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The Integrated Smart Design Technologies for Tall Building Structural Design | 集成化智能设计技术在超高层结构设计中的应用

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Yu Cheng has been involved in the development of many landmark high-rise building projects, including the 528-meter China Zun Tower, the 200-meter Beijing CBD Z3 Tower, and the Tianjin Kerry Center. Cheng is familiar with Chinese Code, with experience in tall building, composite structure, and seismic design, as well as construction.

他参与过诸多地标性建筑包括528米的中国尊、200米的北京核心区Z3项目和天津嘉里中心等。他熟悉中国规范并有丰富的超高层、组合结构设计施工和抗震设计经验。

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Dorothee在复杂几何和超高层方面拥有丰富的经验，从参数模型的设计到结构的分析。她致力于各种类型结构的设计工作，包括钢材和玻璃组合建筑的结构，复合材料的高层塔楼，并善于利用多种不同建筑材料，例如纺织膜结构、玻璃、钢、混凝土和木材。

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然张在悉尼大学获得可持续设计专业设计科学硕士学位。作为项目经理在集成化智能设计工具中的计算机优化及可视化模块中发挥着重要作用。

Abstract | 摘要

A series of integrated smart design tools has been developed to satisfy different design requirements and to achieve an optimal balance between economics and safety. The series of tools combines the functions of parametric modelling, optimization modules, and visualization tools based on the same platform. Through parametric design, the design process as a whole, which includes geometric studies, structural analyses, drawing production, and BIM modelling, are automated. Embedded within the workflow, the structural optimization module enables engineers to efficiently find the optimal distribution of structural elements. Then, a web-based visualization tool and an augmented reality (AR) visualization tool are used so that post-design data can be shown through diagrams to facilitate further design and coordination. These integrated smart design tools have already been successfully applied to several supertall building projects, with heights ranging from 200 meters to 500 meters and beyond. This paper describes the application of the tools in different high-rise buildings and values added to all the participants.

Keywords: Optimization, Parametric Design, Seismic, Structural Engineering, Supertall

为达到结构设计经济性与安全性的平衡，一套集成了参数化建模、优化模块以及可视化功能的智能设计工具被开发出来。其中参数化设计实现了几何研究、结构分析、图纸生成和BIM模型建立等整套设计过程的自动化。流程中嵌入的结构优化模块使工程师可以在设计过程中高效的寻找结构构件的最佳布置方案。基于网页的可视化程序和虚拟现实软件可以将海量数据图形化，从而进一步方便数据后处理以及设计协调。整套集成工具被成功应用在高度从200到500米不等以及更高的超高层项目中。本文将详细介绍其在超高层项目中的应用，以及为项目各参与方带来的附加价值。

关键词：最优化、参数化设计、地震、结构工程、超高层建筑

Background

Nowadays, more and more complex buildings, such as high-rise towers or long-span structures, are springing up all over the world. According to CTBUH statistics, the annual number of completed 200-meter-plus towers has increased from 18 (2004) to 100 (2014) in the last 10 years; of those 200-meter-plus towers completed in 2014, 78 percent are located in the megacities of Asia.

To address the challenges of achieving an optimal and sustainable design during the urbanization process of megacities, some Integrated Smart Design Tools were gradually developed by Arup from 2011 to 2015, by combining structural parametric modelling modules, structural optimization processes, and visualization tools. These tools were applied throughout the entire process of development for the China Zun Tower and several other tall buildings and complex structures. An automatic modelling of structural geometry and analysis models, as well as automated optimization based on multiple pre-set targets, were realized.

背景介绍

如今世界各地正在涌现出越来越多的超高层或大跨度等复杂建筑。根据CTBUH统计，自2004至2014的十年间，每年建成的高度在200米以上的建筑数量从18栋（2004年）增加至100栋（2014年），其中2014年建成的100个项目中有78%位于亚洲的巨型城市中。

为应对城市化进程中面临的挑战，实现最优且可持续的设计，自2011年至2015年，奥雅纳开发的集成化智能设计工具逐步发展成型，其中包括参数化建模模块、结构优化程序以及可视化工具。该智能设计工具在"中国尊"塔楼及诸多其他超高层和复杂结构的设计过程中有着成功的应用，实现了自动化建立几何模型或分析模型、以及多重预设目标下的结构优化等目标。

集成化智能设计工具简介

集成化智能设计工具包括三个自主研发的部分：参数化设计、计算机设计优化和可视化功能。该工作流程（图1）将原有人

Introduction of the Integrated Smart Design Tools

The Integrated Smart Design Tools encompass three major parts of the in-house developed modules which realize the functions of Parametric Design, Computational Design and Optimization (CDO), and Visualization. This working flow (Figure 1) streamlines previously manual/semi-manual work into an automated production process; therefore, design working efficiency is significantly increased.

Parametric Design

Rather than building up a complicated structural analysis model with tens of thousands of variables from engineers, parametric design uses high-level geometric information and structural system configurations as key parameters to generate the structural model automatically. Any changes to these key parameters will significantly change the output structural models and thus, engineers are able to explore a large variety of options. Workflow is integrated with the parametric design software Rhinoceros and Grasshopper, as well as commercial structural design software, such as ETABS and GSA. Since Rhinoceros lacks structural information and the structural design software is short of parametric modeling capabilities, a series of tools (Designlink, Salamander, Etabswriter, and others) were developed to fill in the gaps: Designlink is a data presentation layer describing all of the structural information (like joints, members, sections, materials, and loading); Salamander is a Rhinoceros plugin that sets up a top-down decomposition process within certain parameters; and Etabswriter is responsible for writing model files for these softwares and reading analysis results back.

Once the architectural massing is confirmed, the patterns of structural configuration – in the format of coded parameters – can be applied to create the centerline structural geometric model. It is, in turn, assigned with loading and material/section information, also in the format of coded parameters in accordance with the actual building layout. The complete structural model information is then exported to commercial analytical software through the internally developed interoperable platform and model conversion tools to discover structural behaviors.

Structural Optimization

A structural optimization module is added in order to automatically find optimal lateral stiffness distributions (Figure 2). To keep the overall architectural massing unchanged, structural systems and centerlines are determined from previous parametric designs.

