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Design of Flexible Hanging Curtain Wall Support Structures
柔性悬挂幕墙的支撑结构设计

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Abstract

The 126-story, 632-meter tall Shanghai Tower is sited in Shanghai's Lujiazui Finance and Trade Zone, with a structural height of 580 meters. It will be the landmark of Shanghai once completed. The tower has a unique design with a "double-skin" curtain wall system. A unique hanging curtain wall support structure (CWSS) was developed to suit the building's significant appearance and transparent visual requirements. In order to ensure the successful construction and service of this curtain wall system, several key problems were focused upon in the design process. In this paper, these key problems will be introduced, such as: analysis and control of deformation of the CWSS with the elastic boundary conditions, and analysis of the special complex slipping connection.

Keywords: Shanghai Tower, Curtain Wall Support Structure, Hanging Structure, Interaction, Slipping Joint

摘要

上海中心大厦位于陆家嘴金融区总高度632m，结构高度580m，共126层。建成后将成为上海的地标性建筑。该工程的幕墙设计采用了独特的双层幕墙系统。 为适应建筑的重要的外观及通透的视觉要求，上海中心外幕墙支撑结构体系采用了独特的柔性悬挂体系。为保证外幕墙系统的顺利施工与维护，设计过程中对弹性边界条件下幕墙支撑结构的变形分析与控制，特殊复杂滑动节点分析等数个关键问题在设计过程中进行了重点研究，本文也将进行相关介绍。

关键词：上海中心大厦、幕墙支撑结构、悬挂结构、相互作用、滑动节点

Project Information

The Shanghai Center Tower is 632 meters tall, with a structural height of 580 meters and a total of 126 stories. It will be the tallest building in China and the second tallest building in the world. The inner tower is circular in plan and divided into nine zones by the refuge floors and mechanical floors. In each zone, the inner tower is a cylinder, consisting of 12–15 stories. The cylinders decrease in diameter at each higher zone.

The tower has a unique design with an inner and outer "double-skin" curtain wall system, an interior skin that follows the edge of the typical circular floor slabs, an outer exterior curtain wall which is a triangular, slightly convex, shape in plan with rounded corners resembling a guitar pick. This outer exterior curtain wall twists and tapers around the inner cylindrical building in each floor from the bottom to the top, which causes separations between the inner cylindrical wall and the outer exterior wall within the space. The varying gap between the skins defines huge atrium spaces extending vertically, varying from 12 stories to 15 stories in height. The whole outer exterior curtain wall, with 120 degrees twist from the bottom to the top, creates a twisting and tapering architectural

建筑概况

上海中心为632米高的超高层塔楼，结构高度580米，共126层，将成为中国第一、世界第二高的超高层建筑。内塔楼楼面为圆形，沿高度由避难层和设备层将整个塔楼分隔为九个功能区，每个区由12~15个楼层形成圆柱型内塔的功能区，随着高度上升，分区楼面直径逐渐变小。

该项目的幕墙设计了非常独特的双层幕墙系统，其内幕墙沿着楼板边界呈圆柱形布置。外幕墙平面形状呈一三边鼓曲、三角倒角的等边三角形，酷似吉他拨片；在高度方向，绕着圆柱体楼面逐层旋转、收缩向上。由此导致内外幕墙空间上分离，每个区在内外幕墙之间形成宽度变化并向上延伸的12~15层高流线形中庭空间。整个外幕墙，从底到顶经过120度的旋转上升，创造了形态柔和、螺旋上升的椎体建筑形态，赋予了整个塔楼一个非常独特标志性的造型和外部立面（Poon, et al 2010）。（请见图1）

由于外幕墙与主体结构距离远、建筑造型独特且悬挂在超高层建筑上，为幕墙支撑结构的设计提出了非常大的挑战。该幕墙支撑结构需为外幕墙提供坚实的支撑，将外幕墙重力荷载和水平荷载传递到主体结构上，需做到传力路径直接、造型美观、视觉阻碍小。

Figure 1. Rendering of Shanghai Tower (Source: Gensler)
图1. 上海中心大厦效果图（出自Gensler）

form and gives the tower an unique significant appearance (Poon, et al 2010) (see Figure 1).

Because of the unique architectural style of the exterior curtain walls that are typically far away from the main structure suspended in supertall buildings, there comes a very big challenge for the design of the curtain wall supporting structure. The curtain wall support structure (CWSS) needs to provide solid support for the exterior curtain wall to transfer the curtain wall gravity loads and horizontal loads to the main structure, which must transfer the load path directly, have an attractive appearance, and provide transparent visual requirements.

Introduction of the Curtain Wall Support Structure System

The Shanghai Tower curtain wall system is divided into nine zones from bottom to top. The hanging flexible curtain support structure system in zone 2 to zone 8 is the standard structural layout for exterior curtain walls of the Shanghai Tower.

The Shanghai Tower standard curtain wall support system is the spiral structure system, consisting of the hoop ring pipes (356 mm diameter) and radial struts (219 mm diameter) as well as high-strength hanger rods (80–60 mm diameter). Hoop ring pipes along the vertical direction are set every 4.3 to 4.5 meters to fix the curtain plates and convert the loads suffered by the curtain wall (see Figure 2).

