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New Type of Shear Wall and its Application in High-Rise Buildings

新型剪力墙及其在超高层建筑中的应用

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Abstract

The frame core tube structure is the main form of super high-rise building. The core tube wall bear large vertical gravity load, but also bear the wind load and horizontal seismic action. Although the compressive bearing capacity of the concrete wall is high, but the tensile and shear performance is low. In addition, the large thickness of the core tube wall will increase the weight of structure and earthquake effect; at the same time occupy more usable space.

In this paper, the stress behavior and structure of steel concrete shear wall, steel plate composite shear wall and steel plate shear wall were studied. Significant progress has been made in the steel reinforced concrete shear wall, composite steel plate shear wall and steel plate shear wall, the results has been successfully applied in Shenzhen Kingkey 100 building, the Olympic Tower, green space in Wangjing center, Tianjin international financial Conference Center projects.

Keywords: Steel Reinforced Concrete Shear Wall; Steel Plate Composite Shear Wall; Steel Plate Shear Wall; ,Research; Design

摘要

框架-核心筒是目前我国超高层建筑最主要的结构形式之一。核心筒剪力墙在承担巨大竖向重力荷载的同时，还承担大部分的风荷载与水平地震作用。虽然混凝土墙体受压承载力较高，但受拉、受剪性能较差。此外，核心筒墙体厚度大将导致结构自重与地震效应增大，占用有效的建筑使用空间。

本文对型钢混凝土剪力墙、钢板组合剪力墙以及钢板剪力墙的受力性能与结构构造进行了深入研究，在超厚型钢混凝土剪力墙、组合钢板剪力墙以及开洞钢板剪力墙等方面取得了重大进展，在深圳京基100大厦、奥运瞭望塔、绿地大望京中心、天津国际金融会议酒店等工程中得到成功应用，取得了很好的技术经济效果。

关键词: 型钢混凝土剪力墙; 钢板组合剪力墙; 钢板剪力墙; 研究; 设计

Introduction

With the rapid development of our economy and advancement of urbanization, super high-rise buildings have got rapid development in recent years. Shanghai Tower, Shenzhen Ping An Finance Center, Tianjin high silver financial 117 building are all over 600 meters. Because of the great height of super high-rise building, the high aspect ratio can reach above 7 to 8, which makes the lateral stiffness of structure small, determines the structure's characteristics of "high, narrow, soft", and leaves wind and earthquake as the main factors to be controlled in the designing and building process.

In the design of super high-rise building, how to fully guarantee strength and ductility of structural members is the basic premise of structural safety. By limiting the inter story drift, the lateral stiffness of the structure can be ensured, the cracking caused by wind and frequent earthquakes can be avoid, and the normal operation of the building can thus be guaranteed. While controlling the peak acceleration of the building under wind load,

概述

随着中国经济的快速发展与城市化进程的推进，近年来超高层建筑得到迅速发展，其中上海中心、深圳平安大厦、天津高银金融117大厦的建筑总高度均已超过600m。由于超高层建筑的高度很大，其高宽比一般可达7～8以上，结构侧向刚度小，呈现出"高、细、柔"的特点，风与地震成为主要控制因素。

在超高层建筑设计中，充分保证结构构件的强度与延性是结构安全性的基本前提。通过对结构层间位移的限制保证结构的侧向刚度，可以避免在风与多遇地震下混凝土构件开裂，保证设备正常运行。控制建筑在风荷载作用下的顶点加速度，可以保证建筑在使用期间人员的舒适性。如何增加结构的侧向刚度，并保证其具有足够的延性，是超高层建筑结构设计中需要解决的首要问题1。

对超高层建筑，重力荷载巨大，结构的重力荷载代表值可达数十万吨以上，竖向构件需要承担巨大的轴力。由于采光与使用功能的要求，超高层建筑一般将公共设

the degree of comfort of occupants can be secured. How to increase the lateral stiffness and ensure sufficient ductility of the structure is the primary problem to be solved in the design of super high-rise building (Fan et al. 2011).

Because the gravity load of super high-rise building is large, the representative value of the gravity load can reach hundreds of thousands of tons, vertical component to bear huge axial force. Due to lighting and functional requirements, generally high-rise building will have the public facilities, service rooms, elevator shafts located at the core region of the floor, where more convenient accessibility has and where the light would not be blocked by stairwells. . Core shear wall arrangement is usually combined with vertical shaft transportation and equipment room. In addition to bear large vertical loads, the core shear wall plays an important role in the resistance to wind and seismic. For the most common steel-concrete mixed structures in super high-rise buildings, core tube shear wall can bear about 50% of the total overturning moment, take more than 80% of the total base shear. Thus, as the main component to resist lateral force, shear wall has a very important role to ensure the safety of super high-rise building (Nie et al. 2013).

The concrete core tube is still the mainstream form because of the great stiffness, high seismic resistance, good fireproofing, high technology maturity, and the relative lower cost of the cast-on-site concrete shear wall.

Steel - concrete composite shear wall enjoys the merits of both steel structure and concrete structure, which means it can effectively increase the strength and ductility of the member, reduce the section size, and improve the fire performance. Thus, it has been used more and more in recent years in super high-rise building. How to secure the collaboration of steel structure and concrete structure while avoiding unnecessary duplicate or complicate construction process is the mean dilemma that needs to be carefully and appropriately handled.