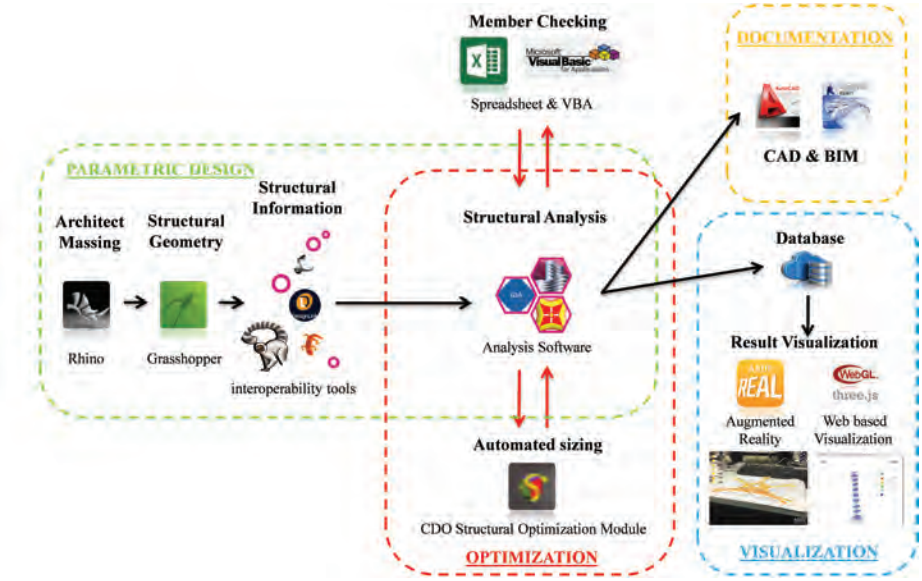


Figure 1. Workflow of the integrated smart design tools (Source: Arup)
图1. 集成化智能设计工具工作流程（来源：奥雅纳工程顾问）

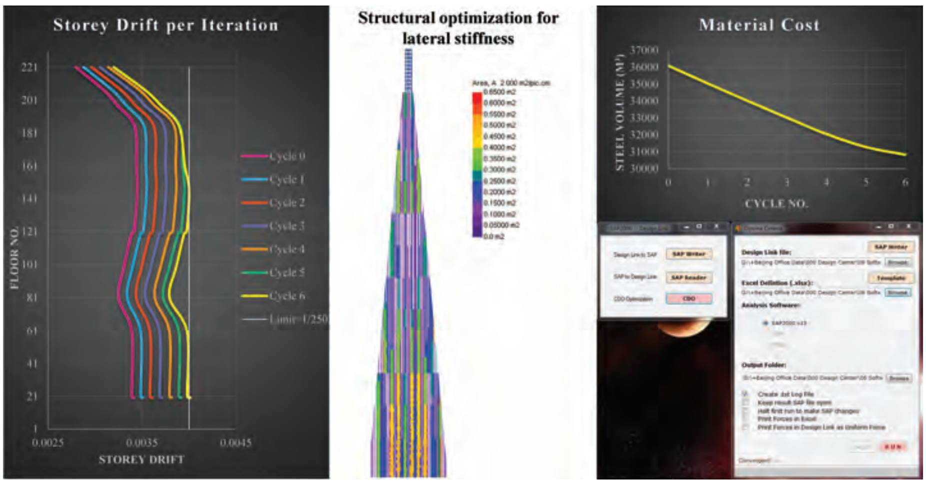


Figure 2. Structural optimization for optimal lateral stiffness (Source: Arup)
图2. 为最优侧向刚度进行结构优化（来源：奥雅纳工程顾问）

工或半人工的工作整合为一套自动化设计流程，极大地提高了设计工作效率。

参数化设计

相较于由工程师手动建立包含成千上万个变量的复杂分析模型，参数化设计将高层次几何信息与结构体系设置作为关键参数，自动化生成结构模型。改变任意参数都可对输出结构产生变化，因此工程师有更大的空间对不同比选方案进行探索。该流程集成了参数化设计软件犀牛（Rhino）与Grasshopper，以及商业设计软件，如ETABS和GSA。犀牛软件缺少结构信息，而结构设计软件缺少参数化建模能力，为此开发出如下所述的一系列工具来弥补这个空挡：Designlink用来描述结构信息的表达层，结构信息包括节点、构件、截面、材料、荷载等；Salamander是犀牛插件，用于建立自上而下地将参数分解的过程。Etabswriter负责将模型文件读入这些软件，并导出分析结果。

一旦确认建筑外形和结构布置形式，并以参数化格式表示，则可以相应生成结构几何中线结构模型。随后依照建筑布局，再赋予荷载及材料/截面等信息。最后完整的结构模型将通过内部研发的文件转换平台导入到商业分析软件中，进而分析结构性能。

计算机设计优化

结构优化模块被进一步加入到此设计流程中以自动化寻找最优的侧向刚度分布（图2）。结构体系及结构中心线由参数化设计确定以保持建筑外形不变。根据预设的优化目标函数（如最小材料用量），以及多个约束条件（如侧向刚度或关键构件在规范要求下的承载力），全部结构构件基于最优准则算法通过多次迭代达到设定范围内的最优尺寸。高层建筑通常由侧向刚度控制，该模块可以有效帮助参数化建模生成的不同方案进行优化，然后再利用软件或电子表格进行构件强度复核。

可视化

参数化设计与优化通常生成大量数据。这些数据需要适合的可视化工具以便于数据的后处理和汇报给客户。基于WebGL three.js引擎研发的网页端可视化，可以将应变能密度、材料利用率等关键信息以数值/彩色云图形式进行展示。同时开发了基于IOS系统的增强现实技术的应用程序，

