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# Seismic Skyscrapers: Three Unique Structural Challenges

## 震撼的摩天大楼 ——三个独特的结构挑战



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代表作品：中央电视台新总部、深圳证券交易所、北京环球金融中心、台北艺术中心等。



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我要介绍的是在中国已建成或正在建的三个项目的结构设计——中央电视台新址大楼、深圳证券交易所和台北表演艺术中心。三个建筑均由工程咨询方奥雅纳 (Arup) 和大都会建筑事务所 (OMA) 合作设计, 每个项目的设计都是独一无二的, 已经成为当地的地标性建筑, 重塑了各自所在城市的天际轮廓线。

### 中央电视台新总部大楼

可以说, 中央电视台新总部大楼 (以下简称央视大楼) 真正地重新定义了高层建筑的形式。央视大楼与众不同的外形为结构设计带来巨大的挑战, 尤其是在高烈度区抗震设防要求的情况下。主要的钢结构斜撑位于大楼外立面, 其疏密根据大楼不同位置所承受的不同应力而有所不同。由此大众能够通过大楼幕墙呈现出的图案“看”到整栋大楼的应力流动。同时, 倾斜的外立面和大型的演播室的不同使用功能需求, 也给工程设计带来了挑战, 使得整个塔楼需要大量的转换桁架。另外项目需要通过超限高层建筑抗震设防专项审查 (EPR), 奥雅纳对大楼采用基于性能的设计方法来对其结构特性进行评估。还有一个结构工程师与工程承包商面临的更大挑战, 就是如何建造并连接两座塔楼。

### 建筑概念

央视大楼位于北京的 CBD 区域, 建筑面积 470 000m<sup>2</sup>。OMA 的设计成功地把所有功能安置在一座建筑内——一个“把各项活动互相连接在一起的循环” (图 1)。234m 高的大楼外形像是一个三维连续弯折的循环, 内部包含整个电视制作过程所需的新闻、广播、演播室、行政办公区及公共区域。大楼的两栋塔楼以 10° 倾斜、13 层楼高的悬臂在 162m 的高空处连接, 底部则是 10 层楼的裙房与 3 层地下室。公共设施包含一个剧院、酒店及电视文化中心 (TVCC), 整个建筑群通过一个专门的服务楼提供全部楼宇设备服务。整个项目在包含外部功能媒体园的 187 000m<sup>2</sup> 场地上进行开发, 总建筑面积 599 000m<sup>2</sup>。

在设计竞赛阶段, 设计团队一直在进行广泛的设计探索和建筑外形的完善, 以及详细的可行性研究, 以确定设计概念的可行性 (图 2)。

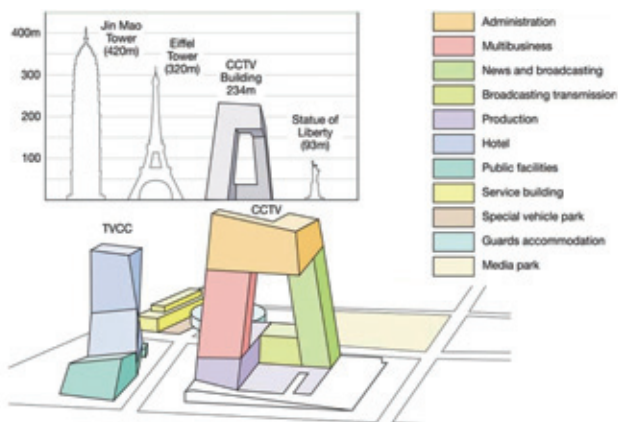


图1 显示不同建筑块分布的建筑概念：互通的循环

This article describes the structural design of three major projects in the greater China region which are either complete or under construction: Beijing's CCTV New Headquarters, Shenzhen Stock Exchange and Taipei Performing Arts Center. All three are landmark buildings set to transform the skylines of their respective cities.

The three projects are all collaborations between engineers Arup and architects OMA (Office for Metropolitan Architecture), and in each case have been developed from a unique, competition-winning architectural concept. OMA and Arup have previously collaborated on many other projects around the world including Porto's Casa da Musica and Seattle Central Library.

### China Central Television Headquarters

#### Introduction

The award-winning new headquarters of China Central Television in Beijing truly redefines the form of the skyscraper. Its unusual shape posed enormous structural challenges during design, not least the need to withstand a high level of seismicity. The primary braced steel structure is located in the skin, and its density varies to suit the large range of stresses experienced in different parts of the tower. The resulting pattern is expressed in the facade, allowing the public to 'read' the flow of stress around the building.

The leaning form and varied functional programme, including large studios, posed many challenges for the engineering design, and resulted in the introduction of a large number of transfer trusses throughout the tower.

In order to gain structural approval a comprehensive Expert Panel Review process was necessary, for which a performance-based analysis was carried out to justify the design. This used state-of-the-art analysis techniques to evaluate the structural behaviour and ensure the building safety under different levels of seismic event.

Erecting and connecting the two massive towers presented the structural engineers and contractors with further design and construction challenges.

#### Architectural Concept

The China Central Television New Headquarters building is located in Beijing's Central Business District. It provides approximately 473,000 m<sup>2</sup> of floor area, (equivalent to three typical high-rise towers) to house all of the studios, facilities and offices needed for CCTV's projected expansion in operations to become an international broadcasting company.

OMA's design was initially unveiled as the winning design in an international competition in 2002 which attracted some of the biggest names in architecture. Whilst the brief required all of the company's facilities to be consolidated on one site, OMA's scheme placed the entire functional programme inside a single building - an "interconnected loop of activities" (Fig. 1).

The 234m high building is a three-dimensional continuous cranked loop which contains the entire TV process, including news, broadcasting, studios and administration, as well as public areas. It consists of two towers leaning at 10



图2 设计竞赛阶段建筑外观的发展过程

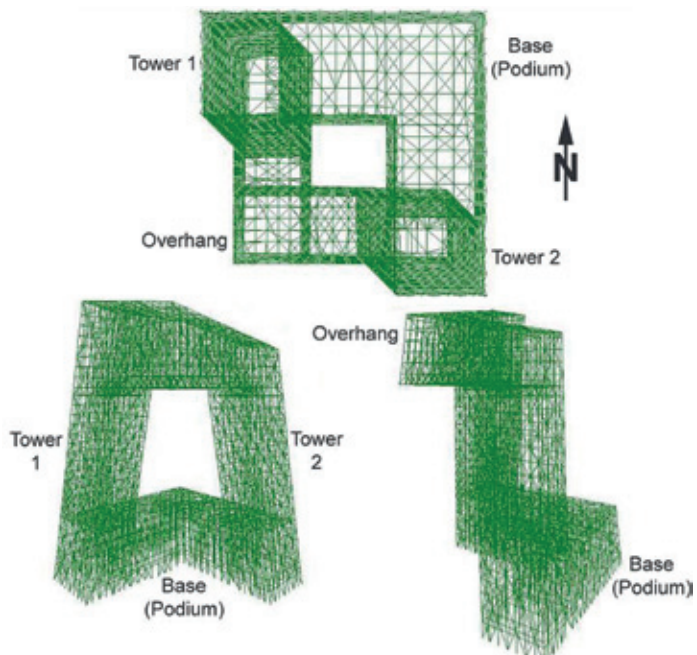


图3 央视大楼的连续循环结构

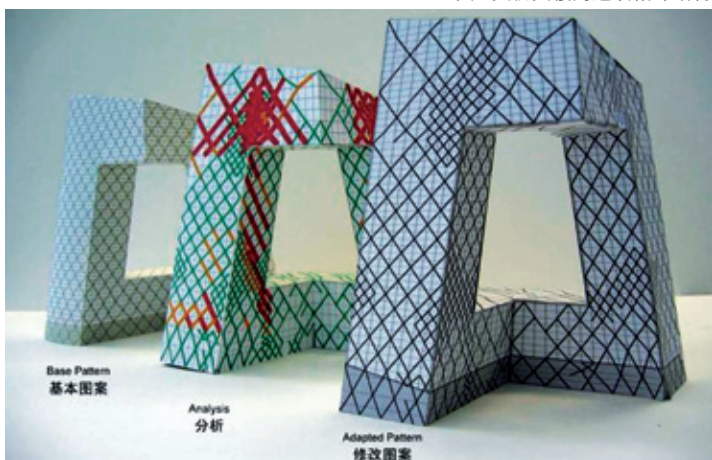


图5 斜撑布置图

### 结构体系

从一开始，项目就确定在整个幕墙上布置结构体系，创造了一个本质上是连续外筒的结构体系，用于抵抗弯折且倾斜的外形产生的巨大弯矩以及风荷载与极端地震荷载。通过在幕墙各个面布满斜撑而形成“筒”（图3），使得斜撑的平面是连续分布的。

