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The Parametric Design of Shanghai Tower's Form and Façade

上海中心大厦造型与外立面参数化设计

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Jun Xia, Principal and Asia Regional Design Director at Gensler, thrives on analyzing the physical, spatial, and behavioral aspects of buildings. He received his B.A. in Architecture from Tongji University and his M.A. in Architecture from the University of Colorado. Under Xia's leadership, the Gensler Shanghai office was established in 2003. His commitment to innovative design has produced some of the most visionary projects in China, including Beijing Chang'An International Center, Shanghai Pudong Development Bank, Chartered Tower, Dongyin Center, JW Marriot Hotel, BM Plaza, Yangtze International Financial Center, and Shanghai Tower.

夏军，Gensler的主创设计师和亚洲区设计主管，专注于建筑的物理，空间，及性能表现等方面的研究。他在同济大学接受了建筑学本科教育，又从卡罗拉多大学获得了建筑学硕士学位。在他的领导下，Gensler上海分部于2003年设立起来。他对革新型建筑的执著使他在中国创作了数栋最具前瞻性的建筑，其中包括北京长安国际中心，上海浦东发展银行，渣打大厦，东银中心，J.W.万豪酒店，上海宝矿国际广场，长江国际金融中心，及上海大厦等等。

Michael Peng, Senior Associate and Senior Designer at Gensler, has been dedicated to the practice of design for the past 10 years. He received his B.A. in Architecture from China Academy of Art. Since joining Gensler in 2007, Michael has been involved in designing the Shanghai Tower. As a core team member, he has used advanced digital design platforms to optimize the systematic design, translating creative and strategic thinking into fast implementation. As an assistant professor, Michael also teaches digital media in the Faculty of Architecture at the University of Hong Kong.

彭武，Gensler的高级项目经理及资深设计师，在过去的十年中致力于建筑设计的发展。他在中国美术学院获得了建筑学学士学位。自从2007年加入Gensler以来，彭就从事与上海大厦的设计工作。作为一名小组核心成员，他运用了高级数码设计平台来优化系统化的设计，将富有创造力与策略性的理念迅速地转换为可执行的方案。彭还是一位大学讲师，他在香港大学建筑学院教授数字媒体课程。

Abstract

The most sustainable super-tall tower in the world was only made possible by using innovative design ideas, integrated technology, and advanced tools. This paper is centered around the Shanghai Tower as a case study on the parametric design platform utilized by the design team to bring this iconic tower to construction. The design process revolved around the use of a series of parametric software programs. These programs allowed the Gensler design team to manipulate and refine the project's complex geometry iteratively. The parametric platform played a pivotal role in assisting the team to define the tower's unique and environmentally responsive high-performance form, façade, and supporting structure.

Keywords: Shanghai, sustainable, super-tall tower, parametric design, façade, Building Information Modeling (BIM)

摘要

世界级最可持续的超高层塔楼只有通过革新的设计理念、一体化的技术和先进工具的运用才能实现。本文围绕上海中心大厦作为范例，分析设计团队使这一标志性塔楼得以实现施工所采用的参数化设计平台。设计过程围绕采用一系列参数化设计软件。这些软件允许设计团队可以迭代式操作和改进项目的复杂几何。参数化设计平台在协助团队定义塔楼的独特及环保的高性能造型、外立面和支撑结构的过程中发挥了关键作用。

关键词：上海、可持续、超高层塔楼、参数化设计、外立面、建筑信息模型（BIM）

Introduction

Shanghai Tower is currently under construction, en route to becoming the largest and tallest double-skin façade structure in the world, and one of the most sustainably advanced. As the last of three super-tall towers of Shanghai's Lujiazui central business district, adjacent to SOM's Jin Mao Tower and KPF's Shanghai World Financial Center, Shanghai Tower will redefine the identity of the city and the world's perceptions of China. Its originative architectural, structural, and MEP design, as well as its innovative design process, exemplify the future of high-rise construction.

The form of the 121-story building is a triangular column that twists and tapers as it rises 2073 feet (632 meters) (see Figure 1). The curved corners of the triangle act to minimize wind loads and create 21 atria between the inner and outer curtain walls. A notch running up one corner adds to the aesthetics and sustainability of the design. Nine zones, 12 to 15 floors each, are stacked to create smaller neighborhoods within the super-tall tower. The resulting unique, complex, and environmentally responsive form helped Gensler win the international competition for its design in 2008. It also called for an

引言

上海中心大厦目前正处于施工阶段，竣工后将成为世界上最大及最高的双层外墙建筑，同时其可持续技术也是最先进之一。作为上海市陆家嘴中央商务区三座超高层塔楼当中的后起之秀，与SOM公司的金茂大厦和KPF的上海环球金融中心比肩而立，上海中心大厦将重新定义城市形象，改写全世界对中国的看法。其原创性的建筑、结构和机电设计，以及其创新性的设计流程，均昭示了高层建造的未来。

这栋121层建筑的造型为一个沿2,073英尺（632米）的高度螺旋上升的三角尖锥形柱体（见图1）。三角形的弧形转角有效地将风荷载降到最小，在内外幕墙之间形成21座中庭。一条切口沿着其中一个转角蜿蜒而上，增加了设计的美感和可持续性。九个分区层层叠加，每个分区设置12-15个楼层，在超高层塔楼内形成规模较小的邻里关系。独特、复杂而又环保的造型使Gensler公司在2008年的上海中心大厦国际设计方案竞赛中一举中标。同时也需要一个创新性的设计手法——参数化设计的创新性使用使构变为现实。

Gensler的上海中心大厦设计团队选择采用参数化设计有几大原因。构筑一栋前所未有的复杂形体建筑需要最富有创新性的工具。参数化设计平台顾及到高度精确的结果和模型与其建成形式之间的默契关

inventive approach to bring it from paper to reality—it called for innovative use of parametric design.