The research of steel plate shear wall has attracted much attention in recent years, and has been applied in some major projects. Because the features of steel, high strength, good toughness, good energy dissipation capacity, light self-weight, have been given full play in steel plate shear wall, steel plate shear wall has excellent seismic performance. Component form of optimization of steel plate shear wall, fire protection and construction installation technology, and need to accumulate through the engineering practice.

Steel Reinforced Concrete Shear Wall

Characteristic of Steel Reinforced Concrete Shear Wall

Steel reinforced concrete shear wall is usually constructed with steel structure attached to both ends of concrete structure or with steel structure installed as the embedded brace while other parts formed by reinforced concrete wall. The collaboration of concrete structure and steel structure in steel reinforced concrete shear wall is ensured by the installation of shear key on the surface of the profile steel. Research on steel reinforced concrete shear wall is mainly concentrated in the aseismicity performance, to observe influence of the shear span ratio, axial compression ratio, concrete strength, steel configuration, concealed column constraints. Because the steel concrete composite members give full play to the advantages of steel and concrete, it has good deformation capacity and ductility. In the structural design of super high-rise building, the main effect of steel reinforced concrete shear wall is to enhance the seismic performance of the structure, reduce the section size of members, and increase the lateral stiffness

施、服务用房与楼电梯井道集中布置在楼层平面的中央区域，核心筒剪力墙通常结合竖向交通井道与设备用房空间布置，除可以承受很大的竖向荷载外，在抵抗风荷载和地震作用方面也发挥了巨大作用。对于目前在超高层建筑中最为普遍的钢-混凝土混合结构体系，核心筒剪力墙可承担总倾覆力矩的50%左右，承担基底总剪力的80%以上。由此可见，剪力墙作为最主要的抗侧力构件，对于保证超高层建筑的安全性具有非常重要作用2。

由于现浇混凝土剪力墙刚度大，抗震性能较好，防火性能好，施工技术成熟，造价较低，混凝土核心筒仍然是迄今为止超高层建筑中的基本结构形式。

钢-混凝土组合剪力墙同时具有钢构件与混凝土构件的优点，可有效增加构件的强度与延性，减小构件截面尺寸，防火性能好，近年来在超高层建筑中得到越来越多的应用。如何保证型钢与混凝土共同工作、避免结构构造与施工工艺过于复杂，是工程应用中需要妥善处理的问题。

钢板剪力墙的研究工作近年来受到高度重视，并开始在重大工程得到应用。钢板剪力墙充分发挥了钢材强度高、韧性好、耗能能力强、构件自重轻的特点，抗震性能优越。钢板剪力墙的构件形式的优化、防火与施工安装技术等还需要通过工程实践不断积累。

型钢-混凝土剪力墙

型钢-混凝土剪力墙的特点

型钢混凝土剪力墙通常是在混凝土墙体的端部设置型钢构件，其他仍为钢筋混凝土墙体，也可以在墙体中配置型钢作为埋入式斜撑。通过型钢表面设置的抗剪键保证钢与混凝土共同工作。型钢混凝土剪力墙的研究工作主要集中在抗震性能方面，考察剪跨比、轴压比、混凝土强度、型钢配置、暗柱约束等因素的影响。由于型钢混凝土组合构件充分发挥了钢与混凝土构件各自的优点，具有良好的变形能力及延性。在超高层建筑的结构设计中，型钢混凝土剪力墙的主要作用是增强结构的抗震性能，减小构件截面尺寸，增加结构的侧向刚度。在结构计算时，应通过调整构件折算弹性模量等方式，准确反映型钢的作用。与纯钢构件相比，型钢外侧包覆的混凝土墙板具有抗火、保温、隔音等作用。

在型钢混凝土剪力墙设计中，通常采用栓钉作为抗剪键。如何保证型钢与混凝土共同工作，简化钢筋的连接配筋构造，避免施工的复杂性，保证混凝土浇筑质量，仍是工程应用中需要解决的问题。型钢混凝土构件在抗震性能方面的优越表现，使其在超高层建筑领域得到了广泛的应用。

型钢混凝土剪力墙工程应用

深圳京基100大厦位于深圳市罗湖区蔡屋围金融中心区，总建筑面积约28万m2，塔楼地上高98层，地下4 层，结构总高度441m，是一幢以甲级写字楼为主，集公司银行业务交易、六星级豪华商务酒店及其它设施于一身的大型超高层建筑，见图1。该工程采用钢筋混凝土内筒、巨型方钢管混凝土外框柱+H型钢框架梁结构体系，设有5道腰桁架作为水平加强层，沿短向设有3道伸臂桁架，并在短向两侧设置巨型支撑，形成三重抗侧力体系。

深圳京基100大厦塔楼型钢混凝土剪力墙最大厚度达1.9m，设计时采用内置王字形钢骨，构造均衡合理，核心筒钢骨混凝土剪力墙配筋构造如图2所示。目前，我国规范尚未包括该类构件的设计方法，在设计中提出型钢混凝土剪力墙设计的基本原则如下:

1. 增加型钢的混凝土保护层厚度，在型钢表面设置栓钉，型钢与周边混凝土的共同工作，箍筋锚固于栓钉形成的

of the structure. Note that properly adjusting the equivalent modulus of elasticity component mode in structural calculation is tied to the accuracy of profile steel's role. Compared with pure steel structure, steel, covered by concrete, has the advantage of fire-proof, heat preservation and sound insulation.