The Hoop ring pipes are connected by 25 vertical hanger rods between the adjacent two levels of the Hoop ring pipes in the vertical direction. The gravity of curtain plates and CWSS is transferred up through the hanger rods, and finally suspended in the hanging beam in the mechanical floor at the top of CWSS. The hanging beam transfers hanging gravity to the radial beam through the two ring beams, and finally transfers the gravity to the radial truss through the hanging columns (see Figure 3). The gravity of the curtain wall and CWSS will be transferred to the main structure by the hanging system.

A typical CWSS in plan (see Figure 4) is shown with a horizontal radial strut that is set along the periphery hoop ring pipe every 8–10 meters to transfer the horizontal loads of the curtain walls to the tower interior

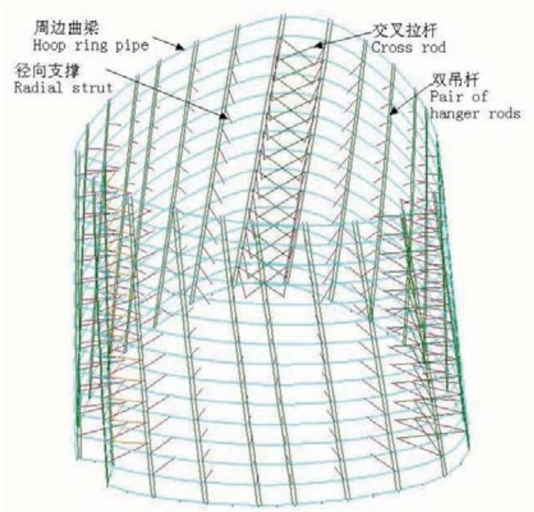

Figure 2. Curtain wall support structure system (Source: TJAD)
图2. 幕墙支撑结构体系（出自TJAD）

幕墙支撑结构的体系构成

上海中心大厦外幕墙系统从下到上共分9个区段，其中，2~8区的悬挂式柔性幕墙支撑结构体系，为上海中心大厦外幕墙的标准结构形式。

上海中心大厦外幕墙标准幕墙支撑结构体系为由水平周边曲梁（直径356mm钢管）和径向水平钢管支撑（直径219mm的钢管）以及高强拉杆（直径80mm~60mm）组成的螺旋上升的结构体系。周边曲梁沿竖向每4.3~4.5米布置用以固定幕墙板块并同时起到转换幕墙所受荷载的作用（请见图2）。

在竖直方向上，相邻两层水平曲梁间用沿曲梁布置的25组竖向吊杆连接，幕墙板块及幕墙支撑结构的重力通过吊杆向上传递，并最终悬吊在幕墙支撑结构顶部的机电层吊挂梁。吊挂梁通过两道环向梁将吊挂重力转换至径向梁，并最终通过径向梁上的吊柱将重力传递至径向桁架，（请见图3）。幕墙及幕墙支撑结构的重力即通过该悬挂体系传递至主体结构。

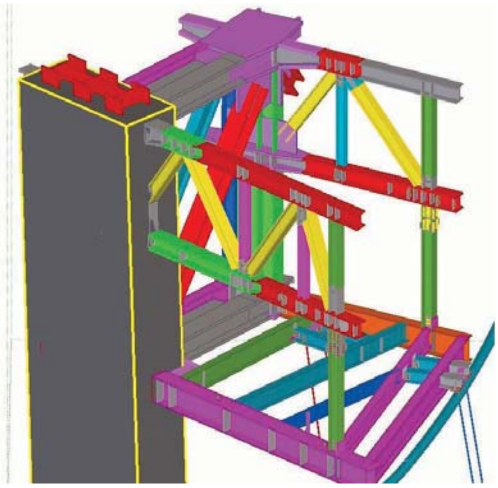

Figure 3. Hanging structure system above the Curtain wall (Source: TJAD)
图3. 幕墙结构顶部吊挂体系（出自TJAD）

典型的幕墙支撑结构平面结构布置（请见图4）， 沿周边曲梁每8至10米设置一道水平径向支撑，用以传递外幕墙的水平荷载至塔楼内部楼板。与楼板边梁的连接采用铰接以允许外幕墙与楼板分开上下活动，并减小拉杆竖向运动引起的径向水平支撑弯矩。

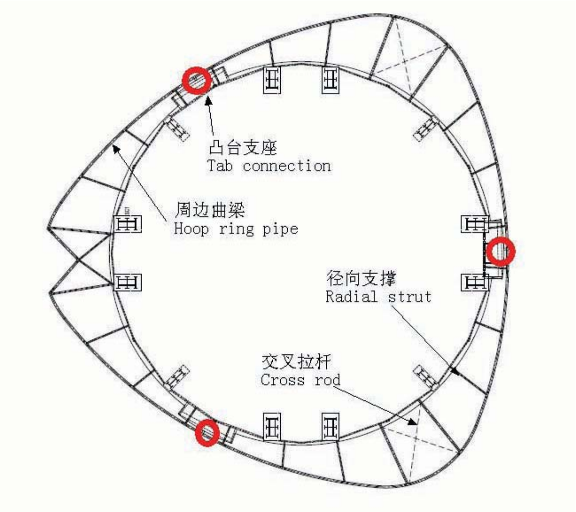

Figure 4. Curtain wall support structure in plan (Source: TJAD)
图4。幕墙支撑结构平面布置（出自TJAD）