The Gensler team for Shanghai Tower chose to use a parametric design process for several reasons. Constructing a complex building shape that had never before been conceived required the most innovative tools. Parametric design platforms allow for highly accurate results and good correlation between a model and its built form. They are very flexible and adaptive, offering instant feedback to changing variables. These nonlinear adjustment tools give architects the ability to affect multiple changes simultaneously. This allows designers to better understand iterative massing studies while observing the relative impact to the overall performance of the systems involved.

Another important reason for the use of parametric design was its assistance in creating Shanghai Tower as a sustainable building. This can be seen in the example of parametrically incorporating wind load data on the building. The location of Shanghai Tower and its proximity to two other super-tall buildings means that these loads can have substantial impact. To address these loads, the design team developed a series of models in a parametric program. Rotation in the models ranged from 90º to 180º. They sent these to Rowan, Williams, Davies & Irwin (RWDI), a wind engineering consultant firm. RWDI tested the series in a wind tunnel with 1/500 physical models. They found that increasing the rotation reduced the wind load on the façade and superstructure, and suggested an option that manifested a reduction of 24% compared to a rectangular form of the same height; this in turn reduced the amount of material of the structural system. Then, the design team generated a detailed model incorporating RWDI's data back into a parametric program. The result was made into a 1:85 scale physical model that RWDI tested in a large-scale wind tunnel. The model was set within the context of its super-tall neighbors as "wind loads on buildings in realistic environments surrounded by neighboring buildings may be considerably different from those measured on isolated buildings." This high Reynolds number test showed an additional 8% benefit, resulting in a 32% total reduction of wind loads. This iterative process allowed Shanghai Tower to save US$58 million in required structural steel. Furthermore, it allowed the project to save money in design loads used to size glass thickness, window unit frame members, and the curtain wall supporting structure.

Shanghai Tower's numerous parametric studies all followed a rigorous process. The Gensler team would first input data, parameters, and conditions into a program. They would then include information driven by formulas, data, and scripts. From this they would receive output in both a data sheet and a 3d model. They would share and analyze the output with their client and consultants to further develop and refine the design. Next they would establish a model and select a system that included responses and comments from the consultants and the client. Then they would repeat the process. In this way the team was able to address some of the project's important design issues so as to produce a high-performance super-tall building.

The team used several parametric software programs to both refine the design and establish the documentation process that would be maintained through execution. Gensler, its client, its contractors, and its design consultants—including Thornton-Tomasetti (structural), Cosentini (MEP), and Aurecon (façade)—collaborated via various parametric and Building Information Modeling (BIM) platforms for a variety of tasks: for architectural, structural, and MEP design and coordination; for analysis of fire safety and energy; and for 3D shop drawings, digital fabrication, construction simulation, and digital preassembly. In this paper, we will focus on how parametric design was

Figure 1. Rendering of Shanghai Tower, a sustainable super-tall tower that will be the largest and tallest double-skin façade structure in the world. (Source: courtesy Gensler)
图1. 上海大厦效果图，一栋可持续性的超高层建筑物，将具有世界上最大和最高的双层表皮结构。（出自：Gensler）

联。这些平台非常灵活且适应性强，能够对不断变化的变量即时做出反馈。这些非线性调整工具让建筑师有能力同时影响多项变更。这允许设计师能够更好地了解迭代体量研究，同时观测对所究涉及系统的整体性能的相对影响。

采用参数化设计还有一个重要的原因，那就是其有助于将上海中心大厦打造成一栋可持续建筑物。这可在参数化合并风荷载数据的建筑物示例中看出。上海中心大厦的高度及其与另外两栋超高层建筑的接近程度意味着这些荷载会产生实质性的影响。为了解决上述荷载，设计团队在参数化程式中发展了一系列参数化方案模型。模型中的旋转角度从90º到180º不等。他们将这些模型发送给风工程顾问公司RWDI。RWDI以1/500比例的实体模型进行了一系列的风洞试验。他们发现更大的扭转可以降低外立面和上部结构上的风荷载，RWDI同时建议采用一个能比相同高度下的矩形造型降低24%风荷载的方案；这反过来也减少结构系统的材料用量。接下来，设计团队制作了一个详细的模型，并将RWDI的数据合并到参数化程式中。结果整合到RWDI在大型风洞中测试的1:85比例实体模型中。将模型置入相邻高层建筑的整体大环境中，"在现实环境中被相邻建筑包围的建筑与单独建筑的风荷载实测可以有明显的区别"。这项高雷诺数试验显示了额外8%的效益，导致风荷载整体下降32%。这一迭代过程容许上海中心大厦在所需的结构钢材上节省5800万美元。此外，在确定玻璃厚度规格、幕墙单元框架构件和幕墙支撑结构的设计荷载上使项目节约资金。

上海中心大厦举不胜数的参数化研究全部遵循一套严谨的流程。Gensler团队首先将数据、参数和条件输入到程序中，然后将由公式、数据和脚本驱动的信息包括在内。通过这一过程，他们会同时得到以数据表和3D模型形式存在的输出结果。为进一步的深化和优化设计，他们与业主和顾问分享并分析输出结果。下一步，他们会再建立一个模型，并选出一套包含顾问和业主的回复和意见的系统。接下来，他们会重复这一流程。通过这种方式，设计团队就能够解决项目的某些重要设计问题，从而打造出一栋高性能的超高层建筑。

团队采用了多种参数化软件程式来改进设计，同时建立了在整个执行过程中可维护的文档流程。Gensler、业主、承包商和设计顾问公司——包括TT（结构）、Cosentini（机电）、Aurecon（外立面）在内，通过各种参数化和建筑信息建模（BIM）平台合作完成各项任务：建筑、结构、机电设计和协调；消防安全和能源分析；3D加工图、数字化制作、施工模拟以及数字化预组装等。在本文中，我们将集中讨论在上海中心大厦的造型、外立面和结构如何使用参数化设计，BIM软件如何帮助改进和协调设计。

used for Shanghai Tower's form, façade, and structure, and how BIM software helped to refine and coordinate the design.

