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Shenzhen Shum-Yip Tower One: A Case Study – A-E Integration – A Broad New Vision

深圳深业上城塔楼一：案例分析 通过建筑-工程协作得到的新的超高层体系

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Chung Yeon Won女士在大型复杂项目设计方面拥有非常丰富的经验。作为高级技术设计师，她负责确保SOM和顾问团队所有技术文件的质量，以及在施工图和管理等项目各个阶段中整合高性能设计。

Abstract | 摘要

Conventional legacy systems in the design of supertall towers employ belt trusses, outriggers, and perimeter-bracing to achieve the required tower performance at the expense of open architecture. The Ladder-Core System developed at SOM presents a novel method in the design of supertall structures, enhancing the flexibility of architecture while providing the ductility, redundancy, and uniformity of stiffness compromised in legacy systems. The Ladder-Core System features eight mega-columns at the perimeter, which form the vertical rails of the ladder on either side of the core. Composite-coupling beams act as the ladder rungs, connecting mega-columns at the perimeter to the interior core, and thereby creating a comprehensively stiff lateral system. Using 28-meter-long beams to funnel perimeter gravity loads to the mega-columns eliminates the tension produced by overturning moments. Overall, the Ladder-Core System is defined by unobstructed occupant views, a simple floor plate, and inherent structural stability.

Keywords: A-E Integration, Composite Coupling Beams, Jumbo Vision Glass, Ladder System, Lateral System Optimization

超高层塔楼设计中的传统经典体系采用腰桁架、伸臂桁架和周边斜撑，以牺牲开敞建筑来实现需要的塔楼性能。由SOM 开发的梯子-核心筒体系提供了超高层结构设计的新方法，这一方法在提升建筑的灵活性的同时， 也提供了在经典体系中被减弱的延性，冗余度，和刚度分布的均匀性。梯子-核心筒体系的特色是周边的八根巨柱，其在核心筒的两侧构成梯子竖向的支杆。作为“梯子踏面”的组合连接梁将周边的巨柱和内部的核心筒连接起来，形成了有良好刚度的综合侧向体系。系统通过28米的大跨梁将周边所有的重力荷载导入巨型柱，消除了由倾覆力矩产生的柱内拉力。无遮挡的使用视野，简洁的楼面板，以及内在的结构稳定性诠释了梯子-核心筒体系。

关键词：建筑-工程一体化、组合连接梁、特大视野玻璃、梯子体系、侧向体系优化

Introduction

Shenzhen Shum-Yip Upperhills is a mixed use development located in Shenzhen, People's Republic of China (Figure 1). Shenzhen is one of the fastest growing cities in China, and its proximity to the Asian financial hub of Hong Kong has been a major factor in its phenomenal growth.

Situated at the northwest corner of the intersection between Huanggang Road and Sunggang Road in the Futian District of Shenzhen, Shenzhen Shum-Yip Upperhills is one of the most ambitious real estate ventures in the city, consisting of Class A office buildings, a luxury hotel complex with banquet facilities, and varied retail development on a single property. The development links Lotus Hill Park and Beacon Hill Park on either side of the property via pedestrian bridges across major arterial roadways (Figure 2).

Due to Shenzhen's economic growth and active construction, the real estate market is poised to have increased demand and supply of leasable office space. The client for this project provided a very clear directive to the

项目简介

深圳深业上城是一个在中华人民共和国深圳的一个多用开发区（图1）。深圳是中国发展最快的城市之一，靠近亚洲金融中心香港也是它飞速发展的一个因素。

坐落在深圳福田区皇岗路与笋岗路交汇处西北角的深圳深业上城是这座城市中最具雄心的房地产项目之一，在一个物权下包括甲级写字楼，一个包括宴会设施的豪华酒店综合体以及不同的商业开发。这一开发通过跨越主公路干线的人行天桥将地块两侧的莲花山公园和笔架山公园连接起来（图2）。

由于深圳的经济发展和积极的建设，房地产市场对于租赁办公空间的需求与供给的增加已经准备好。这个项目的客户为项目团队提供了非常明确的方向：办公空间的质量要把深业上城与房地产市场其它的供应区别开来。在创造优质的办公空间的同时，两幢塔楼的总体体型应该是简洁、但标志性的。塔楼二，两幢塔楼中较小的一幢，300 米高，包括甲级办公空间。塔楼一的目标是高档商业市场，包括在塔楼上部区域的国际品牌五星级豪华酒店。

Figure 1. An architectural rendering of the proposed Shenzhen Shum-Yip Upperhills development (Source: Skidmore, Owings & Merrill)
图1. 深圳深业上城开发的建筑效果图（来源: Skidmore, Owings & Merrill）

本文讨论的塔楼一，有80层，390米高 - 是这个开发的最高建筑。功能包括在下部66层的高档甲级办公空间和上部楼层的酒店客房及相关的休闲区域。最高层是带屋顶花园的餐厅和直升机停机坪（图3）。塔楼一的建筑设计和相配合的结构体系是对客户的愿望的有力的回应。

建筑意图及表现

在实现客户愿望的过程中，建筑和结构设计团队的目标给每一位访问者、租户和员工世界级的开敞体验。考虑到项目的场地，深业塔楼一有独特的机会将深圳的自然美与现代化的城市风貌无缝结合起来。无论是使用上还是视觉上， 其均与笔架山公园和莲花山公园融为一体。尽管塔楼一在城市的都市经济扩张的前沿，它保持了与自然的关系。设计寻求创造一个到公园和繁忙的都市的视线不受阻的扩展的办公空间（图4）。

为了实现这一解放性的视觉平面，设计了可以兼容无柱外立面和大跨无遮挡内部空间的结构体系。承重体系包括八个劲性混凝土组合巨型柱策略性地布置在周边，作为开敞办公空间和优质的、悬挑的、角部办公空间之间的隔墙隐藏起来。通过结构梁板的协调整合，结构框架避免了任何主梁连接到核心筒。将较大深度的构件沿核心筒布置，在其它位置布置较小深度的构件使得每一层可以布置连续的机电设备圈。优化了沿周边布置的横跨巨型柱的组合钢梁确保整个楼层有一致的3.0 米的净高。幕墙采用3.0 米的模块，而不是通常的1.5 米，以进一步减小对向外视野的