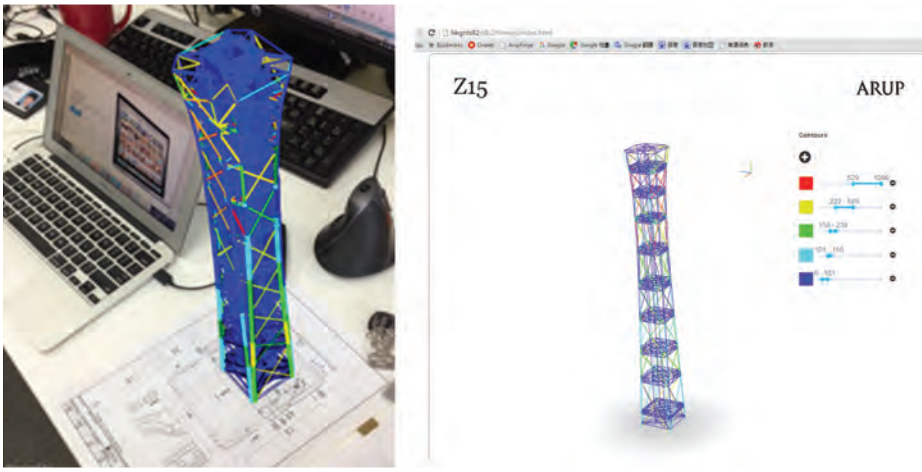


Figure 3. Augmented Reality (AR) visualization IOS app (Source: Arup)
图3. 增强现实（AR）可视化IOS应用程序（来源：奥雅纳工程顾问）

Given a pre-set optimization objective, such as minimal material cost, and multiple constraints, including lateral displacements or the capacity of key structural elements to comply with code's requirement, the dimensions of the whole structural members are sized in iterations based on the optimization algorithm "Optimal Criteria" method, within a given sizing range. Since the structural members of tall buildings are often dominated by the requirement of lateral stiffness, this module can effectively size the members for the various options generated by parametric modeling, together with strength checking data from other software or spread sheets.

Visualization

The parametric design and optimization processes normally generate massive amounts of data, requiring proper visualization tools for post-data analysis and the presentation to clients. Through a development based on webGL three.js 3-D engine, key information such as strain energy density or material utilization were enabled to allow for presentations by value/color contour in 3-D models through a webpage. An Augmented Reality (AR) IOS app was also developed to review the results on iphone/ipad's or other mobile devices (Figure 3).

The Application of the Integrated Smart Design Tools

Case Study of China Zun Tower

The 528-meter-tall Z15 Tower – also known as China Zun Tower – is located in the core area of Beijing's central business district. The façade shape of the tower was inspired by the imagery of a "Zun" – a traditional Chinese vessel for wine. The floor plan of the tower is square with filleted corners. The area of the floor plan contracts as the height increases, reaching its minimum at the upper mid-section of the building before increasing from this point up to the roof.

Architects adopted series of parameters to modify the geometric shape of the Tower parametrically. This provided the pre-condition of creating the smart design framework based on existing parametric geometric studies.

The Study of Megacolumn Geometry

The structural system of China Zun Tower is a dual lateral load resistant system (Figure 4), which consists of a perimeter frame with megacolumns, megabraces, transfer trusses, and a concrete central core with composite shear walls.

The positioning of the megacolumns is one of the most important factors in the structural system on this project. It has a dominant influence on the performance of the structure, and it also determines the position of all perimeter frame components which are closely related to the efficiency of building space usage.

There are four megacolumns from the basement raft to the seventh floor of the tower

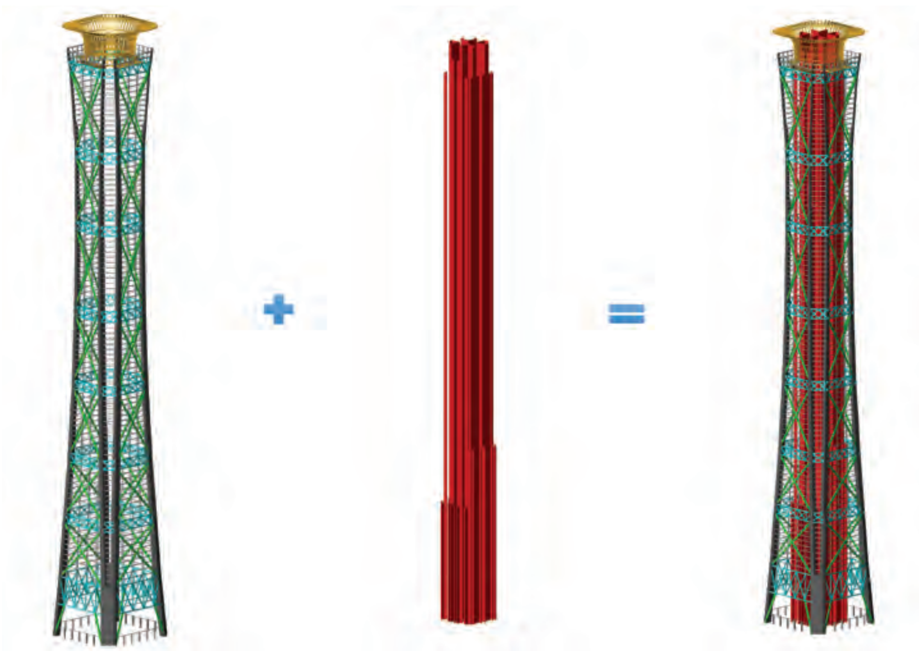


Figure 4. Dual lateral resisting structural system of China Zun Tower (Source: Arup)
图4. 中国尊的双抗侧力结构体系（来源：奥雅纳工程顾问）

工程师可在iphone/ipad或其他移动设备上展示结果（图3）。

集成化智能设计工具的应用

中国尊项目案例研究

528米高的Z15地块塔楼项目，也被称为中国尊，位于北京中央商务区的核心地带。塔楼幕墙形状的灵感源于中国传统酒器“尊”。塔楼楼层的平面为四角倒角的正方形。楼层面积沿高度逐渐缩进，在建筑中上部达到最小，在此之后楼层面积又逐步增加，直到楼顶。