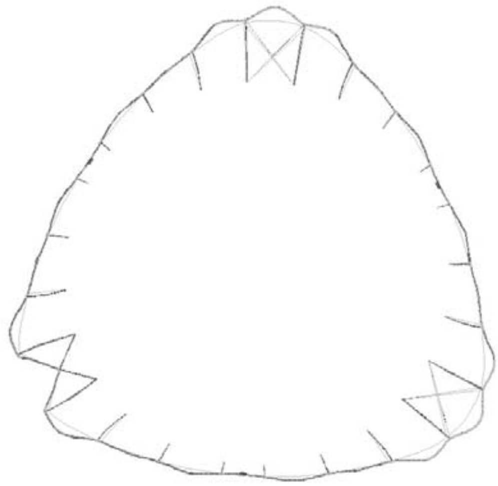

Figure 5. Deformation under temperature effect (Source: TJAD)
图5。温度作用下典型层变形图（出自TJAD）

floors. Connection to the slab edge beam is hinged to allow the exterior curtain walls moving up and down separately to the floors, and reduce moments where the radial strut causes vertical movement of the rods.

The hoop ring pipes at the bottom of each zone are set using vertical bushing (see figure 11) and embedded in the slab of the amenity floor through the pole. This connection provides lateral support to the hoop ring pipes, while allowing the structure to maintain a certain range of vertical deformation and rotation. The CWSS can move relatively independently within the main structure of the tower. In order to prevent a net pressure formed in the rods, the first level hoop ring pipes, located above the amenity floor, are filled with concrete. This can provide sufficient weight to keep tension in the rods, and avoid instability.

Since the entire exterior curtain wall system rises with a geometric rotation, the structural system has a rotation trend around the main structure under its own weight. To resist the torsion effect of the curtain wall system, three tab connections are arranged at the position of hoop ring pipe tangent with the cylinder floor in each level.

Structure Analysis

The Shanghai tower CWSS can be divided into the horizontal loads transmission system and the vertical loads transmission system. The former is a rigid structure system, which consists of the ring pipes and the radial strut being influenced by the horizontal loads and temperature effects, the latter is a flexible structure system which consist of the rods being affected by the gravity loads and vertical earthquake movement.

Analysis of the Horizontal Loads Transmission System

Temperature Effect

The Hoop ring pipe is a closed ring structure, and relatively sensitive to the effects of temperature. Though the expansion joint in the ring beam can reduce the thermal stress effectively, there are other problems that should be considered. Examples include: the weakening of structural integrity, reducing the capacity of structure to resist torsion, complicated joint details, higher cost, difficulties in construction positioning, concentrated temperature deformation being difficult to absorb for curtain plates, wind-induced vibration, and

每区最下方的周边曲梁上设置竖向轴衬，并通过立杆嵌入配套层楼板中（请见图11）。这样的连接方式为周边曲梁提供了侧向支撑，同时允许结构保持在一定范围内的竖向变形和转动。使得幕墙系统在塔楼主体结构内可以相对独立的活动。为了防止吊杆出现净压力，位于配套层以上第一道水平周边曲梁内灌混凝土，以保证其有足够的重量使吊杆保持受拉，从而避免吊杆失稳。

由于整个外幕墙体系以几何形态扭转上升，使该类结构体系在自重作用下即存在绕主结构扭转的趋势，为抵抗幕墙体系的扭转作用，在每层水平曲梁与圆柱体楼面相切的位置布置了三个限位约束。

结构分析

上海中心幕墙支撑结构体系可以分为水平传力体系和竖向传力体系，水平传力体系为由环梁及径向支撑组成的刚性体系，主要受水平向荷载及温度作用的影响，竖向传力体系主要为吊杆形成的柔性体系，主要受重力荷载及竖向地震作用影响。

水平传力体系分析

温度作用

由于环梁是个闭环结构，因此对温度作用相对比较敏感，虽然在环梁中设置伸缩缝可有效的降低环梁因温度作用所引起的温度应力，但是由于采用温度伸缩节点消弱了结构的整体性，降低了结构的抗扭性能，且存在施工定位困难、集中的温度变形使幕墙板块难以承受、节点构造复杂、造价高、风振等问题。因此，最终的幕墙支撑结构取消了大部分楼层环梁的伸缩节点，仅在每区的最低层环梁保留了部分伸缩节点，以避免幕墙支撑结构从主体结构分开单独活动（Hu，2011）。

结构设计考虑±30° C的温差，以升温为例，在温度作用下，曲环梁倾向向外伸展与膨胀，曲率越大，向外变形的趋势越明显（请见图5）。因此，于典型层的环梁和径向支撑结构，在三个角部受力较大，径向支撑限制环梁向外膨胀因此产生较大的轴力，而环梁主要为在平面内的弯矩和轴力。

水平向荷载-风荷载，水平地震作用

幕墙支撑结构的承载力设计采用基于重现期为 100年的风荷载，结构位移计算采用基于重现期为50年的风荷载。幕墙结构的风荷载由RWDI 公司（Rowan Williams Davies & Irwin Inc）提供。数据是根据回归周期为100 年的风速（Vg = 50 m/s），针对不同区域（2~8区）以及三段不同的水平周边曲梁给出的（请见图6

many others. Therefore, most of the expansion joints in the CWSS are essentially cancelled. Only a part of expansion joints at the hoop ring pipe located on the lowest level in each zone were retained, in order to avoid the CWSS moving separately from the main structure (Hu, 2011).