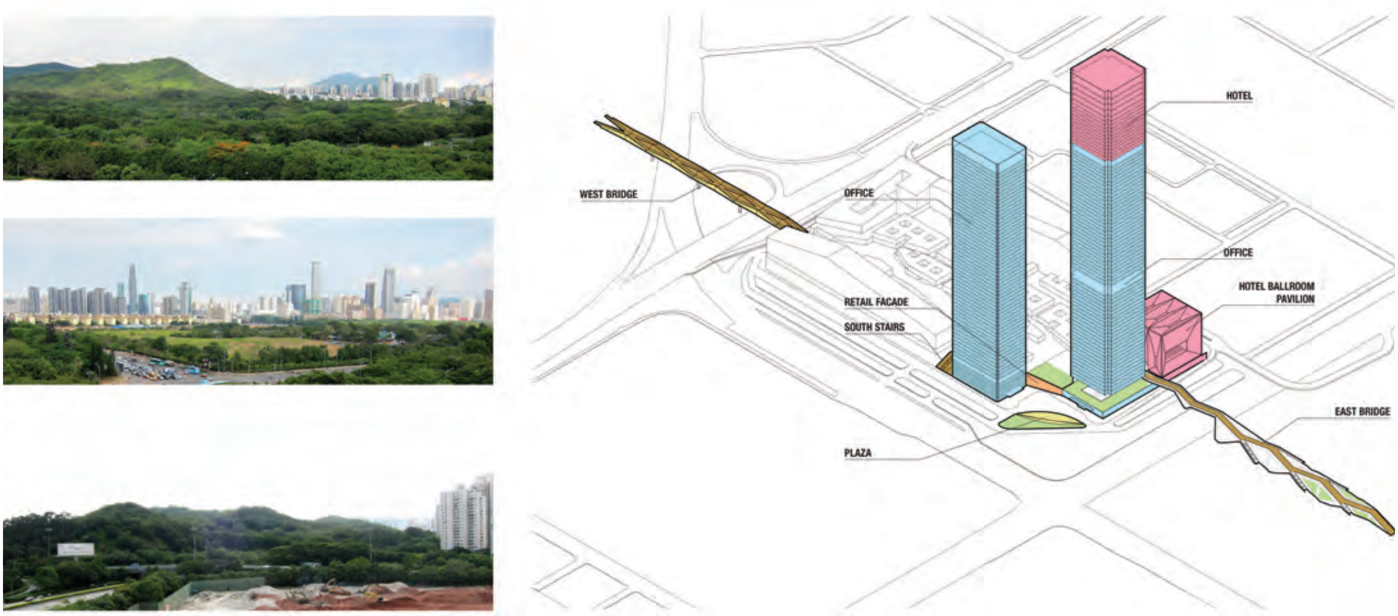

Figure 2. The project site and proposed zoning (Source: Skidmore, Owings & Merrill)
图2. 项目场地及选址（来源: Skidmore, Owings & Merrill）

design team: the quality of the office spaces needs to set Shum- Yip Upperhills apart from other offerings in the real estate market. Along with creating premium office spaces, the overall form of the two towers themselves should be simple, yet iconic in nature. Tower Two, the smaller of the two towers at 300m, contains Class A Office space (see Figure 2). Tower One targets the high-end of the commercial market, with an international brand five-star luxury hotel in the upper segment of the tower.

Tower One, the subject of this paper, contains 80 floors and is approximately 390m tall - it is the tallest building in the development. The program consists of high-end Class A Office space in the lower 66 floors and hotel guest rooms and related amenities on the upper floors. The topmost floor houses a restaurant with roof garden and a helipad (Figure 3). The architectural design and the complementing structural system of Tower One are an emphatic response to the desire of the client.

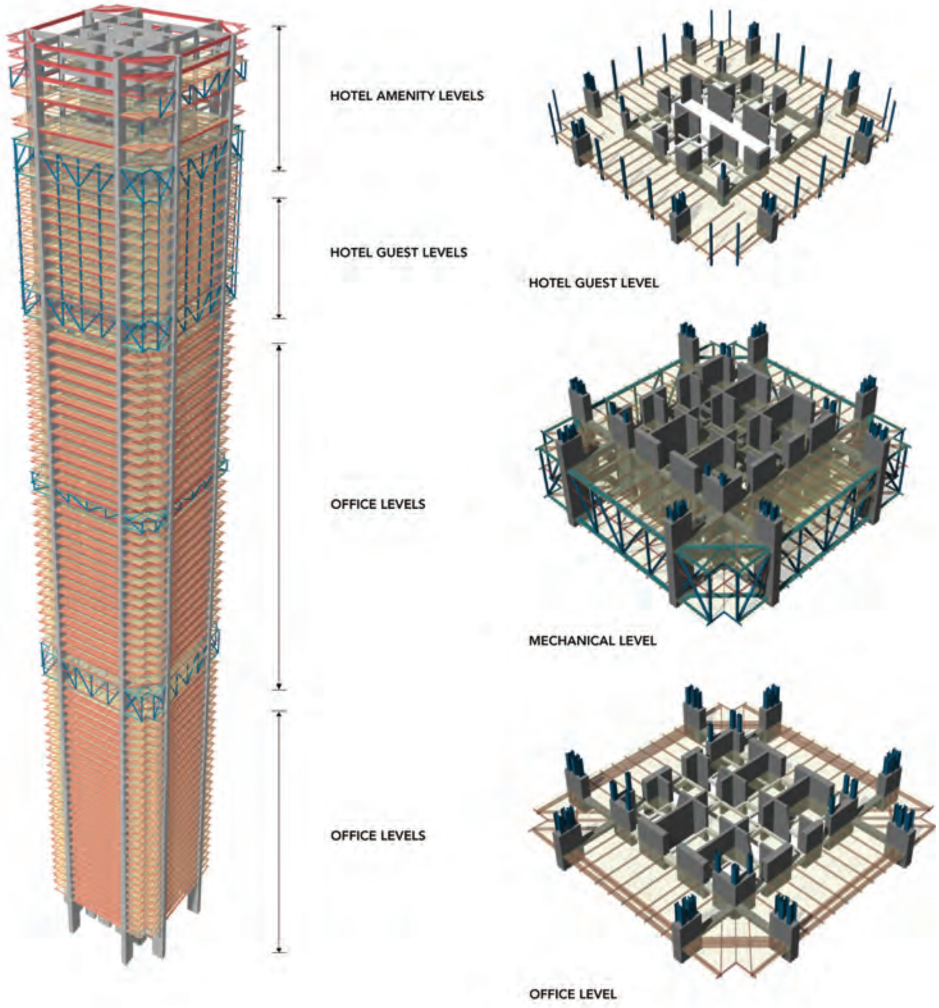

Figure 3. The evolution and concept for the Ladder-Core System (Source: Skidmore, Owings & Merrill)
图3. 梯子–核心筒体系的概念及演化（来源：Skidmore，Owings ＆ Merrill）

Architectural Intent and Expression

In addressing the wishes of the client, the architectural and structural design teams aim to emphasize the world-class, spatial experience for each visitor, tenant, and employee. Given the project site, Shum Yip Tower One has the unique opportunity to juxtapose Shenzhen's natural beauty with its modern cityscape. Connecting to Beacon Hill Park and Lotus Hill Park, Tower One is at the forefront of the city's urban economic expansion, even as it maintains its foothold in nature. The design seeks to take advantage of the expansive space and unobstructed views out to the parks and bustling metropolis (Figure 4).

In order to achieve this liberating plane of vision, the structural system is designed to accommodate a column-free exterior façade as well as a long-span uninterrupted interior space. The gravity system features eight steel reinforced composite mega-columns strategically located on the perimeter, concealed as the divisions between open office space and premium, cantilevered, corner office space. Through structural beam and slab integration, structural framing is devoid of any girders spanning to the core. Orienting the larger depth members along the perimeter and maintaining shallower depths elsewhere allows for a continuous mechanical loop on each floor. The built-up steel girders spanning between the mega-