Form

Shanghai Tower's exterior curtain wall—with a horizontal profile of an equilateral triangle with rounded apexes and a notch in one apex, and a vertical profile that twists and tapers as it rises—means that every floor of the building is different (that is, all floors have the same shape, but each floor is rotated roughly 1% from the floor below, and the floors scale down as the building rises). The design team used parametric software to define the building's complex geometry and to create an associative model integrating the building and façade. Their studies included three aspects of the building's 2D and 3D form: its horizontal profile (the default geometry of the plan), its scaling, and its rotation.

The first challenge was to set the horizontal profile. The Gensler team had already determined in the design competition stage that the basis of the exterior curtain wall would be an equilateral triangle with rounded apexes. They needed to optimize the curvature of these corners to meet aesthetic, functional, and sustainable criteria—that is, to optimize the appearance of the corners and the use of the atria that were created between outer and inner façades, to balance the building's gross floor area (GFA), and to minimize the effect of wind loading. To do this they entered basic data into parametric software and changed the key angle (A1) to produce different corner configurations (see Figure 2). From this study they determined that an A1 of 23.3 degrees created the optimum tangential transition between corners and equilateral sides. It resulted in a smooth building shape that could then be tested for rotation and scaling. The corner transition of each floor of Shanghai Tower, derived from the optimal 23.3-degree A1, would remain constant throughout the height of the building.

The second task in studying the form of the exterior wall was to develop a vertical profile that determined the scale and rotation of the building. Through this process, the design team tested both linear reduction and exponential reduction to find the best possible way of transitioning scale between the floors along with the best overall appearance of the tower. They used the equation

$$y = e^{z*s}$$

where y = the percent of scaling, e = mathematical constant (Euler's number), z = elevation, and s = scaling. By adjusting the scaling, rotation, and elevation in parametric software, the design team could compare the aesthetic results, the GFA, and the floor efficiency of various combinations. An s value below 100 percent yielded models that scaled from bottom to top, while those with s values above 100 percent produced the inverse (see Figure 3). Additionally, and very importantly, the geometrical relationship between the subsequent floors as well as between individual curtain panel units could be understood, iterated, and optimized. After running many prototypes through both parametric modeling studies and physical tests, the design team chose a rotation of 120 degrees and a scaling of 55% from base to top to optimize aesthetics, sustainability, and function (see Figure 4).

In creating an associative model of Shanghai Tower, the team moved through three phases of data gathering. First, they built an initial model of the building with purely geometric data. Next, they created an intermediate model that incorporated the façade and the curtain wall support structure of the building. Finally, they produced a fully developed and detailed model. Parametric design software allowed

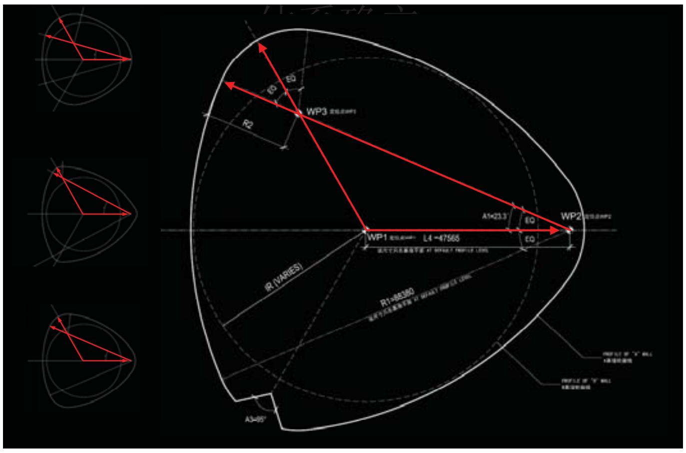

Figure 2. A study in Rhino with Grasshopper to determine the angle, A1, producing the optimum curvature of the corners of Shanghai Tower. (Source: courtesy Gensler)
图2. 运用犀牛软件的Grasshoper来决定角度，A1，制作出上海大厦的最佳转角曲线。（出自：Gensler提供）

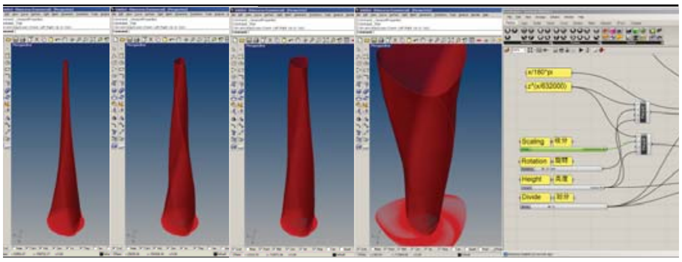

Figure 3. Parametric studies of the scaling of Shanghai Tower. (Source: courtesy Gensler)
图3. 上海大厦缩放比例的参数化研究。（出自：Gensler提供）

造型

上海中心大厦外幕墙——平面为一个圆角等边三角形，其中一个圆角有一个切口，而垂直外形成螺旋状上升——这意味着建筑物的每个楼层平面都不同（也就是说，各楼层的形状是相同的，但是每个楼层在下方楼层的基础上旋转大约1%左右，随着建筑物上升，楼层也在缩小）。设计团队采用参数化软件来定义建筑物的复杂几何形状，同时创建起一个整合了建筑和外立面的联合模型。其研究包括建筑物的二维和三维造型的三个方面：其水平向外形（平面的基准几何）、缩放比例和旋转。

