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Spatially Suspending and Twisting Curtain Walls' Design Essentials
空间悬吊扭转幕墙设计要点

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Abstract

The Shanghai Tower exterior curtain wall has a complex twisting form with a multi-level flexible suspended support system. The curtain wall design is unique and difficult to execute. There are some challenging conditions, such as various panel sizes, concave/convex geometry, and the curtain wall also absorbs the deformation of the flexible steel support system. Therefore, systematic problem-solving proposals are provided for the curtain wall systems and the design essentials in custom curtain wall shapes through several technologies. CAD modeling, BIM analysis, full-scale modeling tests, complete mechanical calculations, focused design, construction technologies and more offer insight.

Keywords: Spatial Suspension Structure, Twisting Curtain Walls, Custom Curtain Wall Shapes, Flexible Support Systems, Bim, Modeling Tests, Stages Of Deformation

摘要

上海中心大厦外幕墙具有复杂扭转体形，是多层柔性悬挂受力体系，幕墙设计要求独特且难度大。例如：多种异型板块，内凹、外凸的几何形状，确定幕墙功能设计和幕墙吸收柔性支撑钢结构的变形措施等，都具有一定的挑战性。为此借用CAD建模、BIM分析、实物测量等技术，结合大型模型试验，完备的力学计算和针对性设计施工工艺等，提出幕墙体系之系统性解决方案，总结了此种异型幕墙设计要点。

关键词：空间悬吊结构、扭转幕墙、异形幕墙、柔性支撑体系、BIM、模型试验、阶段变形

Introduction

When facing supertall and large-scale building curtain wall systems with a large quantity of panels and complex geometric shapes, flexible suspension curtain walls with twisting moments, and unique structural systems, there must be a detailed summary of the implementation in previous large-scale projects in order to select the appropriate technology to utilize. In terms of the curtain wall system characteristics mentioned above for the Shanghai Tower, Yuanda Group has systematically researched and found new technologies, new processes, and new materials in order to solve the problems successfully.

Shanghai Tower's Exterior Curtain Wall and Steel Structural Support System

The Shanghai Tower exterior curtain wall adopted a vertical staged system, and large rectangular glass panels precisely matching the Tower's shape. The support system of the curtain walls adopts a radial flexible steel structure in order to support the exterior curtain walls.

前　言

面对建筑规模宏大-板块数量众多，几何形状复杂-空间扭转缩放以及结构体系独特-大型柔性悬吊的建筑幕墙，需要认真总结过去大型项目的实施经验，正确选择技术路线，才能顺利的实施此类项目。因此，针对上海中心大厦外幕墙系统的以上特征，远大进行了系统性的思考，并努力寻找新技术、新工艺、新材料，试图圆满解决问题。

上海中心大厦外幕墙及其支撑钢结构体系

上海中心大厦外幕墙采用直立阶梯式幕墙系统，大面玻璃板块为矩形并与塔楼外形精确匹配。幕墙支撑系统为轮辐式柔性钢结构体系，用于支撑外幕墙。

上海中心大厦外幕墙成形过程

上海中心大厦项目外幕墙形态复杂，其成形依据建筑设计定义的一套成体系的原则及公式完成。外幕墙总计约13.5万平方米，约2万块单元板块。

上海中心大厦外幕墙通过多面体阶梯式板块创造出曲线锥形的外观：玻璃面始终垂直，向上逐层缩小的平面轮廓创造出凸台平面；由于平面同时沿中轴心逐层旋转，又创造出凹台平面，并导致了凸台尺寸的变化。同时，依据建筑定义的单元划分

The Shaping Process of the Shanghait Tower Exterior Curtain Walls

The shape of the exterior curtain walls of the Shanghai Tower is very complicated; the shaping process is completed based on a set of systematical principles and formulas that are pre-defined by the architectural design. The total area of the exterior walls is approximately 135,000 square meters which consists of roughly 20,000 panel units.

The Shanghai Tower exterior curtain wall presents a curvilinear cone appearance through its arrangement of polyhedral staged panels: the glass surfaces are always vertical and convex planes are created through the shrinking of the plan profile as the height increases creating a ledge; concave planes are made through the rotation of each floor around the central axis which creates a recess in plan. In addition, per the unit modulation principle defined by architectural design, the curtain walls on each floor are divided into 141 units whose sizes are nearly the same, not including irregularity of the ledge condition.

Exterior Curtain Walls and the Steel Structural Support System

The multi-story void between the interior and exterior curtain walls in each independent zone of the Shanghai Tower creates a large atrium. The cavities in different zones vary between 55-65 meters in height. Due to the distance between the exterior curtain wall and the main structure–the maximum distance is approximately 20 meters–the curtain walls cannot be directly connected to the main structure with conventional methods. To make the connection, a steel structural system was designed within the atrium which are called the exterior curtain wall steel support structure. This system in the Shanghai Tower mainly consists of horizontal, curved perimeter beams, horizontal radial support, steel hangers, and a slip anchoring system. The steel support structure shape matches the exterior curtain walls completely. A 400mm space between the center line of the perimeter beams and the exterior curtain walls outer edge is continued throughout. The curtain walls are connected to the perimeter beams of the structure by a set of transfer systems (see Figure 1).

Exterior Curtain Wall Implementation Technology

Again, the total area of the exterior walls is approximately 135,000 square meters which consists of roughly 20,000 panel units. With so much assembly involved, factory production and multidisciplinary integrated design and construction have become inevitable choices.

Factory Production

The exterior curtain walls of the Shanghai Tower requires a large amount of labor for production and installation, and is difficult to execute. To address these issues, most problems should be addressed in the factory to reduce on-site labor and setbacks during installation and ensure the quality of the system.

Through multiple comparative analyses in the design stage, the technical roadmap for the unitized system had been determined (see Figure 2).

Multidisciplinary Integrated Design & Construction

The voids are a major distinguishing feature in the exterior curtain wall support systems of the Shanghai Tower. The 60-meter-tall atria bring great challenges to the construction of the exterior curtain walls. During the installation process, a temporary operation platform is required for all sub-contractors to install façade-related equipment such as mechanical and lighting. Through reasonable arrangements, integrating these professional components into the curtain wall

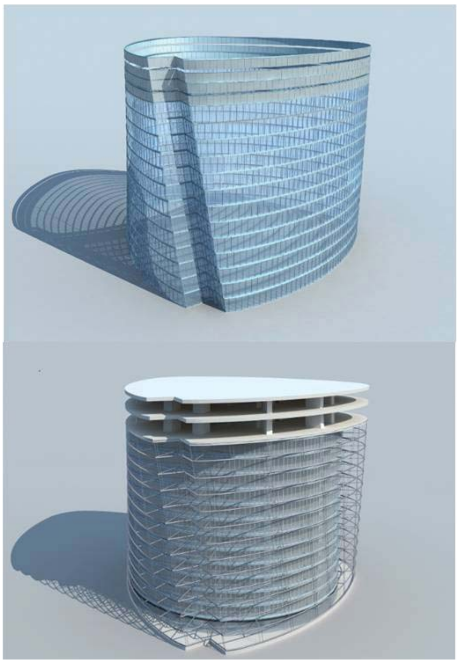

Figure 1. Curtain wall and supporting steel structure model (Source: Bidding documents for the exterior curtain wall by Yuanda Shanghai)
图1. 幕墙及支撑钢结构模型（出自：远大上海中心大厦外幕墙投标文件）