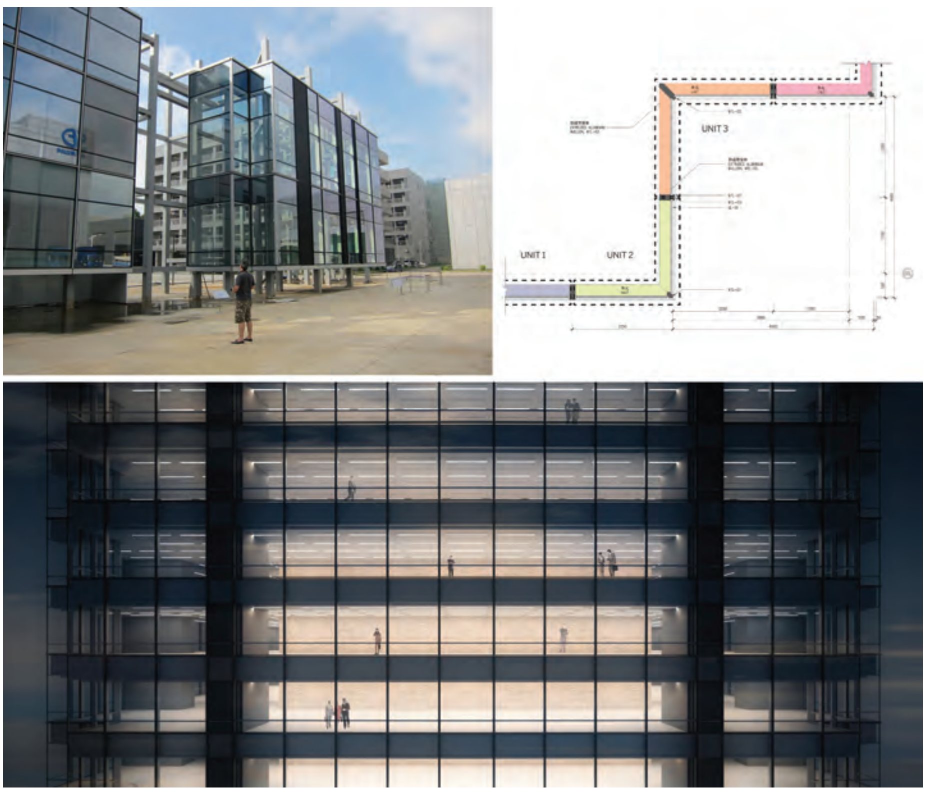

Figure 4. Left: A 3-D view of Tower One's structure; Right: A 3-D view of the typical floor framing (Source: Skidmore, Owings & Merrill)
图4. 左图：塔楼一结构的三维视图；右图：标准楼层的三维视图（来源：Skidmore，Owings ＆ Merrill）

columns along the perimeter are optimized for a uniform 3.0m clear height for the entire floor. Cladding modules of 3.0m width, not the usual 1.5m width, are utilized to further reduce obstructions to outside view. The result is a clear, breathtaking perspective from anywhere in the office.

Pioneering Building Enclosures for Supertall Buildings

With Shum Yip Tower, SOM has pioneered a new model for the enclosure design of supertall towers. Here SOM establishes an innovative, flexible, and highly transparent skin to accommodate the client's desire for the highest-quality office spaces in Shenzhen that maximize the views.

A 1.5m wide curtain wall module is standard when it comes to designing supertall commercial towers. To deliver the desired openness within a pristine envelope, SOM has added dimension to the vision glass, thus minimizing the number of mullions. Here a larger 3m-wide curtain wall units are utilized comprise of thicker vision glass composed of 16mm laminated outer lite and a fully tempered inner lite to maximize the evenness and reduce possible imperfections. In order to achieve the maximum transparency at the tower's notched corners, three 2.25mx2.25m L-shaped glazing units were fabricated. This strategy enabled the design team to relocate the vertical mullions from its typical glazing corners.

Reduced frame ratio also contributes to the sustainable design objectives such as maximizing daylight harvesting for regularly occupied tenant spaces as well as improving the energy performance by reducing the thermal bridges. The 8.5m cantilever to the corner balanced by a 28.5m back span helped achieve deflection criteria associated with conventional slab edges of tall buildings and result in the minimum possible stack joint height.

Integration With Office Planning Modules

The client desired a Class A office space with high floor to ceiling heights and uninterrupted views. The mega-columns are shaped to a uniform 4.5m in depth in the office levels and varying in width along the height of the building to match the typical office module. Columns are strategically placed along the perimeter of the office floors to align with the outer core walls, creating two zones of office spaces: one with 28.5m between columns on the four sides of the floor plan, and another with an expansive view at the four corners of the floor plan. Such "Open Office" spatial arrangement minimizes the visual impact of the structural elements, allows more flexibility for planning for a global workplace, and encourages collaboration and knowledge sharing.

The architectural layout is designed such that the elevator lobbies within the core walls also serve as corridors, allowing up to 4 tenants per floor without adding an additional perimeter corridor. This layout effectively increases the floor efficiency compared to a conventional office floor layout. The internal corridor layout also yields a core with a larger footprint, which is inherently stiffer and results in more optimum use of concrete (Figure 5).

Integration With Mechanical Zones

At mechanical floors, where an unobstructed view is not valued (Figure 6), the floor framing is optimized for heavy loads by introducing a perimeter truss that utilizes the entire height of the floor. Perimeter belt trusses provide required stiffness for mechanical floor operation, including gravity, vibration and acoustic performance. These belt trusses are integrated with louvers for exterior air exhaust and intake.

阻碍。结果是在楼层的任何位置都有清晰的，令人窒息的视角。

对于超高层建筑开创性的建筑围护

为了达到视野最大化的建筑意图，SOM 开创了超高层塔楼围护设计的新模式。这里SOM 建立了一个创新的，灵活的，高度透明的外观以达到客户对于在深圳最大化视野的最高品质办公空间的愿望。

在超高层商业塔楼的设计中，1.5 米宽的幕墙模块是标准的。为了给出想要干净的外层里面的开敞，SOM 增加了视觉玻璃的尺寸，这样将竖框的数量最小化。这里采用3米宽的更厚的幕墙单元，这些幕墙单元由16毫米夹胶外层和完全钢化的内层组成以最大化平整度并减小可能的缺陷。为了在塔楼的有凹口的角部实现最大的通透性，制造了三个 2.25m x 2.25m L 形玻璃单元。这一策略使得设计团队可以将竖框从角部移走，产生全玻璃外墙的典型办公空间。

减小的框架比同时也对可持续设计目标有所贡献，例如在规律使用的租赁空间最大化地采用自然光并通过减少热桥来提升能耗性能。在角部 8.5 m 的悬挑由28.5 m 的平衡跨来平衡，帮助在高层建筑中传统的板边达到变形标准，并可以将节点的高度最小化。

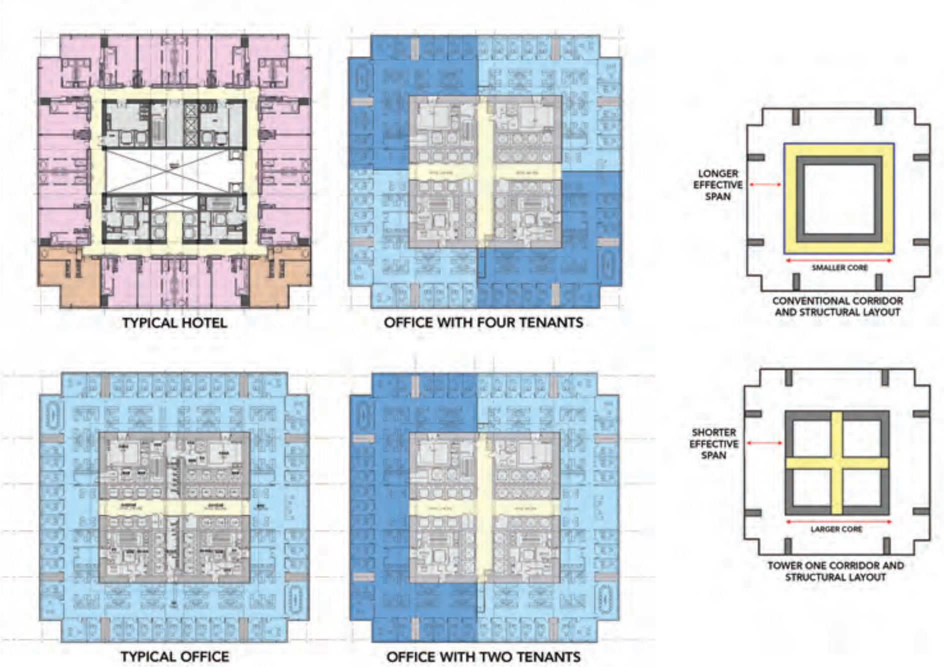

Figure 5. Top: The mega-column layout showing the gravity load path which eliminates tension; Bottom: An architectural rendering of the mega-columns at the tower base (Source: Skidmore, Owings & Merrill)
图5. 上图：巨型柱布置及抗拉重力传递路径图；下图：塔楼底部的巨型柱建筑效果图（来源：Skidmore, Owings & Merrill）