Usually stud is used as the shear key in the design of steel reinforced concrete shear wall. However, how to ensure the joint work of steel and concrete, simplify the reinforcement connection, avoid the complexity of construction, and ensure the quality of concrete pouring are still fatal challenges in practical situations . Due to the excellent performance of steel reinforced concrete member under the seismic performance, it has been widely used in super high-rise building areas.

Engineering Application of Steel Reinforced Concrete Shear Wall

Shenzhen Kingkey 100 buildings located in the Caiweiwu financial center of Luohu District, the total area is about 280000 m^2, with 98 levels on ground and 4 levels underground, the total height of the building is 441 meters; it is a large high-rise building that combined with office space, bank, six star luxury Business Hotel and other facilities. The building is shown in Figure 1. The structural system of this project is composed of reinforced concrete tube, concrete frame giant square tubular column and H type steel frame beam. The building is equipped with 5 waist truss as horizontal strengthened story, 3 outrigger trusses along the short side, and mega braces to both end of the short side, thus form the three lateral force resisting system.

The maximum thickness of steel concrete shear wall in Shenzhen Kingkey 100 tower is 1.9 m, because of adopting the design of built-in Wang shaped steel reinforced, so that the structure is balanced. Figure 2 shows reinforcement structure of core tube steel reinforced concrete shear wall. At present, the design method of this wall is not yet included in the Chinese standard. The design principles of steel reinforced concrete shear wall are as follows:

1. Increase the thickness of protective layer of steel concrete, set studs on the surface of steel, steel and concrete work together, stirrup anchor on the restricted area formatted by steel stud, avoid setting a lot of holes in steel;
2. Considering the maximum thickness shear wall reaches 1.9 m, steel component is arranged in the end of components with wing wall, so the value of restrained edge member range, also consider the requirements of anchorage length of horizontal distributed reinforced;
3. Taking into account the role of steel, properly reduce the ratio of longitudinal reinforcement on the restrained edge member end;
4. Reinforcement ratio and structural measures of longitudinal reinforcement and stirrup follow "Technical specification for concrete structures of tall building" (JGJ3-2002) regulations.

In order to adapt the specific situations of the ultra-thick shear wall and the steel connection in the shear wall, three separated H type steel frame beams are adapted in the design.

In addition, the feasibility of steel component processing, transportation, installation, and reinforcing bar connection, concrete pouring quality control need to be taken into consideration.

钢骨约束区内，避免在钢骨上设置大量的钢筋孔;

2. 考虑到剪力墙最大厚度达到1.9m，且在构件端部与有翼墙的部位设置了钢骨构件，故对约束边缘构件范围的取值进行调整，但同时考虑满足水平分布钢筋锚固长度的要求;
3. 考虑到型钢的作用，对约束边缘构件端部的纵向钢筋配筋率适当减小;
4. 纵向钢筋与箍筋的配筋率及构造措施等遵循《高层建筑钢筋混凝土结构技术规程》(JGJ3-2002)的相关规定。

为了适应超厚剪力墙的具体情况，便于与剪力墙中的型钢相连接，设计时采用了三个分离式H型钢作为连梁的钢骨。

此外，还需要考虑型钢构件加工、运输与现场安装、与钢筋连接以及混凝土浇筑质量控制等方面的可实施性。

钢板组合剪力墙

钢板组合剪力墙的特点

钢板组合剪力墙是将钢板埋置在钢筋混凝土墙体中，通过在钢板表面设置的抗剪键保证钢与混凝土共同工作。常见的钢板组合剪力墙如图3所示。

由于在组合构件中混凝土对钢板提供了侧向支撑作用，避免钢板过早出现屈曲变形，可以充分发挥钢材的强度与变形能力，避免剪力墙刚度和承载力在罕遇地震作用时发生严重退化。与型钢混

Figure 1. Shenzhen Kingkey 100 building (Source: Zhong Fan)
图1 深圳京基100大厦

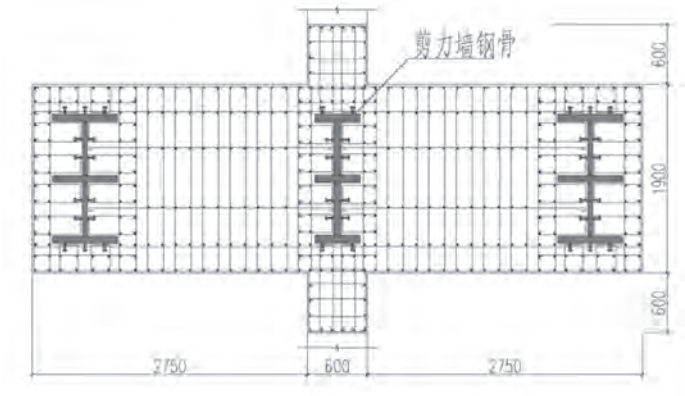

Figure 2. The structure of steel reinforced concrete shear wall (Source: Zhong Fan)
图2 型钢混凝土剪力墙配筋构造

Steel Plate Composite Shear Wall

Characteristic of Steel Plate Composite Shear Wall

Steel plate composite shear wall is a steel plate embedded in reinforced concrete wall, by setting shear key on the surface of the steel plate to guarantee the steel and concrete work together. The structure of common steel plate composite shear wall is shown in Figure 3.