原则，将每层幕墙划分为141块单元，不考虑凹凸台变化的情况下， 玻璃分割尺寸基本一致。

外幕墙与支撑钢结构体系

上海中心大厦塔楼的每个相对独立的分区的内外幕墙之间为上下通高的空间，形成一个大的中庭空腔，各区空腔高度为55~65米不等。由于中庭区域的外幕墙距离主体结构较远，最大部位约20米，因此，无法像传统幕墙一样直接连接于主体结构上。因此，建筑设计在中庭区域设计了一套连接与主体结构上的钢结构体系用于支持外幕墙，称之为外幕墙支撑钢结构。上海中心大厦的外幕墙支撑钢结构体系主要由水平周边曲梁、水平径向支撑、钢吊杆及滑移支座体系组成。支撑钢结构的形态与外幕墙完全匹配，钢结构水平周边曲梁中心线与外幕墙外轮廓线之间始终保持了400mm的相对距离。外幕墙通过一套转接体系连接于支撑钢结构的水平周边曲梁上(见图1）。

外幕墙实施技术路线

上海中心大厦外幕墙面积约13.5万平方米，近2万块单元板块。面对如此巨大的工程量，工厂化生产和多专业集成设计和施工成为了必然选择。

工厂化生产

上海中心大厦外幕墙工程量大，形体形态复杂，幕墙整体实施难度很大。如何解决这些系统性问题，需要从体系入手，将更多的困难留在工厂内解决，减少现场工作量和实施难度，从而更有效的保证幕墙最终品质。

通过方案阶段多重对比分析，最终确定整体单元式幕墙的技术线路（见图2）。

多专业集成设计和施工

“空”是上海中心大厦外幕墙支撑系统的一大特点，中庭区域的60米左右的空腔给外幕墙的施工带来了巨大的挑战。安装时而需要自行搭设临时施工操作平台。对于依附于外幕墙上的机电和灯光这两个专业而言，施工过程存在同样的难题。而通过合理的组织编排，将这些专业部件集成于单元内，可以大大减少交叉施工，缩短工期，保证质量（见图3）。

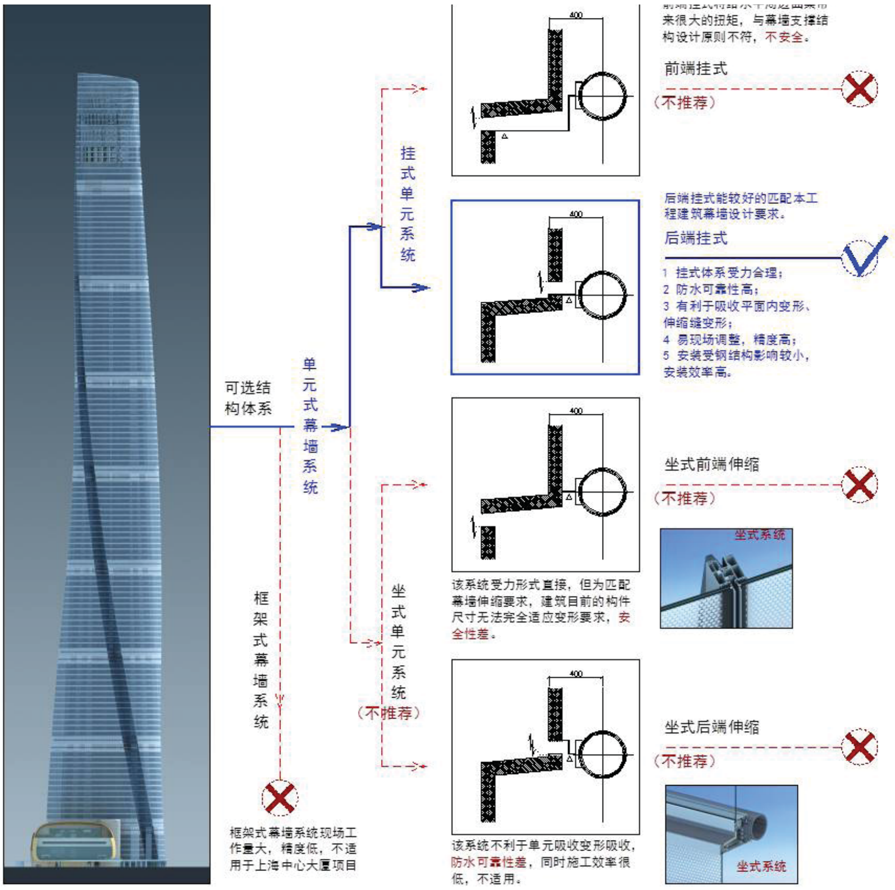

Figure 2. Shanghai Tower's curtain wall system with lectotype technology diagram (Source: Bidding documents for the exterior curtain wall of the Yuanda Shanghai)
图2. 塔楼幕墙系统选型技术线路图（出自：远大上海中心大厦外幕墙投标文件）

units can significantly reduce cross-over construction, shorten the construction period, and ensure quality (see Figure 3).

Displacement Absorbing Capacities and Adjustable Designs

The construction of the flexible steel support structure in the Shanghai Tower is difficult because the Tower's deformation and displacement is complicated. Yuanda has adopted a two-level transfer component as a link system between the exterior curtain walls and the supporting steel structure. The first-level transfer component is a steel shelf, which is directly welded onto hoop ring beams at the factory. The second-level transfer component is an aluminum alloy member that is connected to the first-level transfer components, and from which the curtain wall units will hang. In order to achieve adjustability in three directions, six degrees of freedom, and a high-precision installation and to ensure product quality, a multi-directional flexible connection between components was designed (see Figure 4).

On-Site Construction Technology

Double suspending platforms and construction cranes meet the on-site construction requirements for the curtain wall. The double suspending platforms are horizontally spaced along the façade and move vertically along the cable to reach the installation floor; these are known as stable platform installation systems. The curtain wall units are then lifted up to the respective floor by a crane located at the nearest mechanical level and operated by the workers on the suspended platform. After the curtain wall installation worker operations on the platforms of the double suspending baskets, the installation of the curtain walls is completed (see Figure 5).

变位吸收能力和可调节性设计

上海中心大厦外幕墙的柔性幕墙支撑钢结构体系施工难度大，变形变位状况复杂。远大采用了2级转接件作为外幕墙与支撑钢结构之间的连接系统。第一级转接件为钢板凳，也称为一次转接件，直接于工厂内焊接在环梁上。第二级转接件为铝合金构件，与一次转接件连接，幕墙单元挂于其上。钢板凳与弧形挂座之间有多方向调节的设计，弧形挂座与钢牛腿之间又设计有多方向调节，从而实现”三向六自由度”调整，安装精度高，保证产品质量（见图4）。

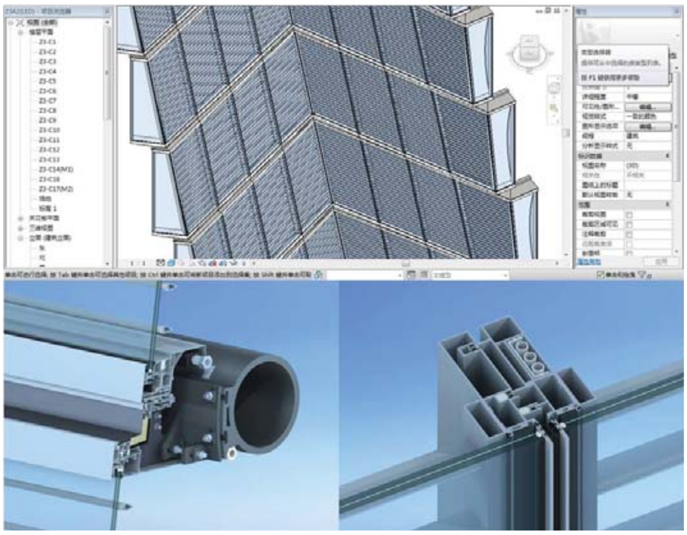

Figure 3. LED Layout at the V recess on the tower and a 3D detail of the unitized curtain wall (Source: Bidding documents for the exterior curtain wall by Yuanda Shanghai)
图3. 塔楼V口LED布置及单元三维节点图（出自：远大上海中心大厦外幕墙投标文件）

