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Haihang International Plaza, Tower A, Main Building's Supertall Structural Design

海航国际广场A座主楼超高层结构设计

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Abstract

The Main Building of Tower A of the Haihang International Plaza is a 54-story out-of-code supertall structure which uses a CFST (Concrete-Filled Steel Tube) structure and a set of outriggers in level 17, 32 and 51 with circular trusses to enhance the lateral stiffness of the structure. Based on this out-of-code structure case, this paper examines the performance objectives and technical solutions to the project. Results from the elastic analysis and elasto-plastic time-history analysis show that all the calculated indexes meet the requirement and the entire design meets code standards.

Keywords: Supertall Structure, Structural Design, Outrigger

摘要

海航国际广场A座主楼为54层的超限高层结构，采用钢管混凝土框架-混凝土核心筒结构体系，在17、32和51层设置了伸臂桁架和环向桁架以提高结构的侧向刚度。针对结构的超限情况，提出了性能目标和超限技术措施。弹性分析和弹塑性时程分析表明，工程各项计算指标比较理想，整体设计满足规范要求。

关键词：超高层结构，结构设计，伸臂桁架

Project Overview

Haihang International Plaza is located in the Jinmao District in Haikou, Hainan Province and faces the Qiongzhou Strait in the north. This project complex consists of Tower A, Tower B, and an annex with a total building area of 215,000 square meters. Tower A has a 54-story new structure where the height of its main structure is 223.6 meters. In addition, the lower levels of Tower A are used for luxury office spaces while the upper levels are used as a five-star hotel. Refuges and mechanical systems are set in level 17, 32 and 51. After the reconstruction of the original structure, Tower B currently has a seventeen-story main building and 5-story extension wing functioning as an office building and auxiliary facilities of the hotel. Tower A, B and the annex have the same three-story basements that do not have permanent deformation joints. Above ground, the annex is connected to Tower B but separated from Tower A by a joint, thus there exists two independent structural systems. Please refer to Figure 1 for the engineering rendering and Figure 2 for the section drawing.

工程概况

海航国际广场位于海南省海口市金贸区，北临琼州海峡，由A座、B座和裙房组成，总建筑面积21.5万m^2。A座为54层新建结构，结构主体高度223.6m，下部为5A级高档写字楼，上部为五星级酒店。在17层、32层和51层设置了避难层和设备转换层。B座主楼17层，裙房5层，在原有结构基础上改造，主要功能为写字楼和酒店附属设施。A座、B座及裙房的地下室均为三层，未设永久变形缝；在地上，B座主楼与裙房连为一体，而A座主楼与B座主楼及裙房设缝分开，为两个独立的结构单元。工程效果图请见图1，剖面图请见图2。

A座主楼的设计使用年限为50年，结构安全等级为一级，抗震设防烈度为8度，设计基本地震加速度为0.30g，设计地震分组为第一组。场地类别为Ⅱ类，但覆土厚度接近于Ⅰ类场地与Ⅱ类场地的分界线，特征周期插值计算为0.31s。重现期100年的基本风压为0.90 KN/m^2，地面粗糙度取A类。

Figure 1. Rendering of Haihang International Plaza (Source: Fujiang Xu)
图1. 海航国际广场效果图（出自：徐福江）

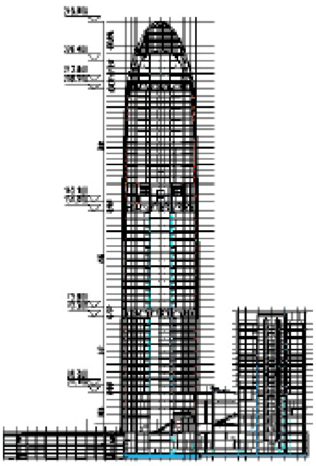

Figure 2. Profile of Haihang International Plaza (Source: Fujiang Xu)
图2. 海航国际广场剖面图（出自：徐福江）

Tower A is designed to have a 50-year service life, first-grade safety classification, eight-degrees of seismic fortification intensity, and a seismic acceleration of 0.30g, which places the design of the earthquake classification to the first group. The site classification belongs to Category II, but the thickness of the cover soil is close to the dividing line between Category I and Category II while the characteristic period interpolation is 0.31s.The fundamental wind pressure in a 100-year recurrence period is 0.90 KN/m^2 with the surface roughness belonging in Class A.