The concrete provide lateral supporting for steel plate, which can avoid steel plate's premature buckling deformation, thus give full play to characteristic of steel plate. Meanwhile, it also can avoid serious degradation of stiffness and bearing capacity of shear wall under the rare earthquake. Similar to steel concrete shear wall, steel plate composite shear wall give full play to the advantages of steel and concrete, it has good ductility, good fireproof performance.

When compared with steel reinforced concrete shear wall, steel plates composite shear wall change discrete steel to continuous steel plate. The thickness of the steel plate shear wall is smaller; the strength of steel is higher than thick steel plate, thus effectively improve the utilization rate of the steel. In addition, with good out-of-plane stability, steel plate composite shear wall is not sensitive to the initial imperfection. The M-N curve of steel plate composite shear wall under eccentric tension, eccentricity is shown in Figure 4.

It should be noted that the rebar structure of steel plate composite shear wall is complex, meaning that the construction is difficult. In addition, due to the low early strength after the initial setting, concrete is easy to crack during construction because shrinkage deformation of concrete is constrained by steel plate.

Application of Composite Shear Wall

Greenland of Wangjing center is located in Beijing business district 1008-627 plots. The project includes a high-rise tower and a retail podium building, 5 floors underground, 55 on the ground floor, building height 260 m, total construction area of 172700 square meters. Tower adopts the frame - core tube structure, column with steel reinforced concrete, the framework uses H type steel beam, and between 42 and 43 layer has a two-story cantilever truss in order to enhance the lateral stiffness of the tower. Cast-in-place reinforced concrete - composite slabs with profiled steel sheet is used as floor Figure 5.

In order to resist tensile stress of shear wall under earthquake, setting shear wall in the following 6 layer height to improve the tensile properties of wall limb. Clearly put forward the construction requirements of shear wall in the design,and the steel plate shear wall test was carried out. The project achieved good effect by adopting improved concrete mixture ratio, strictly control the concrete component surface and internal temperature difference, careful construction, maintenance (Fan et al. 2012).

The Olympic Tower is located in the central area of the Olympic Park in Beijing, the main building adjacent to the landscape avenue. The viewing tower consists of 5 single towers, diameter and height of each tower is different, and the maximum height is 248 m. Each single tower is composed of cylindrical tower and the top crown shaped landscape platform. Because height span ratio of each single tower is large, so it cannot meet the requirements of wind resistance and seismic resistance. In order to enhance the integral lateral stiffness of the structure, set up four connected trusses between five single towers along the height direction, forming a combination of tower structure. The problem that Single tower height to width ratio is too large is

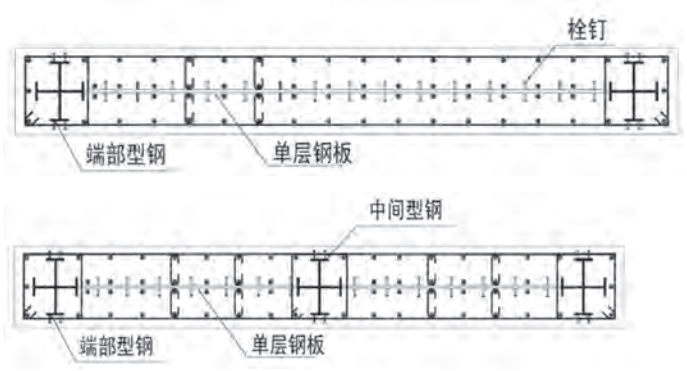

Figure 3. The structure of steel plate composite shear wall (Source: Zhong Fan)
图3 钢板组合剪力墙

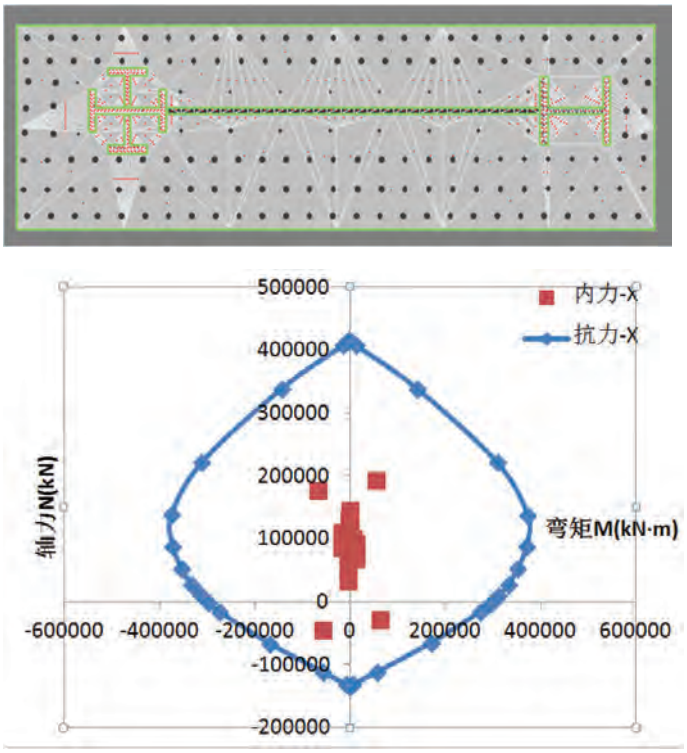

Figure 4. The computing of steel plate composite shear wall (Source: Zhong Fan)
图4 钢板组合剪力墙