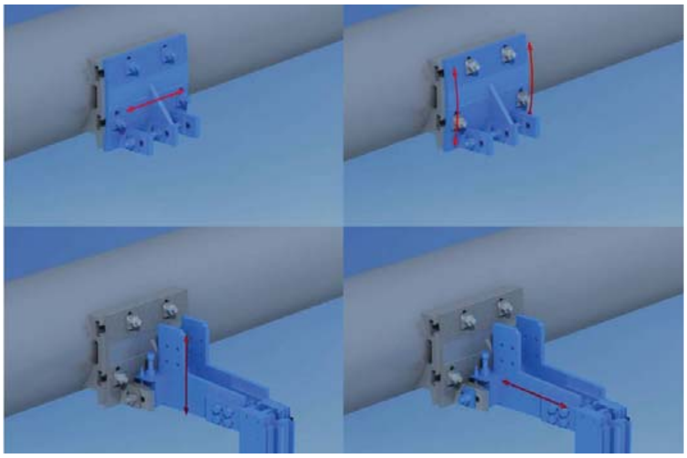

Figure 4. Curtain wall unit anchor components and the three-way adjustable detail (Source: Bidding documents for the exterior curtain wall by Yuanda Shanghai)
图4. 单元转接件及三向可调整节点图（出自：远大上海中心大厦外幕墙投标文件）

Analysis of Large-Scale Model Tests

Due to the difficulty implementing the exterior curtain walls of the Shanghai Tower, the models need to reflect the worst-case scenarios that are most dangerous, most typical, and truest to the actual incidences. Therefore, the models are based large-scale visual and performance mock-ups that include major systems.

Model Overview

A visual model is selected from the recessed "V" location in Zone Two of the Tower and the typical floors of the bilateral regions. The curtain wall system includes A1 and A2 systems. The model width is about 27.6 meters wide (unfolded length) and 13.5 meters tall including three typical floors with a total of 36 curtain wall unit panels (see Figure 6).

Due to the uniqueness and complexity of the project, there were no precedents to refer to. The performance mock-up includes three main curtain wall systems that are installed in the curtain wall support system in order to simulate a variety of possible construction conditions that may occur in reality. The test curtain wall covers five floors, each consisting of 95 unit panels total. Its maximum horizontal unfolded length is up to 36 meters long and 18.6 meters tall. The area of the testing curtain wall is almost 700 square meters. The curtain wall support structure has four vertical levels and the ring beam on each level is up to 44.8 meters long in plan. The area of the entire testing model is almost 902 square meters(see Figure 7).

Once the model is completed, it will break two world records: the first for the quantity of unit panels used and second for the overall curtain wall area represented in a performance test.

Testing Conditions and Programs

To achieve testing for the project, the test facility was set up with an area of nearly 2,000 square meters and two months were spent redesigning and building a test chamber of 8,000 cubic meters based on the characteristics of the mock-up. The test equipment was acquired to allow the following test capabilities: the maximum positive and negative pressure of the pressurization system supplies 12 KPA (250 PSF); the capacity of the pressure measuring device is 12 KPA; the spray device can spray water at a rate of 2.0 liters per square meters per minute [2.0 L/ (m2•min)], 3.4 L/ (m2•min), or 4.0 L/ (m^2•min)]; deflection is measured by over 80 displacement sensor measuring devices; and an aircraft engine can also be used with a high-precision measuring device for hybrid airflows at a rate of 50 m/s (see Figure 8).

The steel structural support system is a flexible suspension system that has a complex shape and unique configuration. As the flexible

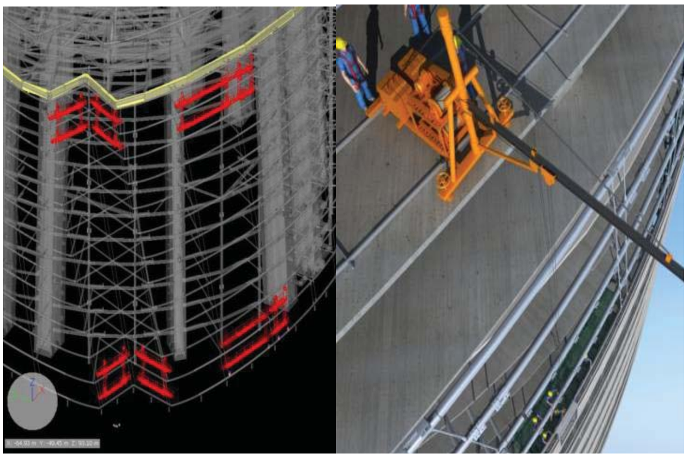

Figure 5. Description. (Source: Bidding documents for the exterior curtain wall by Yuanda Shanghai)
图5. 施工双层吊篮及施工吊机模拟（出自：远大上海中心大厦外幕墙投标文件）

现场施工工艺

通过双层吊篮和施工吊机满足现场单元幕墙施工要求。双层吊篮水平间隔一定距离布置，沿着区域内上下通长的索道运动至安装楼层，横向锁定称为稳定的安装平台体系。单元板块通过布置在每区设备层的施工吊机吊至相应楼层，再由位于双层吊篮平台上的幕墙安装人员操作，从而完成幕墙安装（见图5）。

大型模型试验分析

上海中心大厦外幕墙实施难度很大，模型需以涵盖最危险、最典型和最接近实际情况等因素为原则。因此，需要基于包括了主要系统的大型视觉模型以及测试模型进行系统研究。

模型概况

视觉模型选自塔楼二区V口位置及两侧区域的标准楼层，幕墙系统包含A1、A2两个系统。模型展开宽约27.6M，高13.5M，高度方向包含三个标准楼层，共计36个单元板块（见图6）。

因工程的特殊性和复杂程度，以往的工程都缺乏可借鉴的经验，外幕墙测试模型涵盖主要的三个幕墙系统，模型安装于幕墙支撑系统上，以真实模拟工程中的各种可能工况。测试幕墙共5层由95个单元板块组成，平面最大展开长度近36米，高度18.6米，幕墙测试面积近700平方米，幕墙支撑钢结构共4层，每层环梁平面长度达44.8米，整体测试模型面积达920平方米(见图7）。

此测试模型一经定案便创造了两项世界之最，即同时进行性能测

Figure 6. Visual model substance picture (Source: Yuanda Group)
图6. 视觉模型实体照片（出自：远大原创）

Figure 7. Picture of the testing model (Source: Yuanda Group)
图7. 测试模型实体照片（出自：远大原创）

suspended system is segmented by zone, each section is tall, heavy, and ductile. The curtain wall supporting structure and the main building structure are relatively independent, but the deformation of the main structure has an inevitably significant impact on the curtain walls. As a result, in addition to the conventional four properties of performance testing, tests for the exterior deformation ability of the curtain wall plane, the vertical displacement ability of the overall curtain wall, and the relative vertical displacement ability of the local curtain wall are all required as well.

Performance Test Criteria

According to the performance test programs, the performance test contents and criteria for the Shanghai Tower exterior curtain walls are as follows:

- Static Air Tightness Test
  The air tightness test of the project refers to the National Standard (GB/T 15227) and the American Standard (ASTM E283).
- Static Water Tightness Test
  The water tightness test of the project mainly refers to the American Standard (ASTM E283)(see Figure 9).
- Fluctuating Water Tightness Test
  The fluctuating water tightness test of the project refers to the National Standard (GB/T 15227).
- Dynamic Water Tightness Test
  Water is sprayed at 2.4 liters per square meters every minute [L/(m2•min)] on the outside surface of the mock-up while simulating a 1000 Pa dynamic wind speed in pressure with a propeller for 15 minutes.
  In addition, the contents of the test contain deformation performances under wind pressure, deformation performances inside and outside the plane, and vertical displacement and limits verification.