Structural System

The plan of Tower A resembles a date pit with a height to width ratio of 5.0 and approximately 14.7 for the core. Please see figure 3 for the structural plan drawing for the standard floor. Steel beam and steel truss composite floor slab systems are applied to the floor construction. The CFST (Concrete-Filled Steel Tube) structure system has a strengthened arrangement used in the structure with buckling–restraining braces that are added at four corners on the outer frame.

结构体系

A座主楼平面呈枣核形，高宽比约为5.0，核心筒高宽比约为14.7，典型标准层平面结构图请见图3。采用带有加强层的钢管混凝土框架—混凝土核心筒结构体系，楼面为钢梁+钢筋桁架组合楼盖，在外框架的四个角部设置了防屈曲耗能支撑。

现浇混凝土核心筒是主要抗侧构件，承担了绝大部分的倾覆弯矩和水平剪力。在核心筒内设置了构造钢骨柱和钢骨梁。一方面，内置钢骨框架方便了核心筒与楼面钢梁的连接，另一方面也大幅提高了结构的抗震性能。结构底部核心筒外侧墙厚为1500mm，至顶部收进为500mm。底部混凝土强度为C60，上部混凝土强度为C50。

外框架作为结构抗震体系的第二道防线，在承担竖向荷载的同时，也抵抗了部分倾覆弯矩和水平剪力。框架柱采用钢管混凝土柱，底部楼层框架柱的截面为2.05m×1.35m，顶部楼层柱截面为1.05m×0.85m，含钢率约为10%左右。与混凝土柱相比，钢管混凝土柱构件截面小，有效地提高了建筑使用面积。施工速度快，虽然结构费用较钢骨混凝土柱稍高，但利于施工及工期的缩短，带来的经济效益更大，对超高层结构而言更是如此。框架梁和楼面梁均为钢梁，楼面主楼主梁与框架柱刚接，与核心筒铰接，楼面次梁两端铰接。框架梁主要截面为H 800×400×24×36,楼面梁的主要截面为H 700×300×16×28。钢柱与钢梁的材料均选用Q345B。

为了提高结构的侧向刚度，利用建筑的避难层，在第17层、32层和51层设置了加强层。加强层的伸臂结构采用桁架形式，楼层通高，并贯穿核心筒剪力墙。加强层平面布置图和伸臂桁架立面图请见图4和图5。结构X向刚度较大，因此伸臂桁架仅沿Y向布置。同时，在加强层外围设置了楼层通高的环向桁架，加强了周边框架柱的联系。伸臂桁架与环向桁架共同作用，使周边框架更有效地发挥了抗侧性能，以满足结构侧向位移要求。

海航国际广场A座主楼结构高度223.6m，是目前我国大陆“8度半”抗震设防地区的最高建筑，因此，为了确保结构在地震下的安全，本工程按照超限审查委员会的意见，采用了消能减震措施，在上部楼层的四个角部设置了防屈曲耗能支撑，而下部楼层的角部由于相对位移较小，未设置防屈曲耗能支撑，而以普通钢支撑替代。防屈曲耗能支撑具有较高的刚度和良好的滞回耗能能力。在地震作用时，防屈曲耗能支撑耗散部分地震能量，从而减少结构主体构件的损伤。