凝土剪力墙类似，钢板组合剪力墙充分发挥了钢与混凝土构件各自的优点，具有良好的延性，防火性能优良。

与型钢混凝土剪力墙相比，由于将离散的型钢变化为连续的钢板，构件抗剪性能显著改善。钢板组合剪力墙钢板厚度较小，钢材强度高于钢板较厚的型钢，有效提高了钢材的利用率。此外，钢板组合剪力墙中的钢板面外稳定性好，对初始缺陷不敏感。钢板组合剪力墙墙肢在偏拉、偏压作用下的M-N曲线如图4所示。

但应该指出的是，钢板组合剪力墙钢筋配筋构造复杂，施工难度较大。此外，由于混凝土初凝后早期强度很低，混凝土收缩变形受到钢板的约束，施工期间混凝土容易出现裂缝。

型钢-混凝土组合剪力墙的工程应用

大望京绿地中心位于北京大望京商务区1008-627地块，项目功能包括一幢超高层塔楼和一幢零售商业裙房建筑，地下5层，地上55层，建筑高度260m，总建筑面积17.27万㎡。塔楼采用框架-核心筒结构体系，型钢混凝土柱、H型钢梁外框架，并在42至43层设有两层高的伸臂桁架以增强塔楼的侧向刚度。楼盖采用现浇钢筋混凝土-压型钢板组合楼板，如图5所示。

solved, greatly improving the capability of resisting overturning; meet the comfort requirements under wind load, so as to ensure that the structure meets the safety requirement under rare earthquake. The Olympic Tower is shown in Figure 6.

The structure of Olympic Tower is cylindrical shell system composed of concrete filled steel tubular column, H beam and cross support. For the convenience of setting hole in the wall, the structure change cross bracing to shear wall in the range of the entrance hall, thus greatly improve the fire prevention performance and increase the stiffness ratio of the lower and upper parts of the structure. Circular steel composite shear wall at the bottom of the Olympic Tower is shown in Figure 7, which is the first application of circular steel plate shear wall in engineering.

Steel Plate Shear Wall

Characteristic Steel Plate Shear Wall

Steel plate shear wall is a new type of lateral force resisting structures developed in twentieth Century; its main function is to provide the lateral stiffness, shear strength and ductility of the structure. Steel plate shear wall is composed of surrounding frames and embedded steel plate; it has the characteristics of light weight, convenient installation. Research shows that the characteristics of the steel, good ductility, energy dissipation capacity can be give full play by steel plate shear wall. The steel plate shear wall which has the characteristics of large lateral stiffness, good ductility, good seismic performance, is a super high-rise building resist lateral force component that has broad prospects for development.

The external stiffness of steel plate shear wall without reinforcement is very small, prone to buckling deformation, and may make sound. The installation of steel plate shear wall should be delayed, because the steel plate shear wall main subjected to horizontal shear force, and cannot assume the vertical pressure. But this will often conflict with the progress of construction and interior decoration; it is difficult to avoid bear part of gravity load. With the vertical stiffening rib, steel plate wall can avoid premature buckling deformation. There is a lack of theoretical analysis and experimental study of the vertical stiffening rib plate wall stress mechanism and design method at home and abroad. There are no specific regulations about how to set the vertical stiffening rib of the steel plate shear wall form and space.

The Steel Plate Shear Wall with Vertical Stiffener

In order to improve the stress performance of steel plate shear wall under the control of construction cost, a very practical way is to arrange stiffeners in plate. The main effect of stiffener is reflected in the following aspects:

1. To improve critical load of steel plate shear wall, delay the shear buckling, reduce the out of plane deformation and avoid the thrum of the steel plate buckling;
2. It improves the vertical buckling under critical loads providing a part of vertical bearing capacity of a steel plate shear wall and avoids the plate buckling during the installation while meeting the construction schedule;
3. It also improves the hysteretic behavior of a steel plate shear wall and overcomes the hysteretic curve "pinching" phenomenon of steel, and improves the ductility and energy dissipation ability of the component;

Figure 5. Steel plate composite shear wall (Source: Zhong Fan)
图5 钢板组合剪力墙

为了抵抗中震作用下核心筒剪力墙出现的拉应力，采用在6层高度以下设置钢板组合剪力墙的方式提高墙肢的受拉性能。在设计中明确提出了钢板组合剪力墙的施工要求，并进行了现场钢板组合剪力墙试验，采取改进混凝土配合比、严格控制混凝土构件表面与内部温差、精心进行施工养护等措施3。

