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Structural Design Challenges

结构设计挑战

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Built on soft soils, Suzhou Zhongnan Center relies on concrete bored piles with post-grouting to support the massive tower. An efficient lateral system, namely the "Core-Outrigger-Megaframe" system, provides enough lateral stiffness and strength to resist the significant lateral loads. The location and quantity of outriggers are carefully analyzed to balance structural efficiency and construction economy. Performance-based design is used to verify tower performance under severe seismic events through non-linear dynamic time-history analysis. The floor vibration is studied at the long-span area and cantilever area to verify the occupant comfort level. A supplemental damping system is implemented to enhance building comfort under 10-year wind load.

中南中心地基主要为软土地基，为了支撑塔楼的巨大荷载，基础采用了后注浆的混凝土钻孔灌注桩。"核心筒-外伸臂桁架-巨型框架"结构体系是一种有效的抗侧力体系，为结构提供所需要的抗侧力刚度和强度。针对外伸臂桁架的位置和数量做了详尽的分析研究以平衡结构效力和经济性的关系。性能化设计采用弹塑性动力时程分析的方法复核在罕遇地震作用下结构的性能表现。针对大跨度和悬挑区域进行了楼面振动分析，使其带到舒适度要求。采用了附加阻尼系统提高10年一遇风载情况下的建筑舒适度。

Introduction

Supertall buildings always pose great challenges to the engineers. The structural engineers have to overcome a few unavoidable challenges that originate from the massive gravity loads and large lateral loads (wind and seismic) in supertall buildings. To cope with the design challenges, structural engineers have to find solutions that provide a robust foundation system to support the great gravity loads, an efficient lateral system to resist huge lateral loads, and a lightweight floor system to reduce total tower weight. This chapter covers some general approaches to deal with the design challenges and achieve economical structural design for this megatall building.

Foundation System

Inherent in every supertall building, huge tower gravity loads demand a strong foundation base with great bearing capacity. Unfortunately, soil condition at the building site for Suzhou Zhongnan Center is poor, highlighted by layers of sands and clays that alternate to at least 120 meters below grade and bedrock that is unreachable for practical construction purposes. Based on the soil conditions, the pile foundation is considered the practical solution, but the pile diameter and pile length still need careful examinations by engineers. To optimize the pile design and verify the pile capacity and constructability, structural engineers adopted a pilot test-pile program at the early design stage. Under the pilot test pile program, two 110-meter-long testing piles, with bearing layers set at the fine sand layer (13-2), and two 98-meter-long testing piles, with the bearing layer set at the silty sand layer (13-1), were constructed and tested. The pile length is counted from the grade level. The typical testing pile load-settlement curve (Q-S curve) for a 110-meter-long bored pile is shown in Figure 3.8. End grouting and side grouting are provided to enhance the pile capacity and reduce pile settlement. After evaluating the factors of pile capacity, pile settlement and construction cost, engineers placed 1.1-meter-diameter, 110-meter-long bored piles, with capacities of 1,300 to 1,600 tons, under the core to support the 6.3-meter-deep concrete tower mat.

项目介绍

超高层结构总会给结构工程师带来巨大的挑战。这些不可避免的挑战来自超高层结构巨大的重力荷载和水平荷载 (风和地震作用) 。为了解决这些设计难题，结构工程师需要提供足以支撑塔楼巨大重力荷载的基础体系、有效抵抗水平力的抗侧力体系和能够减轻塔楼重量的轻质楼板体系。本篇论文涵盖了解决超高层经济型结构设计和设计挑战的一般方法。