本工程持力层为中风化玄武岩层，地基承载力特征值为2500kPa，基础采用平板式筏板基础。

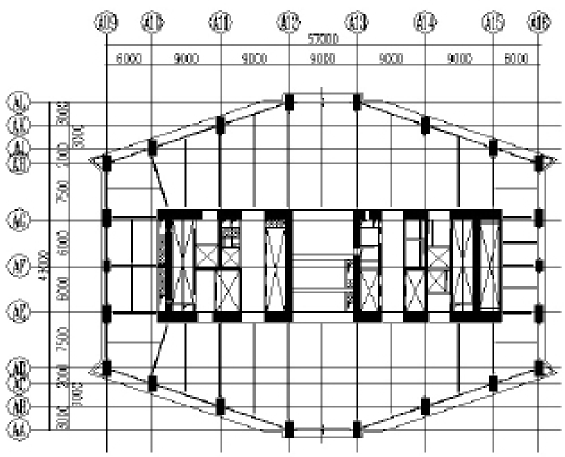

Figure 3. Plan of the standard floor (Source: Fujiang Xu)
图3. 典型标准层平面图（出自：徐福江）

The cast-in-place concrete core is the major lateral resisting component which bears most of the overturning moments and horizontal shear. In addition, steel columns and beams were set up in the core. On one hand, the built-in steel frame makes it easier for the core and the floor-beam connections. On the other hand, it increases the seismic performance of the structure. The sidewall of the core at the bottom of the structure has a thickness of 1500mm, which decreases to 500mm at the top. The concrete strength is C60 at the bottom and C50 at the top.

As the second defense line of the seismic structural systems, the outer frame bears vertical loads and resists part of the overturning moments and horizontal shear forces. CFST columns are used for the frame with a cross-sectional area of 2.05m×1.35m for the lower floors and 1.05m×0.85m for the upper floors which all contain a steel ratio of approximately 10%. In comparison to concrete columns, these CFST columns have a smaller cross section which reduces structure area and decrease the construction time. Even though the CFST columns cost more than normal steel reinforced concrete columns, the shorter construction period will compensate with greater economic benefits, especially for supertall buildings. Both frame beams and floor beams are made of steel. The floor girders are rigidly connected to the frame columns and pinned with the core tubes. The floor sub-beams are also connected in hinged joints at both ends. The main cross-sectional area of the frame beams is H 800 x 400 x 24 x 36; the main cross-sectional area of the floor beams is H 700 x 300 x 16 x 28 for the floors. The steel columns and beams are made of Q345B steel material.

In order to increase the lateral stiffness of the structure and take advantage of the refuge at the same time, strengthened floors are set in the 17th-story, 32nd-story and 51st-story. The outriggers in the strengthened floors are using one-story-high trusses reaching all the way into the shear walls in the core. Please see figure 4 for the plan of the strengthened floor and figure 5 for an elevation of the outrigger. The structural stiffness is stronger in the x-direction so the outriggers are only set in the y-direction. Additionally, circular trusses are arranged on the strengthened boundary layers and reach all the way to the floor which improves its connection to the frame columns. The reliability of outriggers and circular trusses ensures a more effective lateral resistance performance in order to fulfill the lateral displacement requirement of the structure.

The Haihang International Plaza Tower A has a 223.6 m main structure which is currently the tallest building in the "M8.5" earthquake fortification area in China. To ensure structural safety under earthquakes, this project has taken advice from the supertall out-of–code committee and has applied seismic energy dissipation measures and arranged buckling–restraining braces on four corners in the upper levels. However, regular steel braces are used in the lower floors instead because of the relatively small displacements. Buckling–restraining braces have great stiffness and hysteretic energy which can consume seismic energy and prevent major structural components from failure during earthquakes.

A bearing stratum is used in this project for the intermediate weathered basalt layer with a foundation bearing capacity value of 2500 kPa for the basic usage of a flat plate raft foundation.

Supertall Structural Situations and Technical Solutions

Supertall Out-of-Code Structural Situations

The main building structure of Tower A is 223.6m exceeding 150m – the maximum height limit of a composite structure in a M8 seismic