施工期间，斜撑筒体结构为倾斜的塔楼提供足够的刚度，使两塔楼在连接并相互支撑前都能在严格的允许误差范围内安全地施工。此结构亦适合悬臂部分的建造，容许两个半截的悬臂部分在连接前分别临时悬挑于两塔楼之上。除了外部部分柱由于荷载较大的原因而使用了型钢混凝土柱外，大楼内所有的结构支撑构件都为钢结构构件。

筒体的初始设计是以柱、周边圈梁和斜撑有规律地组成两层楼高的典型模块化组件（图4）。之所以选择这种方案，是为了适应塔楼内若干处于二层高的演播室。然而初步分析结果显示，大楼斜撑的受力在结构的不同位置变化相当大，特别是集中于悬臂的根部以及与基座连接的部分。因此在优化过程中，根据设计所需的强度和刚度，以地震分析为准，通过增加或减少斜撑而变化（如翻倍或减半布置斜撑）。该过程中始终与建筑师保持着紧密的合作，因为斜撑的布置决定着外立面是否美观。优化工作亦在一定程度上使斜撑构件截面尺寸标准化（图5，6）。

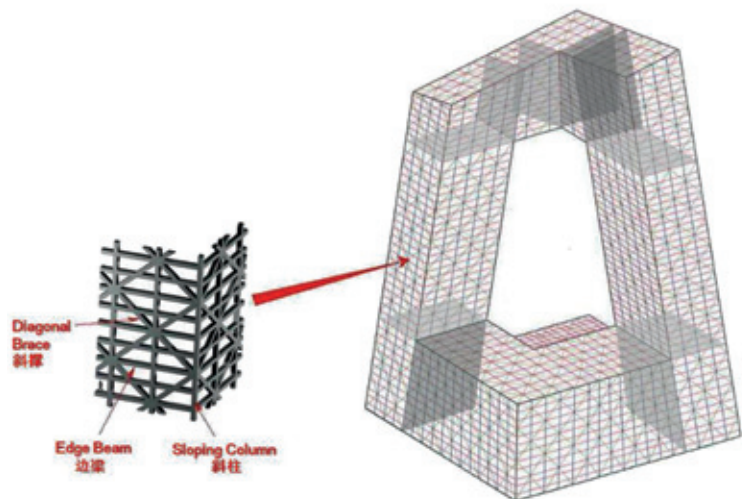


图4 均布的斜撑布置

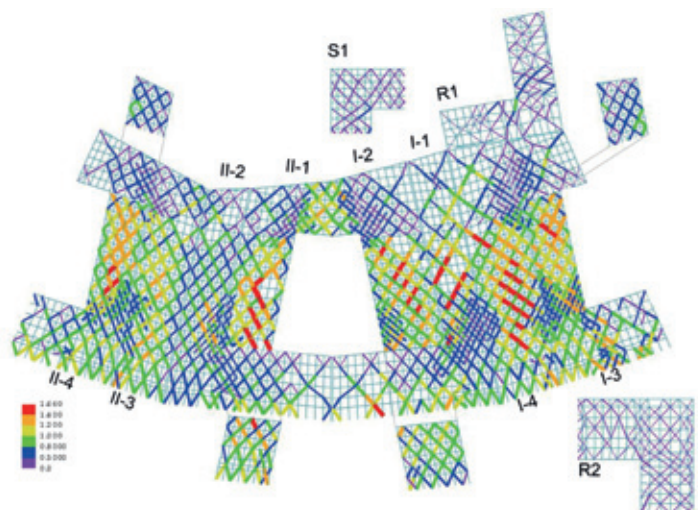


图6 最终斜撑布置展开图

degrees with a 13-storey cantilevering 'Overhang' link some 162m in the air, as well as a 10-storey podium and 3-storey basement.

Public facilities including a major theatre as well as a hotel are in a second building, the Television Cultural Centre (TVCC). The whole development is serviced from a dedicated Service Building. The whole development will provide 599,000m<sup>2</sup> of GFA on a site which covers 187,000m<sup>2</sup>, including a landscaped media park with external features.

Extensive development and refinement of the form took place during the competition stage, together with detailed feasibility studies to confirm the viability of the unprecedented concept (Fig. 2).

Arup provided consultancy for structure, building services, geotechnical design, fire, communications and security. The East China Architecture and Design Institute (ECADI) in China acted as the Local Design Institute (LDI) of record. The design team included a number of other specialist consultants.

### Structural System

From the outset, it was determined that the only way to deliver the desired architectural form of the CCTV building was to engage the entire façade structure, creating in essence an external continuous tube system. This would give the structure the largest available dimensions available to resist the huge bending forces generated by the cranked, leaning form – as well as loads from wind and extreme earthquakes.

The 'tube' is formed by fully bracing all sides of the façade (Fig. 3). The planes of bracing are continuous through the building volume in order to reinforce and stiffen the corners. The system is ideally suited to deal with the nature and intensity of permanent and temporary loading on the building, and is a versatile, efficient structure which can bridge in bending and torsion between the towers, provide enough strength and stiffness in the towers to deliver loads to the ground, and stiffen up the Base to reinforce the lower tower levels and transfer loads to the

