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Designing a Bamboo Shaped Suptertall Tower in Hefei

合肥恒大国际金融中心塔楼——竹型塔楼的结构设计

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Abstract | 摘要

The Evergrande International Financial Center, located in Binhu New Area CBD in Hefei, Anhui Province, China, consists of one iconic108-story, 518m tall tower, one single story podium with 23.3m roof height, and one 4-story basement.

The unique tower profile, inspired by bamboo, which is a symbol for prosperity and continuous growth in Chinese culture, features seven vertical segments and represents challenges to engineers for a feasible structural solution. The "Core-Outrigger-Mega-Frame" system provides an efficient lateral structural system by maximizing the bending stiffness and strength utilization. Flange walls at higher zone slope inward to free more rental space while maintaining an integral core wall. Outrigger locations are carefully analyzed to achieve a most efficient design and meet the strict Chinese codes on lateral stiffness. A robust tower foundation system with a 4.5m mat supported on piles with post grouting is used to support the massive tower and control the settlement.

Keywords: "Core-Outrigger-Mega Frame" System, Mat Foundation, Performance-Based Design, Sloping Wall, Supertall Tower

合肥恒大国际金融中心，位于合肥滨湖新区CBD。项目包括以下组成部分：一栋地标性的塔楼共108层，高518米；一栋单层大空间裙房，屋面高度23.3米；4层大面积地下室。

塔楼的体形独特，以"竹"的概念出发，"竹"在中国文化中象征着繁荣和持续发展；塔楼沿竖直方向分为七个分区，其结构设计极具挑战。"巨型框架–核心筒–外伸臂桁架"体系通过最大化抗弯刚度和强度利用为建筑提供高效的横向结构体系。在高处的核心筒边缘的墙壁逐渐向内收紧在保证核心墙完整的基础上释放出更多可租赁的空间。外伸臂桁架的位置是经过细致分析的，希望达到最高效的设计并同时在抗弯刚度上符合严格的中国规范。4.5米厚的筏板由许多灌注支撑形成了桩稳健的塔楼基座，它用于承受巨大的塔楼并控制沉降。

关键词："巨型框架–核心筒–外伸臂"体系、筏板基础、抗震性能化设计、斜墙、超高层塔楼

Project Description

As the capital and largest city of Anhui Province in Eastern China, Hefei is the political, economic, and cultural center of Anhui. The Evergrande International Financial Center, located in Binhu New Area CBD in Hefei, consisting of one iconic108-story, 518m tall tower, one single story podium with a 23.3m roof height and one 4-story basement, will rise to change the skyline (Figure 1).

Upon completion the tower will be one of the tallest buildings in the world, housing a commercial trading center, offices, serviced apartments and hotels. The podium has a multiple function hall with auxiliary houses. The 4-story deep basement accommodates retail, restaurant, MEP and parking spaces. The project occupies an area of about 28,670

项目概述

合肥市是位于中国东部安徽省的最大城市以及省会城市，同时也是安徽省的政治、金融以及文化中心。合肥恒大国际金融中心，位于合肥滨湖新区CBD。项目包括以下组成部分：一栋地标性的塔楼共108层，高518米；一栋单层大空间裙房，屋面高度23.3米；4层大面积地下室。该项目建成后将改变该地区的天际线（图1）。

塔楼建成后将成为世界最高的建筑之一，建筑功能包括一个商业交易中心、办公、酒店式公寓和酒店。裙房主要为多功能厅，周边布置辅助用房。4层地下室主要用于商业、餐饮、机电以及停车场。该项目占地面积约28,670平方米（308,600平方英尺），地上总建筑面积322,000平方米，其中塔楼为303,000平方米（3,261,000平方英尺），裙房为19,000平方米（204,500平方英尺）。地下室建

Figure 1. Building 3D Rendering View (Source: Gensler)
图1. 建筑三维渲染图（来源：Gensler）

square meters (308,600 square feet) and has a total gross floor area of 322,000 square meters above ground, with 303,000 square meters (3,261,000 square feet) for the tower and 19,000 square meters (204,500 square feet) for the podium. The basement gross floor area is approximately 115,000 square meters (1,237,800 square feet).

The unique tower profile, inspired by bamboo, which is a symbol for prosperity and continuous growth in Chinese culture, features seven vertically stacking segments. Zone 1 to Zone 4 are mainly offices, Zone 5 is serviced hotels, while Zone 6 and Zone 7 are hotel guest rooms. Each segment or zone consists of an average of approximately 16 floors with an outline profile of a hyperbolic curve: the top and bottom levels have a relatively larger floor plate, while the middle levels have smaller floor plates.

Evergrande International Financial Center tower is a square with rounded corners in plan (Figure 2) and takes an overall tapered profile vertically, which helps to meet different floor plate size requirements for varied program and more importantly reduces the tower lateral load.

Tower Lateral System

The lateral system of Evergrande International Financial Center Tower is a "Core-Outriggers-Mega-Frame" system, consisting of three parts: (steel-concrete) composite core, perimeter mega-frame and outrigger trusses (Figure 3).