建筑师根据一系列的几何参数对塔楼的几何外形进行参数化地改变。这为在已有参数化建模工具的基础上进一步发展智能化设计工具提供了先决条件。

巨型柱几何研究

中国尊的结构体系为双重抗侧力体系（图4），包括带有巨型柱、巨型斜撑和转换桁架的外框架，和采用型钢－混凝土组合结构的核心筒。

巨型柱的布局位置是整个结构体系中最重要的因素，对结构的性能起到决定性的影响。它决定全部外框构件的布局，而这些构件的位置与建筑空间的使用效率密切 相关。

设计中在底部基础筏板到塔楼七层的四个角布置了四个巨型柱。从八层直到塔楼顶层，这四个巨型柱分成八个。在设计巨型柱位置时主要考虑了以下建筑结构设计要求和施工因素：

- 结构设计要求巨型柱应尽可能贴近幕墙，从而提供最大的侧向刚度。特别是四个巨柱在塔楼底部的力臂对于塔

in each corner. From the eighth floor to the top of the tower, the four megacolumns split into eight parts. The positioning of the megacolumns was constrained by different demands from architectural and structural designs, and construction:

- In terms of structural design, the megacolumns should be as close as possible to the curtain wall in order to provide maximum lateral stiffness. Specifically, the lever arm of the four megacolumns at the bottom of the tower has a significant influence on the aspect ratio and the lateral load resisting performance of the tower.
- In order to reduce construction complexity, the sectional shape and centerline of the megacolumns should be as simple as possible. A curved megacolumn is constructed as a series of straight sections connected at intersections known as control points (Figure 5); by minimizing the number of these points, construction can be more efficiently facilitated.
- In terms of architectural design, the straight sections of megacolumns between the transfer trusses should keep a reasonable minimum distance from the slab edge to provide enough construction space for the installation of the curtain wall. Also, because the outer surface of the megabraces and the secondary frame columns is flush with the outer surface of the megacolumns, it was in the architects' interests to optimize the distance between the perimeter frame and the curtain wall as much as possible so that the usable floor space of the tower could be maximized (Figure 6).

In order to satisfy all of the previously mentioned demands, numerous options of megacolumn geometry were studied based on pre-set logic through parametric design. Pros and cons were carefully studied and weighed to reach the optimal balance between architectural requirement and structural performance, along with consideration of construction feasibility. The megacolumns were arranged in the following way:

- Twelve control points were set on each megacolumn centerline based on the center of mass of the sections forming the column up the height of the tower. Each centerline was kinked at the control points in order to fit the façade profile of the tower. The segments of the megacolumns between the control points were set straight (Figure 5).
- All of the control points in each of the megacolumns were set at the same elevation as the upper and/or lower chord members of the transfer trusses in order to balance the lateral force caused by their curvature. The options of setting one control point at each transfer truss or setting two control points at each transfer truss were compared. In order to reduce construction complexity and negate the lateral load issue noted above, the decision was made to set two control points on each transfer truss, only in the seventh floor zone. Through adjustment, the maximum kink angle β (Figure 5) in the megacolumn centerlines were also limited to six degrees for efficiency.
- In order to avoid the compound bending of the megacolumns, the control points in each centerline were positioned in a straight line in the plan, so that each centerline would only

楼的高宽比和抗侧性能有显著影响。

- 为减少施工复杂度，巨柱的截面形状和立面柱线应尽量简化。巨型柱弯曲的柱线由一系列直线拟合而成，每段柱线在控制点处相互连接并转折（图5），因此将这些控制点的数量降到最低将减少施工难度。
- 建筑设计要求巨柱在每个区段内的直线结构与弧线幕墙间保持合理的最小距离以满足幕墙安装的最要求。同时巨型斜撑和重力柱均与巨柱的外皮平齐，从使用角度上建筑师希望优化外侧结构与幕墙间的距离从而最大化室内的使用空间（图6）。

为满足以上要求，工程师基于不同的预设逻辑，对大量方案进行比较以达到建筑要求与结构性能的最优平衡点，同时满足施工可行性要求。根据比选，最终巨型柱布置如下：

- 巨型柱质心组成的柱线沿塔楼全高共设置12个几何截面形心控制点。柱

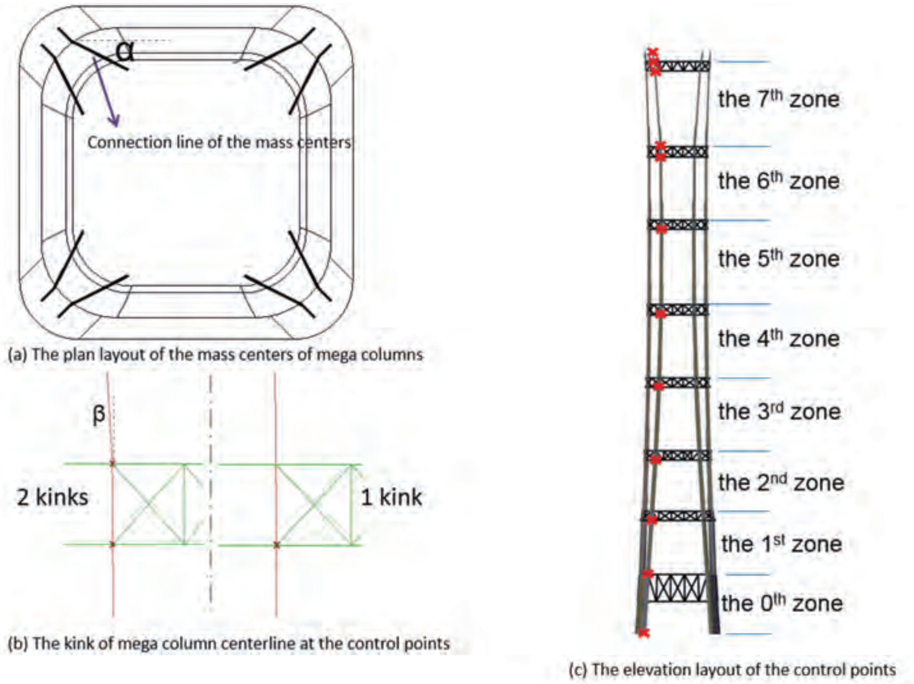


Figure 5. Positioning of the control points of the megacolumns (Source: Arup)
图5. 巨型柱控制点的位置（来源：奥雅纳工程顾问）