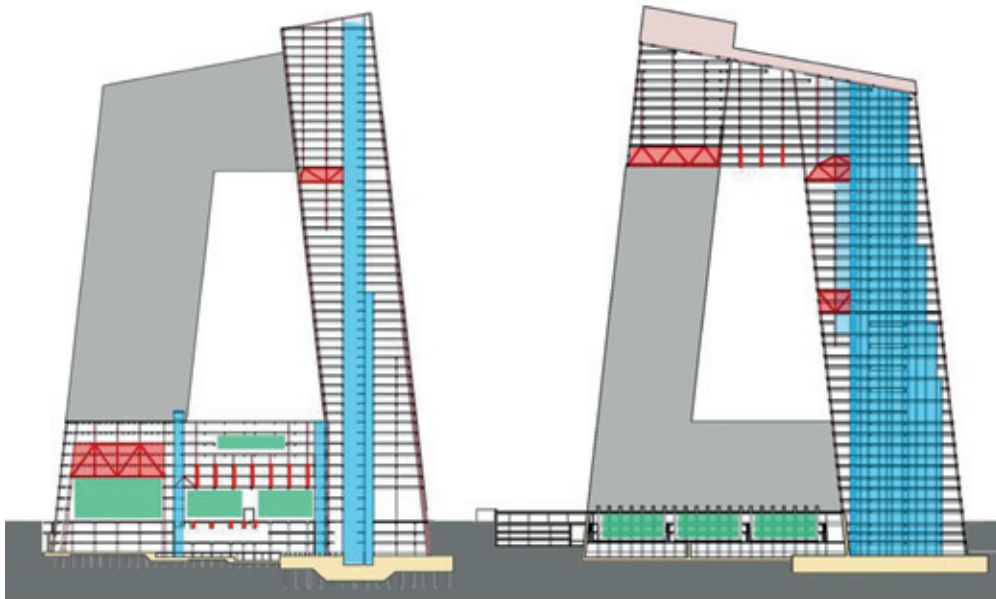


图7 表示内部结构与转换桁架的剖面图

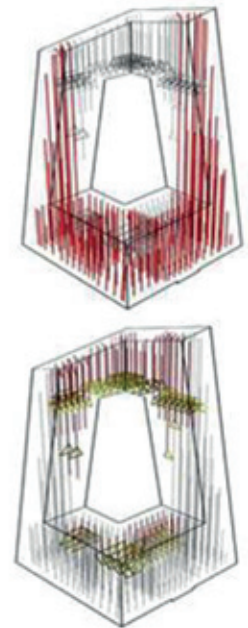


图8 由地面支撑的柱（上）与由转换桁架支撑的柱（下）

内部结构是由核心筒周围竖向钢柱支撑的，核心筒内设有电梯和机电竖井。最初设计曾考虑使用倾斜的核心筒，以配合倾斜的塔楼，并使楼板布置保持一致。然而该方案由于电梯系统采购问题的限制等种种原因而被排除。

倾斜的外立面和内部垂直的核心筒，使得建筑每层楼面布置不同，楼板与核心筒或内部钢柱间的跨度在每个楼层都在变化。随着楼层升高，在向外倾斜的一侧楼板跨度逐渐增加，进而逐渐增加的梁高将对建筑净高产生影响，为此在高层附加了柱，并由转换桁架支承（图7）。

整栋大楼共需要50组桁架，这些两层高的桁架横跨内部核心筒与外部筒体结构（图8）。结构团队与MEP团队进行合作，协调机电层桁架的可行位置，从而使桁架视觉上较为隐藏并使其对楼层的使用影响最小化。

悬臂部分中的楼层由布置在标准柱网上的柱支承，这些柱支承在底部两层桁架上，转换桁架在两个方向上连接于两个塔楼的外筒上。该两层楼用于公共使用，其中包括一个空中的观景大厅（图9）。主要的转换桁架也位于大楼的基座（裙房）部分，这些桁架横跨主要的演播室上空，用于支承上层的柱和楼面。

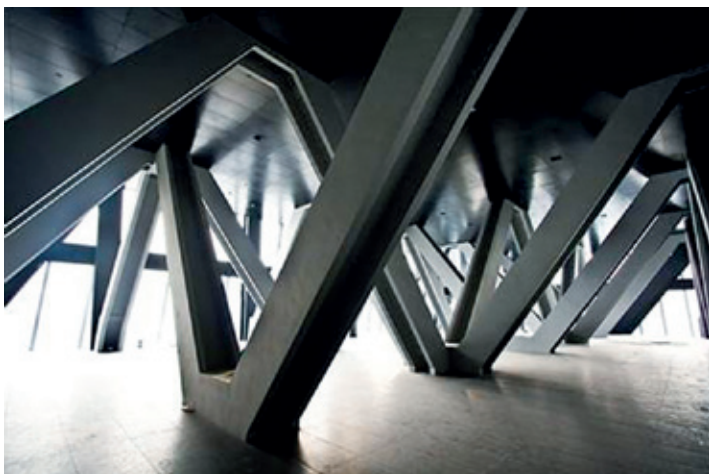


图9 悬臂部分中的公众空中观景大厅

foundations in the most favourable possible distribution, given the geometry.

The braced tube structure gives the leaning towers ample stiffness during construction, allowing them to be built safely within tight tolerances before they are connected and propped off each other. The braced tube system also suits the construction of the Overhang, allowing its two halves to cantilever temporarily from the towers.

The continuous tube has a high degree of inherent robustness and redundancy, and offers the potential for adopting alternative load paths in the unlikely event that key elements are removed.

The form warranted a building constructed primarily in structural steel, for a lightweight solution and enhanced seismic performance. As such, all the structural support elements in the building are of structural steel, except some external columns which are composite steel-reinforced concrete columns due to the magnitude of loads they are designed to carry. The floors are composite slabs on steel beams.

The tube was initially designed as a regular pattern of columns, perimeter beams, and diagonal braces set out on a typically two-storey module (Fig. 4). This was chosen to coincide with the location of several double-height studios within the Towers.

However, results of the preliminary analysis showed that the forces in the braces varied considerably around the structure, with particular concentrations near the root of the Overhang and at the connection to the Base. This led to an optimization process in which the brace pattern was modified by adding or removing diagonals (i.e. 'doubling' or 'halving' the pattern), depending on the strength and stiffness requirements of the design, based on earthquake analysis.

This was an extremely iterative process due to the high indeterminacy of the structure, with each changing of the pattern altering the dynamic behaviour of the structure and hence the seismic forces that are attracted by each element. It was carried out in close collaboration with the architect, since the pattern of visually expressed diagonals was a key aesthetic aspect of the cladding system and reinforces the transparency between structure and architecture. The optimisation also enabled a degree of standardization of the brace element section sizes (Fig. 5 & 6).

The internal structure is supported by vertical steel columns around the cores which house lifts and service risers. Sloping cores were initially considered in the design, in order to align with the sloping towers and to allow consistency of the floor plate layout. However they were ruled out for various reasons including constraints on the procurement of the lift systems.

The combination of a sloping external facade and the vertical internal core leads to unique configurations for every floor of the building. In other words, the floor span between cores or internal columns and the changes on every floor. Moving up the building, the increasing floor spans on the outward leaning sides of the building eventually start to impact on the finished floor height due to increased beam depths, and transfer trusses are introduced to support additional columns (Fig. 7).

These double-height trusses typically span between the internal core and the external tube structure. The structural and MEP teams worked together to identify feasible locations for the trusses on floors with plant rooms so as to be hidden from view and to minimize the impact on floor planning. Detailed analyses were made to



图10 建设中的电视文化中心：部分建成的空间框架后方可见巨型斜撑

### 电视文化中心（TVCC）及服务楼

场地内其他两栋大楼都分别为独立的结构。电视文化中心高 159m，内部为五星级的文华东方酒店以及裙楼，其中包括 1 500 座位的剧院、电影院、录音棚、音像室和展览馆，建筑面积共 95 000m<sup>2</sup>（图 10）。

酒店楼层布置在中厅南北两翼，核心筒位于中厅东侧，形成一个“C”形的平面布置（图 11），为框架-核心筒结构。在动力荷载下，不对称的核心筒以及平面布置会导致扭转变形。因此，大堂西侧设有巨型斜撑，横跨两组带有疏散楼梯的次级核心筒。

裙楼由几组不连续的结构构成，根据楼板跨度使用钢结构或混凝土框架。为实现其建筑外观，整栋大楼屋顶为一个人大跨度的空间钢结构框架，且屋顶在塔楼与裙楼间设有伸缩缝。

服务楼为 23 000m<sup>2</sup> 的两层环形大楼，设有三层地下室（图 12）。大楼内设有为央视大楼和电视文化中心服务的主要设备机房，并通过地下隧道连接，其中还包括央视大楼广播车辆的停车场。服务楼减少了央视大楼屋顶重型设备的数量。该大楼为混凝土框架结构。