第一项挑战是设置水平向外形。Gensler团队在设计竞赛阶段就已确定，外幕墙的基础是带有圆尖端的等边三角形。他们需要优化上述转角的弧度，以达到美学、功能和可持续的准则——也就是说需要优化转角的外观以及在内外幕墙之间所形成的中庭的使用，来平衡建筑物总建筑面积（GFA），同时将风荷载的作用降到最低。为了实现这一目标，他们将基础数据输入到参数化软件中，并且改变关键角度（A1）来产生不同的转角组合（见图2）。通过这项研究，他们确定当A1达到23.3度时，会在转角和等边之间产生最佳的切向转接。这样就会产生一个平滑的建筑造型，可以进行旋转和尺度渐变的试验。上海中心大厦每个楼层的转角转接从优选的23.3度A1衍生出来，在建筑物的整个高度范围内保持恒定不变。

研究外墙造型的第二个任务就是发展竖向外形来确定建筑物的比例和旋转。通过这一流程，设计团队测试了线性缩减和指数缩减，并通过下列公式查找楼层之间转接缩放比例的最佳方式及塔楼的最佳整体观感：

$$y = e^{z*s}$$

其中 y =缩放比例的百分比，e =数学常数（欧拉数），z = 标高，s =缩放比例值。通过调整在参数化软件中的缩放比例值，旋转和标高，设计团队对各种组合的美学效果，GFA和楼层效率进行了比较。若S值小于100%，所见模型从下往上缩小，S值大于100%，则相反（见图3）。此外，更重要的是在其后楼层之间与

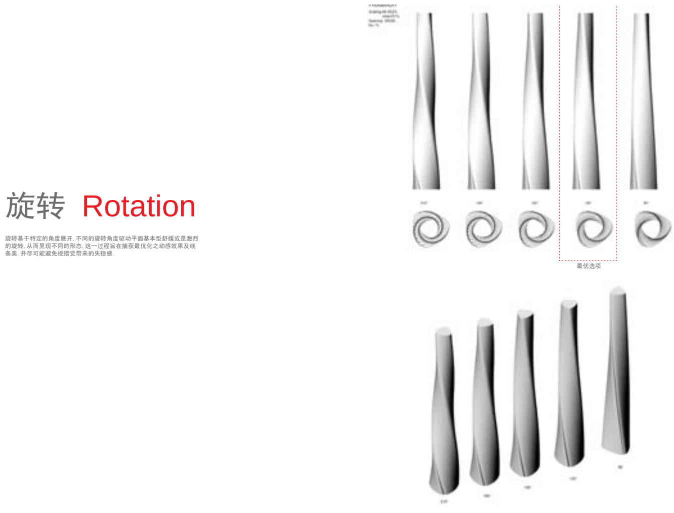

Figure 4. From many studies, the design team chose a rotation of 120 degrees and a scaling of 55% from base to top for Shanghai Tower. (Source: courtesy Gensler)
图4. 经过多次研究，设计团队选择上海大厦从底部往顶端旋转120度及55%的缩放比例。（图片来源：Gensler提供）

Figure 5. A study of the horizontal profile at level 9 of Shanghai Tower with various panel divisions. (Source: courtesy Gensler)
图5. 在上海大厦9楼带多个外墙板块划分的水平向外形研究。（图片来源：Gensler提供）

the team to examine the curtain wall and underlying systems in an appropriate level of detail early in the design process and therefore integrate it as an overall building solution. This integration will be discussed in the following sections.

Façade

The rounded triangular form of the Shanghai Tower's outer façade uses less glass than a rectangular façade with the same area, allowing for significant savings in material costs. Designed with nearly 1.4 million square feet (130 thousand square meters) of more than 25,000 glass panels, the façade would have been very difficult to conceptualize using traditional computer-aided design tools and methods. The design of the façade needed to address, in addition to the complexities aforementioned, Shanghai Tower's specific site and climatic conditions and the experience and capabilities of local fabricators. Using parametric software, the Gensler team was able to develop a façade system that balanced engineering performance, constructability, safety, maintenance, economy, and design.

Their studies began with dividing an exterior wall profile into a number of panels (see Figure 5), then tested numerous panel parameters, including size, shape, and angle. Here the team balanced the intention to make each panel as large as possible to allow for the most open views with the necessity of optimizing each panel size to be fabricated within standard industry capabilities. They chose 138 divisions per horizontal profile as the optimum number. This resulted in a panel length of 7 feet (2.14 meters) at the default horizontal profile. Next, they modeled various panel and connector details to see how these would affect the overall appearance of the façade. Here tests integrated wrap depth and vertical mullion properties (depth, width, glass versus aluminum, continuous versus split, etc.). The team simultaneously studied the feasibility of fabricating various façade systems by sharing their parametric models with their consultants.

