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Structural Design Challenges of Minmetals Capital Tower, Shenzhen | 深圳五矿金融大厦 结构设计挑战

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Abstract | 摘要

Steel braced frames combined with a concrete services core are widely used in tall building design. To meet the special architectural design challenges in the Minmetals Capital South China Tower in Shenzhen, such as the large, column-free spaces at the lower levels, notches in the building elevations, building setbacks at the lower floors, and the unique sail-like building shape of the tower, steel bracing, belt trusses, and moment frames, coupled to a concrete services core were selected for the 150-meter-tall tower. Uniquely-shaped composite columns with embedded steel are used to achieve the large clear spans. Due to the tight site area, shaped like a quadrant of a circle, the tower is located close to the property line. Its columns are in line with the basement wall, which serves as both the retaining wall and the support of the tower columns. A glass-clad skybridge connects the podium (also sited on the property line) to the tower, opening up additional street-level access. The podium features a long-span skylight structure which brings natural light into the space. The skybridge allows for safe access to the podium by the office occupants in incumbent weather.

Keywords: Belt Truss, Composite Columns, Dual Lateral load System, Moment Frames, Skybridge and Steel Bracing

带交叉支撑的巨型框架–筒体结构在超高层建筑的设计中被大量采用。为满足建筑设计的一些特殊要求带来的挑战，比如：底部楼层大空间并且无柱，建筑立面凹槽打断外围框架，建筑底部楼层后退，以及建筑外形特殊的风帆造型，钢支撑+环带桁架+外围框架一起组成外围抗侧力体系，与混凝土核心筒一起作为150米高的五矿金融大厦的抗侧力体系。在底部楼层采用特殊外形的内置型钢的组合柱以获得很大的跨度。 –由于项目的基地特别紧凑狭小，类似于一个四分之一圆的扇形，塔楼被放置到紧贴在用地红线的位置。塔楼的东侧外围柱与地下室外墙位于同一条线，而地下室外墙同时作为地下维护结构（地下连续墙），以及作为塔楼柱的支撑，成为特殊的三合一结构。

关键词：环桁架、组合柱、双重抗侧力体系、框架结构、天桥、钢斜撑

Project Summary

Steel braced frames combined with a concrete services core are widely used in tall building design. To meet the special architectural design challenges in the Minmetals Capital South China Tower in Shenzhen, such as the large column-free spaces at the lower levels, notches in the building elevations, building setbacks at the lower floors, and the unique sail-like building shape of the tower, steel bracing, belt trusses and moment frames, coupled to a concrete services core were selected for the 150-meter-tall tower (Figure 1). Uniquely-shaped composite columns with embedded steel are used to achieve the large clear spans.

Due to the tight site area, shaped like a quadrant of a circle, the tower is located close to the property line. Its columns are in line with the basement wall, which serves as both the retaining wall and the support of the tower columns. A glass-clad skybridge connects the podium (also sited on the property line) to the tower, opening up additional street-

Figure 1. The Minmetals Capital South China Building (Source: Pei Cobb Freed & Partners)
图1. 五矿金融大厦（来源：Pei Cobb Freed & Partners）

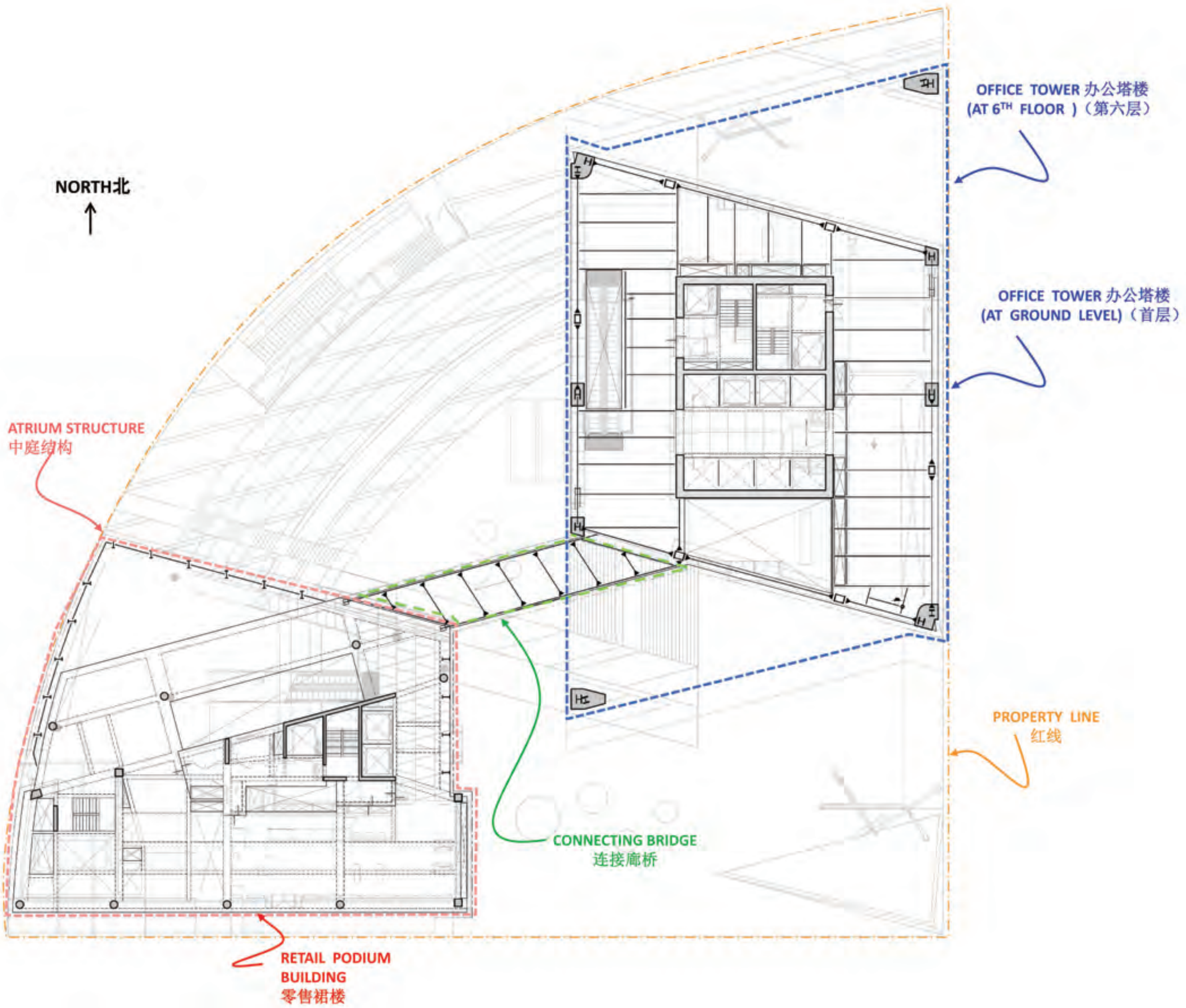

Figure 2. The plan of the project at the third level (Source: Leslie E. Robertson Associates)
图2. 项目三层平面图（来源：理雅结构工程咨询有限公司）

level access. The podium features a long-span skylight structure which brings natural light into the space. The skybridge allows for safe access to the podium by the office occupants in incumbent weather (Figure 2).