Calculation Analysis and Response Measures of Supporting Steel Structure Deformations

The exterior curtain walls of the Shanghai tower are suspended from the structural beam of each zone. As the stiffness of the cantilevered steel trusses and beams are nonuniform, it results in uneven settlement in the suspended curtain wall. To meet the design elevations after installation was completed, a preliminary adjustment to teh supporting

Figure 8. Picture of partial equipment testing (Source: Yuanda Group)
图8. 测试设备局部照片（出自：远大原创）

试的单元板块数量和单元幕墙面积均超出有史以来任何一次幕墙性能测试。

测试条件及测试方案

为满足本工程外幕墙的测试，检测单位设置了一块近2000平方米的场地，根据此测试模型的特点，耗时两个月，重新设计、建造了一个8000立方米的测试箱体，测试设备也全部配套重新定购：加压系统能提供的最大正压及负压为12 KPA（250PSF），压力量测装置的能力达到12 KPA，喷淋装置能以2.0 L/ (M2·MIN)、3.4 L/ (M2·MIN)或4 L/ (M2·MIN)的速率进行淋水，80多个位移传感器测量装置能测量挠度，飞机引擎装置能提供的风速在50M/S，高精度复合气流量测装置（见图8）。

本工程外幕墙支撑钢结构为柔性悬挂体系，系统造型复杂，构造特殊，由于采用分区的柔性吊挂系统，悬挂高度高、重量重、刚度柔，虽然幕墙支撑结构与主体相对独立，但主体结构的变形不可避免的对幕墙产生重要影响。因此，除了常规的四性测试外，还需对幕墙的平面外变形性能、幕墙整体竖向位移能力、幕墙局部相对竖向位移能力进行检测。

性能测试要点

根据性能测试方案，上海中心大厦外幕墙性能测试的内容和要点如下：

- 静态气密性试验
  本工程的气密性能测试采用国标(GB/T 15227)和美标(ASTM E283)相结合的测试方式。
- 静态水密试验
  此试验主要参照美标(ASTM E331)进行测试(见图9）。
- 波动水密性试验
  波动水密性试验的检测标准为国标(GB/T 15227)。
- 动态水密性试验
  在测试模型外表面维持以3.4 L/ (m²·min)的速率进行水喷淋，同时采用螺旋桨模拟相当于1000 Pa试验压差的动态风速，持续15min。
  此外，还包括风压变形性能、平面内及平面外变形性能检测以及垂直位移试验和极限验证试验等。

支撑钢结构变形计算分析和应对措施

上海中心大厦外幕墙悬挂在每区土建结构梁，悬挑钢桁架和梁的刚度不均匀，造成悬挂在幕墙沉降不均匀，为了幕墙安装完成后达到设计标高，在幕墙安装前，需要对幕墙支撑钢结构进行预调。

分析不均匀沉降对幕墙的影响

二区受力由环梁承担水平荷载，竖向荷载由25组拉杆承担，8-20层幕墙及支撑钢结构重量通过拉杆传递土建梁。

- 需考虑的荷载
  需考虑的荷载包括：幕墙支撑钢结构的自重荷载、幕墙单元板块的自重荷载以及附加恒荷载。
- 安装环梁及幕墙过程位移分析思路

Figure 9. Static Water Tightness test spray (Source: Yuanda Group)
图9. 静态水密测试喷淋照片（出自：远大原创）

steel structure was required prior to the installation of the curtain wall system.

Analysis of the Impact of Uneven Settling on the Curtain Wall

For the stresses in Zone Two, horizontal loads are carried by the ring beams while vertical loads are carried by 25 groups of tension rods. The weight of the curtain walls and steel support structure from the eighth to twentieth floors are passed through tension rods to the structural beams.

- Consideration of Loads
  The loads that need to be considered are the self-weight of the steel support structure, the self-weight of the unit panels of curtain walls, and additional dead loads.

- Ring Beam and Curtain Wall Installation Displacement Analysis
  – In terms of the installation sequence of curtain walls and the steel support structure, the ring beams use an up-down installation sequence and the unit panels of the curtain walls use a down-up installation sequence.
  – Regarding the ring beam installation sequence, for the ring beam at the very top, each ring beam being installed on the lower floors will cause a downward displacement. If the first level ring beam installation induces a vertical displacement to the hoist point K1, when installing the ring beam at the i-th floor, the vertical displacement to the hoist point will be Ki. According to the analysis, we can obtain the following results:
  The vertical displacement of the first level ring beam at the top: K=K1+K2+…K12
  The vertical displacement of the second level ring beam: K=K2+K3+…K12
  The vertical displacement of the 12th level ring beam: K=K12
  – Per curtain wall installation analysis, the system is installed from bottom to top. As the ring beam installation is completed, unitized panels are installed on every floor, inducing the hoist point to deform vertically as Mi. As the curtain wall installation is completed, at the same hoist point, vertical deformation on all floors is consistent. Therefore, the vertical displacements on all floors caused by the curtain wall installation are:
  M=M1+M2+……+M12
  – In the analysis of the tension rod elongation changes, ibased on their load characteristics, the top tension rod carries all of the ring beams and curtain walls below while the bottom ring beam only carries the weight of the bottom ring beam and unit panels. The value of the changes between each floor is represented by J.
  – The vertical displacement of the hoist point caused by imposed dead loads is represented by N.

– 幕墙及支撑钢结构安装顺序，环梁是由上而下安装顺序，幕墙单元板块安装顺序由下而上。
– 环梁安装顺序分析，对于最顶部环梁，下面每安装一层环梁，都引起最顶部环梁向下位移。如果安装第一层环梁引起吊点的竖向位移K1,安装第i层环梁，引起吊点的竖向位移为Ki。根据分析结论：
顶部第一层环梁的竖向位移：K=K1+K2+…K12
第二层环梁的竖向位移：K=K2+K3+…K12
第12层环梁的竖向位移：K=K12
– 幕墙安装分析，幕墙是由最下层向上安装，且此时环梁安装完毕，每安装一层单元板块，引起吊点竖向变形为Mi，幕墙安装完毕，同一个吊点，各层竖向变形一致，所以由安装幕墙引起各层的竖向位移为：
M=M1+M2+……+M12
– 拉杆的伸长变化分析，根据拉杆的受力特点，最顶部拉杆承担以下层所有的环梁及幕墙，最下层环梁仅承担最下层的环梁及环梁下层的单元板块重量，层间的变化值为J。
–附加恒载的引起吊点竖向位移值为N.
–环梁的定位标高调整原则
预调高值为安装环梁的竖向值S=K+J+M+N

幕墙支撑钢结构自重竖向变形
（见表1）

幕墙自重竖向变形
（见表2）

幕墙预调高设计如下
（见表3）

结论
土建梁不均匀变形分析找出各个挂点的位移量，施工中根据不同的工况进行分析计算，绘制曲线图如下：（见图10）

BIM应用

BIM的全称是Building Information Modeling。BIM的技术核心是一个由计算机三维模型所形成的数据库，不仅包含了建筑师和建筑幕墙工程师的设计信息，而且可以容纳从设计到建成使用，甚至是使用周期终结的全过程信息，并且各种信息始终是建立在一个建筑幕墙三维模型数据库中(见图11）。