基础系统

对于每个超高层结构来说，巨大塔楼的重力荷载需要一个能过提供足够承载力的基础体系。中南中心地下场地情况较差: 砂层和粘土层至少要延伸到地表以下120米，在施工中基础体系基本无法触及基岩。根据实际场地情况，确定桩基础为可行方案，设计师仍需要进一步确定桩径和桩长。为了优化桩基设计并确保桩的承载力和施工可行性，该工程早在概念设计阶段就进行了试桩。试桩主要考虑了承载层，分别在砂土层 (13-2) 布设两根110米长的桩和粉砂层 (13-1) 布设两根长98米的桩。桩长从地表开始计算。图3.8为110米桩的荷载-沉降量曲线 (Q-S曲线) 。桩基采用了端注浆和侧注浆技术来提高桩基承载力和减小沉降量。通过综合考虑桩承载力，沉降量和施

Figure 3.7. Tower 3D Rendering View (Source: Gensler)
图3.7. 塔楼3D渲染图 (来源: Gensler)

Tower Lateral System

The "Core-Outrigger-Megaframe" system is used as the Zhongnan Center tower lateral system. As its name suggests, the system consists of three components: composite core, perimeter megaframe (supercolumns, corner columns and double belt trusses), and outrigger trusses.

There are nine zones from bottom to top, dividing the tower into different functions. Typically the two top floors of each zone will serve MEP or refuge functions. The core-outrigger-megaframe system utilizes these top floors by having belt trusses serve as the megagirders of the perimeter megaframes, and outrigger trusses to avoid intrusion into more valuable office and residential spaces.

With the help of belt trusses and outrigger trusses, the core wall and 12 perimeter columns will be integrated to take advantage of the full building width to resist the bending caused by lateral loads, making the building stiff enough to meet the strict stiffness requirements specified in the China Tall Building Code.

Steel reinforced concrete (SRC) columns are used as the tower supercolumns at the building perimeter. Compared to traditional concrete columns, SRC columns provide much higher capacity and stiffness with the same area, thus reducing the column sizes and providing more valuable rental spaces. SRC columns also offer better performance during seismic events due to their ductile behavior and higher hysteretic energy decimation capacity. Since the steel provides higher capacity-to-weight and stiffness-to-weight values than concrete, SRC columns also contribute to reduce the overall column weight and tower weight, which benefit the foundation design and reduce the seismic load. Compared to steel columns, SRC columns provide better strength capacity, larger stiffness, better fire rating and better construction economy. The concrete outer layer effectively prevents the embedded structural steel from buckling and enhances durability.

The structural steel embedded in the perimeter columns connect to the outrigger truss or to the belt truss members directly to provide a clear and secure load path. The profiles of embedded steel in perimeter columns are carefully studied to ease construction at connection zones.

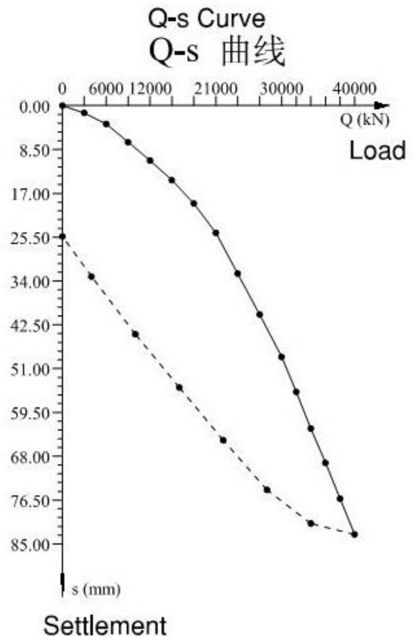

Figure 3.8. Test Pile: load-settlement curve (Source: Shanghai Jianke Technical Assessment of Construction, Co., Ltd)
图3.8. 试桩: 荷载-沉降量曲线 (来源: 上海建科检验有限公司)