### 施工过程

动工仪式于 2004 年 9 月 22 日举行，体积达 870 000m<sup>3</sup> 的三层地下室的挖掘工程亦在 10 月启动，中国建筑工程总公司于 2005 年 4 月成为工程总承包商。打桩工程始于 2005 年夏天，而塔楼的筏板则于同年 12 月动工（图 13）。

第一个柱构件于 2006 年 2 月 13 日完成安装。钢构件共计 41 882 件，总重达 125 000t，在接下来的 26 个月内完成安装，最高峰达每月完成 8 000t。型钢构件由上海宝钢和江苏沪宁完成组装，然后陆运至工地。



图12 服务楼

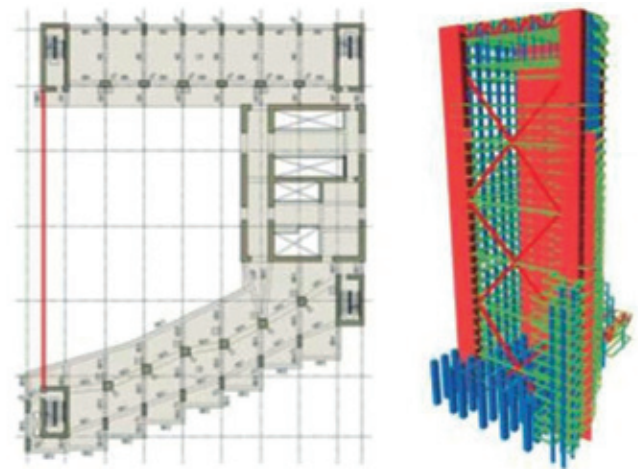


图11 电视文化中心平面图以及分析模型，显示核心筒及巨型斜撑位置

study the impact of these stiff elements on the tower's structural performance and ensure they would not complicate the seismic load path. A total of 50 trusses are required within the building (Fig. 8).

The floors in the cantilevering Overhang are supported by a regular grid of columns landing on a series of transfer trusses in the bottom two storeys, which span in two directions on to the external tube structure. These two floors are used for public functions, including a public viewing gallery (Fig. 9).

Major transfer trusses are also located in the podium. These trusses span over the major studios to support the columns and floors above.

### TVCC and the Service Building

The other two buildings on the site are both major structures in their own right. TVCC is 159m tall and comprises a five-star hotel plus a podium containing a 1500-seat theatre, cinema, recording studios, audio-visual rooms and exhibition space. The floor area is 95,000m<sup>2</sup>(Fig. 10).

The hotel floors are arranged along two wings, to the north and south of a central atrium. The core is located on the east side of the atrium, resulting in a C-shaped floor plan (Fig. 11). Stability is provided by the reinforced core and column frame. However, the asymmetric core location and floor layout result led to torsional behaviour when the building is subjected to earthquake loads. As a result, steel mega braces were introduced on the west side of the atrium, which span between two secondary cores containing escape stairs.

The podium functions are designed as a number of discrete structures, using steel or concrete framing depending on the required floor spans. The entire building is covered by a long span steel space frame roof, to realize its distinctive architectural form. The roof contains a movement joint to separate the podium and tower sections.

The service building is a 23,000m<sup>2</sup> two-storey circular building, with three levels of basement(Fig. 12). It contains all of the major plant for both CCTV and TVCC, to which it is connected via underground tunnels, as well as parking for CCTV's broadcast vehicles. As well as providing efficiencies of scale, the service building concept enabled the amount of heavy plant on the roof of CCTV to be reduced. It is designed as a reinforced concrete frame, and was actually on the critical path during the construction process since it had to be fully commissioned well before



图13 基础施工

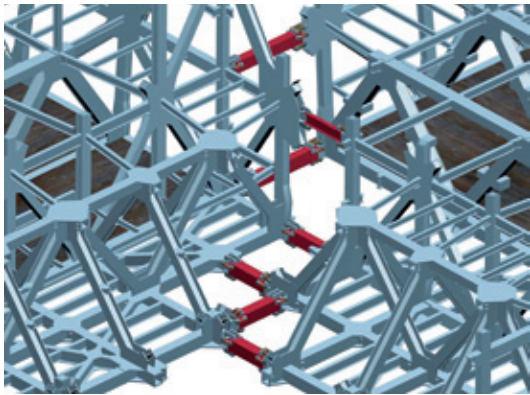


图14 最初的七个连接构件



图15 第一件连接构件的安装



图16 竣工后的建筑

在两座塔楼顶部的钢结构完成后，悬臂部分的施工于2007年8月正式开始，在接下来的五个月内，结构构件从两座塔楼上逐件向外悬挑出来。承包商在最初的连接阶段选择在悬臂内角安装7个连接构件（图14）。在2007年12月8日上午9时左右，7个构件被吊至适当位置后（在10mm的允许误差内）用轴承临时固定后，塔楼慢慢地互相移近（图15）。

2008年3月27日举行的完工仪式标志着整个钢构工程的施工正式完成。然而因为复杂的装修要求，到2012年才开始从央视大楼播出电视频道（图16）。

### 深圳证券交易所

2006年初，深圳证券交易所（简称深交所）宣布将在西面4英里的新商业区福田区建造一幢新的大楼，并面向全球设计招标。

#### 建筑概念

竞赛设计对象是一栋175 000m<sup>2</sup>的总部大楼，大楼拥有各项的证券交易设施（包括交易楼层、登记及结算所、债券信息公司及其他广泛的技术区域），并设有78 000m<sup>2</sup>可租用的办公空间。

OMA选择把所有的证券交易设施置于地上38m的三层悬臂裙楼内（图17，18）。除了成为又一个引人注目的城市地标并提升深圳市的知名度外，此举亦能够释放更多地面的公共空间，用作举办大型活动的场地。塔楼两旁的大堂为办公室及交易所提供独立的进出口，同时亦能作为结构的外筒为悬臂裙楼提供额外的支承。设计独特的全玻璃外墙能使塔楼根据照明情况闪亮并改变外观。塔楼的上部为办公区，办公室沿中心核心筒分布在其周围。机电层沿塔楼高度分布在不同楼层。

塔楼共有45层，高度达240m，标准层楼面大小为55m×55m。裙楼的面积为163m×100m，最大悬臂与支承距离为37m。三层地下室包含停车场及机房，同时一层高的基座占用部分场地并提供零售区域。

初步设计阶段从2007年开始，由OMA鹿特丹办公室和奥雅

completion of the two main buildings.

#### Construction

The ground-breaking ceremony took place on 22 September 2004, and the excavation of 870,000m<sup>3</sup> of earth for the three-storey basement began the following month. China State Construction Engineering Corporation (CSCEC) was subsequently awarded the main contract in April 2005.

Piling works took place during summer 2005, and the tower rafts were constructed in December of that year (Fig. 13). The reinforced concrete slabs each contain up to 39,000m<sup>3</sup> of concrete and 5,000 tonnes of reinforcement. Each raft was constructed in a single continuous pour lasting up to 54 hours. At one stage, 720m<sup>3</sup> of concrete was being delivered every hour, using a relay of 160 concrete trucks from three suppliers. Chilled water pipes were embedded inside the pour and temperatures were monitored for more than two weeks to ensure that the concrete did not experience too high a temperature gradient during curing.

The first column element was placed on 13 February 2006. In total, 41,882 steel elements with a combined weight of 125,000 tonnes were erected over the next 26 months, at a peak rate of 8,000 tonnes per month. Steel sections were fabricated at the yards of Grand Tower in Shanghai and Huning in Jiangsu, and then delivered to site by road.

Construction of the Overhang began in August 2007 after the steelwork for the two Towers was completed to roof level, with the structure cantilevered out piece-by-piece from each Tower over the course of the next five months.