Finding the Structural Form

The Minmetals Capital South China Building is a 29-story, 150-meter (490-foot) tall building located in Shenzhen, China. The project serves as a gateway site of a planned business development in the Nashan District of Shenzhen, and will provide a new regional headquarters for one of the world's leading metal and mining companies. The tower and the adjacent retail podium and basements are designed by Pei Cobb Freed Architects and structural engineers Leslie E. Robertson Associates of New York. The local design institute is Huayi Design Consultants. The project features a variety of different usages including office, retail, restaurant, parking, and event floors. Due to the tower's sail-like

项目概述

带交叉支撑的巨型框架–筒体结构在超高层建筑的设计中被大量采用。为满足建筑设计的一些特殊要求带来的挑战，比如：底部楼层大空间并且无柱，建筑立面凹槽打断外围框架，建筑底部楼层后退，以及建筑外形特殊的风帆造型，钢支撑+环带桁架+外围框架一起组成外围抗侧力体系，与混凝土核心筒一起作为150米高的五矿金融大厦的抗侧力体系（图1）。在底部楼层采用特殊外形的内置型钢的组合柱以获得很大的跨度。

由于项目的基地特别紧凑狭小，类似于一个四分之一圆的扇形，塔楼被放置到紧贴在用地红线的位置。塔楼的东侧外围柱与地下室外墙位于同一条线，而地下室外墙同时作为地下维护结构（地下连续墙），以及作为塔楼柱的支撑，成为特殊的三合一结构。

项目的裙房也紧贴用地红线，通过一个玻璃天桥与塔楼相连接，给塔楼提供了另外一个开放的入口空间。裙房的特色在于一个大跨度的天窗结构，可以将大量的自然光线引入到裙房内。空中天桥也给裙房提供了一条即使在恶劣天气情况下，也可以到达塔楼办公室空间的安全通道（图2）。

探询合理结构形式

深圳五矿金融大厦位于中国深圳，在深圳市南山区，作为一个全新的规划定位为商业中心，本项目为五矿集团在该地区的门户，并且将此定位为其在华南地区的总部，成为该公司在全球金属和矿业公司的领导中心。项目的塔楼和裙房由贝□考□弗建筑师事务所设计，结构工程师由位于美国纽约理雅结构工程咨询有限公司承担。本项目的本地设计单位是香港华艺设计顾问（深圳）有限公司。项目有办公，零售，酒店，停车以宴会厅等多种功能。由于塔楼的风帆造型，导致塔楼的每一个楼层均不一样，而且很多的结构构件是倾斜的，其倾斜变化随每层的建筑几何形状均有变化。塔楼的顶部为大空间高级会务楼层，采用钢管斜撑结构（图3）。实际上，塔楼的许多结构构件是直接暴露在外的，

Figure 3. Event space located at the top of the tower (Source: Pei Cobb Freed & Partners)
图3. 塔楼顶部高级会务空间效果图（来源：Pei Cobb Freed & Partners）

shape, each floor is unique, and much of the structure slopes, with slope changes at each floor, to accommodate the building's geometry. The tower is topped off with an event space enhanced by structural bracing (Figure 3). Indeed, much of the tower's structure is exposed to view, and is designed to work harmoniously with the overall architectural vision.

Early on in the design process, the structural engineer worked closely with the architect to establish a structural system that represented the architect's vision of a sail-like structure (Figure 4). The tower is shaped as a parallelogram in plan, and the curved façades of the northern and southern sides appear to be balanced by the vertically braced planes of the adjacent sides. The overall effect results in a building structure that appears to perfectly balance a dynamic-looking form. Vision glass wraps much of the exterior, and the structural bracing is visible through the translucent glass. At the lower portion of the building, stone cladding is used to provide a sense of strength and of permanence, and here the structural design takes advantage of its opaqueness to locate large concrete columns that are part of a five-story-tall portal frame structure.

Customizing the Structural Systems

The Chinese Building Code requires the use of dual lateral load resisting systems, and stipulates minimum building shears that are to be resisted by the perimeter lateral system. As well, for a building of this height, the Code requires a maximum inter-story drift of H/800

设计成结构构件外露的目的是以此达到建筑视觉效果与结构力度的高度协调。

在项目最初的设计阶段，结构工程师就和建筑师紧密合作以确定一个能够充分表达建筑师设计意图的一个结构形式。建筑师的意图是一个风帆的结构造型（图4），而结构设计的目标就是需要表达风帆的力度感。塔楼的平面形状是一个平行四边形，其在南北立面上的弧形幕墙支撑位于塔楼边缘的竖向钢斜撑。最后建筑物的整体效果完美的体现了建筑师所需要的动感的造型。透明的玻璃包裹了建筑物大部分区域，而结构斜撑可以通过透明的玻璃被清楚看到。在建筑物的底部区域，采用石材幕墙来体现建筑物的力度感，厚重和持久的效果。在这些区域，结构设计采用不透明性来遮挡混凝土巨柱，这些巨柱形成了一个5层高的塔楼巨型框架入口门户。

定制化的结构体系

通常的，中国规范需要给高层塔楼提供双重的抗侧力体系，并且要求建筑物外围框架体系在地震作用下能够承担一定的楼层剪力。而且，对于这样一个高度的建筑物，规范要求建筑物在风荷载和地震作用下楼层最大弹性层间位移角不大于H/800。为满足规范的这些要求，大部分结构工程师会在外围采用框架结构体系。但是，采用斜撑框架，其效率更高，更经济。尽管一些建筑师认为框架架构体系使得建筑布局更方便，但框架结构与斜撑框架相比尺寸大，用料多，效率低。在设计的最初阶段，结构工程师就从其他高层项目的设计积累的经验中知道带钢斜撑的框架能提供足够的刚度以及更有效的使用材料。建筑师对于外围的斜撑体系非常满意，因为钢斜撑代表了帆的主杆件，使得船帆的造型得到强调，同时也带来了其他优点，即较少的外围立柱和很轻巧的外围梁。在建筑概念上需要的时候，带钢斜撑的体系被用到外围。在其他一些位置，建筑师并不需要钢斜撑，因此我们采用钢结构框架结构，此时柱子间距相对较小。此外，塔楼中部的钢筋混凝土核心筒承担了大量的竖向力以及相当的侧向力。

在塔楼顶部和中部的机电层和避难层，设置了环带桁架。环带桁架用来减小外围柱的尺寸，另外，环带桁架还增加了结构的抗侧刚度，为塔楼增加了结构安全的冗余度。环带桁架将位于其中间的，塔楼外周柱上的荷载传递到SRC组合柱，从而使得外周柱尺寸大大减小，同时还减小了相邻柱之间的竖向变形差。环带桁架的作用相当于一个“虚拟的伸臂桁架”，环桁架将核心筒的倾覆力矩传递给外围巨型结构，从而有效减小了核心筒的倾覆弯矩，因此也最大程度的减小了核心筒墙体的厚度，增强了结构的整体刚度。环带桁架上下弦位置的楼板，被特别加强，以提高其对塔楼侧向力的传递。