工成本等因素，该工程最终采用了直径1.1米、承载力1300到1600吨的110米长钻孔灌注桩以支撑6.3米厚的塔楼筏板。

塔楼抗侧力体系

中南中心的抗侧力结构采用了"核心筒-外伸臂桁架-巨型框架"体系。顾名思义，该系统包含了组合核心筒、周围巨型框架(巨型柱、角柱和双环带桁架)以及外伸臂桁架三部分。

塔楼从上到下分为9个区，包含了不同建筑功能，各个区的最上部两层将作为机电层和避难层。"核心筒-外伸臂桁架-巨型桁架"体系在每区顶层布置了环带桁架，作为周围巨型框架系统的巨型主梁;同时在局部区域布置了外伸臂桁架，避免占用办公和住宅空间。

Outrigger Optimization

Potentially, nine (9) sets of outrigger trusses could be placed along the building height with one set in each zone. However, more outrigger trusses do not lead to a more efficient structure. Outrigger trusses are expensive, and the construction time for outrigger floors is much longer than for regular floors, thus the number of outriggers should be kept to a minimum. Engineers have performed outrigger truss sensitivity studies, in which the quantity and location of outriggers are carefully analyzed to achieve the most economical design while meeting the stiffness requirement set by the China Tall Building Code, and to evaluate outriggers' impact on the story drift ratio, which is also a reflection of the overall tower lateral deflection.

After extensive studies with different combinations of outrigger locations, the optimal outrigger truss locations are found, with five (5) sets of outrigger trusses located at zones 2, 4, 6, 7, and 8. This outrigger sensitivity study shows that outriggers at low zones are effective in reducing the building fundamental period, while upper outriggers contribute more to control story drifts 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.

Reducing Tower Weight

For a megatall building built on soft soils, engineers make great efforts to reduce tower weight in order to make foundation construction feasible and reduce the seismic loads. The reduction of seismic load helps reduce the member sizes of the structural elements in the lateral system. To reduce building weight, engineers look into three sources: the lateral system, the floor system and nonstructural elements.

The structural members in the lateral system, such as core walls, supercolumns, outrigger trusses and belt trusses, are crucial elements that provide overall tower strength and stiffness to resist lateral loads. After a few

在环带桁架和外伸臂桁架的帮助下，核心筒和12根外围柱能够有机结合起来，利用结构的全部宽度来抵抗水平荷载产生的弯曲作用，使结构刚度满足《高层建筑混凝土结构技术规程》的要求。

建筑的外围柱采用型钢混凝土巨型柱的形式。与传统的混凝土柱相比，型钢混凝土柱能够在相同的面积下提高柱子的承载力和刚度，可以有效减小柱子尺寸从而提供更多的可用建筑空间。型钢混凝土柱具有很好的延性和较高的滞回耗能能力，在地震作用下有很好抗震性能。由于钢材的承载力/比重和刚度/比重的比值比混凝土高，采用型钢混凝土有利于减小柱和塔楼的整体重量，进而减小地震力的大小，也有利于基础设计。而与钢柱相比，型钢混凝土柱能够提供更高的承载力、更大的结构刚度，经济性和防火性能也更优。柱子外部的混凝土能够有效的防止内埋型钢发生屈曲，从而提高构件延性。

巨型柱中部的型钢可以与外伸臂桁架或环带桁架直接相连，使结构形成了清晰可靠的传力路径。对于巨型柱内埋型钢的截面形式，设计方进行了细致的分析比选以方便连接区域的施工。

外伸臂桁架的优化

从可行性角度，塔楼每个分区均能布置外伸臂，整个塔楼共可布置9道外伸臂桁架。但是，外伸臂桁架越多并不意味着结构体系越高效。外伸臂桁架造价很高，而且外伸臂层施工工期比普通层要长很多。因此，设计应尽量减少外伸臂桁架的数量。结构工程师对外伸臂桁架的性能和位置做了敏感性分析，尽量做到在满足经济性要求的同时使塔楼刚度满足中国规范的要求。敏感性分析主要是分析不同的外伸臂方案对层间位移角的影响，而层间位移角的大小也反应了对塔楼整体侧向位移的大小。