Housing the elevators and MEP spaces, the rectangle core with chamfered corners in plan from Zones 1 to Zone 3 has a dimension of 32.9m x33.3m and is organized into nine-cells (3x3). The core shrinks to 26.1mx27.1m at Zone 4 and Zone 5 with flange wall sloping inward at the middle of Zone 4. The flange walls slope inward again at the middle of zone

筑面积约为115,000平方米（1,237,800平方英尺）。

塔楼的体形独特，以“竹”的概念出发，“竹”在中国文化中象征着繁荣和持续发展；塔楼沿竖直方向分为七个分区。1区至4区主要为办公，5区为酒店式公寓，6区和7区则为酒店。每个分区平均包括约16层，各区建筑轮廓线为双曲线，顶部和底部的楼层平面较大，而中间的楼层平面较小。

塔楼楼层平面为具有弧形切角的正方形（图2），建筑平面从底层到顶部总体来说逐渐变小，这有助于满足各个不同功能分区的平面要求，更为重要的是有助于降低塔楼侧向荷载。

塔楼抗侧力体系

合肥恒大国际金融中心塔楼的抗侧力结构采用了“巨型框架–核心筒–外伸臂桁架”体系。该体系主要包含了劲性核心筒，周围巨型框架以及外伸臂桁架三部分（图3）。

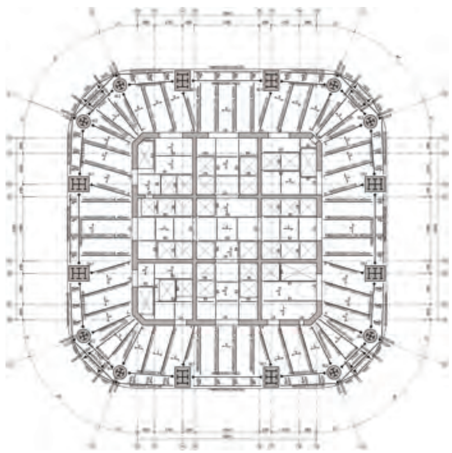

Figure 2. Typical Tower Structural Plan (Source: Thornton Tomasetti)
图2. 典型塔楼结构平面图（来源：宋腾添玛沙帝）

Figure 3. Tower lateral system (Source: Thornton Tomasetti)
图3. 塔楼抗侧力体系（来源：宋腾添玛沙帝）

6 and finally becomes a 22.5mx22.5m square core (Figure 4).

As the main resistor of wind and seismic loads, the core is a reinforced concrete structure and provides the lateral stiffness and strength to resist most story shears and around 40% of overturning moments at the base. Embedded steel columns are provided at the wall corners and intersections between outer and inner core walls to reinforce the wall boundary zones. Facilitating the connection of outrigger trusses to core wall, the embedded steel columns could directly connect to outrigger chords and diagonal members to provide a clear load path from outrigger truss to core wall. Steel plates are embedded in the bottom zone to help increase both axial and shear capacities, reduce the wall thickness and enhance the ductility. Chinese code has requirements on the maximum compression ratio allowed for wall. In the calculation, reinforcement is not considered in the capacity, while steel could be considered; therefore, embed steel could potentially reduce the wall thickness.

The perimeter mega frame includes eight rectangular megacolumns (two at each of the four sides), eight circular corner columns (two at each corner) and seven sets of belt trusses that are approximately evenly distributed along the building height. Connecting to perimeter megacolumns and corner columns, the belt trusses are typically placed at refuge and MEP floors located at the top of each zone, and act as the girder of the mega-frame.

Outrigger Optimization

Outrigger trusses play an essential role in the "Core-Outriggers-Mega-Frame" system by acting as stiff arms engaging perimeter megacolumns to the central core. When the central core tries to tilt, rotations at the outrigger levels induces a tension-compression couple in the megacolumns acting in opposition to the movement, and result in a restoring moment acting on the core. Overall, with the help of outrigger trusses, approximately 60% of the overturning moment will be shared by the perimeter mega-frame. In other words, the bending stiffness of the tower increases significantly with the much larger moment arm, thus reducing the overall building deflection and story drift ratio.

However, the great contributions from outrigger trusses to the tower lateral stiffness do come with a cost. The outrigger trusses are expensive and outrigger floors require much longer construction time than typical floor, thus the number of sets of outriggers shall be kept to a minimum. Engineers performed outrigger truss sensitivity studies, in which the quantity and location of outriggers were carefully analyzed to evaluate outrigger impact on the story drift ratio, which is also a reflection of the overall tower lateral deflection, in order to achieve the most economical and efficient design while meeting the lateral stiffness requirement set by the China Tall Building Code.