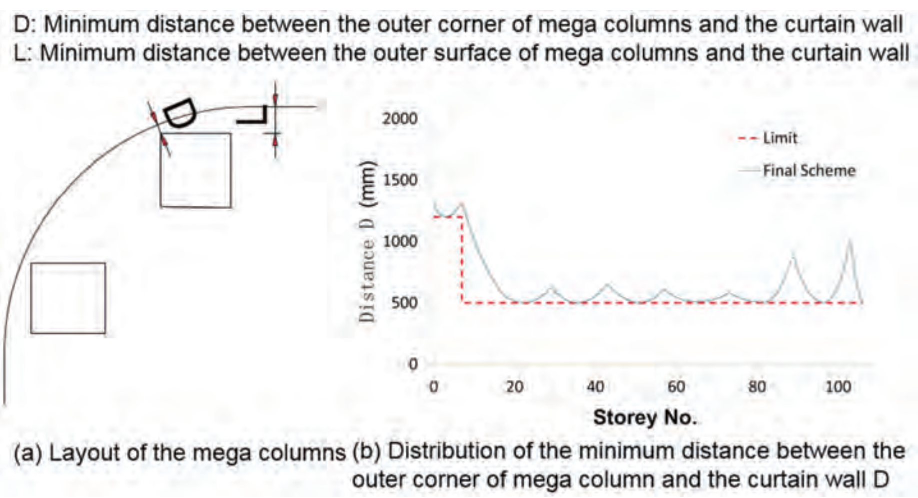


Figure 6. The minimum distance between megacolumns and the curtain wall (Source: Arup)
图6. 巨型柱与幕墙间的最小距离（来源：奥雅纳工程顾问）

Stage	Middle Stage			
Stage No.	Scheme 1	Scheme 2	Scheme 3	Scheme 4
Elevation				
Brief description Top width/Bottom Width	Initial model; 76m/70m	all sides of the tower plan with arch corners; 78m/69m	all sides of the tower plan are straight lines; 78m/70m	all sides of the tower plan are arcs; the fillet radius is increased; 78m/70m
1st Period (s)	7.75	7.745	7.723	7.788
Base shear (kN)	133,145	133,526	134,539	131,295
Shear/weight Ratio (Limit = 2.0%)	1.80%	1.80%	1.81%	1.78%

Figure 7. The structural performance of the four architectural schemes (Source: Arup)
图7. 四个建筑方案的结构性能（来源：奥雅纳工程顾问）

bend in a single plane. To optimize the performance of the structure and the usage ratio of the building area, the centerline angle (α) in the plan of the tower was set to 45 degrees in the bottom floor zone and 27 degrees in the other floor zones.

- The positioning of the megacolumn centerlines in each floor zone was controlled by testing the minimum distance between the megacolumns and curtain wall D with the parametric design plugin Grasshopper (Figure 6). According to different types of curtain wall, the minimum distance between the megacolumns and curtain wall D was set to 1,200 millimeters in the bottom floor zone and 500 millimeters in other floor zones.

After multiple comparisons of different options, the distance between the structure and curtain wall L was optimized from 1.3 meters to around one meter in typical floors, making the lever arm of the megacolumns as large as possible, resulting in a good balance between structural performance and building function.

Comparison of Different Tower Massing

To achieve approval from the planning bureau, in the early and middle design stages, dozens of architectural schemes with different waist heights, planar sizes, functional zonings, and more were generated by the architects. Structural engineers needed to study and compare different options in a short period of time. Each architectural scheme corresponded to a unique layout of megacolumns and perimeter frames. In order to accurately study the influence of the architectural schemes on the performance of the structure, analysis models corresponding to different architectural schemes were built through parametric modeling and analyzed under the same loading conditions. The typical structural comparison of the four architectural schemes (Figure 7).

Through quick comparisons of different architectural schemes, the control parameters in the façade shape of the tower, such as the fillet radius, the waist height, and the planar size of the bottom, were identified; therefore, analysis of the sensitivity of the structural performance to these parameters was carried out, with feedback on each architectural scheme provided accurately and rapidly. The balance between the façade shape of the building and the performance of the structure was achieved. To reduce unfavorable leasing area between the perimeter frame and the façade (Figure 8), different options were compared to confirm the column's angle (α in Figure 5) in plan. Compared with the original layout, the total unfavorable area was reduced by 8,700 square meters in the final scheme, enormously benefitting the client.

The Study of Different Structural Systems

As the design process of the Tower advanced, the function of the building experienced a series of changes. The sequence of the changes

线在控制点处弯折一定角度以使结构尽量贴合建筑的曲线外型，控制点之间巨柱沿直线布置（图5）。

- 以上控制点均位于结构转换桁架的上下弦标高处以利用桁架平衡巨柱弯折产生的水平力。设计中对于每个转换桁架处设置1个还是2个转折点进行了比较。为了减少施工复杂度以及抵消以上所述侧向力问题，在转换桁架设置两个控制点的方案仅在第7区应用。转折点的转角β（图5）也被有效的控制在6度以下。
- 为避免柱线双向弯曲产生双向水平力并增加施工难度，12个质心控制点在平面角度均位于同一直线上以使柱线在同一平面内弯折。经过对结构性能和建筑使用率的比较，柱中心线平面角度在底部楼层确定为45度，其它楼层27度。
- 巨柱在每区通过Grasshopper测试角点至幕墙的最近距离（D）来控制巨柱平面位置（图6）。根据不同的幕墙形式及要求，最小距离在底部区域控制为1200mm，其他区域均为500mm；

经过多方案比选，周边结构与幕墙间的距离（L）在典型楼层被从初始的1.3米优化至约1m左右，同时尽可能加大了巨柱间的力臂，从而达到结构性能与建筑功能间较好的平衡。

不同塔楼外形比较

为获得规划部门的审批，在设计前期建筑师对塔楼的体型提出不同收腰高度、平面尺寸、建筑分区等数十种方案供结构专业在短时间内进行对比研究。每一种方案都对应不同的柱线和外框筒杆件定位。为准确研究各方案对结构性能尤其是剪重比的影响，设计中采用参数化建模在相同的荷载条件下分别对各方案建立了完整的模型，研究不同建筑形体对应结构性能的优劣，典型比较结果（图7）。