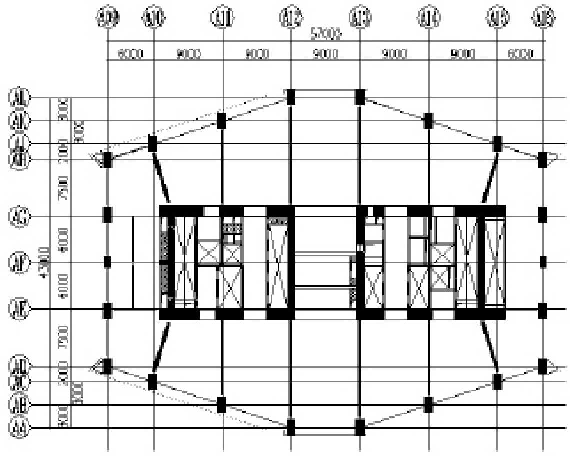

Figure 4. Plan of the strengthened floor (Source: Fujiang Xu)
图4 . 加强层平面图（出自：徐福江）

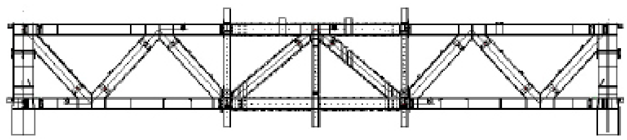

Figure 5. Elevation of the outrigger (Source: Fujiang Xu)
图5. 伸臂桁架立面图（出自：徐福江）

结构超限情况及技术措施

结构超限情况

A座主楼结构高度223.6m，超过了混合结构8度设防时的最大高度限值150m，属于超限高层结构。结构的平面基本规则，扭转周期比为0.85，位移比为1.19。而竖向则同时存在着刚度突变和承载力突变的情况。加强层的下一层，即16,31,50层的承载力均小于上一层的75%，属于竖向承载力突变；酒店的大堂层设在结构的34、35层，层高较高，侧向刚度小于上面三层侧向刚度平均值的80%，属于竖向刚度突变。此外，结构的东西两侧首层入口局部拔柱，通过斜撑结构进行转换，竖向构件不连续。因此，本结构属于平面基本规则，竖向不规则的超限复杂高层结构。

性能目标

根据本工程的特点，结构在地震作用下的性能目标请见表1：

超限技术措施

针对本工程的超限情况，在结构设计中采取了以下技术措施：

- 底部加强区的竖向构件在大震下按照抗弯不屈服，抗剪弹性验算；
- 转换构件按中震弹性验算，包括转换斜撑和斜撑下框架柱，并在大震下确保不屈服；
- 将底部加强区的框架抗震等级提高为特一级；
- 外框架采用钢管混凝土柱，内核心筒设置构造钢骨框架，提高结构的延性；
- 在外框架角部设置防屈曲耗能支撑，提高结构的耗能能力；
- 加强层及其相邻层的核心筒的配筋加强，箍筋全高加密，提高延性；楼板厚度加大，双层双向配筋；
- 对薄弱层的地震剪力乘以1.15的增大系数；
- 采用动力弹塑性分析验算结构在罕遇地震作用下的变形。

Seismic Intentsity 地震烈度		Frequent Earthquake 多遇地震	Fortifiable Earthquake 设防地震	Rare Earthquake 罕遇地震
Performance Level 性能等级		No Damage 没有破坏	Repairable Demage 可修复损坏	No Collapse 无倒塌
Story Drift Angle Limit 层间位移角限值		1/554	-	1/100
Component Performance 构件性能	Frame Column 框架柱	Standard Requirement, Elasticity 规范设计要求，弹性	No Yield 不屈服	Allowable Plasticity; Meet the Shear-Setion-Control Conditions 允许进入塑性，满足受剪截面控制条件
	Frame Beam 框架梁	Standard Requirement, Elasticity 规范设计要求，弹性	Allowable Yield 允许屈服	Allowable Plasticity 允许进入塑性
	Core Coupling Wall 核心筒墙肢	Standard Requirement, Elasticity 规范设计要求，弹性	No Yield 不屈服	Allowable Plasticity,Meet the Shear-Setion-Control Conditions 允许进入塑性，满足受剪截面控制条件
	Core Coupling Beam 核心筒连梁	Standard Requirement, Elasticity 规范设计要求，弹性	Allowable Crack 允许开裂	Allowable Plasticity 允许进入塑性
	Transfer Support 转换斜撑	Standard Requirement, Elasticity 规范设计要求，弹性	Elasticity 弹性	No Yield 不屈服
	Buckling–Restrained Braces 防屈曲耗能支撑	Elasticity 弹性	Yield 屈服	Yield 屈服