After extensive studies with different combinations of outrigger locations and coordination with other disciplines, the

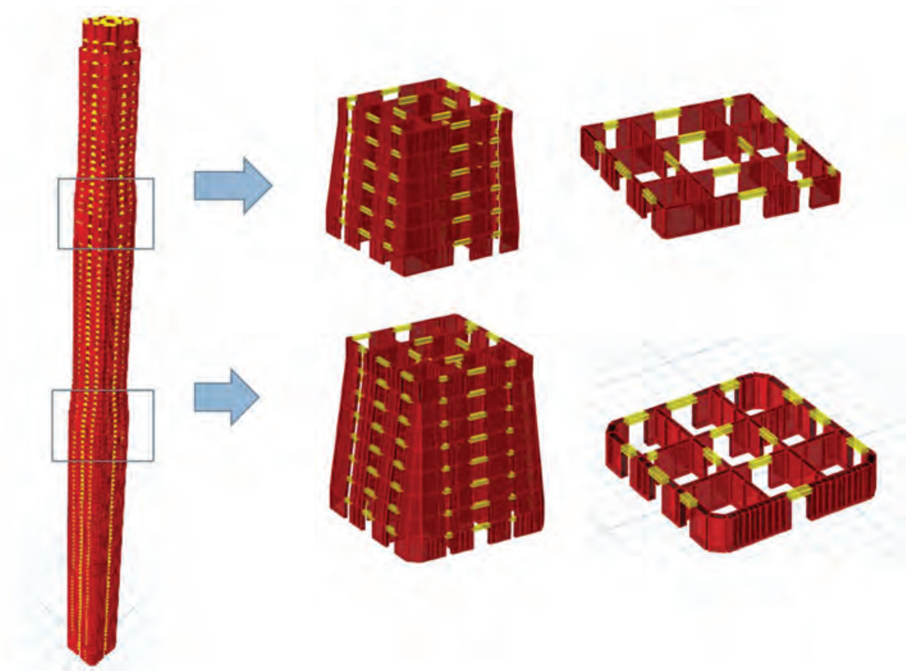

Figure 4. Tower core rendering (Source: Thornton Tomasetti)
图4. 塔楼核心筒示意图（来源：宋腾添玛沙帝）

核心筒内部主要作为电梯和机电空间，核心筒整体为长方形，为经典的九宫格。核心筒在1区至3区尺寸为32.9m x33.3m，四个角有一定切角；外墙在4区中部向内倾斜，核心筒尺寸在4区和5区缩小为26.1mx27.1m；外墙在6区中部再次向内倾斜，最终核心筒尺寸缩小为22.5mx22.5m（图4）。

作为主要抗侧力结构，核心筒主要为钢筋混凝土结构，为塔楼提供了抗侧刚度和抗侧承载力。核心筒承担了大部分的楼层剪力以及约40%的基底倾覆弯矩。在核心筒墙体角部以及核心筒的外墙交叉处布置了型钢以加强墙体的边缘区域。墙体的型钢柱布置也有助于外伸臂桁架和核心筒的连接，外伸臂的弦杆和斜杆可以直接和墙体内埋的型钢柱相连，为外伸臂和核心筒之间的传力提供了明确的路径。墙体在底区内埋钢板，内埋钢板提高了墙体的轴向以及抗剪承载力，有助于降低墙厚以及提高墙体的延性。中国规范对墙体的轴压比有限值要求，而在轴压比计算中，钢筋的贡献不予考虑，但允许考虑型钢的承载力；因此内埋型钢柱或钢板的布置是有利于降低墙厚的。

外周巨型框架包括八根长方形巨柱（建筑四边各两个），八根圆形角柱（四个角各两个）以及七道环带桁架，环带桁架沿塔楼高度近似均匀布置。环带桁架连接周边巨柱和角柱，一般布置于各区顶部的避难层和机电层，起到了巨型框架的框架梁的作用。

外伸臂桁架的优化

外伸臂桁架是“核心筒–外伸臂桁架–巨型框架”体系的重要组成部分，它作为刚性臂将布置在中心的核心筒与外围的巨柱连接起来。当核心筒试图倾斜时，外伸臂楼层的转动将在巨柱产生轴力力偶，该力偶将作用在核心筒上，形成反向的弯矩，降低核心筒的转动。总体上来说，在外伸臂的帮助下，外围巨型框架将分担约60%的基底倾覆弯矩。换句话说，由于将核心筒和外围框架有机结合，塔楼整体抗弯力臂加大，使抗弯刚度大大增加，从而降低了塔楼的侧向变形以及层间位移角。

然而，伸臂桁架对塔楼侧向刚度的贡献是有代价的。伸臂桁架的造价昂贵，同时外伸臂楼层比典型楼层的施工时间长得多，因此伸臂桁架的数量应保持在最低限度。工程师对伸臂桁架进行敏感性分析，仔细分析了伸臂桁架的数量和位置对层间位移角的影响，而层间位移角大小也是塔楼整体侧向变形的重要指标。该分析的主要目的是在塔楼抗侧刚度满足中国规范的前提下，尽可能的达到最经济、最有效的结构设计。

optimal outrigger truss locations were found, with three (3) sets of outrigger trusses located at zone 2, 4, and 5. The outrigger sensitivity study shows that outriggers at low zones are effective in reducing the building fundamental period, while upper outriggers contribute more to control the story drift ratio at upper zones. The location of outrigger trusses is close to a uniform distribution along the building height, which is also recommended by the China Tall Building Code (Figure 5).