外围抗侧力结构体系通过楼面刚性板与钢筋混凝土核心筒绑定在一起。塔楼层与层

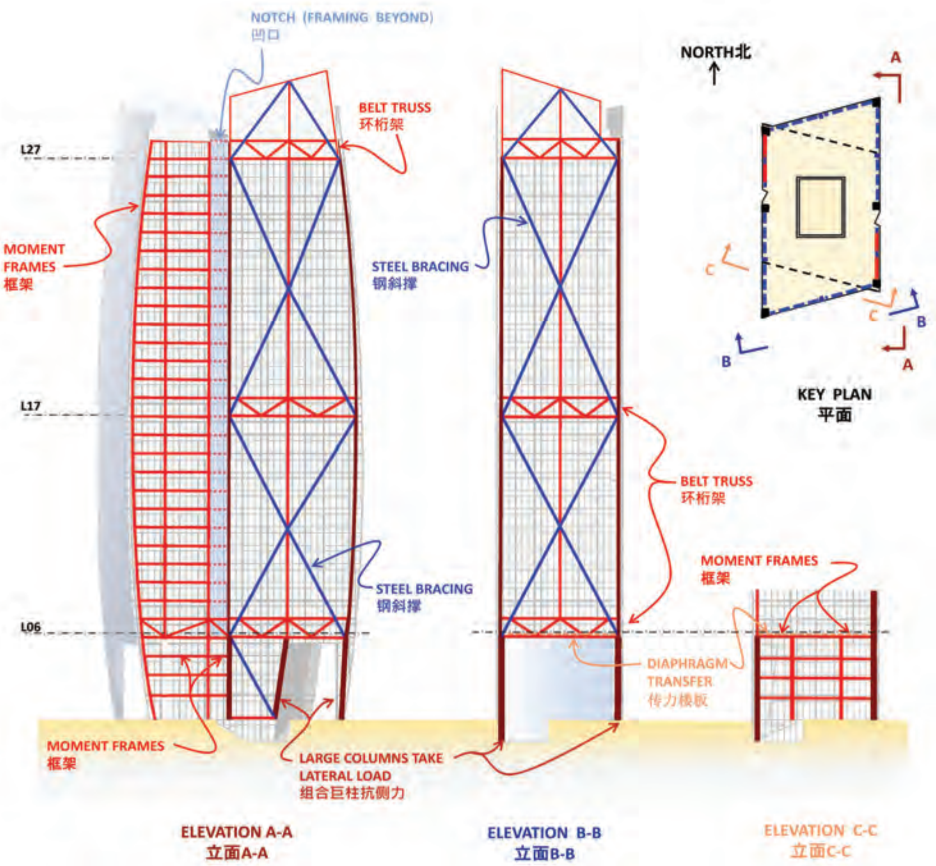

Figure 4. The tower's perimeter structural systems (Source: Leslie E. Robertson Associates)
图4. 塔楼外围结构体系（来源：理雅结构工程咨询有限公司）

under either wind or earthquake loads. To meet these Code requirements, many engineers use moment frames; however, perimeter-braced frames are more cost-effective. Early in the design process, the structural engineers drew from their experience in designing other tall buildings and selected perimeter steel bracing for its stiffness and more efficient use of materials. The architect was pleased that the perimeter bracing system, resembling battens in a sail, accentuated the sail-like form, with the added benefit of fewer perimeter columns and lighter perimeter spandrels. Where the architectural concept allowed, the perimeter bracing was adopted. At some locations where the perimeter bracing was not architecturally desired, steel moment frames and relatively closely spaced columns were used. Reinforced concrete walls around the services core carry a majority of the building's gravity and lateral loads.

Belt trusses are located at the top tower floor and at MEP floors in the middle of the tower. The main function of the belt-trusses is to reduce the perimeter column sizes; moreover, they help provide lateral resistance and increase structural redundancy. The belt trusses transfer loads from the intermediate exterior columns to the composite columns, minimizing the intermediate column sizes and reducing differential vertical displacements between the adjacent columns. Serving as "virtual outrigger trusses," the belt trusses also reduce the overturning moment carried by the concrete core, hence reducing the thickness of the core walls, and increasing the overall lateral stiffness of the building. Strengthened floor diaphragms are provided at levels where the top and bottom chords of the belt trusses are located to further improve the lateral load resistance of the building.

The perimeter systems are tied to the reinforced concrete core wall through the floor diaphragm. The typical floor-to-floor height is 4.5 meters with a floor to ceiling clear height of 3.2 meters. So as to minimize the tower's weight and in keeping with the script of a light sail-like structure, the office floors of the tower are steel framed with slab on truss deck. For this building, a key advantage of a steel floor framing system is the reduction of the building weight, and hence the amount of loads which are required to be transferred at the fifth-floor setback. The lighter weight of the steel-floor system results in smaller columns, and in increased usable floor areas. Further savings are achieved due to the smaller foundation loads. Additionally, the use of steel framing enables increased flexibility for future modifications, such as the addition of stairs, shaft openings, high-density filing, and the like.