BIM在外幕墙系统中的应用
结合BIM应用的需要，我们基于不同的软件平台创建BIM模型，包括犀牛软件和REVIT软件的等。

目前为止，我们在外幕墙的主要BIM应用包括：

- 外幕墙与各专业之间的碰撞检查
  上海中心大厦外幕墙支撑钢结构与外幕墙之间空间很小，通过BIM模型能有效检查外幕墙与支撑钢结构之间的相对关系，基于碰撞检查功能，将可能存在的干涉情况在深化设计阶段预先解决掉。

- 基于BIM模型的加工出图
  基于Rhino + Grasshopper创建的BIM模型，将幕墙单元构件模型与建筑原始模型参数链接，从而快速准确的生成每一个不同单元板块的详细单元模型文件。将这些模型文件拆解标注，即转换为加工图纸。整个流程直观，不易出错，准确度高（见图12）。

- 基于BIM的信息化加工
  采用了基于BIM的信息化加工，从CAD加工图转换至设备开始加工，中间步骤约3~5分钟。上海中心大厦外幕墙7、8、9层约4百多件钢牛腿，基本无一件相同，约花半个月时

Zone 2 Curtain Wall Construction Phases 2区幕墙施工阶段		Before Construction 施工前	Curtain Wall Support Construction Phases 幕墙支撑施工阶段													
		幕墙支撑施工前 Curtain Wall Support Before Construction	幕墙支撑 第1层 Curtain Wall Support Level 1	幕墙支撑 第2层 Curtain Wall Support Level 2	幕墙支撑 第3层 Curtain Wall Support Level 3	幕墙支撑 第4层 Curtain Wall Support Level 4	幕墙支撑 第5层 Curtain Wall Support Level 5	幕墙支撑 第6层 Curtain Wall Support Level 6	幕墙支撑 第7层 Curtain Wall Support Level 7	幕墙支撑 第8层 Curtain Wall Support Level 8	幕墙支撑 第9层 Curtain Wall Support Level 9	幕墙支撑 第10层 Curtain Wall Support Level 10	幕墙支撑 第11层 Curtain Wall Support Level 11	幕墙支撑 第12层 Curtain Wall Support Level 12	幕墙支撑 第13层 Curtain Wall Support Level 13	由支撑产生不均匀位移 Nonuniform Displacement Due to the Support
悬挂点位移 Suspended Point Displacement	1	0.0	0.5	1.3	2.1	3.1	4.1	5.1	5.9	6.8	7.6	8.5	9.3	10.2	11.4	11.4
	2	0.0	0.5	1.2	1.8	2.6	3.5	4.3	4.9	5.6	6.2	6.9	7.5	8.2	9.4	9.4
	3	0.0	0.5	1.1	1.7	2.5	3.3	4.1	4.7	5.3	5.9	6.5	7.1	7.7	8.9	8.9
	4	0.0	0.4	0.8	1.2	1.8	2.5	3.1	3.5	3.9	4.3	4.7	5.1	5.5	6.2	6.2
	5	0.0	0.2	0.4	0.6	1.0	1.3	1.7	1.9	2.1	2.3	2.5	2.6	2.8	3.2	3.2
	6	0.0	0.4	0.8	1.2	1.8	2.4	3.0	3.4	3.9	4.3	4.7	5.2	5.6	6.4	6.4
	7	0.0	0.4	0.9	1.4	2.1	2.9	3.6	4.1	4.6	5.1	5.7	6.2	6.8	7.7	7.7
	8	0.0	0.5	1.2	1.8	2.7	3.6	4.5	5.2	5.9	6.6	7.3	8.1	8.8	9.9	9.9
	9	0.0	0.7	1.8	2.9	4.2	5.5	6.8	7.9	9.1	10.2	11.3	12.5	13.6	15.3	15.3
	10	0.0	0.7	1.6	2.5	3.6	4.6	5.7	6.6	7.5	8.4	9.3	10.3	11.2	12.7	12.7
	11	0.0	0.3	0.5	0.8	1.3	1.8	2.3	2.6	2.9	3.2	3.5	3.9	4.2	4.8	4.8
	12	0.0	0.4	0.8	1.2	1.8	2.4	3.0	3.4	3.8	4.2	4.6	5.1	5.5	6.3	6.3
	13	0.0	0.2	0.5	0.7	1.1	1.5	1.9	2.2	2.4	2.7	2.9	3.2	3.4	3.9	3.9
	14	0.0	0.3	0.5	0.8	1.3	1.7	2.2	2.5	2.7	3.0	3.3	3.5	3.8	4.3	4.3
	15	0.0	0.7	1.5	2.4	3.5	4.5	5.6	6.5	7.3	8.2	9.1	10.0	10.9	12.4	12.4
	16	0.0	0.7	1.7	2.8	4.1	5.3	6.6	7.7	8.8	9.9	11.0	12.1	13.2	14.8	14.8
	17	0.0	0.3	0.9	1.4	2.1	2.9	3.6	4.2	4.7	5.3	5.9	6.4	7.0	7.8	7.8
	18	0.0	0.7	1.5	2.3	3.3	4.2	5.2	6.0	6.8	7.6	8.4	9.3	10.1	11.5	11.5
	19	0.0	0.3	0.7	1.1	1.7	2.3	2.9	3.3	3.8	4.2	4.6	5.0	5.4	6.2	6.2
	20	0.0	0.2	0.4	0.6	1.0	1.4	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.3	3.3
	21	0.0	0.4	0.9	1.4	2.1	2.9	3.6	4.1	4.5	5.0	5.5	6.0	6.5	7.4	7.4
	22	0.0	0.4	0.9	1.4	2.1	2.9	3.6	4.1	4.7	5.2	5.7	6.3	6.8	7.8	7.8
	23	0.0	0.4	0.8	1.3	1.9	2.6	3.2	3.7	4.1	4.6	5.1	5.5	6.0	6.8	6.8
	24	0.0	0.6	1.6	2.7	3.9	5.2	6.4	7.5	8.5	9.6	10.7	11.8	12.9	14.3	14.3
	25	0.0	0.3	0.9	1.4	2.2	3.1	3.9	4.5	5.1	5.7	6.3	7.0	7.6	8.5	8.5

Table 1. Curtain wall support's vertical deformation during construction (Source: Yuanda Group)
表1. 幕墙支撑施工阶段竖向变形（出自：远大计算书）