The structure is designed to consider the temperature range of ±30°C. In this case, when the hoop ring pipes are warming, they tend to expand outward and bulge. The greater the curvature, the more the outward deformation's trend is more obvious (see Figure 5). Therefore, the hoop ring pipe and the radial strut in the three corners allows for more stress within a typical level. The radial strut limits the expansion of the ring beam when its under greater axial force to itself, while the hoop ring pipes mainly sustain the moment in plan and axial force.

Horizontal Loads-Wind Loads, Horizontal Earthquake Action
Bearing capacity design of the CWSS is based on the 100-year return period wind load and structural displacement calculated using the 50-year return period wind load. The wind loads are supported by RWDI (Rowan, Williams, Davies & Irwin, Inc.). The data is given in the return period of 100 years of wind speed (Vg = 50 m/s), for different zones (zone 2 to zone 8) as well as three different horizontal hoop ring pipes (see Figure 6). Four different load conditions were considered based on each horizontal hoop ring pipes, uniform pressure, uniform suction, and two kinds of unbalanced wind loads. At each section, the combination of internal pressure and load conditions above act on the horizontal ring pipes (RWDI, 2009).

The horizontal seismic activity on the CWSS is calculated by the equivalent lateral force method which is based on the non-structural components of the Code for seismic design of buildings (GB 50011-2001). Horizontal seismic activity calculated by a small earthquake response spectrum, adjusts the horizontal seismic shear weight ratio to 40% (Thornton Tomasetti Inc., 2009).

In the horizontal load transmission system, the hoop ring pipes is mainly responsible for the horizontal moment; the radial strut is mainly responsible for the axial force. But its value is less than the internal forces caused by temperature. The horizontal load transmission system design is generally controlled by the temperature effect.

Analysis of the Vertical Loads Transmission System

Adopting a unique flexible hanging curtain wall support structure brings a very big challenge to the structural design. Because of the hanging structure, the interaction between the curtain wall and the main structure is very significant. On the one hand, hanging structure makes the curtain wall structure very sensitive on the boundary conditions. Just as the "foundation" of the CWSS, stiffness characteristics of the main tower structure greatly influence the mechanical characteristics of CWSS. On the other hand, the CWSS has brought some unprecedented new problems to the main structure's design. The interaction between them should be considered in the design procedure of the main structure. Considering the interaction between the CWSS and the main structure, many aspects of the design will be introduced as follows.

Gravity Loads
Under gravity loads, the CWSS takes on the axial force of the steel hanger rods. The biggest axial force of the hanger rods in each position is shown (see Figure 7). When the boundary for the separate curtain wall model is rigid, the load scope of each hanger rod is similar while the axial force of the hanger rods remains uniform. Take zone 2, for example, it has the biggest axial force of each position is between 600–750kN. But, when modeling with the main structure as a whole

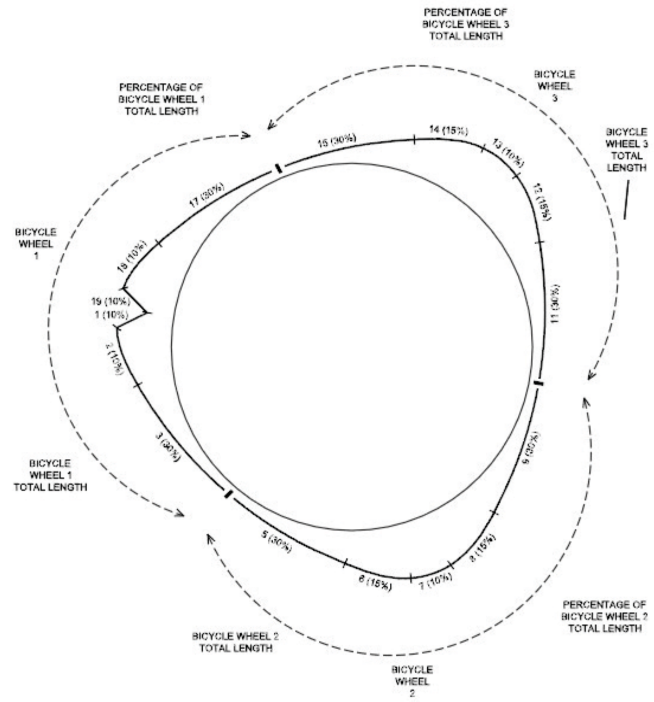

Figure 6. Wind load distribution (Source: RWDI)
图6。风荷载分布（出自RWDI）

）。针对每个水平周边曲梁提供了4种不同的工况：均布压力、均布吸力与两种不平衡风力（RWDI，2009）。

在幕墙支撑结构的水平地震作用根据《建筑抗震设计规范》（GB 50011-2001）有关非结构构件的规定采用等效侧力法计算。水平地震作用按小震反应谱计算，实际的调整后的水平地震剪重比达至40%（Thornton Tomasetti Inc.， 2009）。