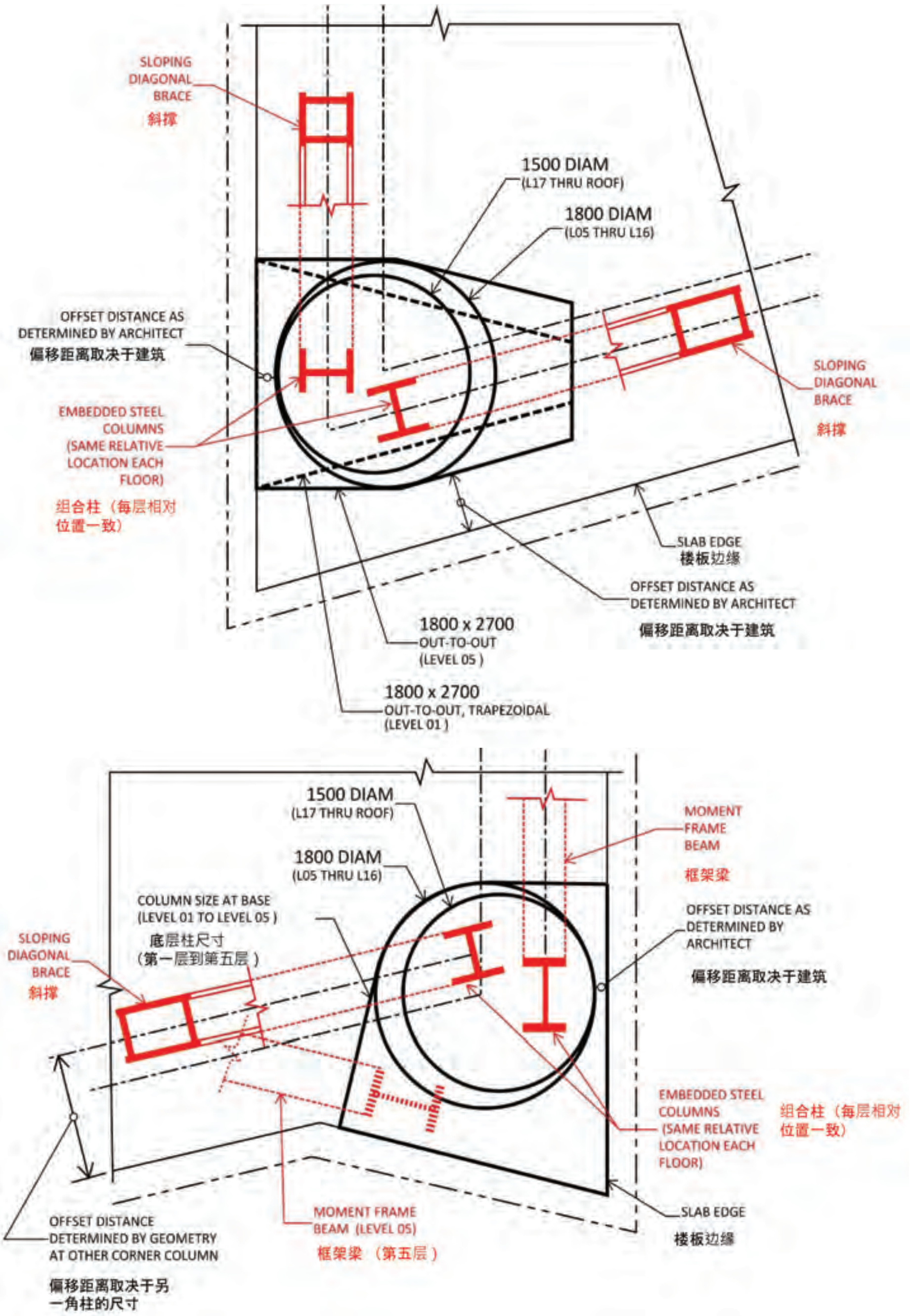

Figure 5. Overlay of composite corner column sizes at various levels of the tower at the southwest (top) and the southeast corners (bottom) (Source: Leslie E. Robertson Associates)
图5. 角部SRC组合柱在塔楼不同楼层的重叠布置图塔楼西南角柱（上图）和塔楼东南角柱（下图）（来源：理雅结构工程咨询有限公司）

The primary columns of the structure are a composite of embedded structural steel shapes and reinforced concrete. Where the bracing diagonals and belt truss members connect to the composite columns, the embedded steel shapes are of a size capable of fully transferring the vertical component of the load. The work points of the steel shapes are offset from the centerlines of the composite columns. This layout simplifies the steel-to-steel connections of the embedded steel shapes to the perimeter structural systems – perimeter braces, moment frames, and belt trusses – but requires careful study of how the embedded shapes and their work points are positioned within the concrete columns (Figure 5). The structural engineer worked with the architect to develop custom concrete column shapes

的建筑高度为4.5米，设计的室内净高约为3.2米。为了尽量减少塔楼的重量，并且保持建筑物能实现轻巧的帆船桅的结构造型，塔楼的楼面结构采用钢梁+组合楼板体系。对于这个项目来说，采用钢梁+组合楼板体系的一个主要优势就是可以减小塔楼整体的重量，也即塔楼的总荷载，这些重量需要在5层楼面位置进行转换。较轻的钢梁+组合楼板体系导致了更小的柱截面，增加了可用的楼面面积。同时，整个项目重量的减少，还减少了基础的荷载，从而减少了基础造价。最后，使用钢梁+组合楼板体系，提高了后续使用的灵活度，更方便将来使用功能的修改，比如增加楼梯，楼板开洞，增加荷载的加固等。

塔楼主要的柱子采用的是内置型钢的钢筋混凝土巨柱（SRC柱），当钢斜撑和环带桁架的构件连接到SRC巨柱时，内置的

that met the desired aesthetic, while also creating column shapes that aligned between floors without offsetting the locations of the embedded steel columns. For example, the corner column changes shape from circular to trapezoidal and the embedded steel shapes are arranged to fit within these shapes at all floors; the arrangement informs how far inboard the structural braces, belt trusses, and moment frames are set from the slab edge.

Exceeding the Chinese Building Code

Several aspects of the architectural design of the tower led to structural systems that exceeded the restrictions of the Chinese Building Code or were not common Chinese construction practices. This required special review and multiple meetings with panels of experts. These aspects included the following:

- The notches along the sides of the building do not allow for continuity in the perimeter lateral load resisting system;
- Due to the very tight site area, the big composite columns on one side of the tower are supported by the diaphragm basement walls; and
- Most importantly, the building footprint steps in dramatically at the sixth level, necessitating a change in the building's lateral stiffness.

To address these Code exceedances, the structural engineer developed specific solutions for the Minmetals Capital South China Tower. To address the discontinuity of the perimeter lateral systems, the structural engineer introduced steel plates at local areas in the floor diaphragms (Figure 6). The plates locally replace the truss deck and are placed on top of the steel beams but below the slab, and are used to properly tie the braced-frame lateral system to the moment-frame lateral system.

Due to the restraints of the site, some of the tower columns land directly on the site's diaphragm wall. The tower columns are eccentric to the piles at the perimeter of the foundation, resulting in additional moments that need be de-coupled and resolved by the tower's pile foundation (Figure 7). This is not common in China, and required careful review considering the possible construction tolerances, review of possible differences in concrete strength, as well as getting local contractors on board.

The Chinese Building Code stipulates that the building's perimeter system attract a

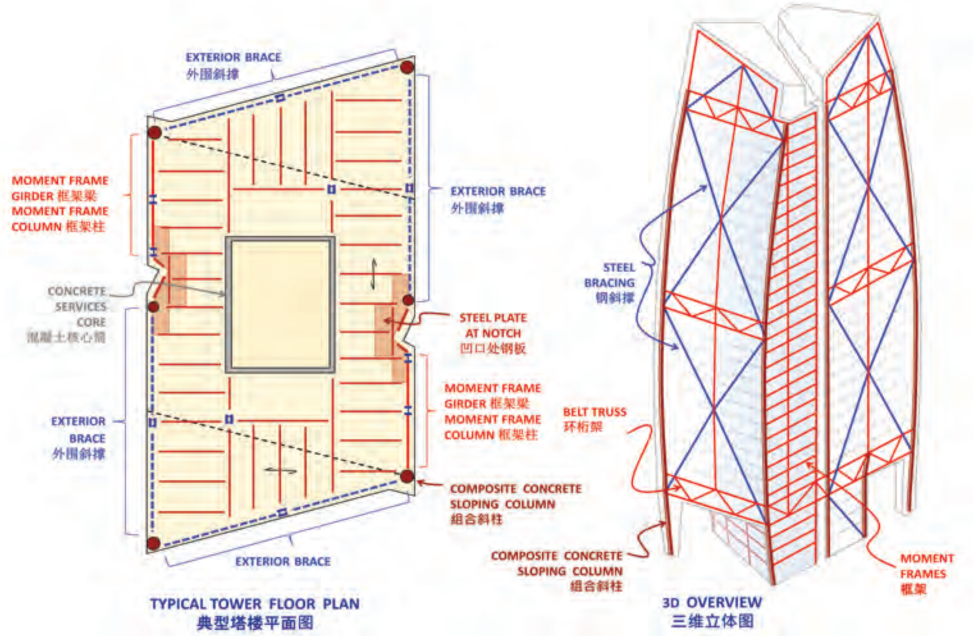

Figure 6. Structural challenges of the architectural notches (Source: Leslie E. Robertson Associates)
图6. 建筑立面开槽带来的结构挑战（来源：理雅结构工程咨询有限公司）