设计方经过对不同外伸臂桁架位置组合方案的广泛研究，确定了塔楼最佳桁架位置。五组伸臂桁架分别位于2，4，6，7，8区。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。该外伸臂布置也满足中国规范建议的沿塔楼高度均匀布置的原则。

减少塔楼重量

针对在软土层上修建超高层结构的情况，工程师们为减小塔楼重量做了很多努力。较轻的塔楼重量有利于提高基础施工的可行性，并减少结构承受的地震力。减小地震力也有助于减小抗侧向力构件的截面尺寸。为了能够减小结构重量，工程师从抗侧向力体系、楼板体系和非结构构件三方面进行优化设计。

核心筒、巨型柱、外伸臂桁架和环带桁架所组成的抗侧力体系为结构提供了抵抗侧向荷载作用的主要强度和刚度。由于抗侧力构件的截面尺寸直接影响塔楼的抗侧刚度，经几番优化之后，抗侧力体系很快减小到容许极限。如果进一步减少抗侧力构件的截面尺寸，塔楼刚度将不能满足规范规定的要求。

楼板体系的重量在结构总重量中占了很大比例。与传统梁板体系相比，组合楼板具有重量轻、工期短等优点，因此在项目初期就确定采用组合楼板作为中南中心的楼板体系。经过对重量、成本、防火等因素的综合考虑，选择了三种类型: 开口型压型钢板、闭口型压型钢板、钢桁架组合楼板。结果表明三种组合楼板均满足基本要求。最终业主决定采用以下方案: 在典型办公区、住宅和酒店的楼板采用125mm厚组合楼板 (65mm混凝土浇筑于波高60mm闭口压型钢板之上) ; 机电层和避难层则采用在200mm厚钢桁架组合楼板。

非结构构件影响塔楼重量但对结构侧向强度和刚度无贡献。因此，对建筑面层和隔墙等非结构构件采用轻质材料将有效减少建筑重量。根据业主对住宅区楼面热量辐射的要求，结构工程师对干、湿两类面板做了研究，决定采用重量较轻的干型面板，最终使结

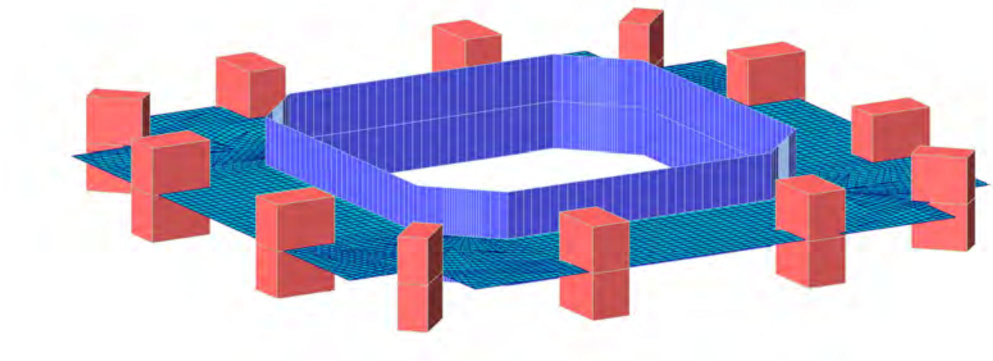

Figure 3.9. Floor Vibration Midas Model (Source: Thornton Tomasetti)
图3.9. 楼面振动的Midas模型 (来源: 宋腾添玛沙帝)

rounds of optimization, the reduction of the lateral system 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 requirements specified in the China Tall Building Code.

The floor system accounts for a big portion of total building weight. A composite slab was selected as the floor system for the Zhongnan Center tower at the very beginning of the project, due to its advantages of light weight and fast construction over conventional concrete beam-slab systems. Three types of composite slab system, built on open-form deck, closed-form deck and steel-truss formwork systems respectively, were carefully evaluated in terms of weight, cost, and fire rating, etc. The evaluation shows each of the three types of composite slab system would be feasible. The owner made the final choice: the 125-mm-thick composite slab (60 mm of concrete above a 65-mm-deep closed-form metal deck) would be used at typical office, apartment and hotel floors, while 200-mm-thick composite slabs would be built on steel-trussed formwork systems at typical MEP / refuge levels.