The contractor chose to connect seven link elements at the inside corner of the Overhang during this initial connection phase (Fig. 14). These were lifted into place – to within 10mm tolerance – and temporarily fixed with pins in the space of a few minutes early in the morning on 8 December 2007, before the Towers started to



图17 悬臂群楼内的证券交易大厅



图18 建筑渲染图

纳北京办公室共同完成，奥雅纳香港和深圳的专家们也为设计提供了支持。设计团队和深圳市建筑设计研究院（SADI）一起完成了设计的工作，而深圳院负责了所有施工文件。

### 结构设计

深圳位于强台风多发区域，且易受中等强度地震的影响，这些都会影响到塔楼的设计。本设计的重点是为悬臂裙楼设计一个稳固、合理且经济的方案。初步的分析表明裙楼及其支承结构将占整栋塔楼60%的用钢量，然而其面积却仅占地上总建筑面积的25%。因此，针对此区域的优化对项目的土建成本有重大的影响。

塔楼的基本结构分为三部分：1）内筒为钢筋混凝土核心筒；2）中层筒为塔楼外围的钢-混凝土组合梁柱框架；3）外层桁架筒为裙楼下支承中庭的柱体（图19）。

塔楼的结构体系由混凝土核心筒和抗弯外框架组成（图20）。外框架采用紧密间隔的组合柱及深钢梁。裙楼下方，钢斜撑框架形成一个围绕着大堂的钢桁架外筒。混凝土核心筒内包含所有的主要竖向运输系统与机电管线，并传递竖向及水平荷载。此核心筒平面为边长约30m的正方形，贯穿整座塔楼。外框架柱

move relative to each other (Fig. 15).

A topping-out ceremony on 27 March 2008 marked the completion of the steelwork installation. However the complex fit-out requirements meant that it was 2012 before television channels began broadcasting from the building(Fig. 16).

### Shenzhen Stock Exchange

In early 2006, SZSE announced an international design competition for a new building in Shenzhen's new central business district in Futian, four miles to the west.

#### Architectural Concept

The competition brief was for a 175,000m<sup>2</sup> headquarters building containing all functions of the stock exchange (including a trading floor, registration and clearing house, a Securities Information Company and extensive technical areas), as well as 78,000m<sup>2</sup> of leasable office space.

OMA chose to place all of the stock exchange functions in a three-storey cantilevering podium that floats 38m above the ground, "lifted by the same speculative euphoria that drives the market" (Fig. 17&18). Whilst providing a striking new addition to the city's skyline and increasing SZSE's exposure, this approach also creates a public plaza in the space liberated at ground level, which can be used to accommodate festivals and gatherings.

Two atria on either side of the tower provide separate entrances for the office and stock market areas, whilst creating an outer tube of structure which provides further support for the raised podium. A textured all-glass façade enables the building to

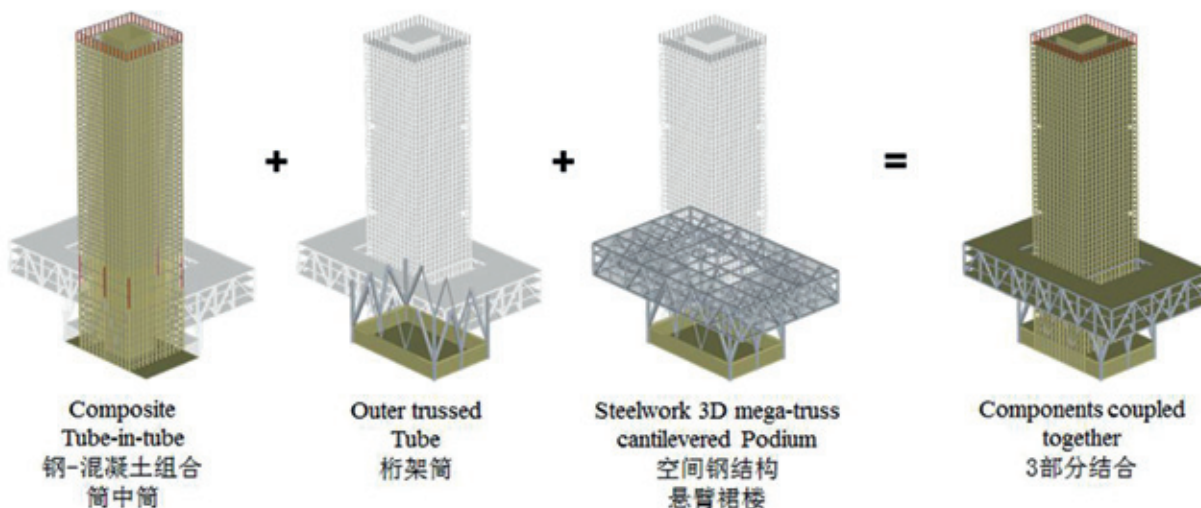


图19 结构概念

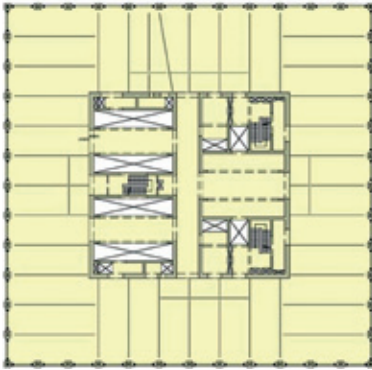


图20 塔楼标准层平面图

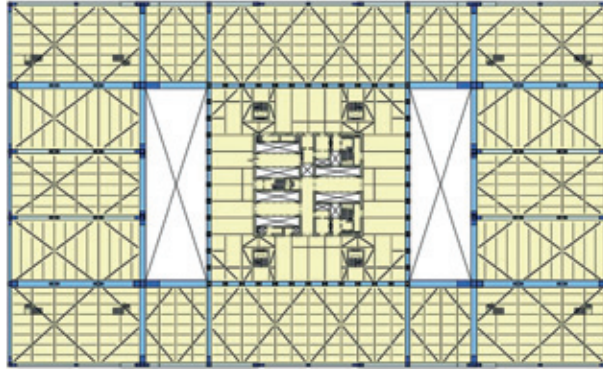


图21 显示桁架布置(蓝色)的裙楼标准层平面图

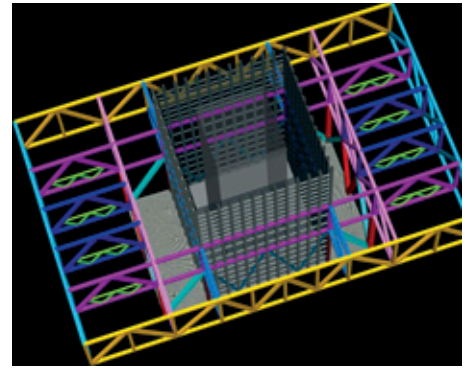


图22 桁架透视图(未显示平面内斜撑)

距为 4.5m, 使用型钢组合柱, 框架梁使用型钢梁。塔楼的抗弯框架从裙楼向下一直通至首层。在裙楼及以下的楼层, 部分柱子为全钢截面或者钢管混凝土箱形柱, 方便和裙楼钢桁架的连接。在首层大堂, 东西两面的外框柱通过位于 4 至 5 层的转换桁架进行转换, 以增加入口大堂处的柱间距。塔楼的楼板为组合楼板, 典型楼面钢梁跨度 13m, 典型楼板厚度为 150mm。吊顶、管线与钢梁整合为一体。

24m 高的裙楼包含三个标准楼层、一个夹层和一个可上人景观顶层。楼面由 2m 高钢梁或桁架弦杆支承, 混凝土楼板厚度为 150mm。桁架沿裙楼全高布置, 主桁架间跨度达到 22m (图 21)。通过诸多方案比选后, 最终选定的桁架方案如图 22 所示。

#### 施工过程

深圳证券交易所于 2007 年 11 月 22 日进行了奠基仪式。开挖与基础工程在 2008 年期间进行, 总承包商中建三局于 2009 年 1 月开始动工。当裙楼的临时支撑移除时, 悬臂末端仅产生 18mm 的竖向位移。钢结构安装于 2010 年 6 月完成, 大楼在 2013 年开始启用 (图 23, 24)。



图23 竣工后的深圳证券交易所

sparkle and change appearance according to the lighting conditions.

