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Structural Design of Sino Steel International Plaza

中钢国际广场结构设计

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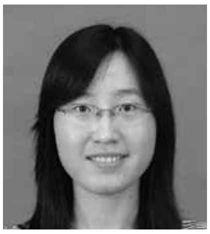

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Abstract

Sino Steel (Tianjin) International Plaza has the first worldwide application of hexagonal grid structure system as its exterior tube of this super high building. Based on the research solution that the hexagonal grid structure is strong in withstanding horizontal loads, but weak in vertical loading resistance, the following structural design key techniques are put forward: all steel floor beams are pinned to connect the core and exterior tube and outriggers are not adopted, minimizing the horizontal beam sections to make them weaker than column sections (six edge member sections not equal); adjusting the inclined angle of corner columns (six inner angles not equal); adopting varied sections for slant columns (slant column sections not equal); adopting effective stiffness of steel beam studs; proposing special construction measures.

Keywords: Hexagonal Grid Exterior Tube, Horizontal Beam Stiffness Weaken, Inclined Angle of Corner Column Straighten Up, Strong Joint Weak Member, Effective Stiffness of Stud

摘要

中钢天津国际广场采用国内外首创六边形网格结构作为外网筒。针对这种结构抗竖向荷载较差，抗水平荷载较好的特点，采取如下重要关键技术：内外筒连接的楼盖钢梁两端铰接、不设伸臂；网筒水平横梁截面弱于斜柱；角部斜柱倾角减小；斜柱截面节点区强化、中部弱化；引入钢梁连接楼板的栓钉的有效刚度；采取专门施工措施。

关键词：六边形外网筒结构、横梁刚度弱化、角部斜柱扶直、强节点弱构件、栓钉有效刚度

Brief of Project

Sino Steel (Tianjin) International Plaza located in Tianjin Xiangluowan Business District. This project has overall building area of 395181m². It is comprised of tower T1 and T2 with a three-story podium, and four levels of extensive basements. Tower T1 has a height above ground level of 102.9 meters, 24 stories and has 65,180 m² of building area. Tower T2 has a height above ground level of 358 meters, 83 stories and has 225,370m² of building area, where the plan dimension of the standard floor is about 53 meters by 53 meters, and a height-to-width ratio is 6.88. The structure of tower T2 is an S.R.C. core incorporated with an exterior hexagonal grid tube. The podium height above ground level is 16 meters and has 11,070m² of building area. The extensive basement has 93,611m² of building area. The color rendering and structural model of this project are shown in Figure 1 and Figure 2.

Foundation Design

Based on the site conditions, this project foundation adopted the drill pour piles with pressure cement mortar. The pile bearing capacities were tested by static vertical

工程概况

中钢天津国际广场位于天津市滨海新区响螺湾商务区滨河南路、滨河西路、坨场北道、滨河路所围成的地块内，占地26,666m²，总建筑面积395181m²，由T1、T2两座塔楼、3层裙房及4层扩大地下室组成。T1地面以上高102.9m，24层，建筑面积65130m²；T2地面以上高358m，83层，标准层平面53m×53m，高宽比6.88，建筑面积225370m²。T2主体结构由型钢混凝土核心筒与六边形外网筒构成。建筑效果及整体结构模型如图1、2所示。

基础设计

根据场地土质条件及施工条件，基础采用后压浆钻孔灌注桩。T1塔楼桩径Φ1000，桩长L=25m，单桩竖向承载力特征值Ra=5000KN。T2塔楼桩径Φ1200，桩长L=54m，桩端置于○9A层粉砂层，单桩竖向承载力特征值Ra=11000KN。扩大地下室及上部局部3层裙房的桩径Φ800mm，桩长L=22m，单桩竖向承载力特征值Ra=2450KN，单桩抗拔承载力特征值Ua=1700KN。