水平传力体系在水平向荷载作用下，环梁主要承担水平向的弯矩，径向支撑主要承担轴力。但其数值均小于因温度作用引起的内力。水平传力体系的设计一般由温度作用支配。

竖向传力体系分析

上海中心大厦的幕墙支撑结构由于采用独特的分区悬挂的柔性结构体系，给结构设计带来了非常大的挑战。悬挂式结构体系的采用使得幕墙与主体结构之间的相互作用非常显著。一方面，悬挂式的结构体系使得幕墙结构对于边界条件非常敏感。主体结构作为幕墙结构的"基础"，其刚度特性对于幕墙结构自身力学特性的影响非常大；另一方面，悬挂式的结构体系也给主体结构的设计带来了一些前所未有的新问题。考虑到幕墙支撑结构与主体结构之间的相互作用，以下将介绍有关的多方面设计。

重力荷载
幕墙支撑结构在重力荷载作用下，主要引起钢吊杆的轴力。各个位置吊杆的最大轴力图（请见图7），个吊杆的负荷范围是基本相似的，同时吊杆的轴力依然保持一致。以2区为例，各个位置吊杆的最大轴力大致在600~750KN之间。当与塔楼模型整体建模，考虑到幕墙上方的设备与避难层时，吊杆的轴力不均匀性增强。与整体模型相比，在单独幕墙模型中的吊杆轴力增加近85%。分析结果表明，吊杆轴力受悬挂结构的刚度影响很大，设计中应多加注意。

结构动态特性. 当考虑了塔楼设备的层刚性时，幕墙支撑结构的竖向振动特性需有一定程度的改变（请见表1，图8）。

从图表可以看出，幕墙结构在整体模型与单独模型中的前几阶主要振动形式均为竖向振动。且主要振动位置均为环梁曲率较大位

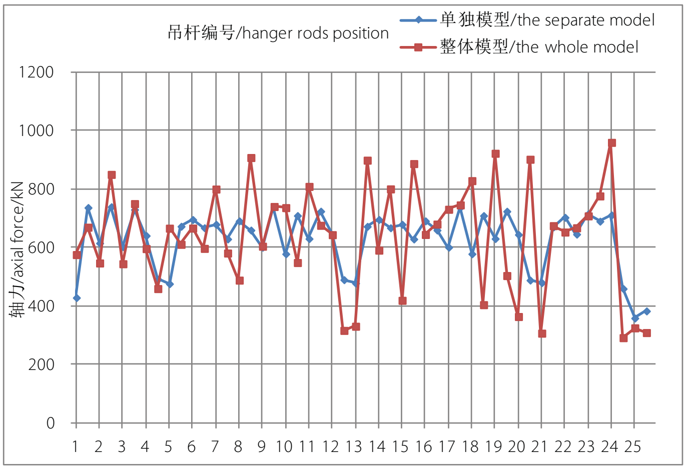

Figure 7. Distribution of axial force in hanger rods (Source: TJAD)
图7. 吊杆轴力分布图（出自TJAD）

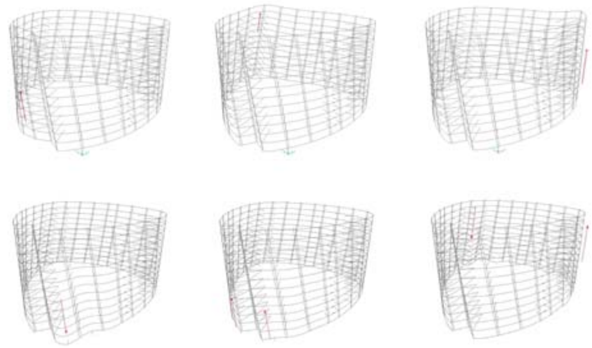

Figure 8. Mode shapes of CWSS. Top three are the first three order mode shapes of the whole model. Bottom three are the first three order mode shapes of the separate model (Source: TJAD)
图8。振型图，上部依次是整体模型前三阶振型，下部依次是单独模型前三阶振型（出自TJAD）

with consideration to the stiffness of the upper mechanical and refuge floor, non-uniformity of the axial force is enhanced. Upon comparing this to the whole model, the axial force of the hanger rods in the separate curtain wall model increases nearly 85%. These results show that the axial force of the rods significantly influence by stiffness of hanging structure – more attention should be paid to this during the design phase.

Structural dynamic performance. Considering the stiffness of the upper mechanical and refuge floor, the Vertical vibration of the CWSS would need to be changed to some extent (see Table 1 & Figure 8).

We can see from the table and figure, in both the separate model and the whole model of the curtain wall, the first few orders of the main vibrations are those of vertical vibrations. And the main vibration positions are positions of the ring pipe with larger curvatures; these are the three corners of the CWSS. Modeling with the main structure, where the hanging boundary of the CWSS is elasticity, the CWSS and cantilever trusses in mechanical and refuge floor will vertically vibrate; the vibration period of the whole model is significantly greater than the separate model.

The vibration modes of CWSS indicate weak vertical stiffness of CWSS. The whole model is weaker than the separate model. The time history analysis of the whole structure showed significant response of CWSS under vertical earthquake movement in the higher zone.