通过对上述外型方案的快速对比，工程师找到诸如圆弧转角半径、收腰处高度及底部平面尺寸等对结构性能有较大影响的外型因素，分析各因素的敏感性，并针对不同建筑要求快速提供反馈意见，达到了建筑外型与结构性能间的平衡。同时为减小外框架与幕墙之间不利于使用的面积（图8），工程师利用参数化建模对于不同柱线的平面角度（图5中α）进行了比较，最终不利于使用的面积比初始方案减小8700m2，为业主创造了巨大的经济价值。

不同结构体系的研究

随着塔楼设计进程的发展，建筑的功能经历了一系列的改变。初期阶段为办公楼+第5区酒店+第67区公寓，中间阶段改为办公楼+第6区酒店，后期确定为办公楼+高端商业和旅游用途。考虑到巨型斜撑会遮挡酒店和公寓的视野，在设计的初期和中期，斜撑仅

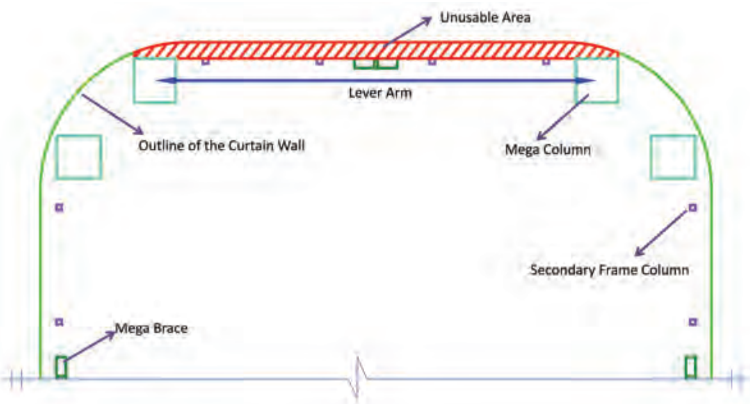


Figure 8. The plan layout of the perimeter frame and the curtain wall (Source: Arup)
图8. 外框架与幕墙的平面布局（来源：奥雅纳工程顾问）

is as follows: office + hotel (the fifth floor zone) + apartment (the sixth and seventh floor zone) in the early stage of design; office + hotel (the sixth floor zone) in the middle stage of design; and office + high-end commercial + tourism use in the final stage of design. In the first two stages, the megabraces could only be assigned below the fourth and the fifth floor zones respectively because the client concerned that the mega braces might block the view from the hotel and apartment; therefore, after the apartment and hotel functions were removed from the tower, the structural scheme changed from a partially braced dense-column perimeter frame (braced in the lower section) to a fully braced perimeter frame (Figure 9).

In the design process, structural analysis models corresponding to different structural systems mentioned above were built within a short period of time by modifying the geometric parameters. The negative influence of significant changes during the design cycle was avoided. In the middle stage of design, a detailed comparison between the partially braced option and the fully braced option was carried out in a timely manner, demonstrating that the latter had a significant structural performance advantage. The comparison also demonstrated the difference between the steel consumption and the construction cycle for the two options if a similar shear-weight ratio and inter story drift angle were required. This discovery provided valid technical information for the client to decide which structural system was best to adopt (Figure 9).

Application of the Optimization Module in 600-Meter-Plus Towers

For a 600-meter-plus tower, located in seismic zone seven of China, the Integrated Smart Design Tools were also applied from the very start of the structural design process. As different structural systems and architectural massing were gradually proposed by consultants and architects, the combination matrix of structural models expanded so quickly that the traditional way of design would be impractical. Through the application of parametric design, engineers were able to get key structural performance and comparison data within a short period; such engineers were involved actively in the architectural massing development through interactive co-ordination. This is particularly advantageous to engineers, as they can have more influence in the architectural form of a development at this early stage. This kind of affection has been shown to significantly improve structural performance.

During the lateral system studies, a major challenge we were facing was to achieve the

分别在第四和第五区以下设置。随着建筑功能的改变，公寓和酒店取消，结构方案从部分斜撑（下部）+密柱外框筒（上部）结构改变为全高斜撑外框架结构（图9）。

以上对应不同结构体系的分析模型通过参数化建模，在很短的时间内便修改完成。避免了设计中重大建筑不利改变带来的设计周期延长。在设计中期，对部分斜撑与全高斜撑方案的细致对比表明在相似剪重比和层间位移角要求下，后者具有显著的性能优势。研究同时提供了不同方案用钢量和施工周期的比较。该信息为业主决策项目业态提供了有效的技术支持（图9）。

计算机设计优化（CDO）模块在600米级塔楼中的应用

集成化智能设计工具同样应用在了某栋位于国内7度区的600米级塔楼。建筑师提出大量建筑方案，每个建筑方案又可以采取不同的结构体系，需要分析的模型数量以矩阵的形式快速增加，以至于传统设计方法难以满足设计进度要求。参数化设计的应用，使工程师在短时间内获得关键的结构性能对比，在设计初期可以有效地参与和影响建筑外形的发展，从而显著提升结构性能、节约土建造价。

塔楼抗侧力体系研究主要面临的挑战是如何取得规范要求与经济性的平衡。对于类

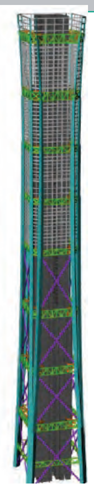
	Early Stage	Middle Stage	Final Stage
Tower Structural System			
Architectural Height/Structural Height	555m / 546m	528m/ 524m	528m/ 521.6m
Floor No.	119 (8 Zones)	108 (8 Zones)	118 (7 Zones)
No. of Outriggers	5	4	0
No. of Beltrusses	9	9	8
No. of Megabace Zones	4	5	8
No. of Moment Frame Zones	4	3	0
1st Period (S)	8.704	7.328	7.300
Shear/Weight Ratio (Limit=2.0%)	1.70%	1.99%	2.00%
Steel Tonnage	-	Compared with middle stage, final stage can reduce the steel consumption by 50kg/m2	
Construction Period	Compared with early stage, final stage saved 4 months saved over a 3-year total cycle, due to elimination of outriggers		

Figure 9. Comparison of the structural performance of different architectural schemes (Source: Arup)
图9. 不同建筑方案结构性能对比（来源：奥雅纳工程顾问）

balance between the material cost and code's requirements. For such a high-rise tower, both the shear/weight and stiffness/weight ratios requested by Chinese Seismic Code dominate the structural member size and whole lateral stiffness. By manually increasing structural sections and the steel ratio to achieve the code's requirement, engineers took a long time to find the effective size distribution of structural materials or elements. Sometimes, simply increasing element sizes has the opposite effect.