Curtain Wall Panel Construction Phases 幕墙板块施工阶段													
幕墙板块第1层 Curtain Wall Panel Level 1	幕墙板块第2层 Curtain Wall Panel Level 2	幕墙板块第3层 Curtain Wall Panel Level 3	幕墙板块第4层 Curtain Wall Panel Level 4	幕墙板块第5层 Curtain Wall Panel Level 5	幕墙板块第6层 Curtain Wall Panel Level 6	幕墙板块第7层 Curtain Wall Panel Level 7	幕墙板块第8层 Curtain Wall Panel Level 8	幕墙板块第9层 Curtain Wall Panel Level 9	幕墙板块第10层 Curtain Wall Panel Level 10	幕墙板块第11层 Curtain Wall Panel Level 11	幕墙板块第12层 Curtain Wall Panel Level 12	幕墙板块第13层 Curtain Wall Panel Level 13	由板块产生不均匀位移 Nonuniform Displacement Due to the Panel
12.5	13.5	14.5	15.6	16.6	17.6	18.7	19.7	20.7	21.7	22.6	23.6	24.6	13.2
10.4	11.4	12.3	13.3	14.3	15.3	16.2	17.2	18.2	19.2	20.1	21.0	22.0	12.6
10.0	11.0	12.0	13.1	14.1	15.1	16.2	17.2	18.2	19.2	20.1	21.1	22.1	13.2
6.9	7.5	8.2	8.9	9.5	10.2	10.9	11.5	12.1	12.8	13.5	14.1	14.8	8.6
3.5	3.8	4.1	4.4	4.7	5.0	5.3	5.6	5.9	6.2	6.5	6.9	7.2	4.0
7.1	7.8	8.5	9.2	9.9	10.6	11.3	12.0	12.7	13.4	14.0	14.7	15.3	8.9
8.5	9.3	10.1	10.9	11.7	12.5	13.3	14.1	14.8	15.6	16.4	17.1	17.9	10.2
10.8	11.7	12.7	13.6	14.5	15.4	16.3	17.2	18.2	19.1	20.0	20.8	21.7	11.8
16.7	18.2	19.6	21.1	22.5	23.9	25.3	26.7	28.1	29.6	30.9	32.3	33.7	18.4
14.1	15.5	16.8	18.2	19.6	20.9	22.3	23.6	25.0	26.3	27.6	28.9	30.2	17.5
5.3	5.8	6.4	6.9	7.4	7.9	8.4	8.9	9.4	9.9	10.4	10.9	11.4	6.6
7.1	7.7	8.4	9.1	9.8	10.5	11.1	11.8	12.5	13.1	13.7	14.3	14.9	8.6
4.3	4.7	5.2	5.6	6.0	6.4	6.8	7.2	7.6	8.0	8.3	8.7	9.0	5.1
4.8	5.2	5.7	6.1	6.6	7.1	7.6	8.0	8.4	8.9	9.3	9.7	10.1	5.8
13.7	15.1	16.5	17.8	19.2	20.5	21.8	23.2	24.5	25.8	27.1	28.4	29.7	17.3
16.2	17.6	19.0	20.4	21.8	23.2	24.6	25.9	27.3	28.6	30.0	31.3	32.6	17.8
8.6	9.3	10.0	10.7	11.4	12.1	12.8	13.5	14.2	14.9	15.6	16.3	17.0	9.2
12.8	14.1	15.3	16.6	17.8	19.1	20.3	21.6	22.8	24.0	25.2	26.4	27.6	16.1

Table 2. Curtain wall unit's vertical deformation during construction (Source: Yuanda Group)
表2. 幕墙单元施工阶段竖向变形（出自：远大计算书）

Curtain Wall Panel Construction Phases 幕墙板块施工阶段													
幕墙板块第1层 Curtain Wall Panel Level 1	幕墙板块第2层 Curtain Wall Panel Level 2	幕墙板块第3层 Curtain Wall Panel Level 3	幕墙板块第4层 Curtain Wall Panel Level 4	幕墙板块第5层 Curtain Wall Panel Level 5	幕墙板块第6层 Curtain Wall Panel Level 6	幕墙板块第7层 Curtain Wall Panel Level 7	幕墙板块第8层 Curtain Wall Panel Level 8	幕墙板块第9层 Curtain Wall Panel Level 9	幕墙板块第10层 Curtain Wall Panel Level 10	幕墙板块第11层 Curtain Wall Panel Level 11	幕墙板块第12层 Curtain Wall Panel Level 12	幕墙板块第13层 Curtain Wall Panel Level 13	由板块产生不均匀位移 Nonuniform Displacement Due to the Panel
6.9	7.5	8.2	8.9	9.5	10.2	10.9	11.5	12.2	12.9	13.5	14.1	14.8	8.6
3.6	3.9	4.2	4.6	4.9	5.2	5.5	5.8	6.1	6.4	6.7	7.1	7.5	4.2
8.2	9.0	9.8	10.6	11.3	12.1	12.9	13.7	14.5	15.2	16.0	16.8	17.6	10.2
8.6	9.5	10.4	11.3	12.2	13.1	14.0	14.8	15.7	16.6	17.4	18.2	19.1	11.3
7.6	8.3	9.0	9.7	10.4	11.1	11.8	12.5	13.2	14.0	14.7	15.4	16.1	9.3
15.6	16.9	18.2	19.5	20.7	22.0	23.3	24.6	25.8	27.1	28.2	29.4	30.6	16.3
9.3	10.0	10.8	11.5	12.3	13.0	13.8	14.5	15.2	15.9	16.6	17.3	18.0	9.5

Table 2 (continued). Curtain wall unit's vertical deformation during construction (Source:Yuanda Group)
表2. （接上页）幕墙单元施工阶段竖向变形（出自：远大计算书）

Suspended Point Displacement Analysis 1号吊点的位移分析表								
Level 层数	Design Elevation 设计标高	Steel Structure Installation Displacement 安装钢结构位移	Curtain Wall Installation Displacement 安装幕墙位移	Imposed Dead Load 附加恒荷载	Imposed Live Load 附加活荷载	Tensile Extension Value 拉杆伸长量	Required Elevation Adjustment 需要调整标高	Elevation Prior to Curtain Wall Installation 安装幕墙前标高
设备层下环梁	92.34	-11.40	-13.20	-7.70	0.00	0.00	32.30	20.90
12层	87.84	-10.90	-13.20	-7.70	0.00	-2.02	33.82	22.92
11层	83.34	-10.10	-13.20	-7.70	0.00	-3.83	34.83	24.73
10层	78.84	-9.30	-13.20	-7.70	0.00	-5.63	35.83	26.53
9层	73.34	-8.30	-13.20	-7.70	0.00	-7.02	36.22	27.92
8层	69.84	-7.30	-13.20	-7.70	0.00	-8.20	36.40	29.10
7层	65.34	-6.30	-13.20	-7.70	0.00	-9.07	36.27	29.97
6层	60.84	-5.30	-13.20	-7.70	0.00	-9.69	35.89	30.59
5层	56.34	-4.60	-13.20	-7.70	0.00	-9.94	35.44	30.84
4层	51.84	-3.80	-13.20	-7.70	0.00	-11.09	35.79	31.99
3层	47.34	-2.90	-13.20	-7.70	0.00	-11.02	34.82	31.92
2层	42.84	-2.10	-13.20	-7.70	0.00	-10.77	33.77	31.67
1层	38.34	-1.20	-13.20	-7.70	0.00	-10.23	32.33	31.13

Table 3. Curtain wall design value (Source: Yuanda Group)
表3. 幕墙预调高设计值（出自：远大计算书）

– The principles of adjustment in ring beam coordination in elevation.
The preliminary height adjustment is the vertical displacement value of ring beam installations. S=K+J+M+N

Vertical Displacement Caused by Self-Weight of the Curtain Walls' Steel Support Structure

(see Table 1)

Vertical Displacement Caused by Self-Weight of the Curtain Walls

(see Table 2)

Preliminary Height Adjustments of Curtain Wall Design

(see Table 3)

Conclusion

the displacement value of all hoist points were identified through structural beam nonuniform deformation analysis and the consideration of different construction conditions, a line diagram has been drawn as follows (see Figure 10).

BIM Applications

BIM is an abbreviation for Building Information Modeling. Its core technology is a database of computer-generated three-dimensional

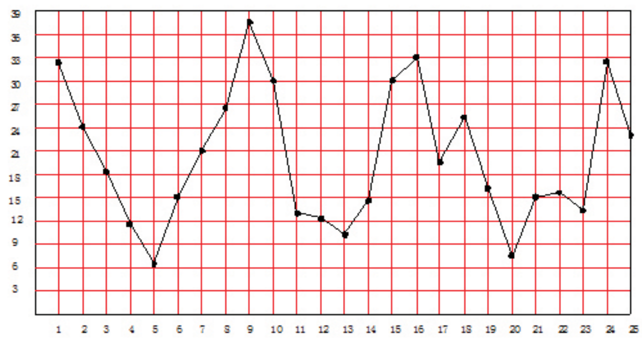

Figure 10. Graph analysis for curtain wall hoisted point deformations (Source: Yuanda Group)
图10. 幕墙挂点变形分析曲线图（出自：远大计算书）

间加工完成。保证精度的同时，效率提升约40%。

- 施工进度模拟
  BIM是拥有全部信息的数字模型，可以将施工模拟变成一个真正可见的现实，并给每个构件加上时间、信息，按照施工方案进行模拟，不断优化施工方案。我们采用Revit与MS Project和Autodesk Navisworks等软件结合而进行的施工模拟等，能够达到优化进度、缩短工期的效果(见图13）。
- 施工设施模拟

models. Not only does the database include design information from architects and curtain wall engineers, but it also contains all the information of the overall procedure starting from design process to its completion and operation, even until the end of its full life cycle. All of the information is generated from one three-dimensional modeling database of the architectural curtain walls (see Figure 11).