The upper tower is used for office functions, arranged around a central core. A number of dedicated building services floors are located at various levels throughout the building height.

The 45-storey tower is 240m tall, with a floorplate size of 55m x 55m. The podium dimensions are 163m x 100m, with a maximum cantilever of 37m from its supports. Three levels of basement contain car parking and plant rooms, whilst a single-storey plinth covers part of the site and contains retail areas.

The scheme and preliminary design phases took place in 2007 and were carried out by OMA in Rotterdam and Arup in Beijing, with specialist support from Arup's Hong Kong and Shenzhen offices. The team worked together with the Shenzhen General Institute of Architectural Design and Research (SADI), who then led the Construction Documents phase.

#### Structural Scheme

Shenzhen is located in a region prone to severe typhoons and subject to moderate seismicity, which would influence the design of the tower. However, the main design focus was to achieve a robust, rational and economic solution for the cantilevering Podium. Initial analysis indicated that the Podium and its supports accounted for up to 60% of the structural steel in the building, despite representing only 25% of the superstructure floor area. Therefore, optimisation of this area would have a significant impact on the final cost of the structure.

During the competition phase, the team decided that the podium and tower should be combined as one structure, with the tower and atrium columns providing vertical and lateral support for the cantilevering structure. The podium itself would be framed by a three-dimensional array of full-depth transfer trusses.

The primary structure can be defined as a triple tube system (Fig. 19):

- Inner tube: central reinforced concrete core
- Intermediate tube: tower perimeter beam-column frame
- Outer trussed tube: braced atrium columns below Podium

The structural system of the tower is a reinforced concrete core with a composite perimeter moment frame (Fig. 20). Below the top of the podium, the steel braced frame around the atrium forms an outer steel trussed tube to support vertical and



图24 施工中的裙楼(临时支撑已移除)



图25 台北表演艺术中心的建筑渲染图

### 台北表演艺术中心

台北表演艺术中心是在台北按照新的国际标准建造的一个表演艺术设施（图 25）。工程预计 2015 年完工。

#### 建筑概念

项目包括一个 1 500 座的大型剧院和两个中型剧院，以及其他相关排练厅、办公室和车间等。OMA 的设计理念是将 3 个剧院所有的舞台部分都安排到中心大方块中，而观众厅则向外突出（图 26）。将舞台连接起来让舞台的使用更加灵活，并增加了以后进行实验性表演的可能性。这个充满活力的新颖舞台和座位安排还包括了一个公共的室内人流环线，将后台的一部分向公众展现出来。

由此设计的中心立方体将是一个 12 层楼的建筑，约 55m 高，50m 见方。3 个剧院的观众厅从立方体向南、北、东三个方向延伸近 37m，并支承于地面的柱子上，这样为地面提供了更多的室外公共空间。

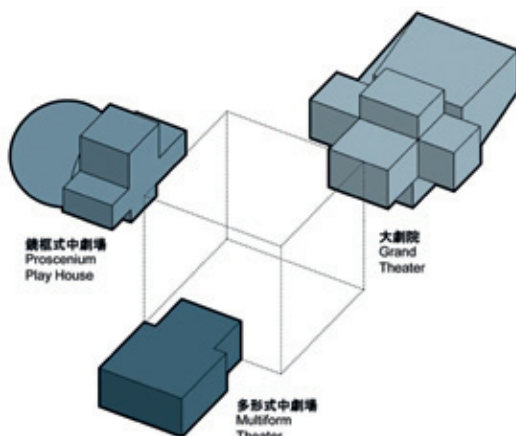


图26 互联礼堂的设计概念

lateral loads from the cantilevering podium, and contribute to the tower stiffness. The floor slabs act as diaphragms to connect the core to the perimeter frames. The combined system carries the vertical and lateral forces into the foundations.

The reinforced concrete core contains all primary vertical transportation and services and carries vertical and lateral loads. It is approximately 30m square in plan, and runs the full height of the building. The internal floor structure within the core consists of an insitu reinforced concrete slab supported by reinforced concrete beams.

The perimeter frame columns are composite steel-reinforced concrete sections spaced at 4.5m intervals, providing a balance of the ductility and compactness of steel and economy of concrete. Frame beams are steel sections.

The tower floor system uses steel beams up to 13m span working compositely with 150mm concrete slabs. The ceiling services zone is integrated with the steel beams.

The 24m-tall podium contains three floors plus a mezzanine and an accessible landscaped roof. The floors consist of 2000mm deep steel floor beams/trusses supporting 150mm thick concrete slabs, spanning up to 22m between primary trusses running the full height of the podium (Fig. 21).

The truss layout was selected after comparison of a number of options, and is shown below (Fig. 22). Truss elements are designed to span unrestrained between nodes. The top and bottom floors of the podium also carry large in-plane forces due to the cantilever action, which are resisted through a combination of the main truss elements and horizontal steel braces.

#### Construction

The groundbreaking ceremony took place on 22 November 2007. Excavation and foundation works continued during 2008, before the main contractor commenced work in January 2009. Just 18mm of vertical movement was measured at the cantilever tip when the Podium was de-propped (note that this took place prior to concreting of the slabs). The structure was topped out in June 2010, with the building expected to open during 2013 (Fig. 23 & 24).

### Taipei Performing Arts Center

#### Introduction

The Taipei Performing Arts Centre is a new international-standard performing arts facility for the capital of Taiwan (Fig. 25). It consists of three theatres that plug

## 结构概念

奥雅纳的工程师将立方体的墙面设计成了带刚性支撑的钢框架。这样的设计不仅可以给礼堂内部空间和其他大型叠堆空间的规划设计带来更多的灵活性，而且和“飞柱”的进一步结合还可以支持和稳固三个向外突出的剧院。

为了减弱地震对建筑影响，整个建筑采用了基础隔震，这样可使结构和建筑表面的受力降低60%左右，减小结构构件的尺寸并使设计更加简单。这个解决方案满足了客户“严重地震后建筑还能运行使用”的要求。

## 结构系统

斜撑的布置受到建筑方面许多的约束，尤其是观众席和舞台之间的前舞台开口。由于观众厅向外突出，没有支撑柱会使3个体块变成悬臂，影响建筑整体的抗震性能，所以观众厅的支撑柱能通过斜撑和整体框架为建筑提供了额外的横向稳定性（图27）。

采用基于性能的设计方法，针对不同的地震等级来设定建筑性能指标并进行设计检查，使用适当的线性和非线性地震分析来验证每个地震等级下结构的性能表现。

在舞台基坑机械下的地下层使用、安装了大概100个隔震装置（图28）。独立的上部结构通过一个700mm宽的节点与下部结构分离开来。主要的工作间都是位于非隔离的下部结构中。台北表演艺术中心则是台湾第一个使用摩擦摆隔震技术的项目。

为了适应建筑设计，采用了能满足剧场大空间框架的大跨度桁架。结构跨度达25m，所以采用了一层楼高的桁架，结构构件尺寸达到600mm×600mm。建筑内部空间没有柱子，除了支撑立方体4个内部主要结构柱，其他所有的柱子都在斜撑上。

