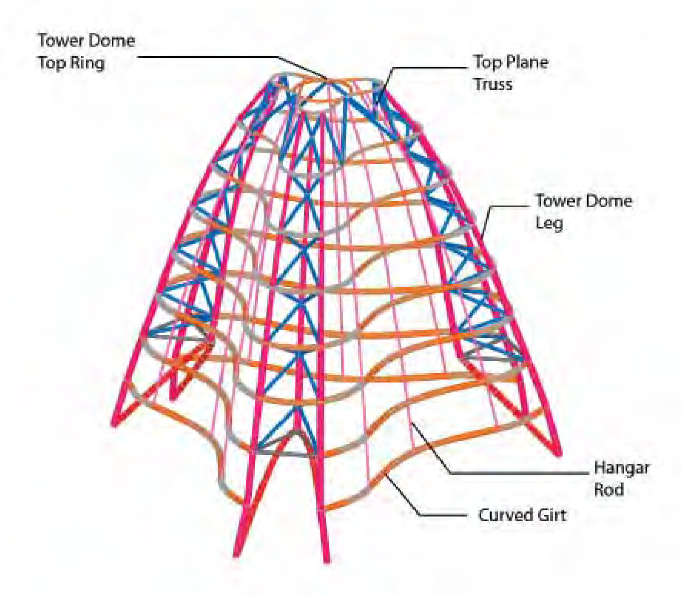

Figure 10. Tower Dome Structure (Source: Thornton Tomasetti)
图10. 塔顶穹拱结构（来源：宋腾添玛沙帝 Thornton Tomasetti）

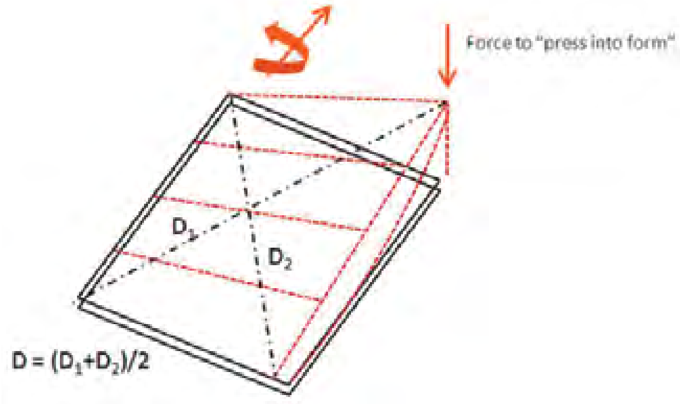

Figure 11. Force Used to Warp or Cold Bending Panels (Source: Thornton Tomasetti)
图11. 作用于冷弯玻璃板的力（来源：宋腾添玛沙帝 Thornton Tomasetti）

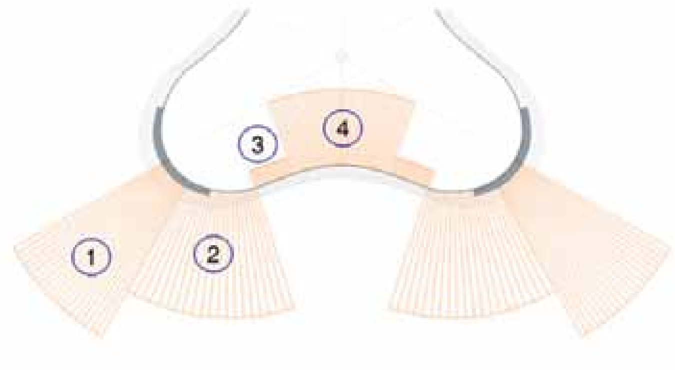

Figure 12. Revised Partial Floor Plan Showing Compound Curve Radii Used (Source: Thornton Tomasetti)
图12. 修改的局部楼面平面图：复合曲线的半径（来源：宋腾添玛沙帝 Thornton Tomasetti）

constructability demands of this massive high-rise tower. Two of the strategies were collaboratively selected, and a revised hybrid approach was established. This approach combined sloped trapezoidal panels -- flat and relatively 'regular' panel shapes capable of creating undulating curved surfaces -- together with panels which would 'step' inward or outward at each floor level.

Based on this approach, the designers returned to the original architectural form, and began to re-generate the overall architectural surface by replacing each of the non-uniform splines with compound curves, a carefully developed series of arcs which were arranged tangentially to mimic the original form of the tower. This was done for the building sections as well as for each plan level. (see Figure 12).

Finally, using Grasshopper, a routine was developed to re-build nearly the entire tower surface by using stepped and sloped trapezoidal panels. At some portions of the tower other geometric strategies for resolving the panelization were adopted that did not rely on stepped forms. The geometric rebuilding process required numerous iterations to determine the optimal panel sizes and alignments, based on practical fabrication and erection limits, as well as the rigorous aesthetic requirements.

Conclusions

The Wuhan Greenland Center Main Tower illustrates ways that collaboration between architect, structural engineer and skin consultant achieves a final design that addresses aesthetics, functionality, load resistance and constructability in a seamless way at all scales, from a 600+m cantilever to panels several meters wide.

幕墙设计师很快地找出了一些以细部设计为原则的应对策略并向建筑师提交了一个采用逐步缩进的方案。这个方案可以满足该项目对施工可行性的要求。（设计者）最后选出了两种设计策略并混合使用，以形成一个修正的混合式方案。这一方案综合考虑了倾斜式梯形板块——平的且相对"规则"并能够形成曲面效果的板块以及楼层处内凹或凸出的板块。

按照这种方案，幕墙设计师对原建筑模型进行了重新生成。用复合函数曲线替换了原来不均匀的样条曲线并用弧线相切的办法拟合了原有的形状。对于剖面和平面都是采用这一方案（参见图12）。

最后，该项目利用Grasshopper的参数化建模方法将塔楼表面划分为若干倾斜且逐渐缩进的梯形板块，以此对大部分塔楼表面形状进行拟合，并发展出一套逻辑原则。。此外，其它一些措施也同时采用，以解决局部特别不规则的问题。几何模型的重建需要进行大量的迭代运算，综合考虑建造工艺、安装和建筑美学，确定最优的幕墙板块尺寸和布置方式。

结语

武汉绿地中心主塔楼是建筑师、结构工程师和幕墙设计师通过高效协作共同完成的建筑杰作。它的每一部分，从几米尺度的板到600米尺度超高层，都是建筑美学、建筑功能、荷载抵抗和施工可行性的智慧结晶。

References（参考书目）：

Specification For Concrete Structures of Tall Building (JGJ 3-2010).