Non-structural members contribute to the tower weight, but do not contribute to the tower overall lateral capacity and stiffness. Therefore, it is very efficient to reduce building weight by using lightweight material for nonstructural elements, such as floor finishes and partition walls. The owner requested a floor-radiation heating system at the apartment floors. The dry style radiation heating system was selected for its light weight, and a final result of 9,500 tons of tower weight reduction when compared to a wet style system. The most popular partition used in high-rise apartment buildings in China is masonry wall, but this is not suitable for a supertall building like Zhongnan Center. With help from the architect, lightweight partitions, which consist of multiple gypsum boards, were adopted, contributing to 10,000 tons of tower weight reduction.

Floor Vibration Study

For floor serviceability, stiffness and resonance are dominant considerations in the design of composite floor structures. With longer spans and lighter steel beams, floor vibration needs to be carefully studied to make sure it meets the desired occupant comfort level.

In the floor vibration studies, engineers created an FEM model with fine mesh for a typical floor at zone 3 to evaluate the floor performance at long-span and corner-cantilever areas (see Figure 3.9). The loading assumptions for floor vibration studies are based on AISC design guide 11, "Floor Vibrations Due to Human Activity," and proper boundary condition assumptions are made to reflect the real floor supporting conditions.

From the finite element analysis of the floor system, the first mode of the floor vibration is shown on Figure 3.10, where the maximum amplitude appears at the middle bay of long span area. The frequency of first mode is 7.03Hz, which meets the 3Hz floor vibration requirement specified in China Code. Several walking paths have been studied to get the most severe floor vibration

构重量减少了9500吨。在中国高层公寓楼中广泛采用砌体墙，但这并不适用像中南中心这样的超高层建筑。在与建筑师协调沟通后，中南中心塔楼最终采用了由多片石膏板组成的轻质隔墙，此方案使结构减少10000吨重量。

楼面振动研究

对于楼板使用性能来说，结构刚度和振动是组合楼板设计主要考虑的两大因素。考虑到组合楼板的大跨度和与钢梁较轻的情况，工程师做了细致的楼板振动分析，确保设计满足舒适度要求。

在楼面振动分析中，工程师对三区的典型楼板建了精细有限元分析模型，主要研究在大跨度区和角部悬臂区楼板的振动情况 (见图3.9) 。楼面荷载假定参考AISC设计规程11"基于人类活动的楼板振动"，而边界条件则假定尽量反映真实楼板的支承情况。

在有限元分析中，楼板振动第一模态出现在大跨度区中部 (见图3.10) 。第一阶模态的振动频率为7.03Hz，满足中国规范对频率大于3Hz的要求。除此之外，对过道的楼板振动加速度情况进行了研究。大跨度中部的最大加速度为3.5gal，角部区域悬臂板最大加速度为4.8gal，两个数据均满足规范对住宅楼板振动加速度不超过5gal的规定。

风荷载作用下建筑舒适度研究

苏州中南中心是高宽比大于8.0的细长型结构。最高的酒店和住宅区标高分别为598和462.6米。风洞试验结果表明，在10年一遇的风荷载作用下，酒店区 (标高598米) 的地面最大加速度为0.274 m/s^2，住宅区 (标高462.6米) 为0.185 m/s^2。这些数据均超过了中国规范对酒店区0.25 m/s^{2}和住宅区0.15