Table 1. Performance objective under earthquake (Source: Fujiang Xu)
表1. 地震作用下的性能目标（出自：徐福江）

zone – which makes Tower A an out-of-code supertall structure. The structural plan is essentially normal with a torsion period ratio of 0.85 and a displacement ratio of 1.19. The stiffness mutation and bearing capacity change also exists in the vertical direction. The floors below the strengthened stories, which are the 16th-story, 31st-story and 50th-story, have a bearing capacity of less than 75% of the strengthened stories above them and they have a vertical bearing capacity of mutation. The hotel lobby is on the 34th and 35th floors and has a vertical stiffness mutation with a lateral stiffness of less than 80% of the average lateral stiffness of the three stories above it. There are no columns on the east and west sides of the entrance and the forces are transferred by the bracing structure, so this can be identified as vertical components that are not continuous. Therefore, the structure of the project has a regular structural plan but an irregular intricate supertall structure in the vertical direction.

Performance Objective

According to the characteristics of this project, please refer to Table 1 for the performance objectives of the structure under seismic activities:

Out-of-Code Technical Solutions

Aiming toward the project's supertall conditions, the following technical solutions can be adopted in the structural design:

- Make sure that vertical members in the strengthened area at the bottom will not yield under bending during major earthquakes, check the shear elasticity;
- Check the elasticity of transfer components under moderate earthquakes, these include transfer braces and frame columns below it in order to ensure the tower from yielding during a major earthquake;

Vibration Mode 振型	ETABS Period (s) 周期(s)	ETABS Vibration Mode Participation Mass Ratio(%) 振型参与质量比(%)			SATWE Period (s) 周期(s)	SATWE Direction Factor(%) 方向因子(%)		
	T	Ux	Uy	Rz	T	Ux	Uy	Rz
1	3.8141	0.00%	48.10%	0.70%	3.8914	0	1	0
2	2.6458	50.70%	0.00%	0.10%	3.0181	1	0	0
3	1.6268	0.00%	0.00%	16.10%	1.8896	0	0	1

Table 2. Period (Source: Fujiang Xu)
表2. 周期（出自：徐福江）

结构计算

弹性分析

分别按照场安评报告和抗震设计规范提供的设计地震动参数对结构进行了计算。由于安评报告提供的反应谱中下降段较快，按照安评报告提供的设计反应谱计算得到的地震作用及结构反应要远小于按照规范反应谱计算的结果。因此，本工程按照规范的设计参数进行抗震设计。

分别采用SATWE和ETABS对结构进行了整体计算，主要结果汇总请见表2至表4：

从上述结果可以看出，本工程为地震作用控制，风荷载不起控制作用。经核算，风荷载作用下的顶点加速度最大值为0.14m/s²，舒适度满足规范要求。结构的周期、位移、剪重比等各指标均满足规范的要求。

Item 项目		ETABS		SATWE	
Structure Dead Loads (kN) 结构总恒载 (kN)		2311000		2329715	
Structure Live Loads (kN) 结构总活载 (kN)		233000		236765	
Total Loads (kN) 总荷载(kN)		2544000		2566480	
Direction 方向		X	Y	X	Y
Seismic Action 地震作用	Foundation Shearing Force (kN) 基底剪力 (kN)	78470	70790	74169	69114
	Foundation Shear-Weight Ratio 基底剪重比	4.50%	4.10%	4.20%	3.90%
	Foundation overturning moments (kN.m) 基底总倾覆弯矩 (kN · m)	9723000	8492000	9631768	8547511
Wind Action 风作用	Shearing Force in the Basement (kN) 基底剪力 (kN)	25540	33970	31221	42310
	Foundation overturning moments (kN.m) 基底总倾覆弯矩 (kN · m)	3325000	4569000	4121069	5727882

Table 3. Actions on the structure (Source: Fujiang Xu)
表3. 结构作用力（出自：徐福江）

- Increase the anti-seismic grade of the strengthened area at the bottom to Primary First Grade;
- Use CFST columns in the outer frame and steel encased frames in the core to increase ductility in the structure;
- Use buckling–restrained braces on all corners of the outer frame to increase the energy dissipation capacity for the structure;
- Increase the strength of reinforcing bars and increase the density of the stirrups in the strengthened floors and adjacent floors to improve ductility; increase the thickness of each floor with a two-way reinforcement;
- Multiply a 1.15 enhancement coefficient to the seismic shear forces in the weak stories;
- Use dynamic elasto-plastic analysis to calculate the structural deformation during rare earthquakes.