The Gensler team studied more than a dozen façade panel schemes and configurations and vetted out many for various irreconcilable challenges they presented. Three main directions—which were named "shingle," "stagger," and "smooth"— resulted from this process and were put through further, comprehensive parametric modeling (see Figure 6). Each responded to the complex geometry of Shanghai Tower in a different way. The shingle design used glass parallelograms with one

及每个独立幕墙单元之间的几何关系是可以被了解，迭代和优化的。通过进行许多参数建模研究和物理测试所建立的原型后，设计团队选择一个从底部到顶端旋转 120度及55%缩放比例的原型，以达到最佳的美学 、可持续性与功能（见图4）。

在建造上海中心大厦的关联模型时，设计团队经过了三个阶段的数据收集。首先，设计团队建立纯几何数据的建筑物初始模型。然后，建立一个中间体模型並结合建筑物的外立面和幕墙支撑结构。最后，生产一个完全成熟及深化的模型。参数化设计软件容许设计团队可以在早期的设计过程就对幕墙和基础系统在一个相称的细节水平上进行检查，从而将其整合为整体建筑解决方案。随后的章节会讨论这种一体化。

外立面

上海中心大厦的圆边三角形外立面与同样面积的方形外立面相比采用较少的玻璃，允许物料成本的显著节约。所设计的立面拟采用两万五千多块玻璃板，共计140万平方英尺（约13万平方米），若采用传统的电脑辅助设计工具和方法会很难进行概念化设计。除上述的复杂性外，外立面的设计还需应付上海中心大厦的特殊场地和气候条件，以及当地加工制造者的经验和能力。使用参数化设计软件，Gensler团队可以发展出对工程性能、可构造性、安全性、维护、经济及设计等各方面平衡的外立面系统。

其研究先把外墙外形划分成数个板块（见图5），然后测试大量的板块参数，包括大小，形状和角度。设计团队既尽可能将每块板块做到最大以容许最开阔的视野，同时又在标准业界制作能力范围内必然性地优化每块板块的尺寸，在两者间取平衡妥协。设计团队在每水平向外形上选择138个划分为最佳数。在默认水平向外形上产生了一个7英尺（2.14米）的板块长度。设计团队然后为各种板块和连接件节点建模，查看这会如何影响外立面的整体外观，并对一体化包裹深度和竖框属性（深度，宽度，玻璃与铝合金对比，连续与并接对比等）进行测试。设计团队还与其顾问分享其参数化模型，同步研究制作各种外立面系统的可行性。

Gensler设计团队研究了十几个外立面方案和配置，并剔除当中许多呈现矛盾的挑战。通过这个程序，致使了三个主流方向被名为---“鱼鳞式”，“交错式”和“平滑式”，并进一步接受更全面的参数化建模（见图6）。这三种方案均以不同的方式与上海中心大厦的复杂几何造型相呼应。鱼鳞式设计采用平行四边形玻璃，其中一角突出幕墙表面；交错式设计将矩形玻璃垂直装入逐层内退的水平向接缝内；平滑式设计将冷弯玻璃装入通过可转动的套管连接的带角度的窗框中。

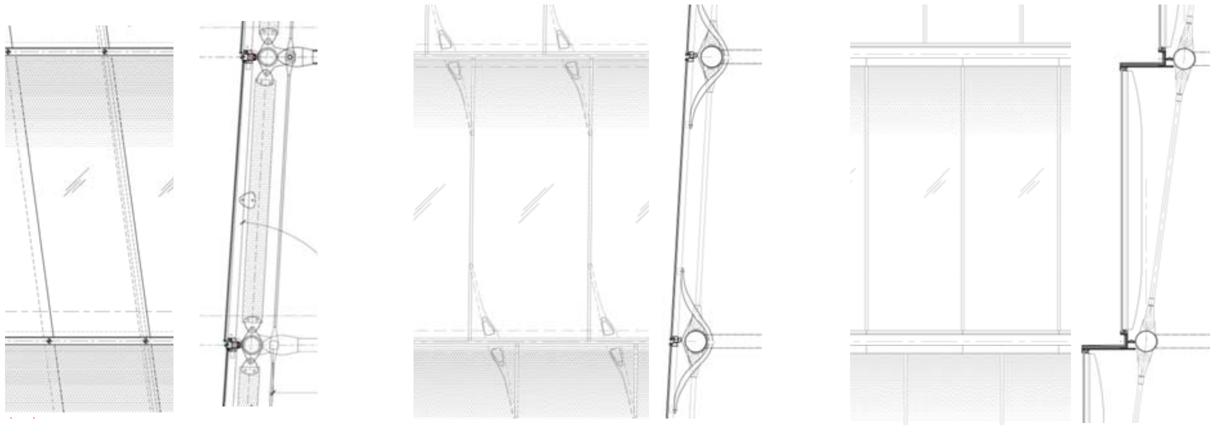

Figure 6. Studies of "shingle," "stagger," and "smooth" models for the facade of Shanghai Tower. (Source: courtesy Gensler)
图6. 关于"鱼鳞式"，"交错式"，和"平滑式"等不同建筑立面的研究。（出自：Gensler提供）

corner projecting from the face of the curtain wall; the stagger model set rectangular panes of glass vertically within joints that stepped back horizontally; the smooth façade used cold-bent glass set in angled mullions controlled by rotational bushing connectors.

The design team ultimately chose the stagger system because it was the best solution for aesthetics, fabrication, and maintenance. In addition, it met the important code requirement that called for the least possible impact of glass reflection to the surrounding area and required that glass be less than 15% reflective. The physics of light suggested that the stagger panel system, with glass set perpendicular to the ground, would shed less sun reflection to the surrounding buildings than the shingle and smooth models, whose glass angled toward the sun. This effect was confirmed in parametric modeling in Autodesk Ecotect (see figure 7).

Curtain Wall Support Structure

The curtain wall support structure (CWSS) of Shanghai Tower's exterior wall addresses not only the complexities already discussed—the rotation and scaling of the form and its triangular plan—but also the complications of connecting this intricate system to that of the building itself and transferring combined loads to the building core and down to the foundation system. The CWSS must resist wind and gravity loads as well as loads parallel to its primary axis, typically resulting from earthquake. The main components of the CWSS are a girt following the curve of the outer wall, coupled sag rods suspended from the complex structure system concealed in the MEP / refuge floor area above and connected to the girt, and perpendicular struts and x-bracing to stabilize the system.