上部结构均采用钢结构，同时结合组合楼板来降低整体结构重量。在外部斜撑与结构柱有交接节点的楼层，楼板会被加

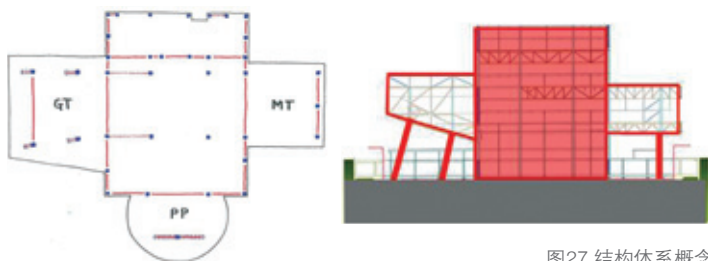


图27 结构体系概念

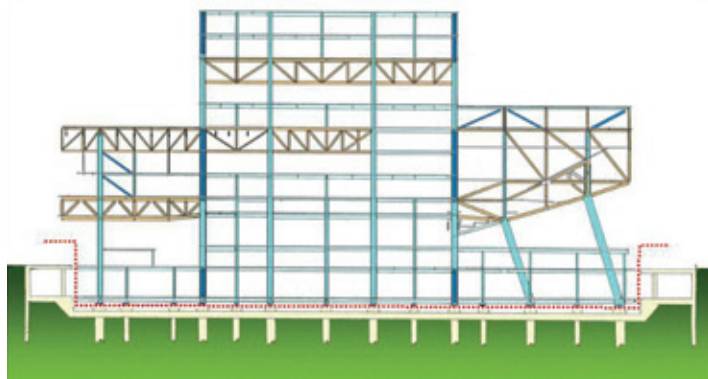


图28 实际基础隔震面（红色虚线）的建筑截面图

into a central cube, combining the stages (and backstages) of the three theatres in a single and efficient whole. Each theatre can be used independently or in combination, offering the possibility for theatrical experimentation and unique views through the stage and into the other auditoriums.

## Architectural Concept

The design brief called for a 1500 seat grand theatre and two medium-sized theatres, as well as associated programme including rehearsal rooms, offices and workshops.

OMA's design concept chose to place all the stage accommodations of the three theatres into a central Cube, with the auditoria of projecting outwards (Fig. 26). Connecting the stages provides more flexibility for use and expands the possibilities for experimental performances. This dynamic new arrangement of stage and seating includes a public circulation route that exposes parts of the backstage to the public.

The resulting Cube is a twelve storey building, approximately 55m tall and 50m square, which contains all of the stage and backstage facilities, lobbies, offices and rehearsal rooms. The auditoria of the three theatres project up to 37m from the Cube on the north, east and south sides, elevated above the ground on columns to provide more outdoor public space at ground level.

## Structural Concept

Arup's engineers used the walls of the Cube to create a robust and versatile structure: a laterally- and torsionally-stiff braced steel box which provides the primary stability. It frees up the interior for planning of the theatres and other large, stacked spaces, and (in conjunction with further 'flying' columns) supports and stabilises the three projecting auditoria.

Due to the high seismicity in Taipei, the whole superstructure is then base isolated in order to attenuate the transmission of ground motions into the building, reducing the forces experienced by the structure and finishes by some 60%. This enables element sizes to be reduced and detailing simplified. The structural system provides the most efficient, economic and highest-performing building possible for the site. In value engineering exercises, base isolation was shown to be more economic than and outperform conventional structural solutions.

This solution enabled the building to achieve the Client's requirement for Operational performance after a severe earthquake, since damage to the structure and finishes is minimised.

## Structure system

The bracing layout was refined to achieve a balanced, symmetric arrangement with optimum lateral and economic performance, yet accommodating the many architectural constraints – in particular the proscenium openings between auditoria and stages. The auditorium support columns provide additional lateral stability, either via bracing or through frame action, since their projecting masses would otherwise cantilever from the Cube braced frame under lateral loading, which could compromise the seismic performance (Fig. 27).

We adopted a performance-based design approach, using state-of-the-art methods to set performance targets for different levels of seismic event and carrying out design checks using appropriate linear and non-linear seismic analysis to verify the structural performance for each.

Approximately 100 isolators will be used, located at basement level beneath the stage pit machinery (Fig. 28). The isolated superstructure is separated from the substructure by a 700mm wide joint. The majority of the main plant rooms are housed in the non-isolated substructure, therefore the main utilities connections etc. do not cross the joint and the number of servicing routes bridging it is minimised.

The gravity system is laid out to suit the architectural planning, using long spans and trusses as necessary to frame the large theatre spaces. These require spans of up to 25 metres, for which storey-deep trusses are generally employed, using elements up to 600mm x 600mm in size. Due to the extensive column-free spaces, only the columns located on the braced elevations plus four internal primary columns run the full height of the Cube.

The superstructure is fabricated in steel, with composite slabs being used to provide a relatively lightweight structural solution. On levels where the perimeter bracing nodes out to the columns, the floors are considered to act as diaphragms and the slabs are thickened to suit.

Steel is also used for the structure of the three projecting volumes. Each has a 3-D network of trusses to carry the loads around the auditoria and circulation spaces, and into the dedicated supporting columns as well as the perimeter frame of the Cube.