Structural Calculations

Elastic Analysis

Structural calculations are prepared with respect to the on-site safety evaluation report while vibration parameters are provided by the seismic design code. Due to the fast decline in the response spectrum from the safety evaluation report, the calculated results of seismic activities and structural responses are much less than the results provided by the code's response spectrum. Thus, this project's seismic design is created in accordance to the seismic design code.

Using SATWE and ETABS to calculate the whole structure, the main results are shown in Table 2-4:

The tower is controlled by seismic activities, not by wind loads. After calculations are completed, the maximum acceleration under wind loads is established as 0.14m/s^2 which meets the comfort criteria. The period, displacement, and shear to weight ratio all meet the code requirements as well.

Elasto-plastic Analysis

The structure is analyzed by a general FEM (Finite Element Method) software ABAQUS. Geometric nonlinearity and material nonlinearity are considered in the analysis taking into account the impact of the construction process on the analysis results.

Based on the results from the elasto-plastic time-history analysis, the evaluation of this project's seismic performances during rare earthquakes is as follows:

- Three groups of Magnitude-8 rare earthquake data and a two-way elasto-plastic time-history analysis show that the maximum roof displacement for the structure is 825mm, maximum story drift ratio is 1/104 which meets the requirement of a stipulated limit of 1/100. Please see figure 6 for the maximum story drift displacement curve. During the entire calculation process, the whole structure is always upright and able to meet the "no collapsing during a big earthquake" specification;
- All of the coupling beams undertaking serious damages create a hinged mechanism while playing a dissipating energy consuming role during rare earthquakes;
- All of the shear walls below the 34th-story take less damage while the shear walls above the 34th-story obtain more failures in the y-direction. It is mainly due to the partial discontinuity of the core tube and high floor height which decreases the lateral

Item	ETABS				SATWE			
	Seismic Action 地震作用		Wind Action 风作用		Seismic Action 地震作用		Wind Action 风作用	
		Y	X	Y	X	Y	X	Y
maximum inter-story drift angle 最大层间位移角	1/1163	1/580	1/3906	1/1230	1/ 958	1/567	1/2375	1/927
floor location 所在楼层	27	41	27	38	41	41	24	38
maximum story drift ratio 最大层间位移比	1.1	1.09	-	-	1.17	1.19	-	-
floor location 所在楼层	2	1	-	-	2	1	-	-

Table 4. Displacement (Source: Fujiang Xu)
表4. 位移（出自：徐福江）

弹塑性分析

采用通用有限元软件ABAQUS对结构进行了动力弹塑性分析。在分析时考虑了几何非线性和材料非线性，同时也考虑了施工过程对分析结果的影响。

根据弹塑性时程的计算结果，对本工程在罕遇地震作用下的抗震性能主要评价如下：

- 三组8度罕遇地震记录、双向作用下的弹塑性时程分析表明，结构顶点最大位移825mm，最大层间位移角为1/104，满足规范限值1/100的要求。最大层间位移角曲线请见图6。整个计算过程中，结构始终保持直立，能够满足规范的"大震不倒"要求；
- 结构中的所有连梁均破坏较重，说明在罕遇地震作用下，连梁形成了铰机制，发挥了屈服耗能作用；
- 结构第34层以下的剪力墙破坏较轻；而第34层以上，Y方向剪力墙破坏较重。主要是由于该位置核心筒存在一定程度的不连续及局部层高较大造成的Y方向侧向刚度及承载力削弱。核心筒剪力墙破坏严重区域请见图7；
- 结构外框架柱、伸臂桁架和环向桁架基本保持弹性，框架梁局部进入了塑性，但程度不大；
- 结构底部的斜撑转换构件未出现塑性，抗震性能达到了大震弹性；
- 防屈曲耗能支撑均进入了塑性阶段，发挥了耗能作用，减少了结构主体构件的损伤。