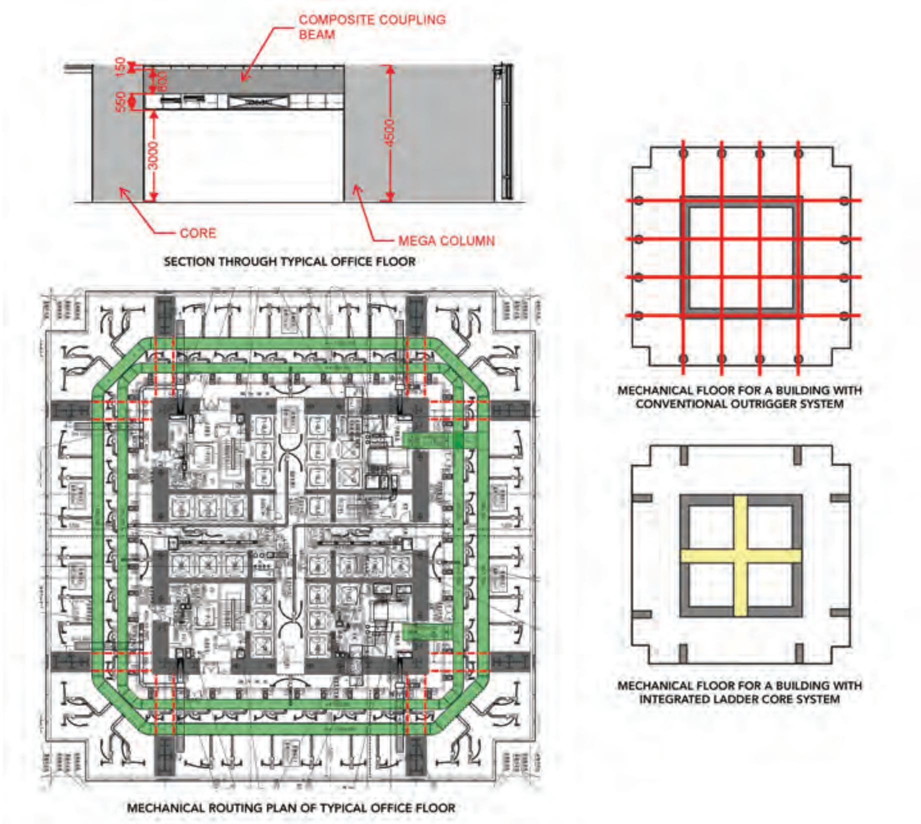

Figure 6. Left: The seamless integration of the architectural layout and the structure of typical office and hotel floors; Right: A comparison of corridor and structural layouts (Source: Skidmore, Owings & Merrill)
图6. 左图：酒店标准层和办公标准层建筑和结构的无缝结合；右图：走廊及结构平面布置的比较（来源：Skidmore，Owings & Merrill）

The large column-free interior spans provide more flexibility for MEP Planning. Absence of outrigger trusses within the floor plate enables more direct mechanical transfers and reduced clashes with structural elements. The open space allows more equipment to be placed on each floor, resulting in the elimination of one mechanical floor from the building stack during the design process (Figure 6).

Integration With Hotel Planning Modules

The mechanical level trusses above and below the hotel floors double-up as transfer mechanisms for perimeter hollow steel square HSS posts at the hotel floors. The vertical members of the perimeter trusses above and below guest rooms are aligned with the hotel guest room module, providing direct support for the HSS posts, which are located in line with the demising partitions between the hotel rooms. The conventional framing at the hotel levels results in shallower perimeter beams and eliminate the need for long- span perimeter girder, reduce story height, and reduce required steel quantities without compromising the architecture of the space.

Progressive collapse prevention is taken into account in the design of the hotel floor gravity system. Redundancy is achieved

与办公平面模块的整合

客户希望一个有大的净高的、无遮挡视野的甲级办公空间。巨型柱的形状为一致的4.5 m 深、宽度沿着建筑的高度变化以配合典型的办公模块。柱子策略性地布置在建筑的周边与核心筒外墙对齐，产生两个办公区域：一个是在楼层四边柱之间28.5 m 的区域，另一个是在楼层四角具有扩展视野的区域。这样一个 “开敞办公室”空间布置将结构构件对视野的影响最小化，给布置全局性的办公室、鼓励协作和知识共享提供了灵活性。

建筑布置设计成核心筒内的电梯厅同时作为走廊，这样在不增加周边走廊的前提下可以允许同一个楼层有四个租户。与传统的楼面布置相比，这一布置有效的提供了楼面的效率。内部走廊的布置可使结构具有更大尺寸的核心筒，加上其本身刚度比较大，这样更优化地使用了混凝土（图5）。

与机电区的整合

在机电楼层不需要无遮挡的视野（图6），楼面框架通过增加利用整个楼层高度的周边桁架进行优化来承受重荷载。周边腰桁架提供了机电层运转所需要的刚度，包括重力、振动和声学性能。这些腰桁架与百叶整合在一起实现外部的空气排放和吸入。

大的无柱内部空间给予了机电设备的布置更多的灵活性。由于楼板内没有伸臂桁架，机电转换可以更直接，同时减少了与结构构件的冲突。开敞的空间允许更多的设备放在每一个楼层上，结果是在设计过程中，建筑的竖向布置中减少了一个机电层（图6）。

与酒店布置模块的整合

酒店层上方和下方的机电层的桁架加倍以作为酒店层周边方钢管柱的转换机制。在客房上方和下方的周边桁架的竖杆与客房的模块对齐，为客房之间的隔墙处的钢管柱提供直接的支撑。在酒店层采用传统的框架使得在不影响建筑空间的前提下，降低了周边梁的梁高，省掉了大跨主梁、降低了层高、节省了用钢量。

酒店层的承重体系设计中考虑了抗连续倒塌。通过在客房区的上方和下方都设置转换桁架并在构件设计中考虑因某个单元失去承载力放大的荷载。这也提供了有效的从酒店区的周边框架到巨型柱的替代传力路径（图7）。

管理重力荷载传力路径

楼面框架梁从混凝土核心筒横跨到周边主梁。从楼面框架的设计角度，巨型柱的位置在每一边产生了平衡的悬挑体系。这样减小了内跨和悬挑跨的深度。双周边主梁提供了到巨型柱的冗余的传力路径（图8）。从周边主梁到巨型柱的传力通过主梁与每一个巨型柱内的预埋件的连接实现。

对于传统的框架体系，不参与抗侧力体系的柱子与巨型柱一同分担重力荷载，巨型柱在侧向荷载下的拉力会给设计带来挑战。对于深业塔楼一，所有周边的重力都被导入到八个巨型柱中，其余的重力荷载被导入在中心的到核心筒。这样就消除了巨型柱和核心筒墙中由于侧向荷载产生的拉力。

入口裙楼的建筑设计大胆地将巨型柱作为建筑设计特色的一部分表现出来， 巨型柱的结构在建筑的底部，大堂的上方展现。没有外包、强调了塔楼的周边结构只有八根巨型柱。

抗侧力体系的优化

抗侧力体系包括在中心的核心筒和八根巨型柱。这些柱与中心核心筒的四个角对齐。每一个巨型柱通过在每一层的组合连接梁与核心筒接合，形成梯子–核心筒体系。

by having a transfer truss both above and below the hotel guest room zone and by designing the members for magnified loads in the event that certain elements lose load resisting capacity. This in effect creates an alternate gravity load path to the mega-columns from for the perimeter frame in the hotel segment (Figure 7).