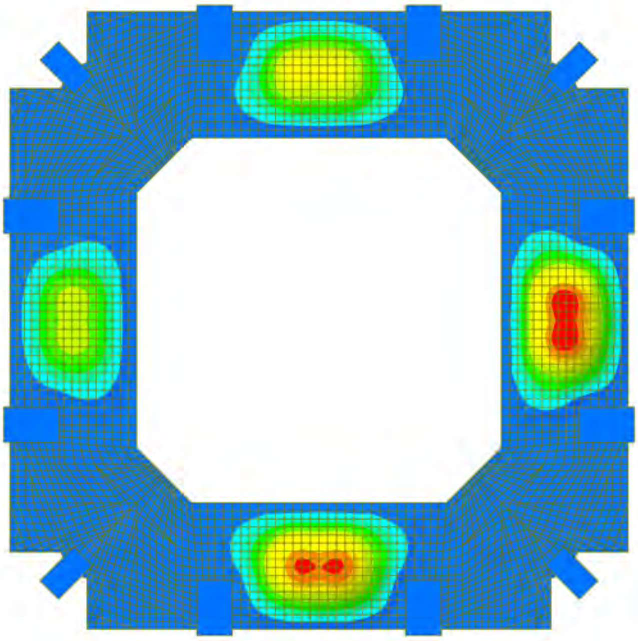

Figure 3.10. First Mode Shape of Floor Vibration (Source: Thornton Tomasetti)
图3.10. 楼面振动的第一模态 (来源: 宋腾添玛沙帝)

acceleration. The maximum accelerations are found to be 3.5 Galileos (Gal) at the middle of the long-span area and 4.8 Gal at the corner of the cantilevered slab area; both maximum accelerations are within the code limit of 5 Gal required for an office or residential floor.

Building Comfort Under Wind Load

Suzhou Zhongnan Center is a slender building with an aspect ratio larger than 8.0. The top hotel and apartment levels are at elevations of 598 and 462.6 meters, respectively. According to the wind tunnel test results, the maximum acceleration at top hotel level reaches 0.274 m/s2 and the maximum acceleration at the top apartment level reaches 0.180 m/s2 under a 10-year wind. Both floor accelerations exceed China code requirements: 0.25 m/s2 for hotel and 0.15 m/s2 for apartment. On one hand, the TMD consultant, RWDI, proposed that a supplemental damping system (SDS) need to be provided to achieve the serviceability performance objectives within the space set aside for the damping system. A tuned mass damper (TMD) will be an effective way to reduce the floor acceleration.

However, due to the space constraint, the TMD alone could not be large or heavy enough to reduce floor acceleration to meet code requirement. Therefore, an additional Tuned Sloshing Damper (TSD) will be provided by utilizing the approximately 600-metric-ton fire water tanks at tower top level to help reduce the maximum floor acceleration. According to the analysis by RWDI, the TMD consultant for Suzhou Zhongnan Center, the supplemental damping system combining the TMD and TSD can reduce the floor accelerations under 10-year wind by approximately 30%, enough to reduce the floor acceleration to be within the code limit.

On the other hand, the consultant from Tongji University proposed an innovative viscous damper, which could be installed at the connection between SRC columns and outrigger trusses. This system will also assist to reduce the acceleration by 30%.

Performance-Based Design

Structural engineers utilized performance-based design (PBD) to evaluate the building's overall behavior and structural member performance under different levels of seismic events.

m/s^{2}的要求。为此，RWDI作为调谐质量阻尼器 (TMD) 的设计顾问，提供了附加阻尼系统的设置方案以达到塔楼舒适度的控制要求。设置调谐质量阻尼器是减小楼面加速度的有效方式; 但是由于空间限制，只采用调谐质量阻尼器不足以满足规范对楼面加速度的控制要求。因此在塔楼顶部，在调谐质量阻尼器下方利用消防水箱作为附加的调谐液体阻尼器 (TSD) 来减小楼面加速度。根据RWDI的研究结果显示，同时运用调谐质量阻尼器和调谐液体阻尼器使楼面在10年一遇的风荷载作用下的加速度减小了30%，满足中国规范楼板地面加速度的控制要求。另一方面，另一顾问方同济大学也创新地提出了粘滞阻尼器方案，在巨型柱和外伸臂连接处布置粘滞阻尼器，该减振体系也能达到30%的减振效果。