Tower Floor System

The main tower of Evergrande International Financial Center has a composite floor system, consisting of concrete slabs, metal decks and steel floor beams. Compared to a traditional concrete beam-slab system, the composite slab system could reduce construction time by eliminating the formwork. Further, with lighter weight, the composite slab system contributes greatly to structural efficiency by cutting down the gravity loads on the foundation and reducing seismic loads on the lateral system. The structural efficiency of the foundation system and lateral system lead to great material savings and more valuable space for leasing, and could offset the relatively high cost of the composite floor system.

When choosing an appropriate composite slab system, engineers need to weigh in multiple factors, such as concrete slab thickness, metal deck profile, fire-proofing, and acoustics, etc. There are three popular types of metal decks in China, locally called "open form," "close form" and "trussed deck," with each deck having its own unique deck profile (Figure 6). After evaluating the local availability, construction practice and material costs, the owner selected the following floor system:

- 120mm thick composite slab built on rebar trussed deck at typical office and hotel floors
- 180 or 200 mm thick composite slab built on rebar trussed deck at typical MEP / Refuge levels, due to the heavier load and acoustic consideration,

从大量不同外伸臂位置组合的分析结果以及经过结构工程师和其他设计团队的协调，最优的外伸臂桁架的位置确定为在2、4、5区，共三道。外伸臂桁架敏感性分析表明低区的外伸臂能够有效减小结构基本周期，而上部的桁架则对控制高区的层间位移有很大的贡献。另外外伸臂布置也满足规范建议的沿塔楼高度基本均匀布置的原则（图5）。

塔楼楼面体系

合肥恒大国际金融中心塔楼的楼面采用组合楼板体系，该体系由混凝土板、压型钢板和楼面钢梁组成。组合楼盖体系 与传统的梁板体系相比较，不需要另外支模，从而可缩短施工工期。此外，组合楼板体系重量较轻，可以降低作用在基础上的重力荷载，进而减小作用在抗侧体系上的地震作用，从而有利于构件优化和提高结构的效率。基础和抗侧力体系的优化可以节省大量的结构材料，加大可租赁的面积，这些优势可以抵消组合楼板自身的相对高成本。

当选择适当的组合体系 ，工程师需要考虑多种因素，如混凝土板的厚度、压型钢板形式、防火、声学等。在中国一般考虑三种类型的压型钢板，即“开口型”、“闭口型”、“钢筋桁架组楼板”，各种类型均有各自独特的压型钢板形式（图6）。在综合考虑项目当地的可用性，施工实践和材料成本，业主选择下面的地板体系：

- 典型的办公和酒店楼层采用120mm厚钢筋桁架组合楼板
- 典型的机电 /避难层采用180或200毫米厚的钢筋桁架组合楼板，主要考虑到荷载较大和声学要求
- 典型的伸臂桁架或桁架所在楼层采用180或200毫米厚的钢筋桁架组合楼板，主要考虑到楼板之间的剪力传递

减少塔楼重量

对于超高层建筑，设计工程师总是要面对由巨大的重量引起的相关挑战。对于这个

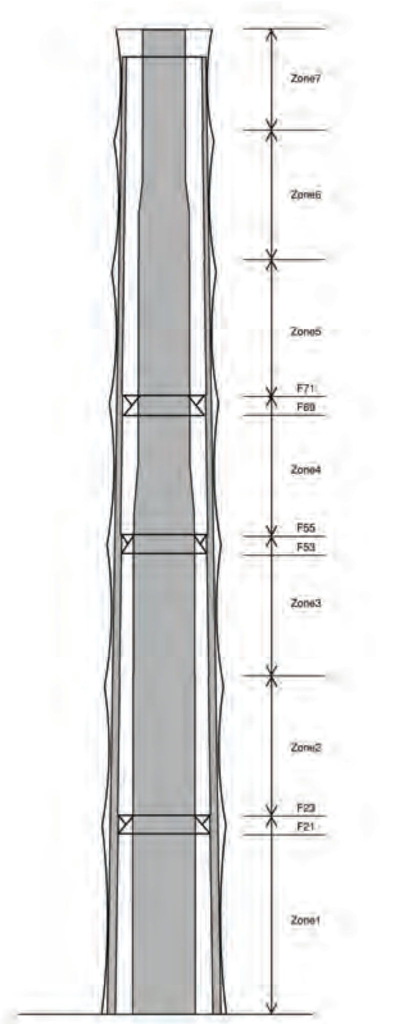

Figure 5. Tower outrigger elevation (Source: Thornton Tomasetti)
图5. 塔楼外伸臂立面图（来源：宋腾添玛沙帝）

地标性大厦也同样如此，设计工程师需要为降低楼楼重量付出巨大努力，从而使基础建设可行并减少地震荷载。地震荷载的降低有助于减小侧向体系中构件的尺寸。为了减少建筑重量，工程师考虑了重量的三个来源：抗侧体系构件，楼面重力体系和非结构构件。