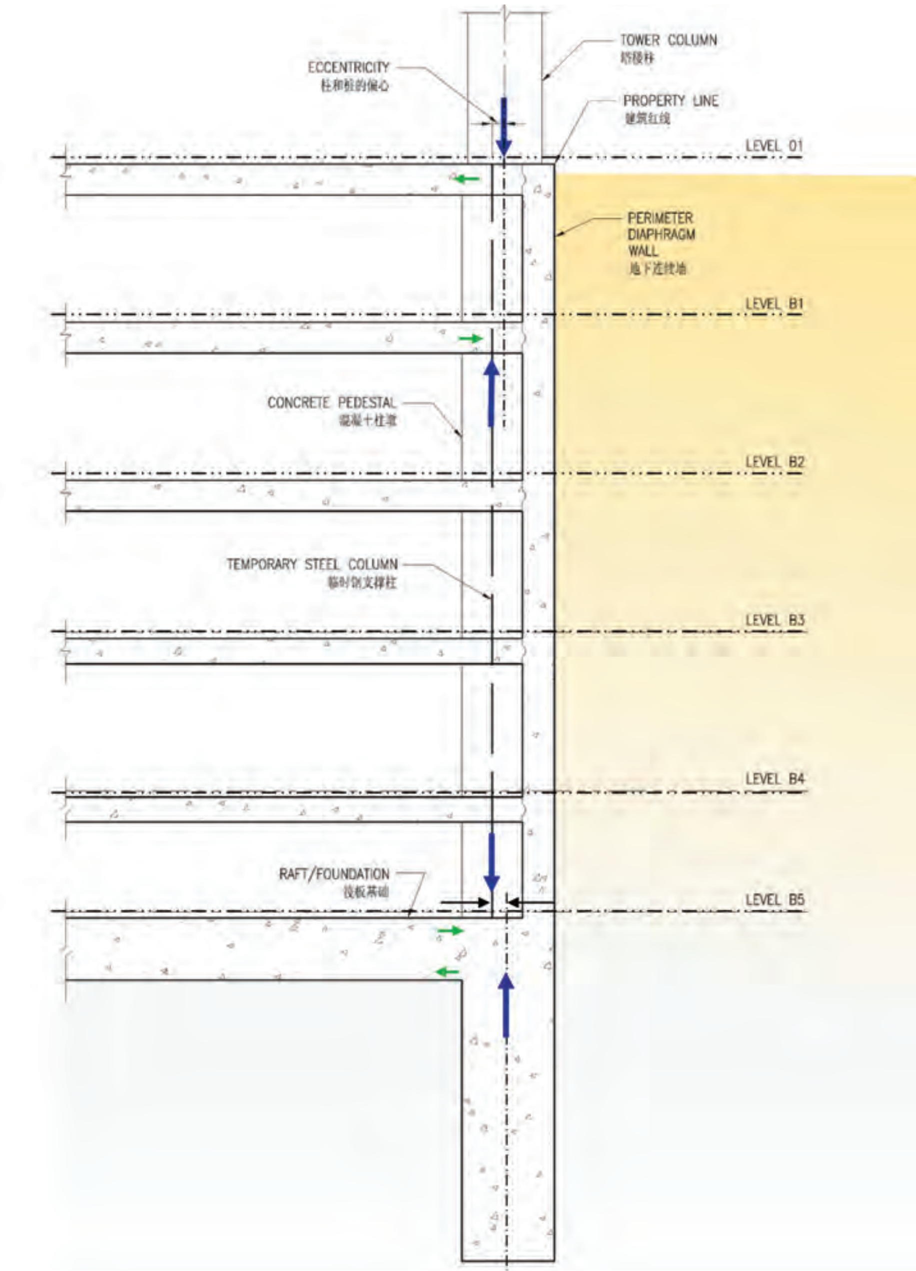

Figure 7. Challenges of diaphragm wall construction at the tower columns (Source: Leslie E. Robertson Associates)
图7. 塔楼柱与地下连续墙合一带来的结构设计施工挑战（来源：理雅结构工程咨询有限公司）

Figure 8. Structural challenges of the tower's setback at the sixth level (Source: Pei Cobb Freed & Partners)
图8. 塔楼在六层缩进带来的结构挑战（来源：Pei Cobb Freed & Partners）

minimum of approximately 15 to 20 percent of the building's story shear at any level. The perimeter bracing system addresses well this requirement at the higher floors; however, at the lower floors of the tower, the northern and southern sides of the building dramatically step inwards resulting in a setback of the floors below the sixth level (Figure 8). To address the discontinuity in the building's perimeter stiffness, the sixth floor is a transition zone for the structural system where the perimeter-braced frame is transitioned to a mega-portal frame, and lateral loads are also designed to transfer to an inner set of moment frames below the sixth floor. Even with these measures, the perimeter system between the first and sixth floors attract less than the Code recommendation. These systems are nevertheless designed with a sufficient capacity for the recommended loads, in keeping with the intention of the Code. To prove the reasonableness of the design, the structural engineer provided Performance-Based Design studies, which were approved by the panel of experts.

Wind and Earthquake Engineering

The wind loads control the design of the primary structural systems of the tower; however, due to the unusual nature of the building's setbacks, considerable studies were done for the building's performance under seismic loading.

The building has multiple features that did not fit in well with the earthquake restrictions of the Chinese Building Code. To demonstrate the suitability of the proposed systems, the

型钢尺寸能够传递所有的竖向力，型钢构件的交点，即合力作用点与SRC柱的形心有偏心。结构的平面布置将斜撑、框架钢梁、桁架的型钢和埋置在柱内的型钢连接到一起，设计中尽量简化这一连接。但在设计中我们还是非常仔细的研究连接节点在混凝土柱中怎么样布置最为合理（图5）。在这一个问题上，结构工程师与建筑师合作制定了柱的外形轮廓，此外形轮廓不仅能满足建筑师想要的建筑美，也能够使得型钢在混凝土柱内不需要因为楼层的变化而变换位置。例如，角部柱子的形状从上部的原型变化至底部楼层的梯形柱时，内部型钢的相对位置在各楼层之间也不需要调整。这一排布显示了钢斜撑，桁架和外框架钢梁在柱内，楼板边界处如何连接。

中国规范结构超限

塔楼某些建筑设计的要求将导致整个结构体系超出了中国规范允许的范围，或者对于中国的常规施工来说是非常罕见的。这些需要一些特别的关注，并且需要与专家进行沟通。主要的有以下几点：

- 塔楼东西两侧立面上开槽，导致侧向力体系中外围框架中被断开。
- 由于场地范围狭小，为充分利用基地面积，塔楼东侧SRC巨柱与用地红线重合，塔楼柱需直接落在地下室外墙上，并且此地下室外墙同时也是围护结构，即地下连续墙。
- 最为重要的一点，塔楼投影在6层以下突然缩进，使得塔楼的侧向刚度产生了突变。

为了解决这一些超限导致的结构不利，结构工程师为五矿金融大厦提供了一系列的解决方案。为解决因立面开槽导致的外围框架抗侧力体系的断开，结构工程师在楼板凹槽所在的位置局部增加钢板（图6）。在这些位置的钢板替代了压型钢板组合楼板，钢板置于钢梁上，混凝土楼板下，这一结构用于将斜撑结构体系与其附近的框架结构体系合理的联系在一起，从而解决外围侧力体系被断开产生的不利影响。