BIM Applications in Exterior Curtain Wall System

Combined with the need for BIM application, BIM models are created based on different software platforms such as Rhino, Revit, etc.

So far, the main BIM applications in the exterior curtain walls include:

- Collision Detection between Exterior Curtain Walls and Other Specialties
  In the Shanghai Tower, the space between the exterior curtain wall and its supporting steel structure is very small. The BIM models can effectively analyze the relative relationship between the exterior curtain wall and its steel support structure. Based on the collision detection, they can also pre-eliminate potential interferences in later design stages.
- BIM Model-Based Processed Drawings
  The accurate creation of every unit module of the detailed model is based on the model generated in Rhino and Grasshopper by connecting a curtain wall unit component model with a model parameter of the original model. The drawings can be easily converted after disassembling and labeling the model files individually. The whole process is simple, straightforward, and less error-prone (see Figure 12).
- BIM-Based Information Processing
  Utilizing information-based processing from BIM, transferring CAD working drawings to equipment machining takes roughly 3–5 minutes. There are approximately 400 unique pieces of steel corbels at levels 7, 8 and 9 in the Shanghai Tower which took about 2.5 weeks to complete machining. This increased the efficiency by up to 40 percent in addition to ensuring the accuracy at the same time.
- Simulation of the Construction Progress
  BIM is a digital model with all types of information. It can truly make the simulation happen in reality. Time and information can be added to the component and simulate the construction progress according to the construction plan with continuous optimization. The construction simulation integrated with Revit, MS Project and Autodesk Navisworks can efficiently optimize the progress and shorten the construction period (see Figure 13).
- Simulation of the Construction Method
  Based on the site construction operating condition model and construction equipment model, one can efficiently test the feasibility of site construction method and optimize the construction plan. As the construction platform shows above, a reasonable position of the platform can be established through the BIM model to ensure no conflicts between panel access and suspended rods.
- Design Revision Implications through BIM
  The graphics below illustrate a quick simulation of the screen appearance effect from the inside of the mechanical floor to confirm whether the final design modifications meets the requirements of the owner and architect through visualization tools (see Figure 14).

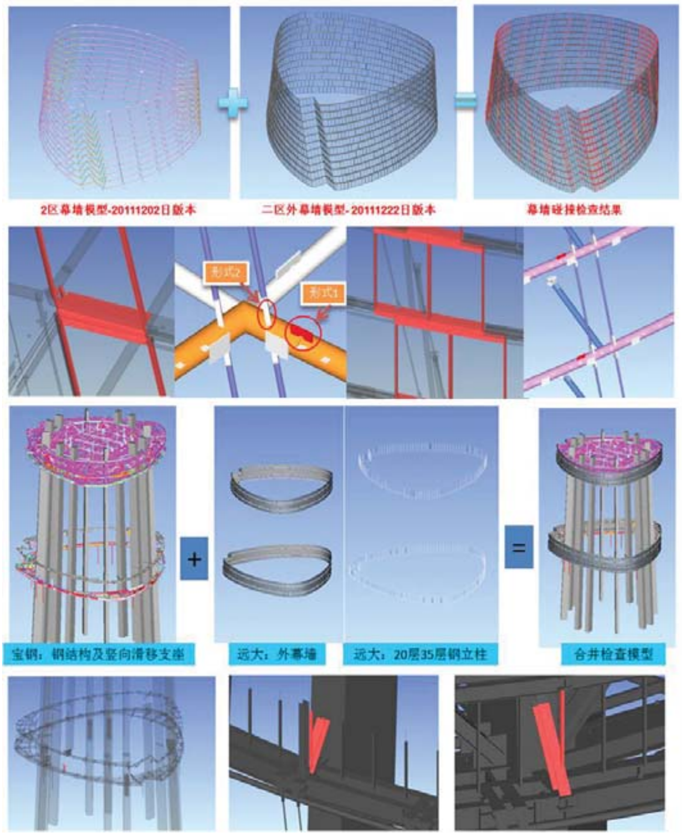

Figure 11. Screenshot from the collision detections of the exterior curtain wall(Source: Yuanda curtain wall BIM report)
图11. 外幕墙与其他专业碰撞检查截图（出自：远大外幕墙BIM报告）

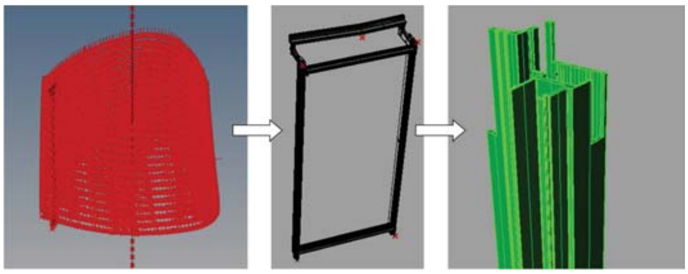

Figure 12. Creation of the unit model based on the software (Source: Yuanda curtain wall BIM report)
图12. 基于软件创建单元加工模型（出自：远大外幕墙BIM报告）

基于创建的现场施工工况模型以及施工机具模型，可以有效检查包括现场施工方法的可行性等，优化施工方案。如上图所示的施工平台，通过BIM模型确定了平台搭设的合理位置，确保单元板块进出时不会与吊杆等干涉。

- 基于BIM模型的设计变更效果确认
  可视化实现，如下图所示，通过对设备层内侧防鸟网效果的快速模拟，确定最终设计变更是否满足业主和建筑师要求（见图14）。

结论

针对上海中心外幕墙几何形状复杂：扭转、悬空、跨多层（15层之多）、板块种类众多幕墙，经认真分析其特点，总结类似大型项目实施经验，选择了以下技术路径，并系统性思考与系列足尺试验研究结合，采用了一些新技术、新工艺、新材料，落实了高标准技术解决方案。

采用工厂化程度更高的整体单元幕墙，对上海中心这样超大型、超高层建筑顺利实施意义重大。随着工业化水平的提高和劳动力

Conclusion

Due to the complexity of the curtain wall's geometric shape of the Shanghai Tower that are twisting, suspending, and spanning through multiple levels (fifteen or more) and the various curtain wall panel types, the following technology methods were chosen after analyzing its characteristics and summarizing the experiences from similar projects. These methods utilize the integration of systematic thinking, a series of full-scale performance tests, and the application of new technology, new crafts, and new materials to finalize high standard solutions.

Utilizing accurately manufactured and integrated curtain wall units are critical for the implementation success for supertall buildings at a large scale such as the Shanghai Tower. As industrialization continues to improve and difficulties in labor force management continue to increase, the level of curtain wall unit production is becoming one of the most important factors for its quality. Even though the design and manufacture of panels is difficult, in terms of quality control and performance, its advantages are certainly obvious. Therefore, after comparing it with other options, it was eventually decided upon.

Building performance and curtain wall reliability can be improved by integrating the design of the system in coordination with the rest of the building.