结构构成

T2采用筒中筒结构体系，外网筒由国内外

Figure 1. Sino Steel International Plaza.
图1. 中钢天津国际广场

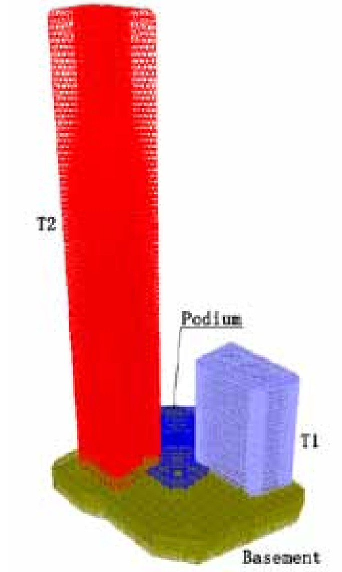


Figure 2. Whole Structural 3D Model .
图2. 整体结构三维模型图

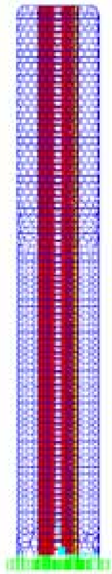


Figure 3. Main structure of T2.
图3. T2整体结构构成示意图

loading on site. The piles of the podium, T1, are 800mm, 1000mm, 1200mm, in diameter and 22 meters, 25 meters and 54 meters in length, respectively. Their bearing capacities are 2450 KN (1700 kN for uplift), 5000 kN, and 11,000 kN, respectively.

Structural Framing of T2

The main structure of T2 is composed of an S.R.C. core and an innovative exterior hexagonal grid net tube, as shown in Figure 3. The typical composite floor structure of T2 is shown in Figure 4.

Exterior Tube: The lower part of exterior tube is the innovative hexagonal grid net structure, with inclined-column adopting rectangular concrete-filled steel pipe and steel pipe. The upper part of the exterior tube is a diagonal grid structure with rectangular steel pipe. The transition zone between lower and upper part adopts abnormal grids with rectangular steel pipe. All the horizontal beams in the exterior tube adopt rectangular steel pipe. In order to satisfy the architectural requirement for the irregular position of openings, the exterior tube from stories one to four and the basement are composed of a concrete-filled steel pipe frame with diagonal bracings. They are shown in Figure 5 and Figure 6.

首创的六边形网格构成，如图3所示。标准层平面布置图如图4所示。

外网筒：外网筒下部由矩形钢管混凝土或钢管构成六边形网格，上部由矩形钢管构成菱形网格；中部由矩形钢管构成异形网格过渡，水平梁均采用矩形钢管，如图5所示。其中钢管混凝土斜柱分布如图8红色所示。为满足建筑不规则开洞要求，底部1-4层由钢管混凝土斜柱及钢管横梁构成。钢管混凝土斜柱进入地下室转为直柱，柱间设400mm厚钢筋混凝土剪力墙，如图6所示。

楼盖：采用型钢梁、混凝土楼板组合楼盖体系，型钢梁两端铰接，顶面设栓钉。标准层楼板厚100~120mm，设备层楼板厚150mm。高度600mm型钢梁腹板开六边形孔，由高度494mm型钢梁经切割拼接形成，同时允许设备管线穿过，以提高建筑净高。