由于场地范围狭小，一些塔楼的柱子（塔楼东侧）直接落在作为地下室外墙和围护结构的地下连续墙上。这些连续墙在施工过程中将会采用泥浆灌注的方法，混凝土强度较低，施工容许偏差较大，没有足够的承载力支持上部塔楼的柱子。因此在每个塔楼柱的下面引入内置型钢的组合桩墙来传递相应的塔楼柱力。然而，塔楼的柱与下部的桩墙（与地下连续墙同时施工的桩）将产生偏心，这一偏心会产生附加弯矩，而这一弯矩需要依靠塔楼下的楼板和楼板基础提供拉压力来予以平衡（图7）。这种设计和施工在中国均很罕见，在这个问题上，我们经过了仔细的研究，并且充分考虑了可能的施工方法以及施工误差，不同混凝土强度在同一位置施工的可行性，在此处三墙合一的设计中，我们考察了多家承包商，并且让承包商尽早进入设计，我们的设计必须结合施工的方法和可行性。

中国规范要求塔楼外围框架系统在每个楼层都能够承担塔楼总剪力的15%～20%，在塔楼上部的带斜撑的框架体系能够很好的满足这一规范的要求，然而，在塔楼底部楼层，即6层以下，由于南北侧向里收进很多，导致抗侧刚度产生突变，为了解决由于结构缩进导致的刚度不连续，6层结构将作为结构体系的一个过渡区，从上部的外围带斜撑框架体系过渡到下部巨型框架结构，此处的侧向力传力也将设计成为部分传至6层框架下部内部框架（图8）。即使采用了这些措施，在1～6层，外围框架体系所吸收的剪力仍然小于规范所要求的值。当然，根据规范的要求，这部分外围体系将会被设计成为有足够的抗剪承载力，以能够承担规范所要求承担的剪力和弯矩。为证明这一设计的合理性，结构工程师提供了结构性能化设计，对6层以下的关键结构的抗震性能提供了保证，这一性能化设计得到了超限审查专家的一致认可。

风工程和地震工程

该项目的主要结构设计均由风荷载所控制。然而，由于项目塔楼的退建不同常规项目，本设计充分考虑了在地震荷载作用下的结构表现。依据中国结构设计规范，深圳属于抗震设防烈度7度，地面加速度为0.10g。

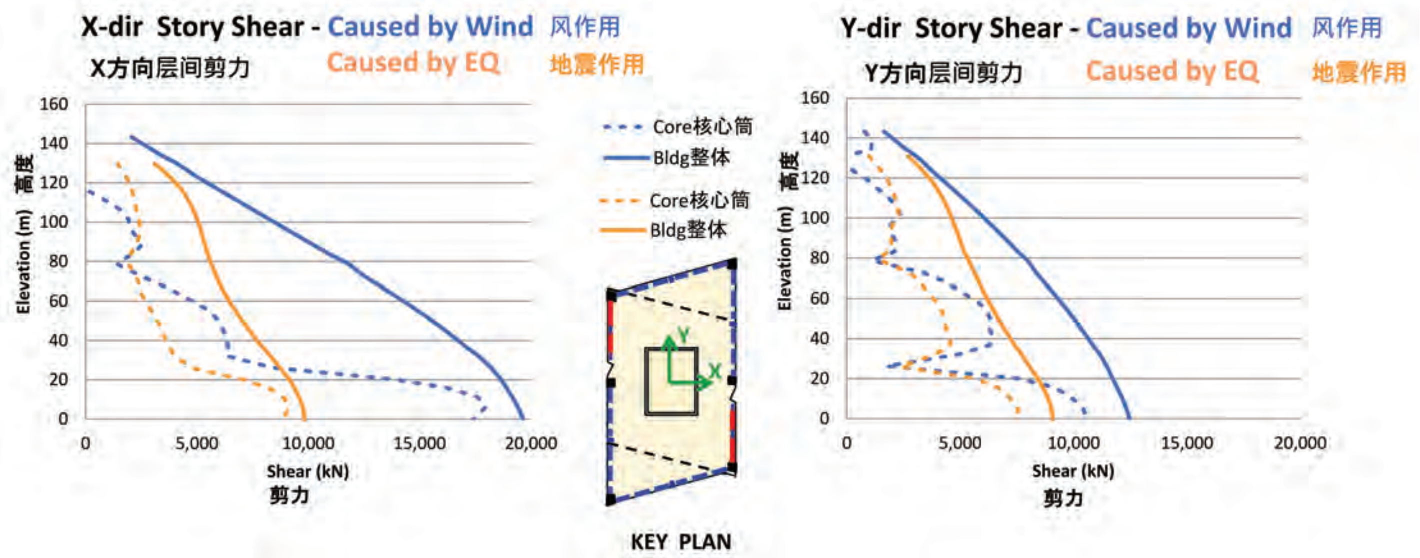

Figure 9. Building and core story shears for wind loads and response spectrum earthquake loads (Source: Leslie E. Robertson Associates)
图9. 塔楼和核心筒在风荷载和地震荷载作用下的楼层剪力（来源：理雅结构工程咨询有限公司）

structural engineer used performance-based design (PBD) of the tower for frequent, medium, and rare earthquake events, in addition to analyses of the Code-prescribed Dynamic Response Spectrums, Real Time Histories, and Artificial Time Histories. With the results of our studies, the seismic experts approved the structural design.

A review of the story shears showed that there may be considerable load transfer between the concrete core walls and the perimeter structural systems, as indicated by the change in story shears in the core between adjacent floors (Figure 9). As expected, the load transfers are most pronounced at the chord floors of the belt trusses, due to the ability of the belt trusses to act as "virtual outriggers". Thicker slabs are used at the belt truss floors, and the floor diaphragms throughout the building are designed to carry diaphragm forces with additional safety factors as defined by the Chinese Building Code. The thicker 200-millimeter (eight-inch) slabs at the belt truss floors work well with the heavier loads of these mechanical floors, as well as providing better acoustics.

Due to the site's close proximity to the Shenzhen Bay, wind loads are of special concern for the tower. There is also a cluster of taller buildings upwind from the tower that may create downwind vortex shedding, with potential adverse effects on the tower. For these reasons, the tower was studied in the wind tunnel by Rowan Williams Davies and Irwin Incorporated (RWDI) using high frequency pressure integration (HFPI) tests. The tests showed wind loads within the range of Exposure B and Exposure C (relatively open and urban surface roughness categories) derived from the Chinese Building Code wind loads, and that the issues of downwind effects on the tower were largely unfounded. The wind tunnel tests did reveal unusually high wind pressures at the top corners of the building, and these pressures were used to design the event space at the top of the tower, as well as the three–story-tall atrium space of the podium (Figure 10).

Podium Structure

The three-story retail podium is designed as a conventional reinforced concrete frame – shear wall system. This system includes rigid reinforced concrete frames and shear walls around the elevator shafts and stair wells designed to resist lateral loads, and reinforced concrete beam-slab system to support the gravity dead and live loads. Long-span, steel, built-up girders are used at the bridge structure connecting the retail podium to the office tower.

The tight geometry of the site posed difficulties in fitting the many functions of the podium, as well as the below ground basement. Many of the podium columns transfer or slope to achieve architecturally desirable geometries as well as to fit in multiple parking ramps below ground. Meeting the architectural and programmatic restraints of the site resulted in a structural system where 75 percent of the podium's columns are transferred.