By adopting the in-house developed optimization module, engineers were enabled to set material weight/cost as the target and provide multiple constraints, according to the code's requirements which control the structural key performance including: stiffness/weight and shear/weight ratios, inter-story drift, and the axial force ratio of the core. The optimization process tested all possibilities of structural sections between the ranges pre-set by engineers, ending with the least structural self-weight and cost. In the meantime, all of the constraints were pushed to the limit of codes' requirement, resulting in the most efficient and economical design. The iteration of the optimization process of the 600-meter-plus tower, which applied the Integrated Smart Design Tools in the early stage for selecting and adequate structural system (Figure 10).

Figure 11 shows the comparison of key indicators between the original and optimized models (Figure 11). By rationalizing the distribution of structural elements, more materials were assigned to the structural members, which contribute the most to lateral stiffness. Meanwhile, section sizes were reduced where they are less sensitive to the key performance. Although the total material tonnage of the tower was reduced, indicators of stiffness (period, stiffness/weight ratio, shear/weight ratio) were better. The inter-story drift and core axial force ratio were further pushed to the limit of code's requirements for economical reasons. The steel and concrete tonnage were reduced by 7.2 and 13 percent, respectively, based on same architectural massing and same structural system (no change in number of belt-truss and outriggers) and geometry.

Visualization and BIM Interoperability

The Integrated Smart Design Tools can be considered as an extension of BIM in structural engineering in that it extends "information" to "knowledge," enabling software to demonstrate a higher level of design intelligence; thus, it is convenient for the smart design framework to output data to any BIM platforms, including:

- Exporting accurate geometric models to BIM environment;

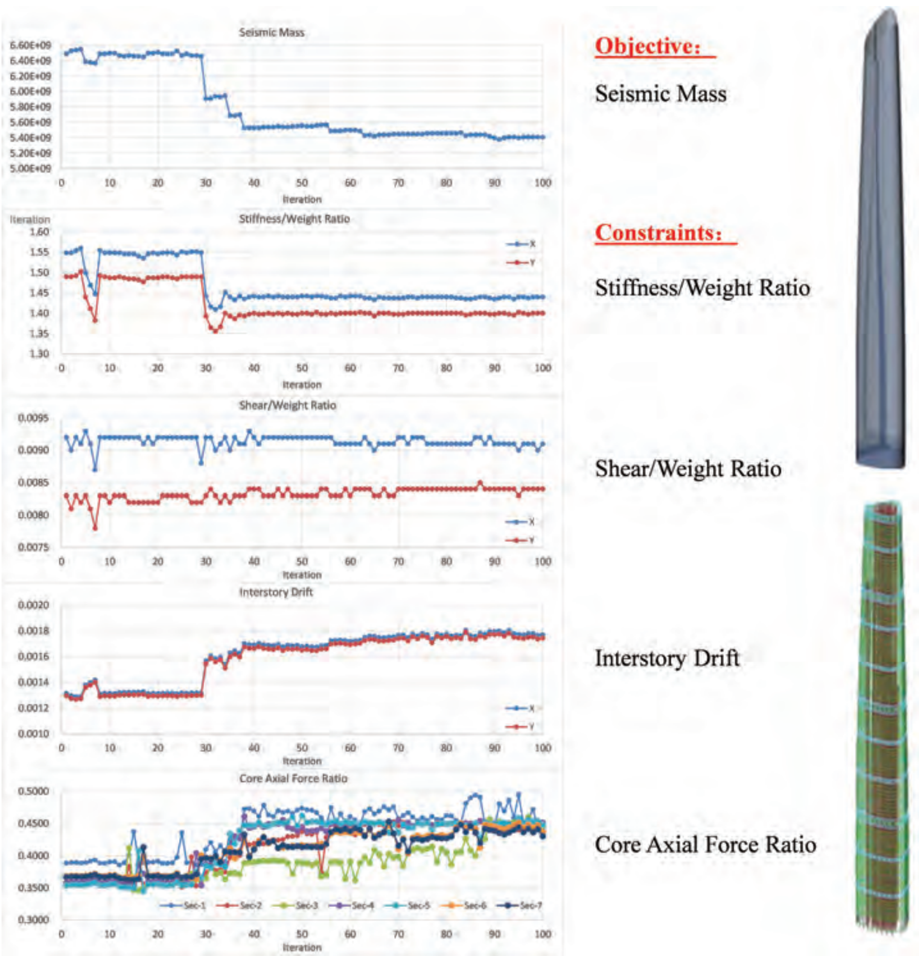


Figure 10. Optimization process given multiple constraints (Source: Arup)
图10. 依据多重约束条件的优化过程（来源：奥雅纳工程顾问）

似高度的塔楼，剪重比、刚重比等中国规范指标均对结构构件尺寸和整体刚度起控制作用。通过人为的增加构件截面和含钢率来满足规范要求需要花费大量的时间尝试不同方案，有时简单的增加构件截面还会起到相反的效果。

采用自主开发的计算机优化模块和算法，设计中将材料重量/造价作为目标，根据规范要求设置控制结构关键性能的多重约束条件，包括：1）刚重比，2）剪重比， 3）层间位移角，和4）核心筒轴压比。该优化流程在工程师限定的截面区间内自动测试不同截面对应的所有组合，最终获得最少的结构自重和结构造价。约束条件也被优化至接近规范限值，达到经济合理的设计。该600米级塔楼在方案阶段使用集成化智能设计工具比选结构体系的优化迭代过程（图10）。

初始模型与优化后模型的结构性能对比（图11）。通过结构构件尺寸调整和分布的合理化，更多材料被分配到可以提供最多侧向刚度的位置。对于结构性能不敏感的构件截面被减小。由下表可知，虽然总体材料用量有所减少，但刚度指标（周期、刚重比、剪重比）均获得提高。层间位移角与核心筒轴压比也逼近至规范限值。在相同建筑外形、结构体系（腰桁架和伸臂桁架数量不变）和结构几何的条件下，钢材与混凝土用量分别减少7.2% 与13%。