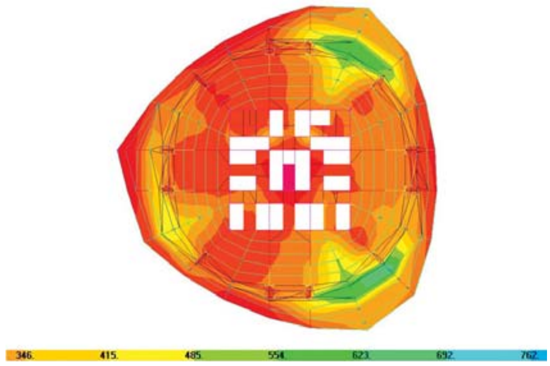

Figure 9. Distribution of tension force in floor (Source: TJAD)
图9。楼板拉力分布图（KN/m）（出自TJAD）

置，即幕墙支撑结构的三个角部；幕墙与主体结构建模时，在幕墙的吊挂边界为弹性边界，幕墙与设备层外伸桁架竖向振动；整体模型振动周期均显著大于单独模型。

幕墙支撑结构的振动模式反应出幕墙结构的竖向刚度较弱，整体模型较单独模型更弱。整体结构的时程分析也表明，位于高区的幕墙支撑结构对竖向地震作用反应显著。

设备层楼面应力分析与设备层楼面结构设计

在幕墙支撑结构的重力荷载作用下，每个分区的幕墙支撑结构是

	Period 周期	The Cwss + The Main Structure 幕墙+主体结构	Vibration Characteristic 振动特征	The Separate Curtain Wall Model 幕墙单独模型	Vibration Characteristic 振动特征
	T1	0.589	Vertical Vibration 竖向振动	0.314	Vertical Vibration 竖向振动
	T2	.533	Vertical Vibration 竖向振动	.313	Vertical Vibration 竖向振动
	T3	.518	Vertical Vibration 竖向振动	.307	Vertical Vibration 竖向振动
Vibration Modes 振型	T4	.505		.304	Vertical and horizontal coupled 竖向，水平耦合
	T5	.479		.29	Vertical and horizontal coupled 竖向，水平耦合
	T6	.477		.286	Vertical and horizontal coupled 竖向，水平耦合
	T7	.475		.278	Vertical and horizontal coupled 竖向，水平耦合
	T8	.471		.272	

Table 1. Vibration modes of CWSS (zone 2)
表1. 幕墙振动模态信息（二区）

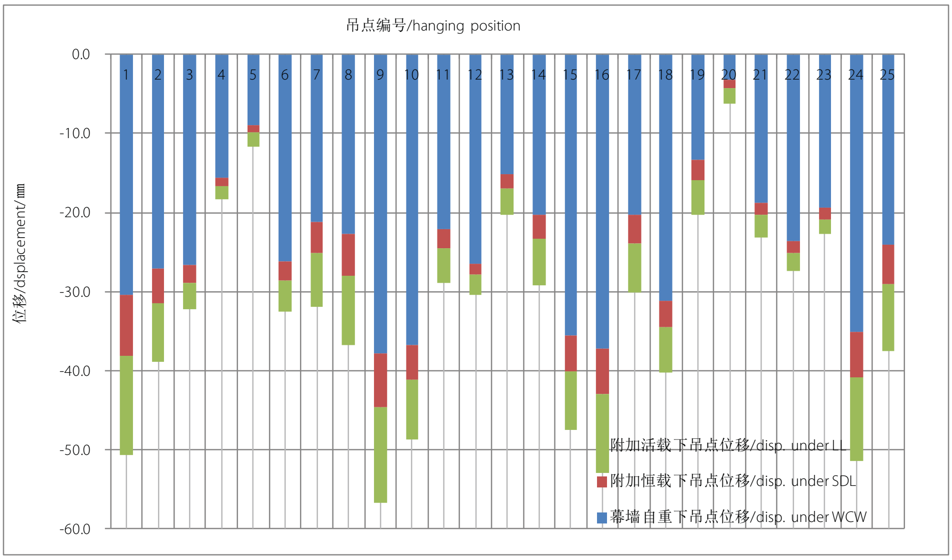

Figure 10. Total deformation of hanging position (Source: TJAD)
图10。吊点总变形（出自TJAD）

Stress Analysis And Structural Design Of The Mechanical Floors

The CWSS in each zone is hung on the mechanical floors by cantilever trusses, under the gravity load of CWSS. The up chord of a cantilever truss can withstand tension and drives the floor deformation which leads to the floor to produce tensile stress. The structural design should deal with the tension and avoid the floor from cracking in a service state. At the same time, it is necessary to ensure that the floor can provide a reasonable stiffness so that the curtain wall deformation is in a reasonable range. Under the load combination of 1.2D+1.4L, larger floor tension distribution would appear in three corners in the floor where the cantilever trusses are longer (see Figure 9).

The analysis result indicates that, the stiffness of refuge and mechanical floors has a great influence on the deformation of a curtain wall, and the cracking of floors in the corner of an amenity floor will increase the vertical non-uniform deformation of curtain wall by approximately 10mm. To avoid these negative impacts, the three corners with the higher stress have been reinforced by laid steel plate locally, which is effective to control the non-uniform deformation of CWSS.