奥运瞭望塔位于北京市奥林匹克公园中心区内，主体建筑紧邻中轴线景观大道。观景塔由5个直径与高低各不相同的单塔组成，最大高度约为248m。每个单塔均由圆柱状塔身与顶部树冠形的景观大厅与景观平台组成。由于每个单塔的高跨比很大，无法满足结构抗风与抗震要求。为了增强结构的整体侧向刚度，在五个单塔之间沿高度方向设置了四道连接桁架，形成组合塔式结构，解决了单个塔身高宽比过大问题，大大提高了结构的抗倾覆能力，满足风荷载作用下的舒适度要求，保证结构在罕遇地震作用下的安全性。连接桁架高度约3.0m，宽度约2.7m，并在主塔一侧设有加腋。连接桁架同时可以作为各塔之间的联络通道。奥运瞭望塔如图6所示。

Figure 6. The Olympic Tower (Source: Zhong Fan)
图6 位于北京奥运公园的奥运瞭望塔

Figure 7. Steel plate composite shear wall of Olympic Tower (Source: Zhong Fan)
图7 奥运瞭望塔底部的圆形钢板组合剪力墙

4. The steel plates prevent the tension area formed by acting directly on the frame column, thereby protecting columns from tensile failure;
5. Improves the lateral stiffness of steel plate shear walls, and controls the lateral deformation of high-rise building structures.

The optimal arrangement principles of stiffening rib can be in accordance with the "steel plate shear wall buckling does not precede yield" goal, also can follow the principal that "stiffened plate buckling stress is equal to the grid plate buckling stress".

In order to effectively play the role of stiffening rib stiffener, the relation of the bending stiffness and the thickness of steel plate need to controlled. The definition of the vertical stiffener rib stiffness ratio during the design as follows:

$$\gamma = \frac{EI_s}{D\mathrm{b}}$$

Where E is the elastic modulus of steel plate; D is stiffness of steel plate; I_s is the moment of inertia of single stiffener; b is the space of vertical stiffening rib; t is the thickness of steel plate; v is the Poisson's ratio.

$$D = \frac{Et^3}{12(1-v^2)}$$

Use single-layer single span frame with embedded steel plate shear wall as the analysis model. The pulling stress on the top and button of the steel frame beam are approximately balanced to the intermediate layer of the shear wall, so the frame beans can be regarded as a rigid rod, which means the compressional stiffness EA and flexural stiffness

奥运瞭望塔的塔身由钢管混凝土柱、H型钢梁与交叉支撑组成的筒壳体系。在入口大厅的范围内，将交叉支撑改为钢板组合剪力墙，便于在墙体上设置洞口，大大改善了室内钢结构的防火性能，有效增大了结构下部与上部的刚度比。奥运瞭望塔底部的圆形钢板组合剪力墙如图7所示，这也是圆形钢板组合剪力墙在工程中的首次应用。

钢板剪力墙

钢板剪力墙的特点

钢板剪力墙是20世纪70年代发展起来的一种新型抗侧力结构，其主要作用是提供结构的侧向刚度、抗剪强度和抗震延性。钢板剪力墙由周边框架和内嵌钢板组成，具有自重轻、安装方便等特点。研究表明，钢板剪力墙可以充分发挥钢材延展性好、耗能能力强的特点，结构侧向刚度大，构件延性性能好，具有出色的抗震性能，是一种具有广阔发展前景的超高层建筑抗侧力构件。

国外在工程中主要采用无加劲的钢板剪力墙，此类墙板面外刚度很小，容易发生屈曲变形，在使用过程中可能会发出响声。由于钢板剪力墙主要承受水平剪力，不承担竖向压力，在施工过程中需要滞后安装。但由于常常与施工进度及室内装修发生矛盾，难以避免承担部分结构重力荷载，采用带竖向加劲肋钢的板墙可以避免钢板过早出现屈曲变形。目前国内外对带有竖向加劲肋的钢板墙的受力机理与设计方法还缺乏系统的理论分析与试验研究。在我国现行结构设计规范中尚无对钢板剪力墙设计的具体规定，对钢板剪力墙设置竖向加劲肋的形式与间距等目前无具体规定。

带竖向加劲肋的钢板剪力墙

为在控制建造成本的前提下改善钢板墙的受力性能，在钢板上布置加劲肋是一种非常实用的方式。加劲肋的作用主要体现在以下几个方面:

EI are all infinite. To the frame column, when the size of sectional dimension is much larger than steel plate thickness, it's flexural stiffness can be considered infinite. The vertical stiffener use square shape formed by double channel, with a size of 120* 240 * 10. A comparison of the first shear buckling mode of 20 mm thick steel plate shear wall is shown in Figure 8. The buckling modes of steel plate wall under shear have great relation with the stiffness and space of the stiffener. When stiffness ratio of ribbed plate is about 30, the buckling mode of steel plate shear wall is that the plate and stiffener both reach buckling, and the buckling deformation of stiffener and plate is the same, then the deformation limit of shear buckling that vertical stiffening rib act on the steel plate is moderate.

In the design of steel plate shear wall, refer to the current "code for design of steel structures" GB50017 regulations about directly subjected to dynamic loads on the crane girder constructional stiffener, the maximum space of steel plate shear wall that have vertical stiffening rib is determined by:

$$\frac{b}{t_w} = 80\sqrt{\frac{235}{f_y}}$$

Where ***b*** is the net distance between the steel plate shear wall stiffener; is the thickness of stiffener; is the yield strength of steel.