抗侧体系的结构构件，如墙、巨型柱，伸臂桁架和桁架，是至关重要的结构组成部分，为塔楼提供了抵抗侧向力的强度和刚度。减小结构构件的重量或尺寸是设计优化的过程，由于抗侧体系中的结构构件直接影响到塔顶的刚度，所以优化的空间是有限的。进一步减小侧向体系构件的尺寸，将使塔楼抗侧刚度不足，难以满足中国高层建筑规范中对塔楼刚度的严格的要求。

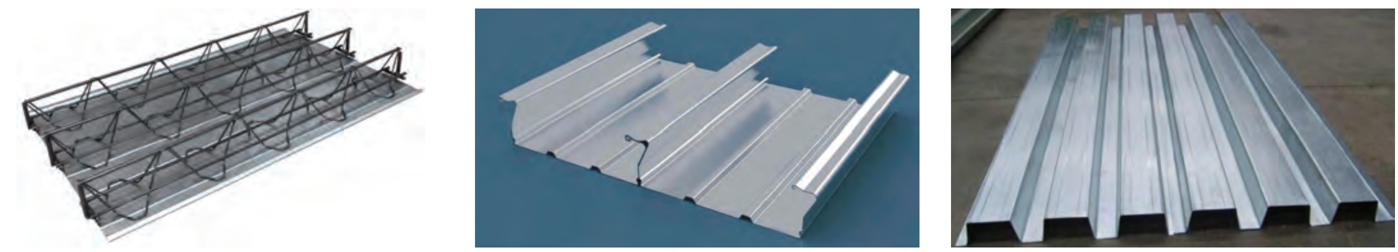

Figure 6. Tower floor composite decks – trussed deck (Source: Thornton Tomasetti)
图6. 组合楼板：钢筋桁架组合楼板（来源：宋腾添玛沙帝）

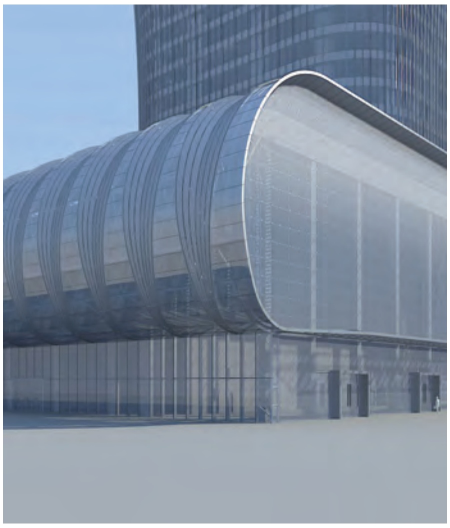

Figure 7. Podium 3D Rendering View (Source: Gensler)
图7. 裙房三维渲染图（来源：Gensler）

- 180 or 200 mm thick composite slab built on rebar trussed deck at typical outrigger truss or belt truss levels, due to horizontal floor shear transfer in the floor slabs

Reducing Tower Weight

For supertall buildings, one common thing design engineers face is the great challenge induced by the massive weight. The design engineer for this landmark tower also encountered the same issue and needed to take great efforts to reduce tower weight in order to make foundation construction feasible and to reduce seismic loads. The reduction of seismic loads helps reduce the member sizes of structural elements in the lateral system. To reduce building weight, engineers looked into three sources: lateral system, floor system and nonstructural elements.

The structural members in lateral system, such as core walls, megacolumns, outrigger trusses and belt trusses, are crucial elements that provide overall tower strength and stiffness to resist lateral loads. Reducing the weight or size of structural members for the design optimization process is not enough, as the reduction of lateral systems reaches its limit quickly because structural members in the lateral system affect the tower lateral stiffness directly. Further reduction of the lateral system makes the tower structure not stiff enough to meet the strict limit on tower stiffness specified in the China Tall Building Code.

A composite slab system is already used for the tower to minimize the weight from the floor system.

Non-structural members also contribute a good portion to the tower weight, typically treated as superimposed load (dead load and live load) from a structural engineer's perspective. Non-structural members do not contribute to the tower lateral stiffness or strength. Therefore, it is very efficient to reduce building weight by using lightweight material for non-structural elements, such as floor finishes and partition walls. The most popular partition used in high-rise apartment buildings in China is the masonry wall, but it is not suitable as a general practice for a supertall building like the Evergrande International Financial Center. With help from the architect, acoustic consultant and owner, light weight partitions, which consist of multiple gypsum boards or composite plates, are adopted for most areas on office and hotel floors.

Podium

Located on the north side of tower, the single story podium is connected with the tower without any seismic joint. The main podium structure is a concrete moment frame structure with a single-story multi-function hall located in the center with a roof height of 23.3m. The main entrance and lobby is placed at the west side, while service and MEP room are located at the mezzanine floors at the other sides.

Due to architectural function requirements for a column free area in the hall, there will be long span roof of 73m by 42.5m; a 3m deep steel truss and composite slab is used on the long span roof.