结构抗震性能设计

结构工程师采用基于性能的抗震设计理念来评估在不同地震作用下结构的响应。结构的性能目标在概念设计阶段确定，并符合中国抗震规范和抗震专家的要求。在确定结构性能目标后，基于性能的抗震设计分析包括了以下步骤:

- 建立结构的非线性分析模型
- 根据工程场地情况确定地震波时程曲线
- 进行非线性动力时程分析
- 根据性能目标评估整体结构和构件的抗震性能

中南中心的分析模型 (见图3.11) 是为了分析和评估在50年地震超越概率为2%或者2475年一遇的罕遇地震作用下的结构响应情况。根据中国抗震规范的要求，一共采用了7组地震波进行时程分析，每组地震波均包括两个水平方向和一个垂直方向。

根据通用的评价标准，结构工程师经过对结构在罕遇地震作用下的性能表现进行分析评估，得到以下结论:

- 整体上，塔楼达到了"生命安全"的性能水平
- 7组罕遇地震动力时程作用下的平均最大层间位移角满足规范小于1/100的要求
- 大部分连梁进入塑性阶段，发挥屈服耗能作用

Performance objectives were determined in the early design stage and are in compliance with the requirements specified in China Seismic Code and requirements from seismic experts. After the performance objectives were set, the PBD analysis could start, taking the following steps:

- Create a mathematical model incorporating the nonlinearity of the structural members
- Select the appropriate ground motion time-history curves for the project site
- Perform nonlinear dynamic time-history analysis
- Verify the building overall performance and member performance based on the acceptance criteria

The mathematical model of the Zhongnan tower, shown in Figure 3.11, was created to evaluate the structural performance under severe earthquake, which is defined as 2% exceedance probability in 50 years, or a 2,475-year earthquake. Seven sets of ground motion records (curves) were picked, based on the rules specified in China code. Each set of ground acceleration records includes two orthogonal horizontal components and one vertical component acting simultaneously.

Using the acceptance criteria, engineers evaluated the tower performance under a severe earthquake and drew the following conclusions:

- Overall, the tower achieves the "Life Safety" performance level
- The average of the maximum story drift from seven curves is within the code limit of 1/100 under severe seismic event
- Most link beams exhibit plastic behavior, thus dissipating the seismic energy

Figure 3.11. Tower Non-linear Mathematical Model (Source: Thornton Tomasetti)
图3.11. 塔楼的弹塑性分析模型 (来源: 宋腾添玛沙帝)

Through the nonlinear time-history studies, structural engineers could identify the weak regions of the tower and enhance the strength and ductility of structural members of those regions.

经过进行非线性动力时程分析，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。

Conclusion

The Zhongnan Center tower brought great design challenges to and resolutions from structural engineers: a feasible foundation solution to support a heavy tower on soft soils, an efficient lateral system to satisfy the strict story drift ratio, a lightweight floor system that meets floor vibration criteria, a damping system to enhance the building comfort level, and a robust and ductile system that can achieve desired performance levels under a severe earthquake. Structural engineers resorted to innovative structural systems and state-of-the-art analysis techniques to overcome the design challenges and achieve an efficient and economical structural design.

结论

中南中心给结构设计师提出一系列的设计挑战: 在软土地基上支撑巨型塔楼的基础体系; 满足层间位移角要求的高效抗侧力体系; 满足楼面振动控制要求的轻质楼板体系; 提高结构舒适度的阻尼系统; 在罕遇地震作用下能够达到性能目标要求的坚固而具有足够延性的结构体系。结构工程师通过结构体系的创新和先进的分析技术克服了设计挑战，从而实现了高效经济的结构设计目标。

References (参考书目):

GB50011-2010, **Code for Seismic Design of Buildings**.

JGJ3 (2010), **Technical Specification for Concrete Structures of Tall Buildings.**