Steel Plate Shear Wall with Opening

In order to meet the function requirements of open window, open hole, open channel and pipeline focus traversal, and the need to reduce its seismic effect by adjusting the shear stiffness in structural design, the proposed scheme is to use open hole steel plate shear wall as the main component to resist lateral force. Through numerical analysis and experimental study of open hole steel plate shear wall force mechanism, the main factors affecting the mechanical properties

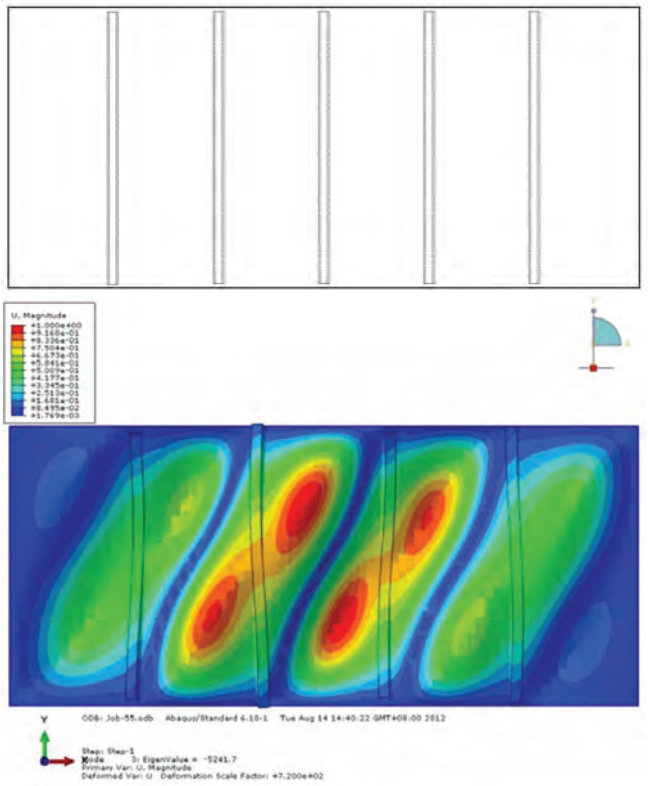

Figure 8. The steel plate shear wall with vertical stiffener; shear buckling model (Source: Zhong Fan)
图8 带竖向加劲肋钢板剪力墙的墙板; 钢板剪切屈曲模态

1. 提高钢板剪力墙的水平屈曲临界荷载，延缓剪切屈曲的发生，减小屈曲后钢板面外的变形量，避免钢板频繁弹性屈曲发出的响声;
2. 提高钢板剪力墙的竖向屈曲临界荷载，可以提供部分竖向承载能力，避免钢板在安装时出现屈曲，满足施工进度与实际需求;
3. 改善钢板剪力墙的滞回性能，克服无加劲肋时钢板滞回曲线的"捏拢"现象，提高构件的延性与耗能能力;
4. 防止钢板形成的拉力带直接作用在边框柱上，保护柱子不发生受拉破坏;
5. 提高钢板剪力墙的抗侧刚度，控制高层建筑结构的侧向变形。

加劲肋的最优布置原则可以按照"钢板剪力墙屈曲不先于屈服发生"的目标，也可以按照"加劲板屈曲应力等于各区格钢板屈曲应力"的目标。

为了有效发挥加劲肋的作用，需要控制加劲肋的抗弯刚度与钢板厚度的关系。在进行钢板剪力墙设计时，定义竖向加劲肋的肋板刚度比如下:

$$\gamma = \frac{EI_s}{D\mathrm{b}}$$

其中E为钢板的弹性模量; D为墙板的刚度，；为单个加劲肋的截面惯性矩; b为竖向加劲肋的间距。

$$D = \frac{Et^3}{12(1-\nu^2)}$$

分析模型采用单层单跨框架内嵌钢板剪力墙。对于中间层钢板墙，边框梁上、下所受到拉力近似平衡，故可以近似将边框梁近似视为刚性杆，即边框梁的抗压刚度 和抗弯刚度 均为无穷大。对于边框柱，当边框柱截面尺寸远大于钢板厚度时，其抗弯刚度可视为无穷大。竖向加劲肋采用双槽钢形成的"□"形截面，尺寸为□120×240×10。20mm厚的钢板剪力墙的抗剪一阶屈曲模态对比如图8所示。承受剪切作用的钢板墙的屈曲模态与加劲肋的刚度与间距关系很大，当肋板刚度比 为30左右时，屈曲模态为板件与加劲肋均发生屈曲变形，且加劲肋的屈曲变形量与板件基本相同，此时竖向加劲肋对钢板剪切屈曲变形的约束作用较为适中。

在钢板剪力墙设计时，参照我国现行《钢结构设计规范》GB50017对直接承受动力荷载吊车梁腹板设置构造加劲肋的规定4，钢板剪力墙设置竖向加劲肋的最大间距按下式确定:

$$\frac{b}{t_w} = 80\sqrt{\frac{235}{f_y}}$$

其中，b——钢板剪力墙加劲肋之间的净距， 为钢板的厚度， 为钢材的屈服强度。

开洞钢板剪力墙

针对工程实践中建筑要求满足开窗洞、开门洞、开通道与管线集中穿越等使用功能, 以及结构设计中通过调节剪力墙刚度来减小其地震作用的需要, 提出了采用开洞带肋钢板剪力墙作为抗侧力构件的方案。通过数值分析和试验研究对开洞钢板剪力墙的受力机理进行了研究, 对影响其力学性能的主要因素进行了探讨, 为该类结构构件的工程应用提供了参考5。