To create a magnificent view that maximizes transparency at the main entrance, a cable wall system is proposed at the west side of the podium. The cable wall system has a big load imposed on the supporting structure and it has a strict requirement for the deformation of cable support location to allow the cable function properly. A cantilever truss is provided to support the cable. The north and south sides of the façade protrude out as a curve at the top portion and form multiple leave shapes in the elevation view (Figure 7).

Basement

There are four levels of basement with main function of MEP, retail and parking spaces. With a typical column grid of 8.5m by 8.5m, the basement structure is mainly a concrete structure.

A one-way slab-beam system is used at B3, B2, B1 and B1 mezzanine levels to maximize the clear floor height and thus achieve a smaller

楼面体系则已考虑采用组合楼板使重量最小化。

非结构构件也是塔楼重量的一个重要组成部分，从结构设计角度出发，通常被视为附加荷载（恒载和活载）。非结构构件对塔楼抗侧刚度或强度没有贡献。因此，通过使用轻质材料，对降低建筑非结构构件的重量非常有效，如采用轻质的地板和隔墙。在中国的高层公寓楼常用的隔断墙是砖墙/砌块墙，但它不适合作为如恒大国际金融中心一样的超高层建筑。在建筑师，声学顾问和业主的帮助下，办公室和酒店大部分区域将采用轻质隔墙，由多层石膏板或复合板组成。

裙房

单层裙房位于塔楼的北部，与塔楼之间不设抗震缝而直接相连。裙房的主体结构为混凝土框架结构，裙房中间为单层高的多功能厅，屋顶高度23.3m。多功能厅的主要入口在裙房西侧，其他侧边局部有夹层，作为服务和机电用房。

由于多功能厅的无柱大空间要求，屋顶处有73m乘42.5m的大跨空间，大跨处布置了3m高的楼面桁架。

为了营造一个通透感最大化的壮观效果，西立面入口采用了拉索幕墙体系。拉索体系给支撑结构施加了巨大的荷载，同时为了拉索可以正常工作，该体系对拉索支撑点的变形也有严格要求。结构上布置了悬挑桁架来支撑拉索。裙房的外幕墙在南北里面突出呈弧形，同时东西方向呈凹凸状，形成竹叶型（图7）。

地下室结构

四层地下室结构的主要功能是为机电用房、商业和停车场提供空间。地下室部分主要为混凝土结构。典型柱网采用8.5m乘以8.5m。

地下三层、二层、一层以及一层夹层均采用了单向梁板体系，可最大化楼层净高，从而有利于降低地下室深度，对降低开挖成本、施工时间以及优化基础设计均较为有利。

为了能够支撑地面绿化景观和消防车荷载，根据规范要求，地面层采用加腋大板体系，有利于结构优化设计，降低结构高度，节省材料用量。

基础体系

对于每个超高层结构来说，设计一个足以承担塔楼巨大重力荷载以及倾覆弯矩的基

floor height, which will reduce the basement depth and benefit in savings of excavation cost, construction time and optimization of foundation design.

To support the heavy loading of landscape and fire truck, as specified in the China Loading Code, a haunch plate is used at ground floor for a more efficient structural design by minimizing the structural depth and saving material cost.

Foundation

Foundation design is always challenging for tall buildings due to huge gravity loads and large overturning moments from wind and seismic loading. With the benefit of a 20.4m deep basement and relatively strong and stiff soil at the project site, the tower has a 4.5m think mat foundation, supported on 441 cast-in-place bored piles with 1.1m in diameter, distributing the massive tower loads to the medium weathering argillaceous sandstone (layer 9). The piles have 35m effective lengths and count on both end bearing and friction for their capacity. Grouting provided at pile ends help increase pile capacity to 16,500kN (characteristic value of the compressive strength).

Adjacent to Chaohu Lake, the project site has a high water table, with uplift design water table just 1m below the ground level. Under the tower footprint, self-weight is more than sufficient to offset buoyancy, while the foundations at lower podium and pure basement areas will have to resist net uplift forces due to high buoyancy forces. The spiral cast-in-place piles with 400mm in diameter and 12m effective length are used to "anchor" the foundations of the podium and basement to the soils.

The significant gravity load difference between tower and adjacent podium will cause settlement differences. To reduce the effects of differential settlement, a delayed-pour strip is provided. The loads and deformations during different construction stages with independent and combined cases are considered in mat design, and additional reinforcement is provided locally at the interface of tower and podium.

Performance Based Design

Structural engineers utilized Performance Based Design (PBD) to evaluate the overall building behavior and structural member performance under different levels of seismic events. In PBD for Hefei Financial Center Tower, the nonlinearity and ductility of structural members is explicitly defined in a mathematical model, so that the performances of structural members could be evaluated under the seismic events. Performance objectives are determined in the early design stage and are in compliance with the requirements specified in the China Seismic Code and requirements from seismic experts.

Performance goals for the overall structural system and structural components are summarized in Figure 8 (Figure 8).