To evaluate the CWSS, the Gensler team divided the triangular plan of each horizontal profile into six segments and designed one segment of it. Each segment in turn was divided into 5 subsegments containing 2, 6, 6, 6, and 3 panels each (from the tangential point where the exterior triangular façade met the interior circular façade to the centerline of the triangle's apex). The team established a series of work points (WPS1) at the places where these divisions met the centerline of the girt. They connected WPS1 to the center point of the building with lines. The points where these lines intersected the support of the circular interior façade became other work points (WPS2), and the lines connecting WPS1 to WPS2 became the locations of struts. In this way, the positions of 4 struts were set in 1 segment. The team then mirrored this segment to form one angle of the triangle, duplicated

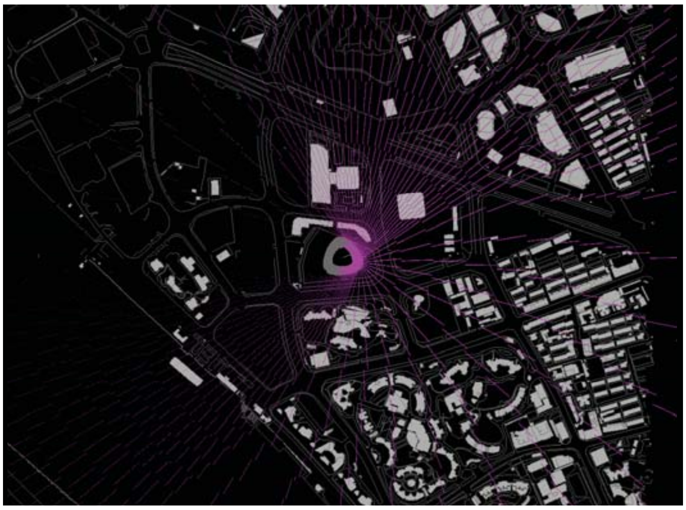

Figure 7. Autodesk Ecotect analysis of light reflection from Shanghai Tower. (Source: courtesy Gensler)
图7. 用Ecotect分析上海大厦所产生的反射光。（出自：Gensler提供）

设计团队最终选择了交错式系统，因为这一系统整合了美观、制造及维护的最佳解决方案。此外，该系统也满足最小化玻璃反射对周围区域的影响（玻璃反射率低于15%）这一项重要的规范要求。光的物理学暗示交错幕墙系统，和玻璃与地面垂直，玻璃与太阳成角度的鱼鳞式和平滑式方案相比，对周围建筑造成的光反射影响较小。采用Autodesk Ecotect进行参数化建模进一步证实了上述说法（见图7）。

幕墙支撑结构

上海中心大厦的幕墙支撑结构（CWSS）不仅解决了上述复杂问题---旋转且缩少而上的建筑造型其三角形平面，同时也处理了这复杂外墙系统连接所致的建筑主体复杂性，以便将结合的荷载传送至建筑物核心筒，并向下传送至基础系统。幕墙支撑结构（CWSS）必须能承受风荷载和重力荷载，以及与其轴向平行的荷载，这通常由地震所引起。幕墙支撑结构（CWSS）的主要构件包括与外墙曲线平行的环梁，双吊杆暗装悬吊于机电/避难层的合成结构系统上，并与环梁相连接，以及用于固定整个系统的正交撑杆和X型斜撑。

为了评估幕墙支撑结构（CWSS）， Gensler设计团队将每个水平向外形的三角平面分成6块，逐一进行设计。每块又被细分为5小块，分别包括2块，6块，6块，6块和3块面板（从室外三角形外立面与室内圆形内立面的交接切点到三角形顶点的中心线）。设计团队在这些分块与环梁中心线的交接处建立了一系列的参考点

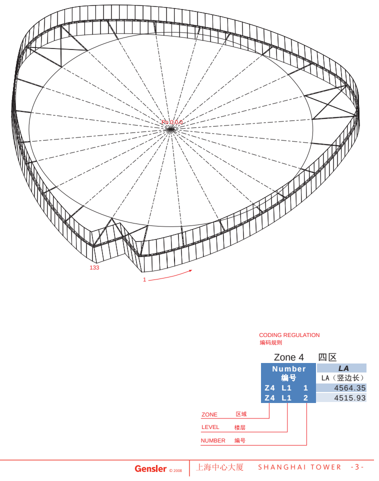

Figure 8. Parametric study of the CWSS for one floor of Shanghai Tower. (Source: courtesy Gensler)
图8. 对上海大厦某一楼层的幕墙支撑结构（CWSS)的参数化研究。（出自：Gensler提供）

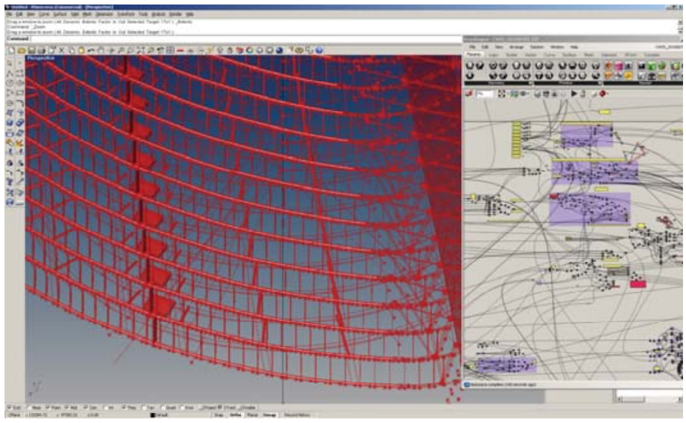

Figure 9. One zone of the full CWSS model of Shanghai Tower. (Source: courtesy Gensler)
图9. 上海大厦某区间的整个幕墙支撑结构（CWSS）全模型。（出自：Gensler提供）