The ellipsoidal form of the Proscenium Playhouse is made up from a

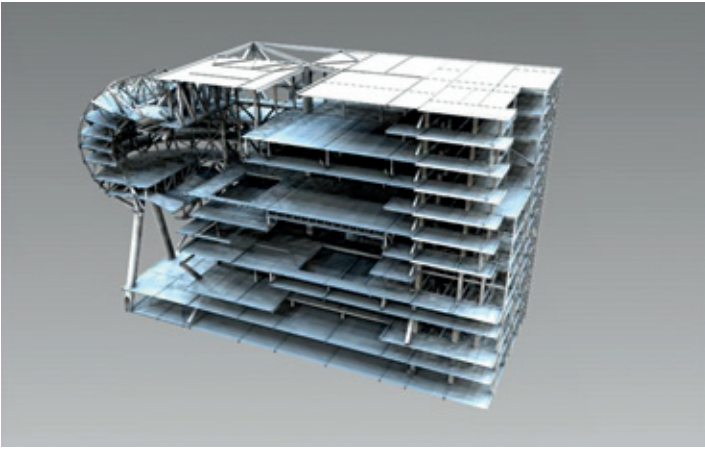


图29 显示礼堂结构的结构分析模型渲染图

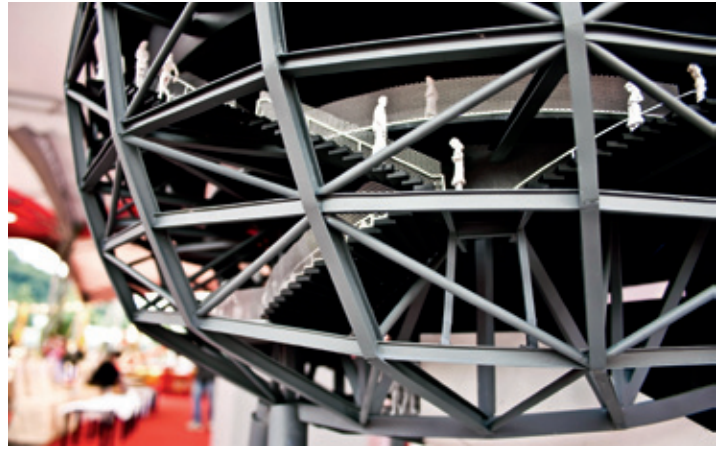


图30 舞台剧院物理模型

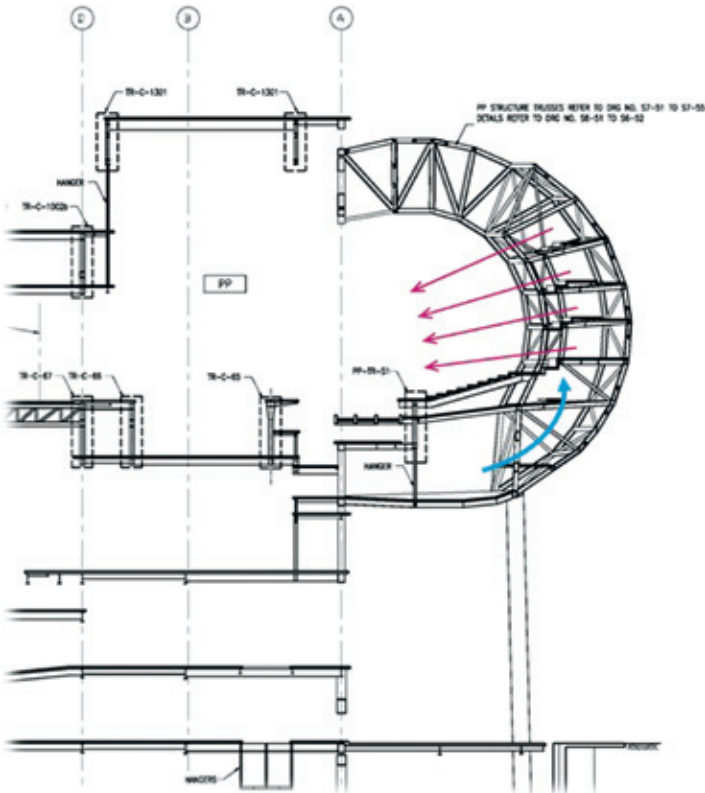


图31 扩展舞台剧院结构

厚。3个舞台部分也采用了钢结构。每个建筑都用网架来承受观众厅和流动空间的荷载，并将荷载传递到支撑柱和立方体的结构框架上。

椭圆球形的舞台剧场由双层网壳结构构成。这种结构的冗余度是必不可少的，这样内壳和外壳才可被打通作为阳台开口、人流路线或安装照明设备等（图29~31）。

### 施工进度

开工仪式在2012年2月举行，地下室的施工目前进展顺利。整体结构预计2014年初完成，而表演艺术中心将在2015年对外开放。

### 结语

奥雅纳将3个独特建筑设计变为现实，提供了创新的解决方案，设计工作严谨的本质对这些建筑的成功至关重要。（译/赵欣，校/吴春花）

faceted double shell structure which provides a highly redundant structural system. This redundancy is essential to allow the inner shell and intra-shell zones to be “eroded” to suit openings for balconies, circulation routes, ceiling lighting, etc(Fig. 29-31).

### Construction

The groundbreaking ceremony took place in February 2012, and construction of the basement is now well advanced. The structure is due to be completed in early 2014, with the centre scheduled to open in 2015.

### Conclusions

This paper has attempted to introduce the technical complexities and innovative structural solutions that were necessary for realising three unique architectural visions. The rigorous nature of Arup’s design work has been of vital importance to the success of these buildings.

The projects demonstrate that buildings with many complex technical challenges can be delivered successfully within a tight programme. In all cases, an international team was mobilized to make best use of the firm’s experience and knowledge, which required seamless co-ordination between a number of locations and cultures. Furthermore intensive coordination with OMA was required during the design stages – at certain times, this led to an almost permanent presence in their offices.

The performance-based seismic design approach pioneered on CCTV has since been used successfully for many other projects in China. **AT**

### 图片来源

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图24 © Marcel Lam/奥雅纳

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台北艺术表演中心

### 主要信息

#### 央视大楼

建筑功能：行政管理、多功能使用、新闻制作、广播、节目制作、人员设备、停车场、服务楼

场地面积：187 000m<sup>2</sup> 建筑面积：473 000m<sup>2</sup>

建筑设计：OMA（由Rem Koolhaas，前OMA合伙人Ole Scheeren（至2010年），合伙人 David Gianotten 和项目经理 Dongmei Yao领导设计，合伙人Shohei Shigematsu，Ellen van Loon 和 Victor van der Chijs密切参与了设计协作过程）

工程咨询：奥雅纳（结构、建筑设备、岩土工程、防火工程、安全工程）

本地设计院：华东建筑设计研究院（ECADI）

幕墙：Front Inc. 声学：DHV 舞台：dUCKS Sceno

#### 深圳证券交易所

建筑功能：证券交易（交易大厅，登记和结算处，证券信息公司和各项技术领域），办公室租金

场地面积：39 100m<sup>2</sup>

建筑面积：175 000m<sup>2</sup>

建筑设计：OMA（由合伙人 Rem Koolhaas，David Gianotten 和 Ellen van Loon 以及助理建筑师Michael Kokora领导设计）

工程咨询：奥雅纳（结构、建筑设备、建筑外立面、建筑可持续性、防火工程、灯光工程、通讯工程）

本地设计院：深圳市建筑设计研究总院（SADI）

#### 台北艺术表演中心

建筑功能：一个1 500个座位的剧院和两个800个座位的剧院，相关设施

场地面积：20 750m<sup>2</sup>

建筑面积：50 000m<sup>2</sup>

建筑设计：OMA（由合伙人Rem Koolhaas 和 David Gianotten领导设计）

工程咨询：奥雅纳（结构、建筑设备、建筑可持续性、防火工程）

其他参与方：Artech（助理建筑设计）、Evergreen 工程咨询（助理结构设计）、Heng Kai Inc.（助理设备工程）、I S Lin & Associates 工程咨询（助理设备工程）

幕墙：ABT 声学：DHV 舞台：dUCKS Scéno

### KEY FACTS

#### CCTV

Function:Administration, multi-purpose, news production, broadcasting, program production, staff facilities, parking, service building

Site area:187,000m<sup>2</sup>

Floor area:473,000m<sup>2</sup>

Architect:OMA led by Rem Koolhaas, former OMA partner Ole Scheeren (until 2010), partner David Gianotten and project manager Dongmei Yao in close collaboration with partners Shohei Shigematsu, Ellen van Loon and Victor van der Chijs.

Engineer:Arup (Structure, Building Services, Geotechnics, Fire Engineering, Security)

LDI:ECADI (East China Architectural Design & Research Institute)

Façade: Front Inc. Acoustics: DHV Scenography: dUCKS Sceno

#### Shenzhen Stock Exchange

Function:Stock Exchange (trading floor, registration and clearing house, a Securities Information Company and extensive technical areas), rental office

Site area:39,100m<sup>2</sup>

Floor area:175,000m<sup>2</sup>

Architect:OMA Led by partners Rem Koolhaas, David Gianotten and Ellen van Loon and associate Michael Kokora

Engineer:Arup (Structure, Building Services, Façade, Sustainability, Fire Engineering, Lighting, Communications)

LDI:SADI (Shenzhen General Institute of Architectural Design & Research)

#### Taipei Performing Arts Centre

Function:One 1,500-seat theatre and two 800-seat theatres; associated facilities

Site area:20,750m<sup>2</sup>

Floor area:50,000m<sup>2</sup>

Architect:OMA Led by partners Rem Koolhaas and David Gianotten.

Engineer:Arup (Structure, Building Services, Sustainability, Fire Engineering)

Others:Artech (Associate Architect),Evergreen Consulting Engineering Inc. (Associate Structural Engineer),Heng Kai Inc. (Associate Services Engineer),I S Lin & Associates Consulting Engineers (Associate Services Engineer)

Façade: ABT Acoustics: DHV Scenography: dUCKS Scéno