结构设计关键技术

六边形网格结构工作性能研究

六边形网格结构节点刚接是保证六边形结构正常工作，不成为可变机构的关键。

竖向荷载作用：六边形网格结构在竖向荷载作用下产生较大的下沉变形及一定量级的侧向变形，主要来源于斜柱弯曲剪切变形的

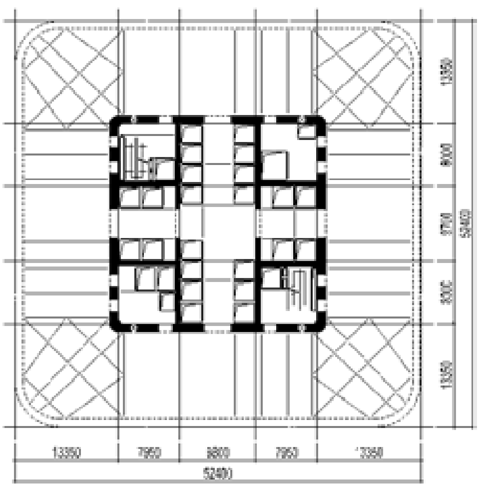


Figure 4. The typical standard floor structure of T2.
图4. T2标准层平面图

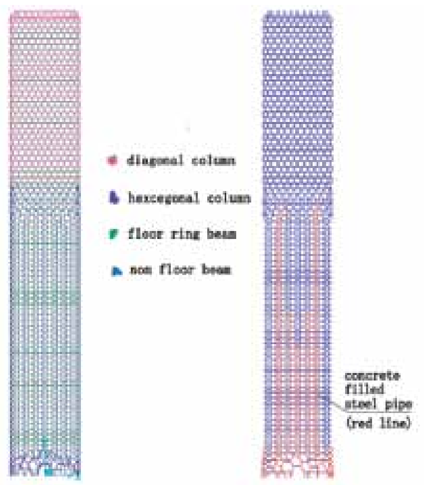


Figure 5. Exterior Tube.
图5. 外网筒构成示意

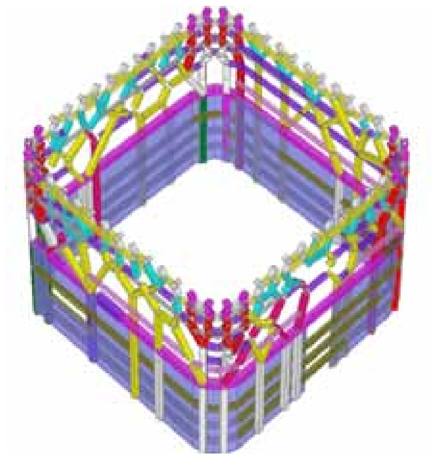


Figure 6. Bottom of Exterior Tube
图6. 底部构成

Floor: It is a composite structure with steel beam and R.C. slab. Pin joints are designed at both ends of the steel beam, and the concrete slab is connected to the steel beams by studs. The thickness of the slab typically varies from 100mm to 120mm, whereas 150mm was used for MEP floors. The 600mm high web of steel beam has hexagonal openings and is cut from rolled steel beam with the height of 494mm, the openings can allow the equipment pipelines to get through so as to increase the clear height of the building.

Key Techniques of T2 Structural Design

Exploration of the Characteristics of Hexagonal Grid Structure

Rigid joint connection of hexagonal grid structure is the key to ensure the structure overall stability.

Effect Under Vertical Loading. Hexagonal grid structure has a relatively large deflection under vertical loads due to the contribution of bending moments and shear in inclined columns, so the structural stiffness is weak in the vertical direction. The relative displacement of two ends of an inclined column results in a contraflexure point occurring in the member, and the resultant bending moments in the ends are basically self-balanced. The main structural internal forces are ends' bending moments and shear forces in the inclined column, where the bending stress is approximately 60-70% of total stress, as shown in Figure 7 and Figure 8.

Effect Under Horizontal Loading. The inclined columns and horizontal beams can work together very well under horizontal loading as shown in Figure 9, and its drift has the features of shear-bending. The lateral stiffness is more than a normal frame structure. Along with the increase of horizontal loads, the horizontal beams could be designed to arrive yield point firstly. Then the hexagonal grid structure becomes multi-span and a multi-story hinged frame with folded columns. Until the bottom of the inclined columns reach yield, which means enhancing the bottom zones to be necessary similar to shear-wall structure.

Solution. The pin connection of floor steel beam is the reasonable material which could accommodate the differential deformation between the core and exterior tube. Not using outriggers is a good choice too, which could reduce the moment upon the exterior tube under horizontal loading and raise the efficiency and safety of the whole structure.

Weakness of Hexagonal Grid Horizontal Beams Sections

Horizontal beams of hexagonal grid structure have lower stress levels

贡献，结构竖向刚度较差。斜柱上、下端点相对线位移迫使每根斜柱发生反弯变形，产生的斜柱杆端弯矩基本自平衡，斜柱杆端弯矩和剪力上升为结构主要内力，斜柱弯曲应力占总应力的60－70%。如图7、8所示。

水平荷载作用：六边形网格结构斜柱、水平梁协同工作，如图9所示，呈现剪弯型变形特性，其抗侧刚度大于普通框架结构。随着水平荷载增大，可设计非楼面梁先进入屈服，随后楼面梁逐渐进入屈服，六边形网格结构逐步退化为多跨多层折线柱排架结构，直至网格结构斜柱根部进入屈服，类似剪力墙结构，需设底部加强区。