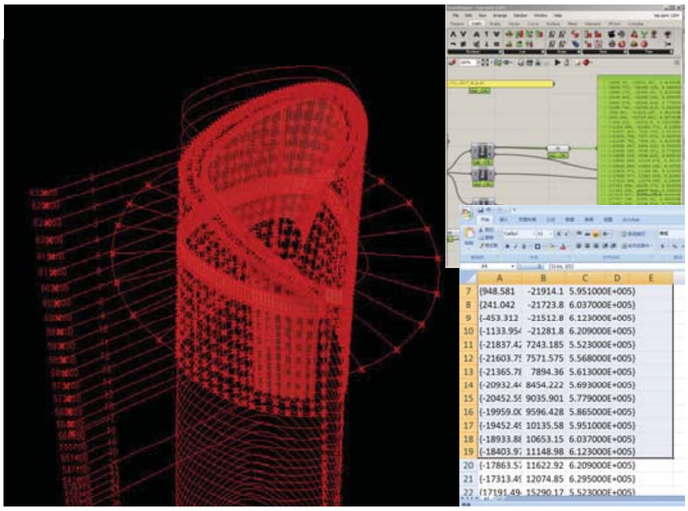

Figure 10. Grasshopper model of the CWSS of the crown of Shanghai Tower. (Source: courtesy Gensler)
图10. 上海大厦楼顶冠的整个幕墙支撑结构幕墙支撑结构（CWSS）的Grasshopper模型。（出自：Gensler提供）

this segment two times to complete the triangle, added the V-shaped notch in one corner, and thus created the CWSS for a full floor (see Figure 8). Once this system was established for one horizontal profile through the algorithmic computation described above, data was entered into the parametric program to generate the CWSS for the entire building (see Figure 9). Parametric software thus constructed a complete CWSS model for Shanghai tower, including the floor plans and the geometry of the steel members.

The results generated by the parametric programs used to design the CWSS were integrated with data from other software to achieve the desired results. An example of this complex integration can be seen in the design process used for the CWSS of the tower crown. Special consideration was given to the top of Shanghai Tower, which, unlike the pointed tops of most super-tall buildings, is an opening that allows for the sustainable features of wind turbines and rainwater collection. The split-parabolic curve of the outline of the tower was technically challenging to resolve. Data from the curtain wall geometry was exported from Grasshopper to Excel (see Figure 10). Resulting data was then reintroduced to Grasshopper to generate a steel structure parametric model using the structural engineer's parameters. Steel geometric data—including the end coordinates of straight steel members and the radii and sweep angles of curved steel members—was then exported back to Excel. The resulting data was imported into Autodesk Revit to generate the steel structure model. So that Revit could read the Excel file directly without any exchange file, the design team wrote a script with Microsoft Visual C# that ran between Grasshopper and Revit. Finally, the team utilized the Revit model to generate the construction drawings for the crown. This use of Revit is one example of the integration of Building Information Modeling in the design of Shanghai Tower. Additional information on this integration follows.

Building Information Modeling

Today the use of Building Information Modeling (BIM) is standard practice within Gensler, but in 2008, during the design of the Shanghai Tower, BIM was in its early adoption at the firm. The use of Autodesk Revit BIM platform was essential for many aspects of the design process, from documentation through multidiscipline coordination (see Figure 11). Revit was not the driving force behind the parametric development of the building, however Gensler established an

(WPS1)，将WPS1与建筑中心用线相连。这些线与圆形内立面相交的点设为第二批参考点(WPS2)，沿WPS1和WPS2的连线为撑杆位置。这样，1块内就设有4个撑杆位置。设计团队将该块镜像作为三角形的一角，再复制两次形成一个完整的三角形，在一角添加V型凹槽，进而形成了整个楼层的幕墙支撑结构（CWSS）（见图8）。一旦通过上述算法计算建立一个水平向外形的支撑系统，则可通过在参数化程序中输入数据，生成整个建筑物的幕墙支撑结构（CWSS）（见图9）。参数化软件因此建立了上海中心大厦的整个幕墙支撑结构（CWSS）模型，包括各层平面和钢组件的几何形状。

用于设计幕墙支撑结构（CWSS）的参数化程序所生成的结果与其它软件所得的数据相结合，以达到预期的结果。这样复杂的集成例子可在塔冠幕墙支撑结构（CWSS）的设计过程中看见。有特别考虑到的上海中心大厦顶部不像其它超高层塔楼的尖顶，而是采用了一个开放式的塔冠，具有可容许设置风力涡轮机和雨水收集系统的可持续特征。解决塔楼的拆分抛物线轮廓给是设计技术性的挑战。幕墙几何的数据从Grasshopper导入Excel（见图10）。结果数据又重新导入Grasshopper，并根据结构工程师的参数，生成钢结构参数模型。钢结构几何数据，包括直钢构件的端部坐标以及弯曲钢构组件的半径和掠角，再导入Excel。将结果数据输入Autodesk Revit来生成钢结构模型。Revit不用交换文件可直接读取Excel文档，设计团队用Microsoft Visual C#编写可在Grasshopper和Revit之间运行的脚本。最终，团队采用Revit模型生成了塔冠的施工图纸。Revit的使用是在上海中心大厦的设

innovative and efficient workflow between the parametric software and BIM. This was accomplished with the utilization of Scripting and file formats such as DXF, SAT and IFC, as well as extensive Excel integration. Today, with the development of BIM technology and the interoperability between software, many of the restrictions Gensler experienced in designing the Shanghai Tower have been lifted. In addition, BIM is an integral part of the construction process of the tower, and this has had an impact on BIM's adoption within the overall China market.