Seismic Hazard Level		Frequent Earthquake	Moderate Earthquake	Severe Earthquake
Performance Level Description		No damage or negligible damage	Little Damage, Repairable	Serious Damage, No Collapse
Structure Behavior Description		No damage, structure basically in elastic range	Allow minor damages , structure substantially retains original strength and stiffness	Allow serious damage, but no fracture of major connection joint; no shear fracture of super columns and core walls
Story Drift Ratio Limit		h/500	h/200	h/100
Member Performance	Core Wall	Elastic, Strength design per code: - factored seismic load - material design strength	Code-based strength design At outrigger floors: - factored seismic load - material design strength At other floors: - unfactored seismic load - material ultimate strength	Plastic hinge rotation: θ<IO at bottom levels θ<LS at other levels Shear forces<= ultimate shear capacity
	Link Beam		Allow plastic hinge; Code-based strength design	Plastic hinge rotation: θ<LS and <=0.02 rad
	Super Column		Elastic, Code-based strength design - factored seismic load - material design strength	Plastic hinge rotation: θ<IO at bottom levels θ<LS at other levels Stress in reinforcement. f > fy but < fu
	Belt Truss		Elastic, -factored seismic load -material design strength	Elastic, steel stress f < fy
	Outrigger		Code-based strength design -unfactored seismic load -material ultimate strength	Plastic deformation: θ<LS and stress f < fu

Figure 8. Performance Target and Acceptance Criteria (Source: Thornton Tomasetti)
图8. 抗震性能目标和标准说明（来源：宋腾添玛沙帝）

础总是充满了挑战。本项目地下室20.4m深，场地地基强度和刚度均较大，塔楼下设计采用了4.5m厚的筏板，筏板底下布置了441根直径1.1m的灌注桩，将塔楼的巨大荷载传递至中风化泥质砂岩（第9层土）。桩的有效长度为35m，岩土承载力包括了端承和摩擦力。灌注桩采用了桩端注浆，使桩的抗压承载力特征值提高至16,500kN。

本项目毗邻巢湖，场地的地下水水位较高，抗浮设计水位达地面以下1m。在塔楼范围内，塔楼自重足以抵消水浮力，但较矮的裙房和纯地下室部分则需要采取措施抵抗高水位引起的上浮力。裙房和纯地下室采用了400mm直径，有效长度为12m的螺旋灌注桩将基础“锚固”在土层上。

塔楼和相邻裙房的巨大重力荷载差异将引起不均匀沉降。为了降低沉降差的影响，塔楼周边将布置后浇带。不同施工阶段的荷载以及变形均在筏板设计中考虑，另外设计中也考虑了独立模型和整体模型的分析，在塔楼和裙房之间的筏板布置了额外的配筋进行加强。

结构性能化设计

结构工程师采用抗震性能化设计理念来评估在不同地震作用下结构的整体表现以及各个结构构件的性能。在合肥恒大国际金融中心塔楼性能化分析中，结构构件的非线性和延性均在数学模型中明确定义，这样结构构件的性能就能按分析结果进行评估。结构的性能目标是在项目设计初期确定，符合中国抗震规范和抗震专家要求。

结构体系整体以及各结构构件的性能目标汇总情况见图8（图8）。

在确定结构性能目标后，性能设计分析包括了以下步骤：

- 建立考虑结构构件非线性响应的分析模型
- 确定适用于工程场地的地震波时程曲线
- 进行非线性动力时程分析

根据性能目标评估结构整体以及各构件的性能表现塔楼的数学模型（图9）采用了Perform 3D软件进行建模分析，以评估结构在50年地震超越概率为2%即2475年一遇的罕遇地震作用下的反应情况。根据中国抗震规范的要求，一共采用了7组地震波进行分析。每组地震波数据均包括两个水平方向和一个垂直方向，各方向的输入比例为1：0.85：0.65。

根据中国规范的评价标准以及参考《旧有

Figure 9. "Perform 3D" model (Source: Thornton Tomasetti)
图9. “Perform 3D”模型（来源：宋腾添玛沙帝）

After performance objectives are set, the PBD analysis could start, taking the following steps:

- Create mathematical model incorporating the nonlinearity of the structural members
- Determine appropriate ground motion time histories
- Perform nonlinear dynamic time-history analyses
- Verify the building overall performance and member performance based on the acceptance criteria

The mathematical model of the tower (Figure 9) is created using the Perform 3D analysis program to evaluate the structural performance under a severe earthquake, which is defined as 2% exceedance probability in 50 years or a 2475-year earthquake. Seven sets of ground motion return period waves are selected based on the rules specified in Chinese code. Each set of ground acceleration includes two orthogonal horizontal components and one vertical component acting simultaneously at a ratio of 1:0.85:0.65.

Using the acceptance criteria per Chinese code and referencing "Seismic Rehabilitation of Existing Buildings" (ASCE/SEI 41-06), engineers evaluated the tower performance under a severe earthquake and drew the following conclusions:

- Overall, the tower achieves the "Life Safety" performance level
- Average of the maximum story drift from 7 sets of waves is within code limit of 1/100 under severe seismic event. The drift curve is shown in Figure 9 (Figure 10).
- Most link beams exhibit plastic behavior, thus dissipating the seismic energy as expected.