The atrium of the podium, like much of the Minmetals Capital South China Tower development, is intended to be exposed to view, and here the public space is comprised of structural shapes painted with intumescent paint. The structural engineer and architect worked together to design a series of built-up shapes that worked both aesthetically and structurally to vertically span 18 meters (59 feet) and horizontally span up to 13.5 meters

该项目塔楼有较多不能符合中国结构设计规范中的对于抗震设计的要求和限制。为了证明所采用结构体系的适用性，除了根据规范要求进行反应谱分析，时程分析（采用天然时程曲线和人工时程曲线进行）之外，结构工程师还对于塔楼在频遇地震、设防烈度地震和罕遇地震等各工况进行了性能化设计。根据我们的详细分析所得到的结果，项目得到了深圳市超限审查专家们的认可。

根据下图所示的楼层剪力（图9），在混凝土核心筒和周边支撑框架结构体系之间在环带桁架楼层位置有相当大的侧向力转移。正如预期的那样，侧向力转移最明显的是带状桁架弦杆所在的楼层，是由于环带桁架作为“虚拟伸臂桁架”导致的。在环带桁架楼层，设置了比较厚的结构楼板，以承担加强层楼板较大的侧向

Figure 10. The Tower (Source: Pei Cobb Freed & Partners)
图10. 塔楼效果图（来源：Pei Cobb Freed & Partners）

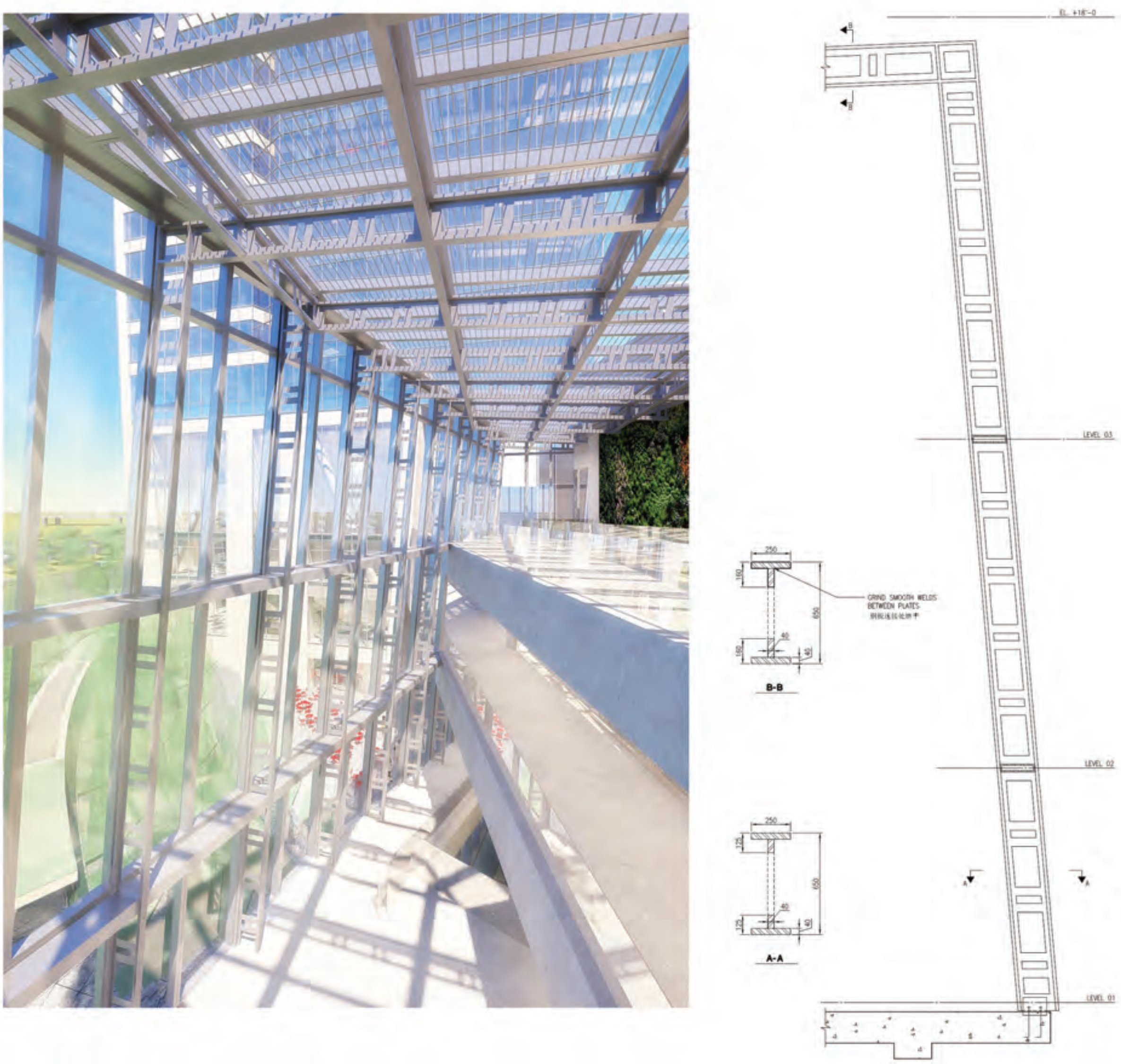

Figure 11. Structure of the podium atrium (Source: Leslie E. Robertson Associates and Pei Cobb Freed & Partners Pei Cobb Freed & Partners)
图11. 裙房中庭结构（来源：理雅结构工程咨询有限公司和Pei Cobb Freed & Partners）

(44 feet) over the atrium. The built-up shapes resemble an I-shape in section, with each 650-millimeter-deep (26-inch) shape having a series of openings in the webs to lighten the member. These members are designed for the gravity loads of the atrium façade, as well as the wind loads (inward and outward) on the members (Figure 11).

Robustness and Redundancy

In keeping with the philosophy of the structural engineer, the structural system of the tower is designed to accept the accidental loss of a multitude of structural elements. For example, at any level the steel perimeter columns or perimeter bracing are able to be accidentally removed without the disproportionate collapse of the surrounding structure. Members of the belt trusses may be removed as well without disproportionate collapse. For these accidental load cases, potential alternative load paths were reviewed, and the surrounding members designed

力，并且根据中国规范的要求，将这些侧向力进行放大。没有削弱的钢筋桁架楼板被用于这些加强层楼板，楼板厚度采用200mm（8英寸），这样的板厚不仅仅可以承受用作设备层的较重的荷载，同时在设备层和办公楼层之间提供一个很好的隔音效果。

深圳和香港类似，属于台风区。中国荷载规范规定50年一遇基本风压为0.75kPa。由于项目地理位置靠近深圳湾，风荷载是塔楼设计中需要特别关注的。同时，由于项目附近有很多更高的建筑物，这些建筑物会对塔楼产生顺风旋涡脱落，产生对于塔楼的潜在不利影响。由于这些原因，本项目聘请风工程师RWDI进行风洞试验，并用高频压力积分方法（HFPI）。试验结果表明，本项目的风荷载长度粗糙度位于B类和C类之间（粗糙度类似于相对开阔的城市区域），与规范规定所计算得到的风荷载值有较大程度的偏离。顺风向的涡旋脱落对塔楼的影响并没有出现。不过，风洞试验显示在建筑物的顶部角落处有异常高的风压力，这些高的风压被用于设计在塔楼顶部位置包括幕墙在内的一些构件，以及三层裙房的构件（图10）。