小结：内外筒楼面钢梁两端铰接，且不设置伸臂，可适应内外筒的竖向变形差及其变化，同时减小水平荷载下外筒承受的倾覆弯矩，提高结构安全性和有效性。

六边形网格横梁截面弱化

六边形网格横梁在重力荷载作用下应力水平较低，水平荷载下应力水平较高，且以受弯为主，与高层建筑剪力墙连梁工作状态十分相近。适当弱化横梁截面，在保证结构重力荷载作用下正常工

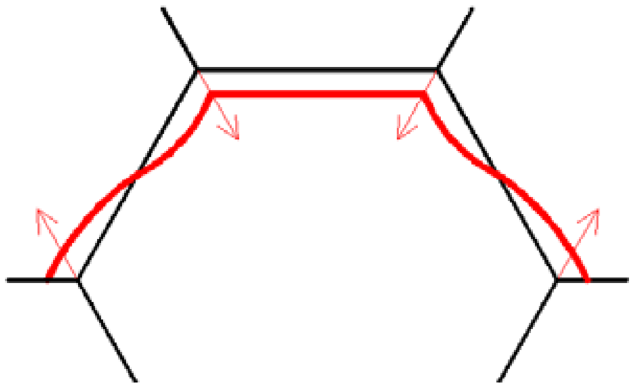


Figure 7. Deformation under Vertical Loading
图7. 竖向荷载下六边形网格变形图

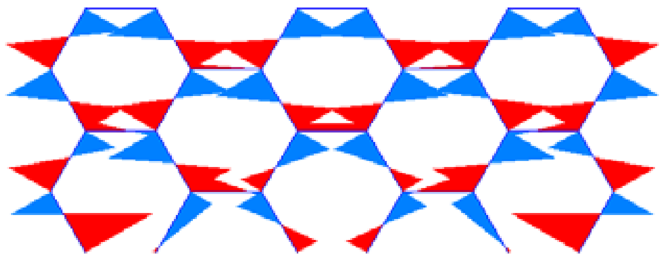


Figure 8. Moment under Vertical Loading
图8. 竖向荷载下六边形网格结构弯矩图

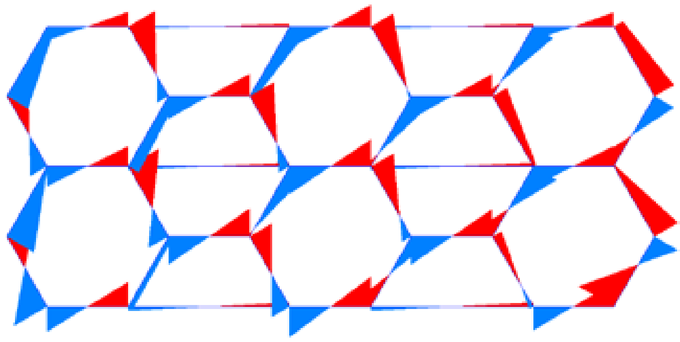


Figure 9. Moment under Horizontal Loading
图9. 水平荷载下六边形网格结构弯矩图

under vertical load and higher stress levels under horizontal load from bending moments. They are very similar to the working conditions of link beams in shear walls. Proper weakness of horizontal beam sections will be beneficial for them to enter bending yield first under maximum earthquake, to provide better ductility for the whole structure, to avoid progressive collapse and achieve certain economic benefit too.

Adjustment of Inclined Angles of Slant Columns of Hexagonal Grid Structure

Without affecting the windows of the building elevation, when the angle α of the inclined columns of a hexagonal grid structure is reduced, the height of sections of columns will also be reduced. It is required that the section will still be within the original structural scope line in satisfaction of architectural requirement. Refer to the sketch Figure 10.

Straightening inclined columns will reduce the geometrical length of columns and the horizontal arm of force under vertical load action as well as the bending moment. Therefore it reduces vertical deformation from bending moments under vertical loading and increases the vertical stiffness of the structure. With the decrease of the angle, the sectional area and inertia of slanted columns reduces and its axial force increases. But with the decrease of bending moment and bending stress in inclined column, the total stress of inclined columns will not be changed.

Considering the anti-shear action of the web of the exterior tube, the center-zone inclined columns will keep their original angle of 30 degrees, four corner columns will be changed from 30 degrees to 19 degrees to raise vertical stiffness of the four corners, therefore the lateral stiffness and anti-collapse capacity of the integral structure are improved.