- The integration of the supporting steel ring beams and curtain walls (nonuniform settling): since the supporting steel ring beams hang from the main cantilever truss, and the main structural trusses have varying stiffness at each hoist point, a deformation will occur which will vary based on its load action (for example: settling deformation). Settling can be mitigated through raising the intallation height of the hoist points and curtain wall connections, and increasing the curtain wall stack joint height value to gradually absorb the nonuniform settling.
- Integration of LEDs and curtain wall system (Space).
- Integration of anti-condensation hot water pipes and curtain walls (installation space clearance coordination, construction sequence, etc.).
- Integration of BMU and the curtain walls.
- Combination of wind power generation and curtain walls: by embodying green building concepts of wind power generation equipment and its disturbance on curtain walls. The vibration of connected curtain walls will increase as well, therefore, an upgrade to a more rigid structural system can be utilized.

For complex geometrically-shaped curtain walls, the application of BIM technology takes advantage of visualization, an increase in design efficiency, a decrease in error rate, coordination improvements across specialties, and an increase in document transmission speed. It is capable of achieving BIM associated design and control, minimizing its uncertainty, and improving its controllability in design, fabrication, measurements, pre-assembly, installations, and future maintenance planning. In terms of solving technical problems of complex geometrically shaped curtain walls, BIM will certainly be the future trend in this field due to its unique advantages.

The Shanghai Tower has "flexible" curtain wall characteristics that can exhibit accurate design adjustments and dynamic calculation updating in medium- and large-scale models. These are the keys to high performance designs. On one hand, the utilization of continuously tunable and scalable systems meets the requirement of reliable high-precision designs. Experiments have verified that it also meets

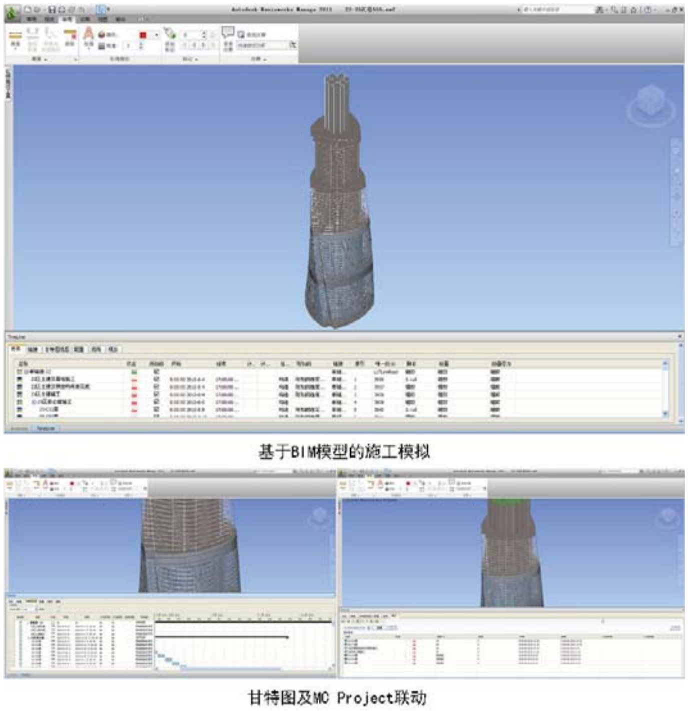

Figure 13. Screenshot of 4D construction progress simulation animation (Source: Yuanda curtain wall BIM report)
图13. 4D施工进度模拟动画截图（出自：远大外幕墙BIM报告）

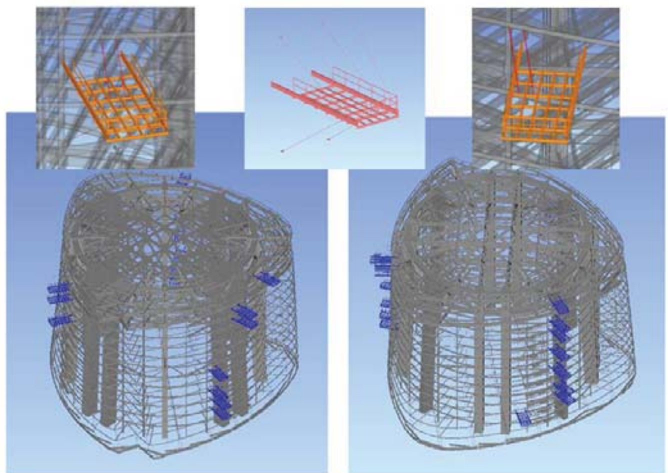

Figure 14. BIM model of the curtain wall construction on steel planes (Source: Yuanda curtain wall BIM report)
图14. 幕墙施工钢平台BIM模型（出自：远大外幕墙BIM报告）

管理难度的加大，幕墙工厂化程度成了影响幕墙品质的重要因素之一。整体单元幕墙尽管在设计、制造方面难度大、要求高，但在控制品质、保证性能方面有其优势，故最终对比优劣后，选择了整体单元体系。

采用集成设计理念，使幕墙和相关配套设计更加协调，以求建筑乃幕墙本身性能更可靠。

- 支撑钢环梁与幕墙集成（不均沉降）：由于支撑钢环梁悬挂于主体悬挑桁架上，具有主体结构特性，而且每一处吊点处主体桁架刚度不同，从而其荷载作用下变形（例如：下沉变形量）也不同，只能通过吊点、幕墙连接件调高安装和提高幕墙上下插入量等手段，逐级消化不均匀沉降对幕墙产生的不利影响。
- LED与幕墙集成（空间）。
- 防结露热水管与幕墙集成（协调安装空间、作用、施工顺序等）。

the requirements of the adaptation of structural displacements under integrated loads of wind, temperature, and earthquakes. On the other hand, dynamic calculations correspond to different work conditions which include construction conditions that can guide the whole installation process.

After a series of experiments and research, the double suspended platform system and associated tracked cranes were developed and planned to respond to the twisting and suspending curtain walls which improves construction conditions. As a supertall project, it is the same as other great buildings. A rational technological strategy is a good start for project implementation. However, due to the uniqueness of the geometrically shaped curtain walls in the Shanghai Tower, selecting a proper technology strategy is not enough. During the construction process, scientific and efficient management and strict monitoring and adjustment of measurements must be done to deliver a qualified curtain wall.

It will be a glorious but arduous undertaking!

Acknowledgements

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- BMU与幕墙集成。
- 风力发电与幕墙结合：体现绿色建筑设计理念的风力发电装置对幕墙风环境带来扰动，同时增加与它相连幕墙震动，为此采用增强的防松构造体系。

针对复杂几何形状幕墙，采用BIM技术，利用其可视化、可提高设计效率、降低错误率、改善不同专业间协调性和加快文件传递速度等优势，在设计、制作、测量、预拼装、安装和未来维护策划方面运用，实现了BIM联动设计及控制，降低不确定性，提高可控性。在复杂几何形状幕墙技术问题处理方面，BIM技术具有独特优势，将是这领域内发展方向。

上海中心外幕墙突出特点是“柔”，这决定了高性能设计中大尺度而精准调整设计、动态计算监控是成为关键。为此一方面，采用连续可调和长度可分级连接件系统，满足高精度和可靠性能要求。并通过试验验证了，在温度、风荷载和中震等荷载与作用综合作用下构造变位适应能力满足要求。另一方面，进行包括施工工况在内的不同工况对应的动态计算，实现全过程指导安装。

经认真研究，开发应用适用于扭转、悬空幕墙的滑移双层吊蓝系统和配套轨道式吊机，为灵活方便的施工创造条件。作为超大型项目，跟其他伟大的建筑一样，合理的技术路线是项目实施的良好开端。但由于上海中心外幕墙几何形体极富个性，选择合理的技术路线是不够的，在幕墙施工过程中，必须进行科学有效地管理、严格测量监控和精心调整，才能交付精品幕墙。

这将是光荣而艰巨的任务！

鸣谢

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