Managing Gravity Load Paths

Floor framing beams span between the concrete core and the perimeter girders. From the floor framing design perspective, the location of the mega-columns creates a balanced cantilever system along each side. This reduces the depth of the interior span as well as the cantilever span of the perimeter girder. A double perimeter girder provides a redundant load path to the mega-columns (Figure 8). Load transfer between the perimeter girders and mega-columns is achieved by the connection of the girder with the embedded steel in each mega-column.

For a conventional framing system, where columns which are not part of lateral force resisting system share gravity load with the mega-columns, designing for tension due to lateral loads in mega-columns can be challenging. In case of Shum Yip Tower One, all gravity loads at the perimeter are funneled through the eight mega-columns, while the rest of the gravity loads are directed towards the center core. This has eliminated tension in Mega-Columns and Core walls due to lateral loads.

The Architectural design of the entrance podium boldly expresses the mega columns as part of the key architectural design features. Without a veiling enclosure, it celebrates the fact that the perimeter structure of the tower consists only of eight mega columns.

Lateral Load Resisting System Optimization

The lateral system is comprised of a center concrete core and eight mega- columns. These columns are aligned with the four corners of the center core. Each mega-column is engaged with the concrete core by a composite coupling beam at each story level, forming the ladder-core system.

From the lateral system point of view, the elongation and alignment of the mega columns with the exterior core walls creates an efficient lateral load path. Locating the mega-columns at the extreme edge of the building footprint produces the largest coupling moment arm with the core (Figure 9). This results in maximized lateral load resisting capacity for the system and an aspect ratio of 7.2 to resist overturning.

从抗侧力体系的角度来看，拉长并与核心筒外墙对齐的巨型柱产生了一个有效的侧向荷载路径。将巨型柱放在建筑平面的边缘可以与核心筒形成最大的力耦（图9）。这样的结果是一个最大的侧向荷载承载力和一个7.2 的高宽比以抵抗倾覆。

在顶部楼层梯子作用很强，梯子–核心筒体系贡献了更高比例的侧向刚度，通过减小混凝土核心筒的刚度提高了效率。核心筒墙内的开洞尺寸沿着高度逐渐增加，并在腹墙设置开洞（图10）。

为了确保较高的延性，每个组合连接梁中的型钢都与巨型柱中的预埋钢构件进行抗弯连接。周边主梁也与巨型柱中的预埋钢构件进行抗弯连接，提供抗弯框架作用，作为对梯子–核心筒体系的补充。

梯子核心筒体系与传统的伸臂桁架体系相比有诸多优势。在每一层提供连接梁有效地把理想比例的楼层剪力传递到建筑的周边。结构整体的性能是均匀的，楼层刚度沿高度的变化是稳定的。组合连接梁提供了出色的延性性能并且在不同的位置产生更多的塑性较。这样确保了高的能量耗散和更多的冗余度。

塔楼一的梯子–核心筒体系的设计根据中国标准来抵抗不同水准的极端风和地震作用效应。对五十年回归周期的风荷载达到了所有的正常使用标准，构件按照100年回归周期的风荷载进行设计。深业塔楼一的抗震性能目标根据常遇地震、设防烈度地震和罕遇地震来设定。常遇地震对应的50年超越概率为63%，或者50年的重现期。设

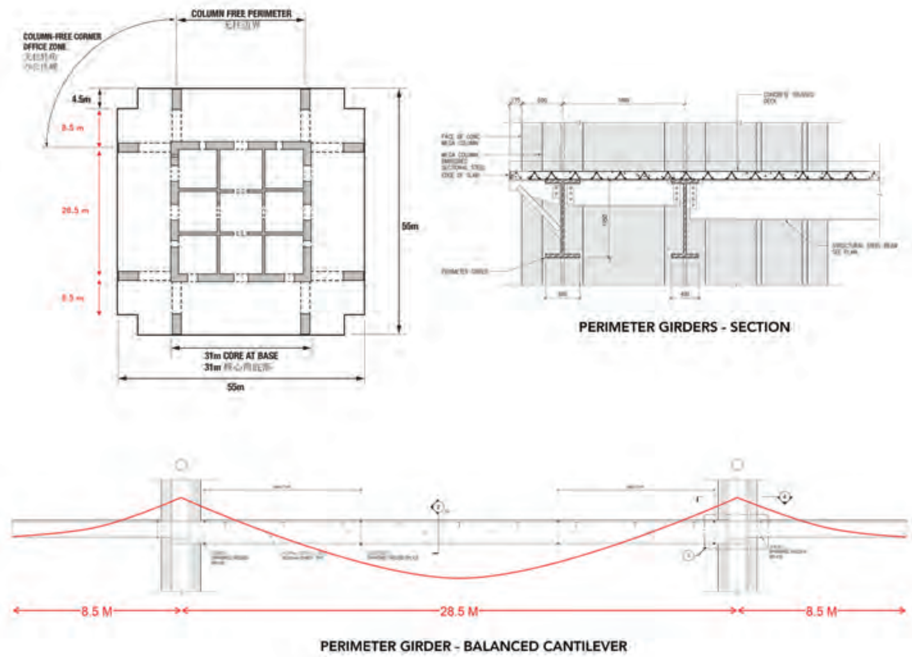

Figure 7. Left: A typical office floor mechanical routing plan and section; Right: A mechanical floor comparison showing the optimization of space (Skidmore, Owings & Merrill)
图7. 左图：标准办公层的机械布置平面图和剖面图；右图：机械层及空间优化对比（Skidmore, Owings & Merrill）

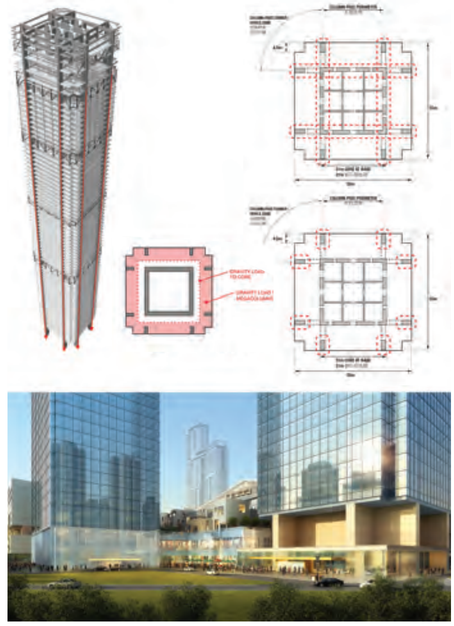

Figure 8. A perimeter girder plan and sections showing the optimal use of the balanced-cantilevering concept (Source: Skidmore, Owings & Merrill)
图8. 周边主梁平面及剖面图以及优化的平衡悬挑概念（来源：Skidmore, Owings & Merrill）

On upper levels where the ladder action is strong and ladder-core system contributes higher percentage of lateral stiffness, efficiency is achieved by reducing the concrete core stiffness. Opening sizes within the core walls are gradually increased along the height and web wall openings are introduced (Figure 10).

To ensure highly ductile performance, the steel section in each composite coupling beam is moment connected to the embedded steel in the mega-column. The perimeter girder is also moment connected with the embedded steel in the mega-columns, providing moment frame action which complements the ladder-core system.

The ladder-core system provides numerous advantages over conventional outrigger systems. Providing coupling beams at each level effectively distributes an ideal percentage of story shears to the perimeter of the building. Overall performance of structure is uniform and results steady variation of story stiffness along the height. Composite coupling beams provide excellent ductile performance and produce more plastic hinges on various locations. This ensures higher energy dissipation and greater redundancy.