裙房结构

三层商铺裙房被设计成一个常规的钢筋混凝土框架-剪力墙系统。该系统包括钢筋混凝土框架和电梯井和楼梯间的核心筒，组成裙房的抗侧力体系，采用钢筋混凝土梁板系统，来抵抗重力荷载和活荷载。大跨度钢梁用于连接到办公楼和商铺裙房的廊桥结构。

与地下室情况类似，由于场地非常狭窄，以及场地几何外形问题，导致裙房的多种功能布置造成困难。许多裙房的柱通过转换或斜柱的方式才能实现建筑所要求的理想的几何造型，并且实现多个地下停车坡道的功能。为满足建筑设计和功能要求，导致在这样的一个裙房结构， 有约75%的裙房柱通过转换或者斜柱来实现。

裙房的中庭，与五矿集团所开发的大部分其他项目类似，意在展现给世人一个结构外露的空间，因此在裙房大空间范围，采用外露钢结构和超薄的防火涂料。并且，结构工程师和建筑师一起设计了一系列集美观与结构合理性于一身的和结构竖向跨度18米（59英尺）和横向跨度13.5米（44

for the loads. For example, for the loss of a perimeter-bracing member, the alternative load path results in at least two resultant loads: (1) a tension load carried up to the bracing node above and then transferred to the bracing and then down through the concrete columns at the building's corners; and (2) a horizontal load that is transferred by the floor diaphragm back to the interior core wall (Figure 12).

Concluding Thoughts

Many of the new buildings under construction today have exciting architectural features backed by structural systems which are not apparent or visible. The structural systems are placed so as to enable the architecture "to happen", without acknowledging the structural systems. For the Minmetals Capital South China Tower, the architect Pei Cobb Freed embraced the structure as part of the larger design vision. Much of the structure is expressed, and even celebrated. At the public and event spaces, the difference in what is structure and what is architecture may be indiscernible. This is the fruition of close and collaborative work between the architect and the structural engineer, and results in a dynamic architectural form and efficient structural systems.

Special thanks needs to be given to Design Partner Yvonne Szeto and Project Manager Bruce White – both of Pei Cobb Freed and Partners.

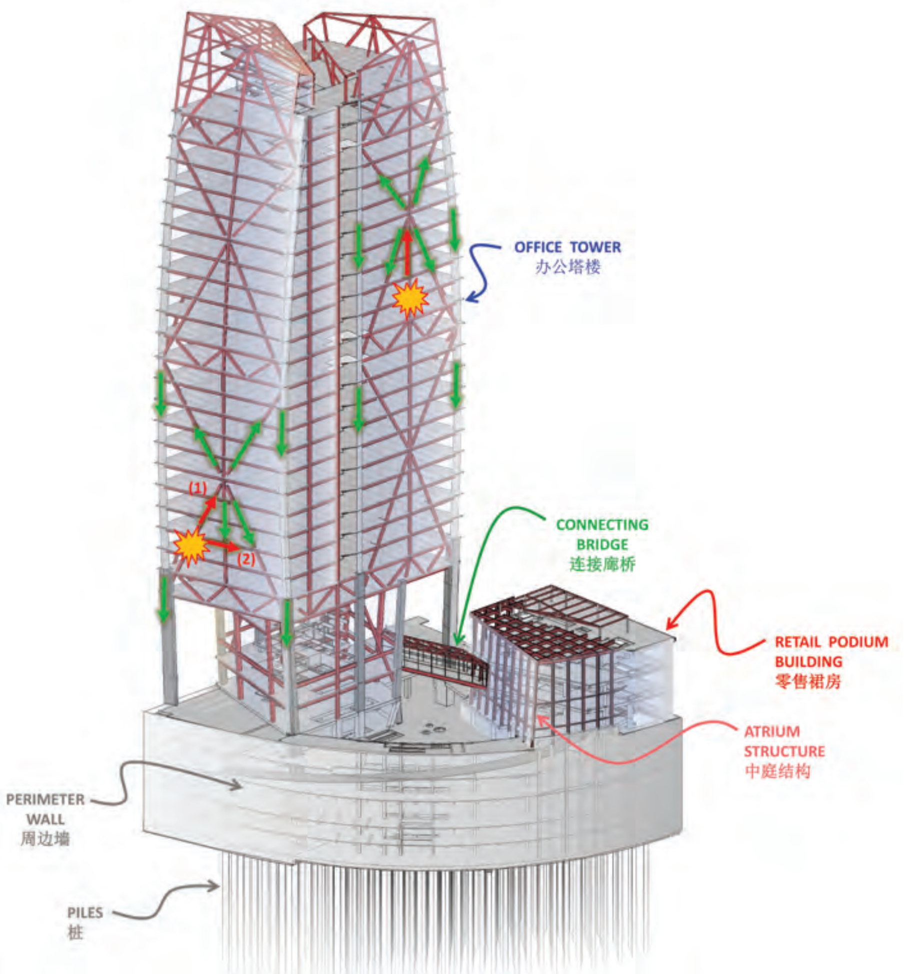

Figure 12. BIM model of the tower, podium, and basement structures: arrows indicate some disproportionate collapse scenarios (Source: Leslie E. Robertson Associates)
图12. 塔楼、裙房和地下室的整体BIM模型，箭头显示在抗连续倒塌时冗余的荷载传力途径（来源：理雅结构工程咨询有限公司）

英尺）焊接型钢中庭结构。组合的形状类似于工字截面，在650毫米（26英寸）截面高的范围内有一系列的开孔腹板组成，这些开孔从视觉上减轻了结构构件的重量。这些焊接工字型截面的承担了中庭所有的重力荷载以及风荷载（图11）。

结构冗余性

根据结构工程师的基本设计哲学，塔楼的结构系统要能够承受大量的结构元素的意外损坏，而不致于导致塔楼的整体倒塌。例如，在任意某个楼层周边钢柱或周边钢斜撑因意外情况导致失效的情况下，不会产生周围结构的连续崩塌。此外，环带桁架的某个构件的意外损坏也不会造成塔楼的连续崩塌。对于这些意外的荷载情况，我们对潜在的替代荷载传力路径进行了设计，结构设计中考虑到周围的结构构件能承受因某些构件失效而导致的附加荷载。例如，在一个周边钢斜撑构件的损坏失效后，荷载传力路径的改变至少导致俩种荷载：（1）加载于钢斜撑节点上，然后转移到上部钢斜撑的拉力，最后传递到建筑角部的混凝土柱，和（2）一个由楼板系统转移到内部核心筒墙的水平力（图12）。

总结与思考

时至今日，许多新兴建筑都有着令人着迷的建筑造型和建筑效果，而背后支撑的结构体系却为人所忽视，或者并不被显现出来。结构系统通常总是为了能够让建筑物能够“实现”，而不是着重体现结构体系本身。对于深圳五矿金融大厦，建筑师Pei Cobb Freed视结构为设计视野中重要的一环。大部分的结构构件被充分表现出来，甚至作为重点突出。在公共空间以及重要的会务空间，甚至人们无法清晰辨认什么是结构元素，什么是建筑元素。这就是建筑师和结构工程师紧密配合，通力合作的成果，也充分体现了动态的建筑美和高效的结构美。

特别感谢建筑设计总监Yvonne Szeto，项目经理Bruce White，这两位来自Pei Cobb Freed建筑事务所的建筑师。

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