Strong Joint-Weak Member Ductility Design

As mentioned above, the maximum bending moment always occurs at the corner of a slanted column under gravity and horizontal loads. The maximum bending stress will change to zero at the middle of the column.

Based on this fact, the equal section slant column is changed to varied section as shown Figure 11, where the section in the joint zone (1/3 member length) is strengthened, and the section in the mid zone (1/3 member length) is weakened.

CABR(China Academy of Building Research) carried out the joint test (scale 1:5).

It is found that from test results and Ansys FEM analysis, with the loading increasing, the end of the mid zone will yield and be destroyed first. The idea of strong joint-weak member is realized and the ductility is ensured, meanwhile the material is utilized efficiently.

Effective Stiffness of Steel Beam Studs in Hexagonal Exterior Tube

The horizontal floor ring beams in the hexagonal exterior tube are subject to tension and compression alternately, which will result in tensile and compressive stresses in the connected floor slab.

Studs are used for the shear connection between floor slabs and the exterior tube steel ring beams. Because of the deformation of studs and the surrounding concrete, the shear stiffness of studs will be limited, and the hypothesis of rigid connection between steel beam and floor slab will be not correct.

Considering the limited shear rigidity of the studs, floor tensile stress under load design combination will be decreased and the maximum tension stress will be reduced from 5MPa to 2.3MPa. Meanwhile, the tension stress of the ring beams shall be increased to a maximum value

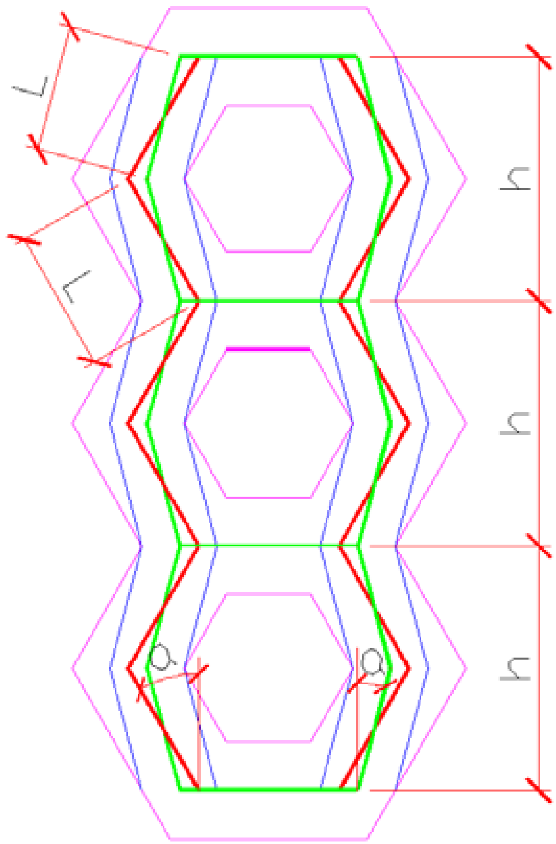


Figure 10. Straightening up inclined columns
图10. 斜柱扶直示意

作同时，有利于横梁在大震下首先进入弯曲屈服，为结构提供较好延性，有利于整体结构抗震及抗连续倒塌，且具有经济效益。

研究表明，六边形网格横梁截面为斜柱截面的30%～80%时，可保证六边形网格结构在重力、水平荷载下正常工作。

六边形斜柱倾角减小

不影响建筑立面开窗，六边形斜柱倾斜角度α减小，斜柱截面高度随之减小，可使之仍处在原结构范围线之内，满足建筑立面要求，如图10所示：

斜柱扶直减小斜柱的几何长度，减小竖向荷载作用下的水平力臂及斜柱杆端弯矩，从而减小斜柱弯曲变形及其总竖向变形，提高结构竖向刚度。随着斜柱倾斜角度的减小，斜柱截面面积和截面惯性矩减小，轴力增大，轴向应力略有增大；同时斜柱弯矩减小，弯曲应力有所减小，斜柱总应力水平基本持平。