可视化及BIM转换

集成化智能设计工具可以被认为是建筑信息管理（BIM）在结构工程中从“信息”到“知识”的扩展，使软件可以展示更高级别的设计智能。在此平台上可以方便的将设计数据与建筑信息管理软件连接（BIM），包括：

- 输出几何模型至BIM
- 生成二维图纸
- 生成有限元节点模型甚至弹塑性分析模型。

文件转换能力的概念并不新颖，但是，该智能化设计框架可以使不同软件下的模型根据最新的设计变更进行更新，实现实时和精确的设计。

为方便读取应变能密度、材料利用率等结构性能，进一步开发了移动端基于IOS系统

Model	Original Model	Optimized Model
Period (s)	9.59	9.32
Seismic Mass (kN)	6,141,529	5,541,060
Stiffness/Weight Ratio	1.41	1.43
Shear/Weight Ratio	0.78%	0.79%
Interstory Drift	1/592	1/523
Core Axial Force Ratio	0.39	0.44

Figure 11. Comparison of structural performance between the original and optimized models (Source: Arup)
图11. 初始与优化模型结构性能对比（来源：奥雅纳工程顾问）

- Producing 2-D drawings directly;
- Exporting model information to non-linear, elasto-plastic analysis software to avoid repeats in the modeling;
- Exporting accurate geometry for 3-D finite element analysis (FEA) for connections. The FEA software carries out fine meshing based on 2-D/3-D geometry, material, and loading information gained from the latest model in the smart design framework.

The concept of this interoperability is not new; however, with a parameter-based smart design framework, all of the models used in various software programs are updated with any late design changes, enabling a just-in-time (JIT) delivery and accurate design.

By applying the IOS app Arup Real, key information such as strain energy density, material utilization, and structural performance can be shown in Augmented Reality (AR) 3-D models by mobile devices such as iphones/ipads. This provides a more interactive and visually impactful way of presentation and post-data analysis (Figure 3).

Benefits to the Design Industry

For the scheme design of the 600-meter-plus high-rise tower project which adopted this technique, 50 models were generated in a single month, as compared to other projects of a similar scale that would normally produce 10 models in three to six months. This demonstrates a significant increase in productivity, and gives more time and freedom to engineers to explore several options.

In summary, the Integrated Smart Design Tools will benefit the entire design industry in the following aspects:

- Enable a broader design exploration: The whole automated process enables structural engineers to create models automatically based on available architectural information; therefore, the design cycle can be significantly reduced and structural engineers can be liberated from the time-consuming and complicated processes of creating and updating models manually. Different geometric options may also allow engineers to explore the effects of architectural massing in regards to wind engineering.
- Deliver cost effective and sustainable design: The Integrated Smart Design Tools enable structural engineers to have a better understanding of the key parameters controlling the performance of a structure. It also conducts the optimization of the system by comparing and modifying different geometric and structural parameters. The final design is, therefore, delivered through a much more informed and refined design process which is justified to be the most cost effective, and hence sustainable, solution.
- Provide additional values to all participants of a project: This design process alleviates difficulties in balancing structural performance, complexity of construction, and the efficiency of building usage. As the framework itself links to 2-D and 3-D CAD systems, it can generate 3-D models for Rhinoceros, Revit. Once an optimized structure and its geometry is determined, the product can be passed to architects, building services engineers, and others for their further input and drawing production. Because of this, the benefits of the framework are not just directed towards structural engineers, but the whole design team, saving time in drawing productions and fostering coordination.
- Facilitate construction: With the flexibility of future extensions, the framework could also be easily linked with other modules. From projects like China Zun Tower, the framework also produces optimized connection geometry and details (with stiffeners) in the Tekla X-Steel format. The contractor can use the product to assist in the preparation of shop drawings. Furthermore, the framework can also be easily extended with other modules, so that it can be expanded from 3-D to 4-D (construction time) and 5-D (construction cost); a reduction in the construction period can hence be achieved.

的应用程序： Arup Real 。它通过增强现实技术将三维模型和结构信息在iphone/ipad上进行显示。提供一种交互的、可视的数据后处理和展示方式 （图3）。

为设计行业带来的好处

上述600米级塔楼在方案阶段中使用集成化智能设计工具，在1个月内完成50以上个模型的分析比选，而相同体量的项目比选10个模型一般需要3到6个月。两相比较，结构工程师使用集成化智能设计工具具有更高的效率，并且拥有更多的时间和精力探索和研究优化方案。

总结以上内容，集成化智能设计工具在以下各方面为整个设计行业带来好处：

- 拓展更广阔的设计探索
  整个自动化的设计过程使结构工程师可以基于建筑信息自动化地生成模型，因此设计周期可以被显著地缩短，将结构工程师从耗时繁琐地手动建立和更新模型的工作中解放出来。使之获得更多的时间去探索更多不同的结构方案，并可以更专注于设计创新。不同的几何方案同时允许结构工程师研究在风环境下不同建筑外形的效率。
- 提供经济和可持续的设计
  该设计框架使结构工程师对控制结构性能的关键参数有深入的研究和理解。并且可以通过调整参数和几何结构进行优化。这样具有更大的信息量和更精细设计过程理所当然的带来了最经济并且可持续的设计。
- 为项目的所有参与者提供附加价值
  整个设计流程降低了结构性能、建造难度和建筑使用效率平衡设计的难度。由于设计框架联系到2D和3D的CAD系统，它可以生成Rhino和Revit需要的3D模型。一旦确定优化后的结构设计，成果将方便地传递给建筑师、设备工程师和各参与方。该智能化设计工具不仅有益于结构工程师，也为整个设计团队在施工图设计过程和协调过程中节省大量时间。
- 提供施工的便利性
  该集成化工具可以连接其他扩展模块。在中国尊项目中集成Tekla X Steel软件对节点几何和细部构造(如加劲板）进行优化，钢结构厂家使用优化后的结果准备图纸。更进一步，该集成化工具通过扩展模块可以由3D进阶成4D（包含施工时间）甚至5D（包含施工造价）等等。由此施工周期可以有效缩短。

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