Initially, BIM was not required as a deliverable. However, Gensler and the design team understood the value and necessity of BIM technology for the project. As a broader understanding grew of what BIM could deliver, it was embraced by other associated groups, including the client. Gu Jianping and Ge Qing of Shanghai Tower Construction and Development Co., Ltd. say they use BIM on their projects because it allows them to "plan, coordinate and control all aspects of the work." They expect that BIM will also supply benefits in post-occupancy. "We will take advantage of the model to optimize the operation scheme, equipment management, real estate management, and emergency management, to realize the greatest returns for the developer."

Conclusion

Shanghai Tower is a model of innovation and integration, a symbol of how super-tall buildings can and should be designed in the future. To achieve the complex form, façade, and structure of the tower, the Gensler design team relied on an advanced parametric tool platform, which offered three main benefits to the project. First, it allowed the team to visualize the complexity of the design in a simple way. The triangular, twisting, tapering shape of the form, the multiple glass and joint configurations of the façade, and the complexities of its structure were all modeled with parametric design. Second, it permitted iterating and testing of design options during a very fast design schedule. For example, developing one default horizontal profile into a complete vertical profile through parametric modeling was exponentially faster than building every line per every floor, as in traditional computer-aided design. Third, it assisted in developing a methodology that could be used across the multiple disciplines needed to realize the building. Structural, MEP, and façade engineers, glass and steel fabricators, and the project's client communicated through models developed in parametric design. Ultimately parametric design tools allowed the Gensler team's unique architecture to be built efficiently and safely, to be a solution for its client's intent, and to provide an iconic image for Shanghai, with economy and sustainability always in mind.

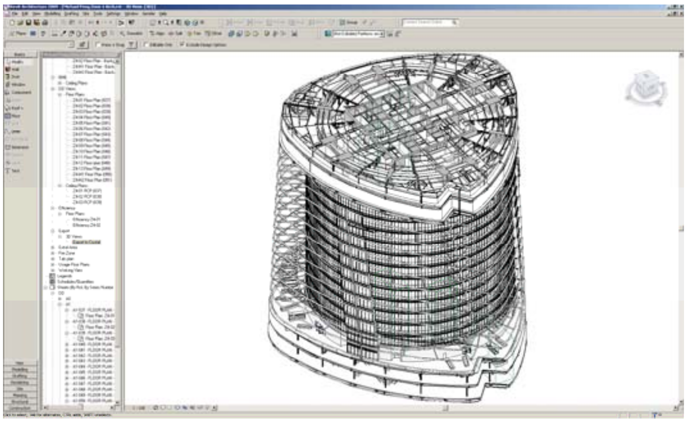

Figure 11. BIM modeling of Shanghai Tower allowed the design team to avoid collisions of structure, ducts, shafts, etc. (Source: courtesy Gensler)
图11. 上海大厦的信息化模型使得设计团队避免了结构、管道、及井道之间的冲突。（出自：Gensler提供）

计中的其中一个建筑信息模型集成案例，这集成的更多信息将在随后讨论。

建筑信息化建模

今天，对Gensler来说，建筑信息模型(BIM)的使用已是一个常规应用，但在2008年，设计上海中心大厦时，BIM才刚刚开始在公司使用。从文件编制到多专业协调，Autodesk Revit BIM平台的采用对于设计过程中的很多方面都至关重要（见图11）。Revit并不是建筑物参数化发展背后的驱动力，但是Gensler通过使用脚本语言，和DXF，SAT和IFC等文件格式，以及广泛的Excel整合，在参数化软件和BIM之间建立了一套创新且高效的工作流程。今天，随着BIM技术以及软件之间互用性的发展，Gensler在设计上海中心大厦时所经历过的限制已不存在了。此外，BIM是塔楼建设不可缺少的一部分，并在整个中国市场都有一定的影响。

尽管最初并未要求采用BIM，但Gensler和设计团队非常了解BIM技术对项目的重要性和必要性。随着对BIM价值的更广泛理解不断加深，相关方包括业主也接受了BIM。上海中心大厦建设发展有限公司的顾建平和 葛青谈到他们之所以使用BIM， 是因为BIM可帮助其“规划、协调并控制工程的各个方面”。他们期望BIM在后期项目交付使用中能继续发挥作用，“我们会利用该模型来优化运营方案，设备管理，物业管理和紧急事件管理，为开发商实现最大的投资回报。”

结论

上海中心大厦是创新和集成的典范，标志着在未来可以或应该如何设计超高层建筑。为了实现复杂的塔楼造型，外立面和结构，Gensler设计团隊依靠先进的参数化平台，对项目提供三个主要好处。首先，它容许设计团队通过一种简洁明了的方式使复杂的设计可视化。通过参数化设计，三角形，扭转，锥式的造型，外立面的多种的玻璃和连接配置，以及结构的复杂性均被模型化。其次，在快速的设计计划内它容许设计选择方案的迭代和测试，比如通过参数化建模，将一个基准水平向外形变为一个完整的垂直外形比用传统电脑辅助设计建立每个平面内的每条线要快出好几倍。最后，它有助制定一套可以让多专业跨使用来实现建设所需的方法。结构，机电及幕墙工程师，玻璃与钢材制造商，以及项目业主通过参数化设计所建立的模型进行交流。参数化设计工具最终使Gensler团队的独特建筑设计能有效及安全地建造，并对其客户的意图给于一个解决方案，同时为上海打造一个象征经济与绿色的地标。

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