考虑发挥外框筒腹板抗剪作用，中部斜柱不扶直，仅扶直角部斜柱，提高角部斜柱的竖向刚度，提高整体结构抗侧刚度和抗倾覆能力。本工程角部斜柱倾斜角度由30度扶直至19度后，角部结构竖向刚度有所提高，整体结构平动周期、竖向周期和扭转周期均略有减小。

强节点弱构件延性设计

由六边形网格结构受力特性分析可知，重力荷载、水平荷载作用下均为斜柱转折处弯矩最大，应力水平最高，该弯曲应力沿杆长衰减很快，杆件中部弯曲应力为零。

据此，设计将等截面斜柱改为不等截面，节点区1/3杆长的杆件翼缘加厚，腹板适当减薄，杆件中部1/3杆长的杆件截面翼缘、腹板减薄，同时翼缘厚度大于腹板厚度。如下图11所示。

中国建筑科学研究院进行了1：5节点试验。

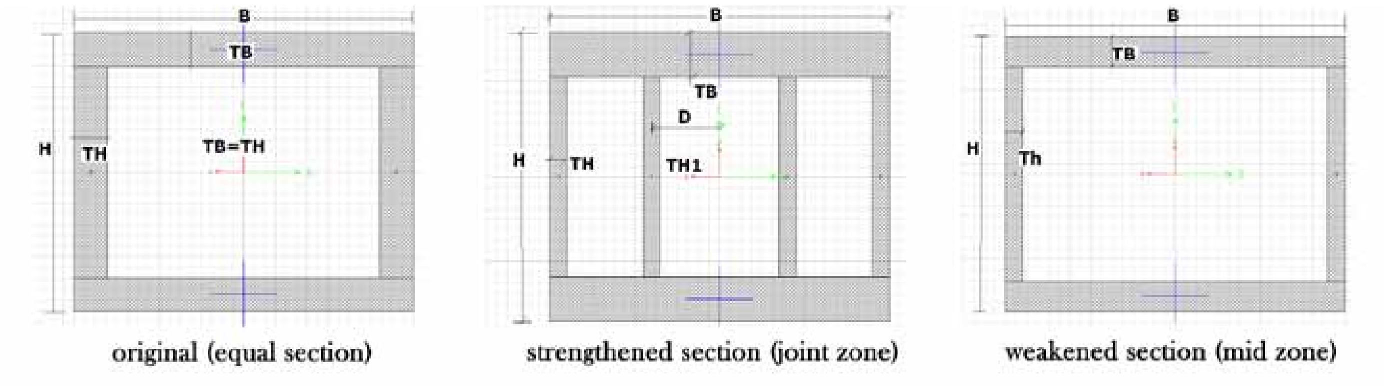


Figure 11. The section of slant column
图11. 设计改进前后截面示意图

of about 100MPa. These results are very helpful for steel beam and slab design.

Adoption of Special Construction Measures

Under horizontal loading, the inclined columns in corner zones will resist greater bending moment, shear force and axial force than those in the middle zone. Therefore, the stiffness and section of inclined columns in corner zones should be greater than the middle zones. As a result, part of gravity loads in the middle zone will move to the corner zone. As the section of corner inclined columns is increased, the more gravity loads will be absorbed; this vicious circle makes corner inclined column design very difficult and complicated, shown in Figure 12(a).

The structural self-weight holds up to 54% of the total gravity load. Adoption of special construction measures could cut the shifting path of the middle zone structure self-weight to the corner zone, which will dramatically improve the condition of corner structure and increase safety and economy of the integral structure.

Construction Measure 1. From Figure 12(b), it could be seen that there are bending moments and shear forces of floor horizontal steel beams, under structural self-weight in the construction stage. Taking construction measure 1– releasing these beams in construction, the transfer route will be cut, the middle zone structure will take their structural self-weight by themselves. These loads will go down directly. After completion of the main structure, these beams will be connected to the main structure.