The ladder-core system of Tower One is designed to resist various levels of extreme wind and seismic loads per Chinese Standards. All serviceability criteria are fulfilled for a 50 year return period of wind loads and elements are designed for a 100 year return period. The seismic performance objectives set for Shum-Yip Tower One refer to Frequent, Moderate, and Rare levels of seismic loading. Frequent earthquake loading corresponds to a probability of exceedance in 50 years, or a 50 year return period. Moderate earthquake loading corresponds to a probability of exceedance of 10% in 50 years (or a 500 year return period); and Rare earthquake loading corresponds to a probability of exceedance of 2% in 50 years (or a 2500 year return period) (Figure 11).

A superior set of design objectives were selected for the essential elements of ladder-core system. Mega-columns and composite coupling beams are expected to remain elastic under Frequent and Moderate earthquake loading and non-yielding under Rare earthquake loading. Reinforced concrete core wall corners are also expected to remain elastic under Moderate earthquake loading and non-yielding in shear under Rare earthquake loading.

Additionally, from a lateral system performance point of view, the belt trusses positioned at the regular intervals along the height of the building provide added coupling between the core and perimeter. In addition to transferring the heavy mechanical gravity loads to the mega columns, the trusses

防烈度地震对应的是50年超越概率为10%（或重现期为475年）；罕遇地震荷载对应的为50年超越概率为2% （或重现期为2500 年）（图 11）。

对于梯子-核心筒体系的关键构件采用了一系列高的设计目标。巨型柱和组合连接

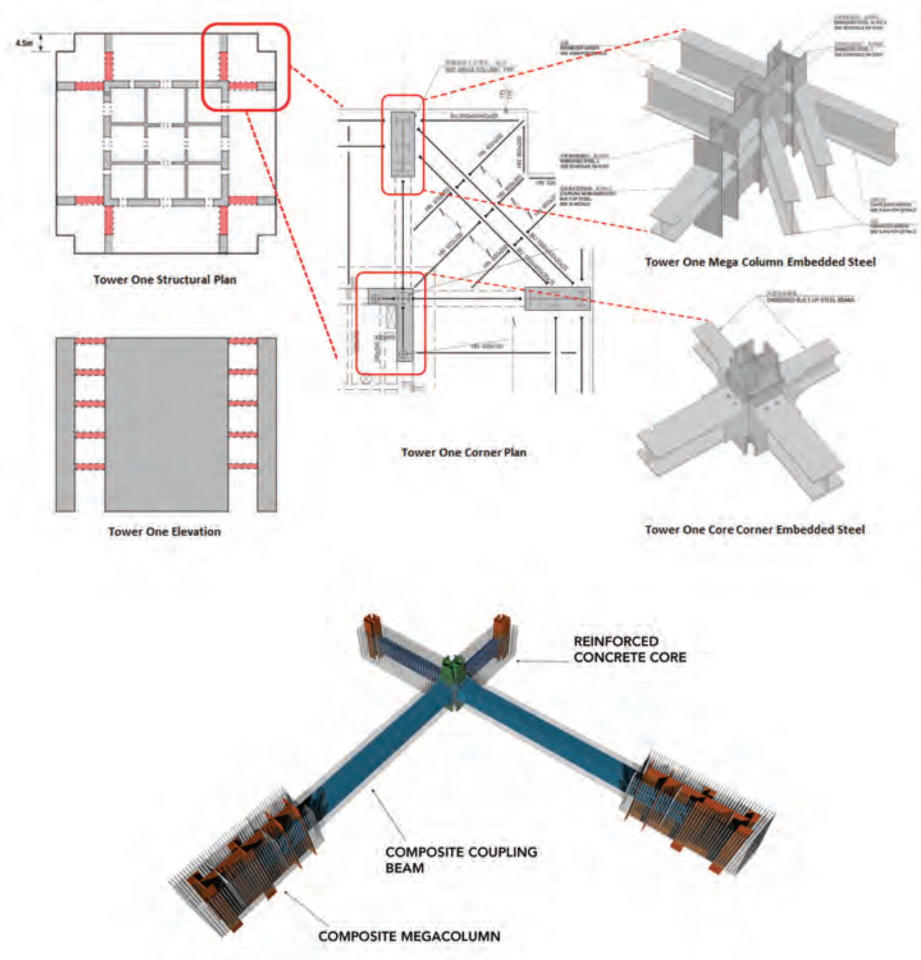

Figure 9. Top Left: A photograph of the curtain wall mock-up; Top Right: A large curtain wall module and the unique corner unit; Bottom: An architectural rendering of a typical office showing a minimal obstruction due to mullions (Source: Skidmore, Owings & Merrill)
图9. 左上图：幕墙模拟图片；右上图：超大幕墙模块及独特的角部单元；下图：标准办公层极少遮挡的建筑效果图（来源：Skidmore, Owings & Merrill)

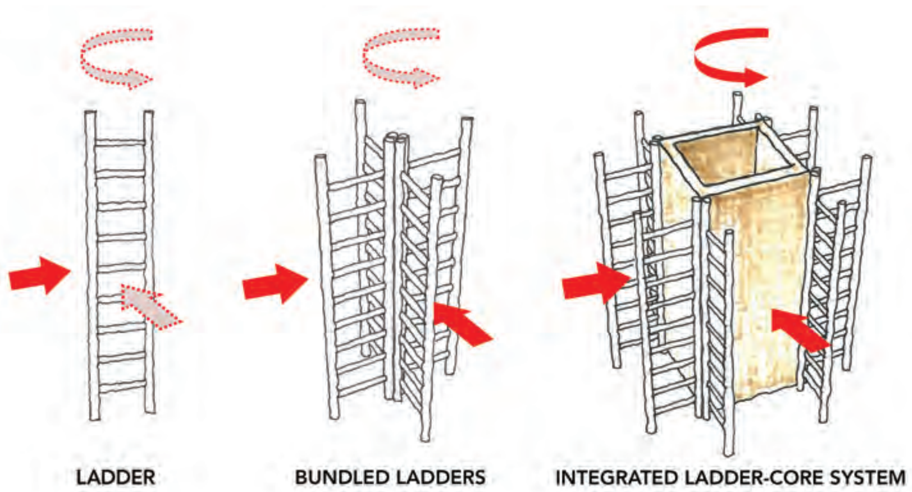

Figure 10. Top: The mega-column and core corner embedded steel detail; Bottom: A 3-D view of the composite coupling beam and its connections (Source: Skidmore, Owings & Merrill)
图10. 上图：巨型柱和核心筒角部预埋钢构件详图；下图：组合连接梁及连接部分的三维视图（来源：Skidmore, Owings & Merrill)