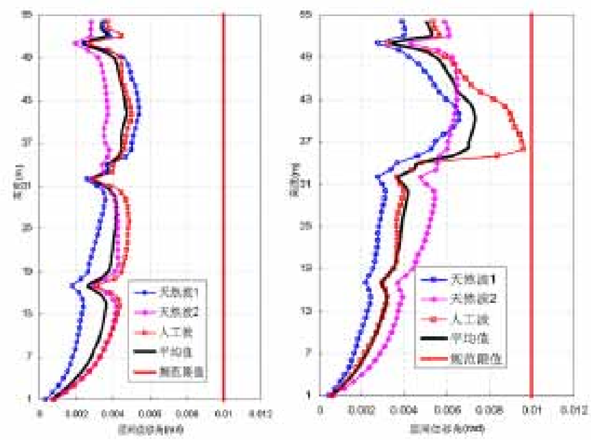

Figure 6. Curve of maximum inter-story drift displacement (Source: Fujiang Xu)
图6. 最大层间位移曲线（出自：徐福江）

stiffness and bearing capacity in the y-direction. Please see figure 7 for the location of the major failures in the core tube shear wall;

- Outer frame columns, outriggers, and circular trusses essentially maintain their elasticity, and parts of the frame beams have some plasticity but do not have a significant impact;
- The transfer braces at the bottom of the structure have no plasticity which means that the seismic performance has reached its elasticity during severe earthquakes
- Buckling-restrained braces have entered the plastic stage, producing energy consumption effects, which decrease the destruction of major members.

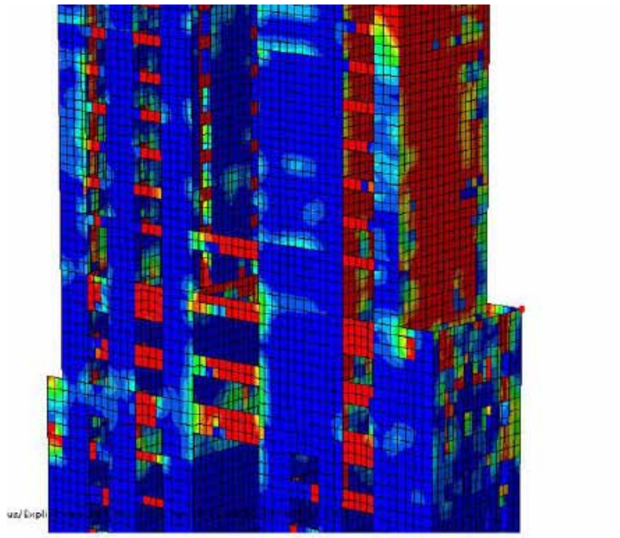

Figure 7. Partial failure of the core (Source: Fujiang Xu)
图7. 核心筒局部破坏情况（出自：徐福江）

Conclusion

The Haihang International Plaza is currently the tallest building under construction in the "M8.5" seismic fortification intensity area in mainland China. The complex supertall structure of the building upholds characteristics such as a regular plan, lateral stiffness mutation, partial discontinuity of vertical components, and floor bearing capacity mutation. However, by means of rational structural arrangement and certain performance objectives, the structure achieves excellent seismic performance. According to analysis, each index in the project has met the requirements of codes and standards.

结论

海航国际广场是目前中国大陆“8度半”抗震设防区域在建高度最高的建筑，属于平面基本规则、侧向刚度突变、局部竖向构件不连续、楼层承载力突变的超限复杂高层结构。通过合理布置结构、确定性能目标，并针对结构的超限情况采用相应的技术措施，使得结构具有良好的抗震性能。分析计算表明，工程各项指标均满足规范要求。

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