试验及节点ANSYS有限元分析表明，荷载逐渐增大，中间1/3杆长区端部应力水平发展较快，先屈服，其后该区域塑性应变发展较快，最终先破坏。改进设计延性发展较充分，杆件应力应变高于节点应力应变水平，节点核心区未先破坏，实现了强节点弱构件的设计理念，保证了结构延性发育，钢材获得充分利用。

楼面钢梁栓钉的有效刚度引入

重力荷载下六边形网格结构楼面钢环梁拉压交错，与之相连楼板亦拉压交错。

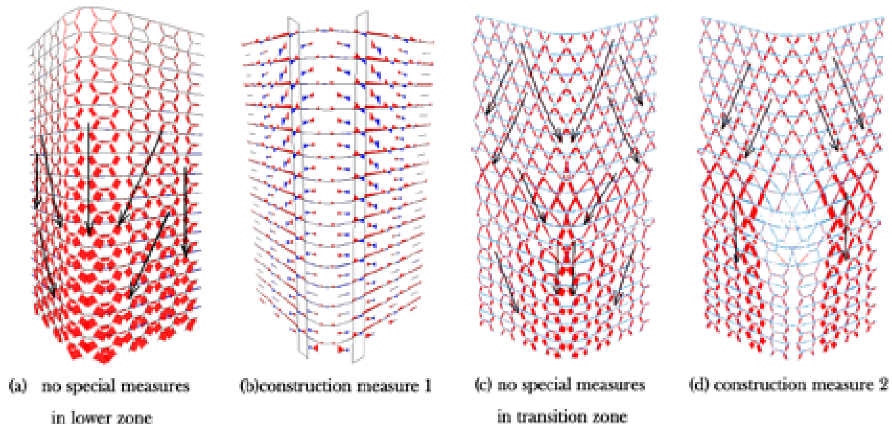
楼板与钢环梁之间通过栓钉剪切连接，栓钉剪切刚度有限，栓钉及其周围混凝土变形，将使楼板与钢梁的受剪连接成为有限刚度连接，楼板受力及其刚度贡献均会有所退化。

考虑栓钉有限剪切刚度，重力荷载设计组合下楼板拉应力退化，最大拉应力2.3MPa，环梁拉应力增加，最大拉应力达100MPa。整体结构模态、性能指标基本没有变化。

施工措施改善六边形网格结构重力荷载下受力性能

六边形网筒结构角部斜柱与中部斜柱截面相同时，重力荷载可以分别直接向下传递。水平荷载作用下，角部斜柱受力大于中部斜柱，角部斜柱截面需增大以满足结构设计承载力的需要。此时由于六边形网格结构节点刚接，角部斜柱截面大，将导致部分中部重力荷载向角部转移，重力荷载传力不直接，角部斜柱负担加重，如图12（a）所示。角部斜柱截面继续增大，重力荷载将转移更多，形成恶性循环，角部斜柱截面设计较为困难。

本工程外筒承担结构自重占其承担的总重力荷载54%，采取施工措施，设法让中部结构自重自承担，不让其向六边形网格角部斜柱转 。



(a) 不采取施工措施 下部结构轴力 | (b) 施工措施 1 释放连接梁弯矩、剪力 | (c)不采取施工措施 中部结构轴力 | (d)施工措施 2 释放角部八根斜柱

Figure 12. Special Construction Measures
图12. 专门施工措施

	Period 周期	Participation factor of Mass 质量参与系数							
	Sec	UX	UY	UZ	SumUX	SumUY	SumUZ	RZ	SumRZ
1	5.982	0.009	0.558	0	0.009	0. 558	0	0	0
2	5.946	0.555	0.01	0	0.564	0. 568	0	0	0
3	1.872	0	0	0	0.564	0. 568	0	0. 741	0. 741
9	0.629	0	0	0.504	0.863	0. 867	0. 504	0	0. 854
16	0.338	0	0	0.058	0.919	0. 923	0. 746	0	0. 894

Table 1. Main Modes of T2.
表1. T2模态分析结果

	d_{max}/h		Δ / H	
	X direction X方向	Y direction Y方向	X direction X方向	Y direction Y方向
Wind load from (China Code) 规范风荷载	1/911	1/1012	1/1287	1/1397
Wind load from (Wind tunnel test RWDI) RWDI风洞试验结果	1/1126	1/1230	1/1536	1/1688
Mild earthquake(China Code) 小震作用	1/515	1/505	1/726	1/718

Table 2. Maximum story drift ratio.
表2. T2各工况下最大层间位移角

Direction 工况	base shear 基底剪力		Ratio of base shear to total gravity(%) 剪重比（%）	
	Qx (KN)	Qx (KN)	X direction X方向	Y direction Y方向
X	88995	1034	3.06	
Y	1029	88594		3. 04