Several Key Problems

Deformation Analysis

As the hanging stiffness of the mechanical floor is non-uniform, the deformation of CWSS under gravity loads is different in each hanger rod position. To ensure the construction and service is successful, a detailed analysis of vertical deformation is necessary. Details of Curtain wall plates should absorb the relative deformation between the adjacent rods of CWSS.

According to the actual construction procedure, the considered loads in the deformation analysis of CWSS include the loads which influence deformation of a curtain wall after installing the CWSS. The loads mainly have: (1) weight of curtain wall system (WCW), (2) superimposed dead loads (SDL), (3) live loads (LL).

According to the technical requirements from the curtain wall company, the relative deformation of adjacent hanger rods are less than 30mm. An adjustment to the floor beam system of the hanging floor had been carried out to achieve the deformation requirements.

The deformation of a hanging position after adjustment is listed (see

通过悬挑桁架悬挂在设备层上。悬挑桁架上弦将承受拉力，并带动楼板变形从而使楼板产生拉应力。结构设计应对妥善处理该拉力，以避免在正常使用状况下出现楼板破裂，并同时保证楼板能提供合理的刚度使幕墙在合理的范围内变形。在1.2D+1.4L荷载组合下，在楼面三个角部桁架悬挑较大的部位出现较大的楼板拉力分布（请见图9）。

分析表明，设备与避难层楼板刚度对于幕墙变形有较大影响，配套层角部区域的楼板拉裂后会增大幕墙竖向不均匀变形约10mm。为避免该不利影响，在应力较大的三个角部区域,局部铺设钢板，可有效控制幕墙支撑结构的不均变形。

几个关键问题的处理

变形分析

当设备层吊挂刚度不均匀，幕墙支撑结构在重力荷载作用下的各个吊杆位置的变形也不尽相同。为保证幕墙板块的顺利施工与正常使用，需要对幕墙支撑结构的竖向变形情况进行详细分析，幕墙板块的节点应能承受幕墙支撑结构的相邻吊杆之间的相关变形。

根据实际的施工过程，幕墙变形分析需要考虑的荷载包括所有在幕墙支撑结构安装后会对幕墙变形产生影响的荷载，这些荷载主要有：（1）幕墙自重：幕墙支承体系自身重量。（2）叠加恒载（3）活载。

根据幕墙公司提供的技术要求，幕墙板块悬挂要求相邻组吊杆间的变形差不大于30mm。根据以上要求，对幕墙悬挂层的楼面梁系进行了相关调整，以使其达到变形要求。

（请见图10）为调整后幕墙吊挂位置的变形值，从图中可以看出，幕墙吊挂点的变形主要受幕墙自重的影响，叠加荷载恒载对变形的影响最小。且在9，16，24等径向桁架悬挑最大的位置幕墙竖向变形最大。

分析结果表明，幕墙吊点的总变形不超过60mm。 幕墙自重下：相邻组吊点变形差不超过20mm，幕墙自重包括叠加垣载与活载下：相邻组吊点总变形差不超过30mm。 幕墙体系的一致性在3种荷载累积作用下满足相关技术要求。

特殊连接的处理

上海中心大厦幕墙支撑系统能够有效运作的前提是幕墙与主体塔楼能够在竖向相对自由变形，从而避免由于主体结构变形对幕墙

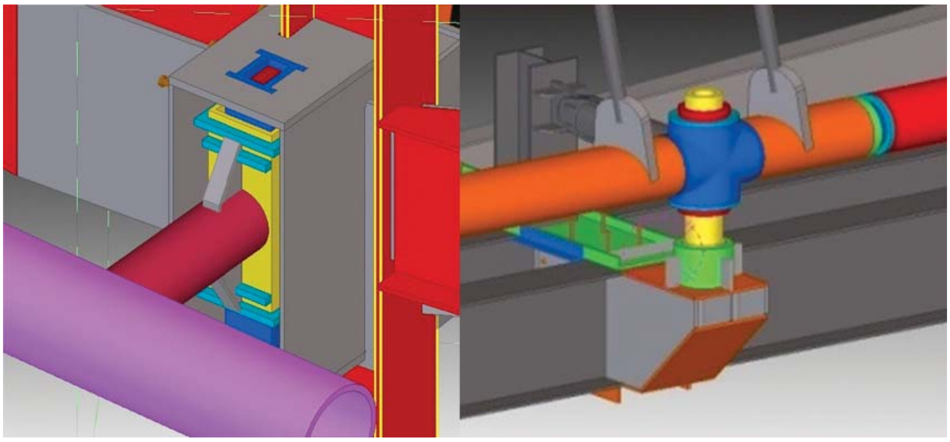

Figure 11. Slipping joints. the left side is inner end joint of short radial strut and the right side is vertical expansion joint of bottom ring pipe (Source: TJAD)
图11。幕墙滑动节点，左侧是短支撑内端节点，右侧是底环梁竖向伸缩节点（出自TJAD）

Figure 10), the maximum influence of deformation is the weight of the curtain wall system while the superimposed dead loads has minimum influence. The largest deformation occurs at the position where a radial cantilever truss is longer like 9,16, 24 and so on.

The analysis results show that the total deformation of a hanging position is less than 60mm. The relative deformation of an adjacent hanging position is less than 20mm under weight of the curtain wall system, and 30mm under weight of curtain wall system including the dead and live loads. The uniformity of the curtain wall under accumulation of three types of loads can meet technical requirements.