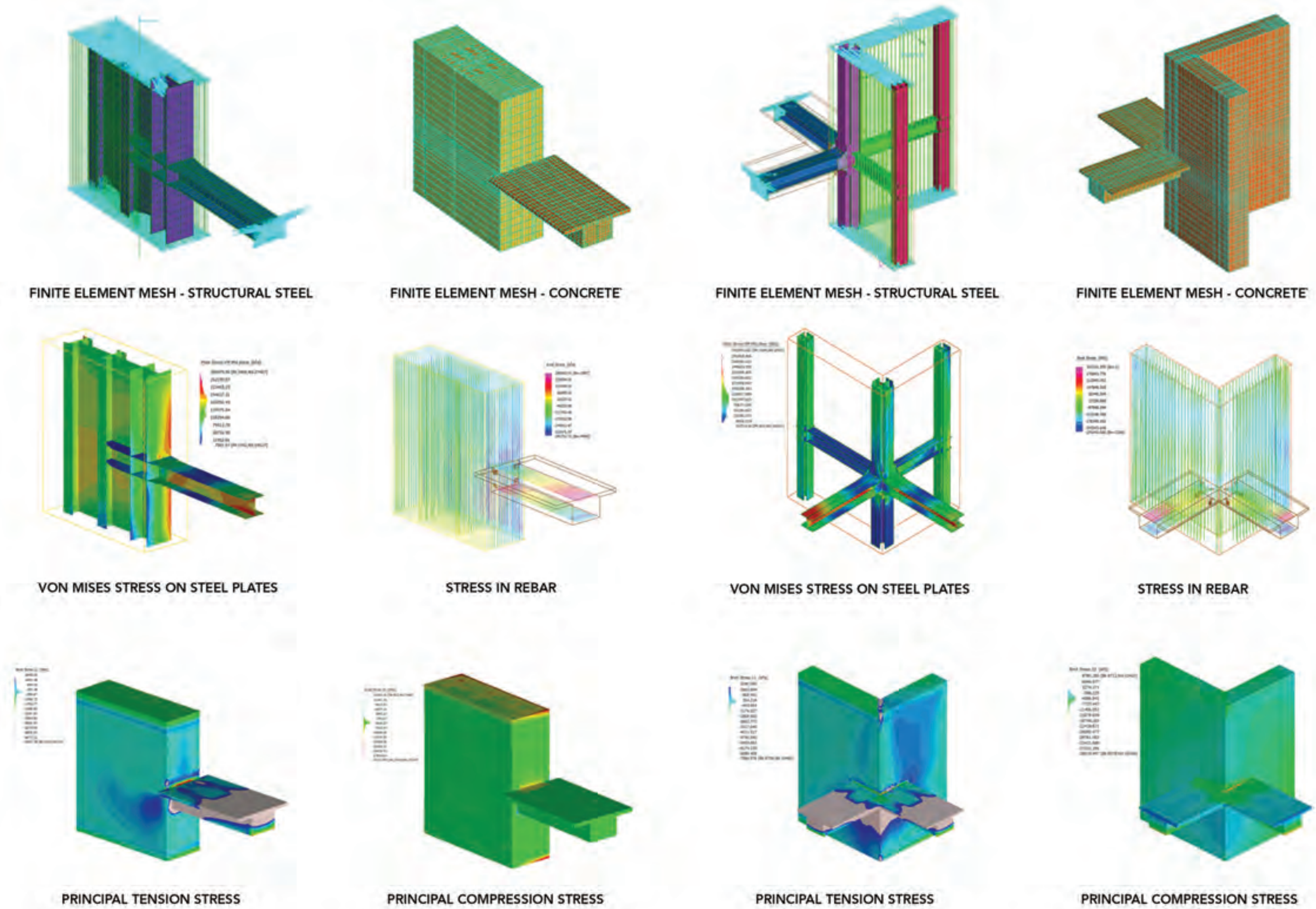

Figure 11. 3-D finite element modeling and the results of coupling beams to mega-column and core wall connections (Source: Skidmore, Owings & Merrill)
图11. 连接梁与巨型柱和核心筒连接的三维有限元模型及结果（来源：Skidmore, Owings & Merrill）

increase stiffness along the height of the tower, limiting deflections under lateral loads. Under severe lateral loads, such as an extreme earthquake event, the combined effect of belt trusses and mega-columns produces a mega-frame action and induces a second line of defense when hinges start forming in certain lateral elements such as the link beams and composite coupling beams.

Ladder-Core System Concept

Rather than a lateral system with outriggers at discrete locations, the Ladder-Core System, by linking the mega-columns and the core walls with steel embedded composite coupling beams at every floor, has been adopted on this project (Figure 12). At early stages during the design process, a study was done to compare the performance of an outrigger system and the ladder-core system. The result of the study shows that the ladder-core system presented the following advantages:

Firstly, due to the stiffness of the coupling beams, a more evenly distributed axial stress ratio is observed between the mega columns and the core walls which results in better creep and shrinkage performance. Secondly, rather than having the lateral stiffness concentrated at the outrigger floors, the composite coupling beams uniformly distribute stiffness and load path throughout the height of the building, preventing sudden changes in lateral stiffness and producing a smoother curve when looking at the building drift for wind and seismic loads. Lastly, the Chinese code requires the frame to take a certain percentage of the base shear at every floor outside of the "strengthened floor", i.e. floors with outriggers or belt trusses. With the large column spacing, it not possible to achieve the frame shear ratio with the outrigger system. The composite coupling beams effectively engage the mega-columns in shear at very floor and an average of 8% of the base shear is achieved in the frame at every floor through the ladder-core system.

One other advantage not to be overlooked is the level of redundancy in the interlocking of the core and the mega-column that is achieved by linking the two at every floor level rather than at select levels with outrigger

梁预期在常遇地震和设防烈度地震下保持弹性，在罕遇地震下保持不屈服。钢筋混凝土核心筒墙角也预期在设防烈度地震下保持弹性，在罕遇地震作用下保持抗剪不屈服。

另外，从抗侧力体系的性能角度来看，沿建筑高度间隔规律布置的腰桁架增加了核心筒与周边的耦合。 在将重机电重力荷载传递到巨柱的同时，桁架增加了沿塔楼高度的刚度，限制了在侧向荷载作用下的变形。在极端的侧向荷载，比如强震作用下，腰桁架和巨型柱的组合效果产生了巨型框架作用，这样当一定的抗侧力构件，比如连梁和组合连接梁中开始形成塑性铰时，可以作为二道防线。

梯子–核心筒体系概念

本项目采用通过将巨型柱和核心筒墙在每一层用组合连接梁连接起来而形成的梯子–核心筒体系而不是采用伸臂桁架的侧向体系（图12）。在设计进程的早期做了一个研究来对比一个伸臂桁架体系和梯子–核心筒体系。研究的结果表明梯子–核心筒体系提供了如下优点：

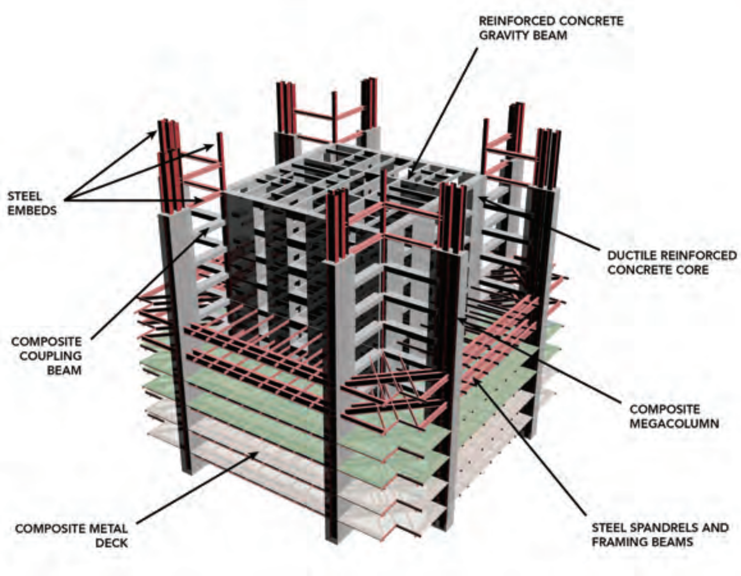

Figure 12. Left: The Ladder-Core System – the proposed construction sequence; Right: A photograph of Tower One under construction (Source: Skidmore, Owings & Merrill)
图12. 左图：梯子–核心筒体系的计划施工顺序；右图：塔楼一的施工照片（来源：Skidmore, Owings & Merrill）

truss along the height of the building. This very repetitive nature of the Ladder-Core System will also lead to simplifying and speeding up construction compared to a conventional outrigger system.