Through the nonlinear time history studies, structural engineers could identify the weak portions of the tower and enhance the

房屋的抗震加固》（ASCE/SEI 41–06），结构工程师经过对结构在罕遇地震作用下性能表现的评估，得到以下结论：

- 整体上说，塔楼达到了“生命安全”的性能水平
- 7组罕遇地震作用下的平均最大层间位移角满足规范小于1/100的要求（图10）
- 大部分连梁进入塑性阶段，屈服耗能

经过进行非线性时程分析，结构工程师能够找到塔楼的薄弱区域，从而有针对性地提高薄弱区域结构构件的强度和延性。

结论

作为重塑合肥天际线的重大项目，合肥恒大国际金融中心是一个复杂的建筑，由一栋518m高的塔楼，一个与塔楼直接相连不设缝的单层大空间多功能厅裙房以及一个大面积的地下室组成。塔楼的抗侧体系采用了高效的“核心筒–外伸臂桁架–巨型框架”体系；楼面体系采用了钢筋桁架组合楼板以降低塔楼重量和施工时间；基础体系采用了典型的桩筏基础以支撑沉重的塔楼；塔楼的性

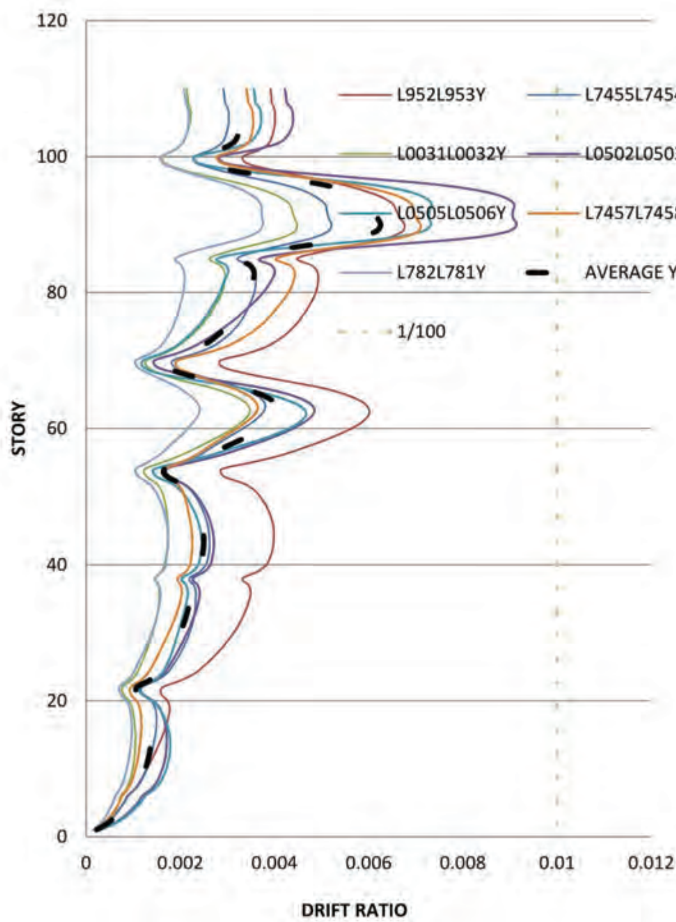

Figure 10. "Perform 3D" story drift results for curve-X (Source: Thornton Tomasetti)
图10. “Perform 3D”结果–层间位移角曲线–X方向（来源：宋腾添玛沙帝）

strength and ductility of structural members at the weak portions.

Conclusion

Reshaping the skyline of Hefei, the Evergrande International Financial Center is a complex highlighted by a 518m supertall tower, a single-story spatial hall connected to the tower without any joints, and one large basement. An efficient "Core-Outriggers-Mega-Frame" system is used as the tower lateral system; a composite slab system with a concrete slab built on a special rebar trussed deck is adopted to reduce the tower weight and construction time; and a classic pile-supported mat system proves to be a feasible solution to support the heavy tower. State-of-art PBD analysis is used to evaluate the tower performance instead of the prescriptive code-based design approach. The structural systems are crafted to achieve high structural efficiency and integrate with the architectural functions seamlessly.

Project Design Team Credits

Client: Hefei YueTai Business Operations Management Co., Ltd.

Architect: Gensler

Structural Engineer: Thornton Tomasetti Inc.

MEP Engineer: Parsons Brinckerhoff

Local Design Institute: Eastern China Architectural Design & Research Institute CO., LTD

Wind Engineering Consultant: Rowan Williams Davies & Irwin Inc. (RWDI)

能表现分析采用了顶尖的抗震性能化分析的理念来代替以规范为基础的描述性设计方式。所采用的结构体系充分发挥了结构的效率，并实现了与建筑的完美结合。

项目设计团队

业主：合肥粤泰商业运营管理有限公司

建筑设计公司：Gensler（晋思）

结构设计公司：Thornton Tomasetti Inc（宋腾添玛沙帝）

机电设计公司：Parsons Brinckerhoff（柏诚）

国内设计公司：中国华东建筑设计研究院

风工程顾问公司：Rowan Williams Davies & Irwin Inc.（RWDI）