Table 3. Ratio of base shear to total gravity under mild earthquake spectrum of china code.
表3. T2小震作用下剪重比

Earthquake level 地震烈度水准			Mild 小震	Design 中震	Maximum 大震
Exterior hexagonal grid tube 外筒水平构件	Floor ring beam 楼面环梁		Elastic 弹性	Not yield 不屈服	Partially into plastic state 部分进入塑性
	Non floor beam 非楼面横梁				
	Inclined column 斜柱	1-4 Story 底部1-4层		Elastic 弹性	Elastic 弹性
		Conner zone 5-49 story 上部角部		Elastic 弹性	Elastic 弹性
		Middle zone 5-49 story 上部中部		Not yield 不屈服	Not yield 不屈服
Exterior diagonal grid tube 外筒菱形交叉斜柱	Inclined column of 50-83 story 50-83层的斜柱			Not yield 不屈服	Small amount into plastic state 少量进入塑性
Core 内筒	External wall 外墙			Bending Not yield 抗弯 不屈服	Steel plates: elastic Other : Partially into plastic state 钢板剪力墙内钢板弹性 其他混凝土墙体部分进入塑性
				Shear elastic 抗剪 弹性	
	Internal wall 内墙			Not yield 不屈服	Not yield 不屈服
Link beam 内筒连梁				Small amount into plastic state 少量进入塑性	Partially into plastic state 部分进入塑性

Table 4. Structural performance of T2 under the combined earthquake action.
表4. T2各类型构件抗震性能目标

Construction Measure 2. From Figure 12(c), it could be seen that because the corner column section is larger than those in middle zone, the part of self-weight of the middle zone above 30 stories of the diagonal net structure will still be transferred to the corner slant columns of the lower hexagonal grid tube. Taking construction measure 2– not joining the eight slanted columns at each corner on top of the transitional zone in construction, the self-weight of the upper diagonal net structure will only be transferred to the lower middle zone of the hexagonal grid tube, as shown in Figure 12(d). After completion of the main structure, the eight slanted columns at each corner will be connected to the main structure.

施工措施1：主体结构施工期间，释放连接下部六边形角部斜柱的楼面水平钢梁（图12(b)中圈示部位）的杆端弯矩及剪力，就可切断六边形网格中部结构自重向角部斜柱转移的路径，中部六边形网格区域结构自重自承担，不向角部转移，主体结构生成后，将此横梁与主体结构节点外伸短梁焊接连接。

施工措施2：由于六边形网格角部斜柱截面大于中部斜柱截面，上部30层菱形交叉网格结构中部自重仍将被部分转移至下部六边形网格角部斜柱，如图12(c)所示。主体结构施工期间，不连接过渡区顶层每个角部8根斜柱，上部交叉网格结构自重只能向中部六边形斜柱传递，可进一步减轻角部斜柱负担，如图12(d)所示，主体结构生成后，将此斜柱与主体结构节点外伸短管焊接连接。

Structural Performance of T2

The main structural performances of T2 are shown in Tables 1–4.

Summary: The stress of exterior tubes is less than 0.7fy (fy is steel design strength) under gravity; less than 0.75fy under the combination of gravity and wind; less than 0.8fy under the combination of gravity, wind and mild earthquake.

T2整体结构性能

T2主要结构性能如表1-4所示。

外筒重力荷载设计组合下应力水平低于0.6～0.7；风荷载设计组合下应力水平低于.75；小震反应谱设计组合下，竖向构件应力水平低于0.8。

Conclusions

Sino Steel (Tianjin) International Plaza has the first worldwide application of a hexagonal structure as its exterior tube of this super high-rise building. Elastic and plastic dynamic analysis shows that this project can achieve good seismic performance. Three invention patents have been applied for in the China Patent Bureau.

结语

六边形网格结构在中钢天津响螺湾国际广场工程中的创新研究应用，为实现天津市“蜂巢”地标性建筑做出了成功探索，已在中国专利局申报了三项发明专利，罕遇地震下动力弹塑性分析表明，该工程能达到设定的抗震性能目标。

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