Composite Coupling Beam Performance

The advantage of the Ladder-Core System lies in its multiple connections between the core and the perimeter, uniformly distributed throughout the height of the building and in not having a few connections concentrated at discreet locations along its height. Thus performance of the Ladder-Core System, consisting of the mega-columns, the composite coupling beams, and their connectivity to the corners of the core, is crucial to the success of this structural system. Because of their critical nature, the design for these Ladder-Core System elements is based on the stringent seismic performance objectives set forth in the Lateral System Optimization section.

3D FEM analysis of composite coupling beam connections to the mega-column and core corner walls are used to visualize and verify stress levels and transfer under Moderate and Rare earthquake load combinations. The connections are analyzed by means of the general purpose finite element software Strand7.

The detailed modeling of the Ladder-Core System is also utilized to verify the following:

1. Constructability of the connection, with the inclusion of rebar, embedded steel elements, and concrete cover and clear spacing requirements
2. Restraint of the Composite Coupling Beam by the Mega-Column
3. Continuity of the Mega-Column embedded steel section through the connection
4. Full engagement of the embedded steel section in the Mega-Column by the embedded steel section of the Composite Coupling Beam by the use of stiffeners
5. And full development of Coupling Beam steel reinforcement within the Mega-Column cross section.

The loads for the finite element models are extracted from the overall building ETABS model.

Several cases of these already conservative elastic forces are then considered for the FEM.

Analysis, including maximum axial force on the mega- columns, maximum bending moment in the mega-columns about both axes, and maximum differential axial load on the two mega-columns framing into the core corner connection. Results for the governing Moderate and Rare earthquake load combinations from Chinese Code are shown below.

As shown below, in each type of composite coupling beam connection, steel plates in the connection stay elastic under Moderate earthquake loading. Steel reinforcement also remains elastic under Moderate earthquake loading, although some cracking of the concrete occurs. Concrete crushing does not occur under Moderate earthquake

首先，由于连接梁的刚度，在巨型柱和核心筒体墙之间得到了一个更为均匀分布的轴向压力比，这样得到了更好的收缩和徐变性能。其次由于组合连接梁沿建筑高度均匀地分布刚度和荷载路径而不是将刚度集中在伸臂桁架楼层，避免了侧向刚度的突变同时在观察风荷载和地震荷载作用下的建筑侧移时产生了一条平滑的曲线。最后，中国规范要求框架在加强层(例如有伸臂桁架和腰桁架的楼层)以外的每一层承担一定比例的底部剪力。在柱距很大的情况下，伸臂桁架体系不可能实现框架剪力比。组合连接梁有效地地使巨型柱在每一层参与抗剪，使梯子–核心筒体系的框架的每一层达到了平均8%的底部剪力。

与在沿建筑高度选定的楼层将核心筒和巨型柱连接起来相比，其另外一个不应忽视的优点是通过将二者在每一层连接起来所得到的这二者连锁的冗余度水平。与传统的伸臂桁架系统相比，梯子–核心筒体系的这一高度重复性的特点使得施工可以简化并加快。

组合连接梁的性能

梯子–核心筒体系的优点在于核心筒与周边的多重连接均匀地沿建筑高度分布，而不是几个连接集中在沿建筑高度离散的位置。所以由巨型柱、组合连接梁以及它们和核心筒角部的连接所构成的梯子–核心筒体系的性能是这一结构体系成功的关键。由于他们的关键性，这些梯子–核心筒体系的构件是基于侧向体系优化一节中所设定的严格的抗震性能目标进行设计的。

针对组合连接梁与巨型柱以及与核心筒墙角部的连接进行了三维有限元分析来观察并验证在设防烈度地震和罕遇地震下的应力水平和应力传递。采用通用有限元程序Strand7 来分析这些连接 。

loading. The performance objectives for the Ladder-Core System elements are met for the Moderate earthquake load level.

For the Rare Earthquake load level depicted in the stress diagrams above, the performance of each connection is similar to that of the Moderate earthquake load level. Stresses in the steel plates of each type of connection remain below yielding levels. Stresses in concrete are below crushing levels. Although cracking occurs in the concrete under Rare Earthquake loading, tensile stresses in rebar are below yielding stress.

By meeting the high performance targets set for these crucial elements, we ensure that the Ladder-Core System has a robust performance even during an extreme seismic event and there is no potential for development of a weak zone or failure mechanism, anywhere in the system.

Conclusion

The Ladder-Core System of Tower One provides a superior performance by utilizing the entire depth of the tower footprint, without comprising ductility, redundancy and regularity of stiffness along the height of the tower. Having the mega-columns as the only gravity load resisting system for the entire perimeter fully utilizes the compression due to gravity to counterbalance the tension due to the lateral loads, resulting in net zero tension at the base of the building for wind and earthquake loading. No tension in the composite columns allows optimum use of both concrete and steel, and therefore a reduction in overall steel quantities.

Other projects in China with similar objectives of creating large open unobstructed perimeter have had to introduce a perimeter brace system in order to achieve the proportional lateral load sharing between the interior core and the secondary perimeter system stipulated in the Chinese building codes. However, in case of Shum-Yip Tower One, the strategic location of composite mega-column and double perimeter girder system in a closed loop connected to the central core with uniformly distributed composite coupling beam achieved the required ratio of lateral load distribution without utilization of obtrusive perimeter bracing system.

The project has been approved by the Chinese Authorities and is currently under construction with completion slated in late 2017.

对梯子–核心筒体系的详细的模拟还被用来验证下列事项：

1. 连接的可施工性、包括钢筋、预埋钢构件和混凝土保护层以及净距的要求

2. 巨型柱对组合连接梁的约束

3. 巨型柱预埋的型钢在通过连接处的连续性

4. 组合连接梁中预埋型钢通过采用加劲肋对巨型柱中的型钢的完全接合

5. 在巨型柱截面内组合连接梁钢筋的完全锚固

有限元模型的荷载从整体建筑的ETABS模型中导出。在有限元分析中考虑了几个已经保守的弹性力的工况，包括巨型柱中最大轴向力、巨型柱中沿两个方向的最大弯矩、连接到核心筒同一个角部的两根巨型柱的最大轴力差。

在设防烈度地震作用效应下，各种组合连接梁的钢筋和连接件中的钢板均保持弹性。尽管混凝土有一些裂缝，没有混凝土压溃现象出现。

在罕遇地震作用效应下，各连接的性能与在设防烈度地震作用效应下类似。每一种连接件钢板中的应力在屈服水平以下。混凝土中的应力也在压溃应力以下。尽管在罕遇地震作用下混凝土有一些裂缝，钢筋的应力也低于屈服应力。

通过满足对这些关键构件的性能目标，我们确保了梯子–核心筒体系有稳定的性能，即使在极端地震情况下，在体系任何位置没有发展软弱区或者破坏模式的潜在性 。

结论

塔楼一的梯子–核心筒体系通过利用塔楼平面的整个深度提供了优异的性能，没有降低延性、冗余度和刚度沿建筑高度的规则性。 巨型柱作为整个周边唯一的承重体系，其充分利用了重力荷载引起的压力来抵消侧向荷载引起的拉力。组合柱中无拉力，可使混凝土和钢均优化利用，由此减小整体的用钢量。

有类似的无遮挡、大开敞周边的设计目标的中国其它项目中，不得不引入周边支撑体系来取得中国建筑规范规定的内部核心筒和二层周边体系的按比例的侧向荷载分配。然而，在深业塔楼一的案例中，策略性地布置组合巨型柱和双周边主梁体系形成闭合的环通过均匀分布的组合连接梁与中心核心筒进行连接，在没有使用遮挡视线的周边支撑体系的情况下实现了要求的侧向荷载分布比率。

这一项目已经被中国的权威机构批准并正在施工，预计在2017年年底竣工。