Treatment of Special Joints

Free relative deformation in the vertical direction of a curtain wall system and main structure is the premise of CWSS working effectively. It can avoid the additional effects brought on by the deformation of the main structure. Several types of slipping joints are used to ensure relative deformation. The two typical slipping joints are shown (see Figure 11).

Inner End Joint Of A Short Radial Strut

When a radial strut length is less than two meters, the joint is placed in the inner end of radial strut which can reduce the moment caused by vertical deformation of the radial strut and provide torsion and radial constraint to the hoop ring pipe.

Vertical Expansion Joint Of A Bottom Ring Pipe

The joint placed in the bottom ring pipe of each zone can absorb relative deformation between CWSS and main structure. Meanwhile, restraining horizontal movement and torsion of hoop ring pipe.

Design Difficulties of a Slipping Joint

- The pressure in bushes, which is generated by joint force, forms friction which can block the joint sliding. When the driving force of a structure is less than the friction, the joint may be self-locking.
- Relative deformation between the main structure and the hoop ring pipe of a CWSS is complex. And the allowable displacement of a slipping joint is difficult to determine.

支撑结构带来的附加影响。为保证幕墙与主体结构的相对自由变形，在上海中心大厦设计中采用了若干滑动的节点形式，较典型的有以下两类（请见图11）。

短支撑内端节点

当径向支撑长度小于2m时，于径向支撑内端设置接缝，用于降低因径向支撑的竖向变形所引起的弯矩，并对环梁提供径向和扭转约束。

底环梁竖向伸缩连接

设置于各区的底部环梁，用于约束环梁的水平活动及扭转，承受幕墙与主体结构间的相对变形。

滑动连接的设计难点

- 在轴衬的压力由连接力所产生，形成可阻碍连接滑动的摩阻力。当结构驱动力小于摩阻力时将使连接自锁不能滑动。
- 主体结构与幕墙支撑结构环梁间相对变形关系复杂，支座容许滑移量确定困难。

连接分析

滑动位移的确定

滑移连接应能容纳幕墙支撑结构与楼面在正常使用下的各种位移，如吊点的竖向变形、因温度和自重所引起的吊杆伸长、风荷载等；以及考虑幕墙支撑结构施工完成后塔楼收缩及徐变所构成的影响；同时尚需保证幕墙支撑结构在地震作用下达到一定的性能水准（中震弹性）。

综合考虑以上因素，幕墙支撑结构最终确定的短径向支撑内端的位移为向上80mm向下180mm。底环梁竖向伸缩连接的位移为向上80mm向下220mm。

滑动连接自锁的解决办法

为减低摩阻力及保证连接的正常滑动，对滑动连接进行了节点优化，采取的主要措施包括：（1）在轴衬内采用一对抗摩组件以减低摩阻力。（2）优化抗摩组件的设置位置降低法向压力。（3）优化在幕墙支撑结构的滑动连接的节点构造、数量、及设置位置，从而减少摩擦力。（4）在施工过程中释放内力，从而降低摩阻力。为保证滑动安全性，优化后所有连接的滑动安全系数均保持在2以上，即结构的驱动力均大于2倍的滑动连接摩阻力的2倍。

Joint Analysis

Determination Of Slipping Displacement

A slipping joint should be able to accommodate a variety of displacement between the CWSS and the floors in a service state such as vertical deformation of hanging positions, the extension of hanger rods under gravity and temperature effect, and wind loads. The influence of shrinkage and creep after completing construction of CWSS is also considered. At the same time, the certain performance (elastic under moderate earthquake) under the earthquake action should be met.

Considering the above factors, finally, the displacement of inner end joint of a short radial strut is 80 mm up and 180 mm down. The displacement of the vertical expansion joint of the bottom ring pipe is 80 mm up and 220 mm down.

Solution Of Self-Locking On A Slipping Joint

In order to reduce the friction and ensure slide of the joint, some measures are taken to optimize details of the slipping joint as follows: (1) Reducing the friction by adopting a pair of anti-friction components in bushes. (2) Reducing normal pressure by optimizing the position of anti-friction components. (3) Reducing the friction by optimizing details, quantities, and positions of slipping joints in CWSS. (4) Reducing the friction by releasing the internal force during the construction. After optimization, to ensure safety of slip, the Slipping safety factor of the joints is greater than 2. This means that the driving force is greater than 2 times the friction of the slipping joint.

Conclusion

The flexible hanging curtain wall support structure system (CWSS) of Shanghai Tower is a light, innovative, structure style. For usage of a flexible hanging system, the controls of the stiffness at hanging position should be paid attention to. Design specifications should be determined by analyzing the interaction between CWSS and the main structure using the whole model including CWSS and the main structure. At the same time, vertical deformation and special joint details should be analyzed heavily to ensure construction safety and service.

结论

上海中心大厦外幕墙采用的悬挂式柔性幕墙支撑结构是一种轻盈的新型结构形式。由于采用了柔性的悬挂体系应尤其注意其悬挂位置的刚度控制，并应对该类结构与主体结构进行整体建模，分析其相互作用来确定最终合理的设计指标。同时，应对幕墙支撑结构的竖向变形和特殊节点构造给予重点分析关注，以保证悬挂式幕墙体系的顺利安装与正常使用。

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