对于钢板墙开洞部位，上下层洞口之间的边框梁形成洞口连梁，其变形量集中，构件较早进入屈服状态。为了确保结构的侧向稳定性，在洞边有楼板一侧应设置水平侧向支撑梁。在首层与顶层，应尽量不设洞口连梁，或对其进行显著加强。

were discussed, it provides references to such kind of structural components of engineering application. (Nie et al. 2013)

The coupling beams between the upper and lower edge of an opening hole on a steel plate shear wall has a concentrated deformation. They will yield very early. To secure the lateral stability of the structure, horizontal lateral beams need to be set beside the opening hole on the floor side. It is better not to have coupling beams on the first floor or the top floor, unless they are significantly enhanced.

The stress state of coupling beam of steel plate shear wall with opening and reinforced concrete structure has a certain degree of similarity. Due to its concentrated stress and large deformation, it is the first line of defense in structure anti-seismic, thus playing a significant role in ensuring the structure ductility, as well as improving the energy dissipation performance. The design method and construction requirement for coupling beams is close to energy dissipation area of eccentrically braced steel frame beam. The axial force of steel plate shear wall coupling beam is small through calculation and analysis.

Coupling beams are identical in function and shape as the frame beams in a steel plate shear wall with the same span. However, they have quite different construction requirements. To minimize the bending stiffness of coupling beams, in addition to avoiding too large of a frame column section area, designers should consider narrowing the section area on purpose.

In the calculation of bearing capacity of coupling beams, a shear type calculation model element will be better, and avoid directly connects to the frame column. The ratio of free extended length of beam flange, b_1 and its thickness t_f should be consistent with equation below. In order to coordinate the width and frame beam of other steel plate shear wall, the flange near opening can be narrowed. The structure of steel shear wall with opening and Mises stress under horizontal force is shown in Figure 9.

$$b_1 / t_f \leq 8\sqrt{235/f_y}$$

Conclusion

Super high-rise building is an important direction of vertical city development in the future, application of new type of shear wall in super high-rise is of great significance to sustainable development of structure design. Application of steel concrete shear wall, steel plate composite shear wall and steel plate shear wall with vertical stiffener and with opening, greatly improve the seismic performance and efficiency of structure, also effectively increase the usable space.

开洞钢板剪力墙洞口连梁的受力形态与钢筋混凝土结构中的连梁具有一定的相似性。受力非常集中，变形量大，是结构抗震的第一道防线，对于保证结构延性、提高耗能性能具有重大作用。洞口连梁的设计方法和构造要求与偏心支撑钢框架的耗能梁段比较接近。通过计算分析可知，对于钢板剪力墙洞口连梁，轴力一般较小。

洞口连梁与同跨钢板剪力墙的边框梁为同一个构件，但其构造要求存在很大差异。为了使洞孔连梁弯刚度不致过大，在设计时可以考虑将其截面人为减窄，避免洞口边框柱截面尺寸过大。

洞口连梁承载力计算时，洞口连梁宜为剪切屈服型，避免与边框柱直接相连。洞口连梁翼缘的自由外伸长度与其厚度之比应符合下式。为了避免与其他钢板剪力墙边框梁宽度的协调性，可将洞口部位翼缘局部减窄。开洞钢板剪力墙的构造与水平力作用下的Mises应力如图9所示。

$$b_1 / t_f \leq 8\sqrt{235/f_y}$$

结语

超高层是未来垂直城市发展的重要方向，新型剪力墙技术在超高层中的应用对结构设计的可持续发展意义重大。钢混凝土剪力墙、组合钢板剪力墙以及带竖向加劲肋和开洞钢板剪力墙等新型剪力墙构件，结构抗震性能得到显著提高，提高了结构效能，有效增加建筑的使用空间。

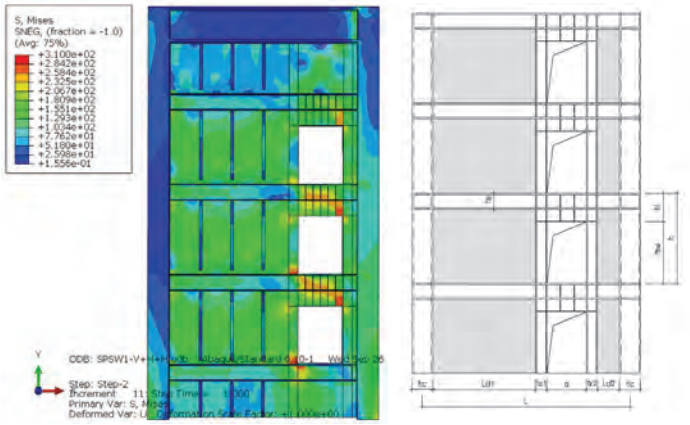

Figure 9. Steel plate shear wall with opening; Mises stress Under the action of horizontal force (Source: Zhong Fan)
图9 开洞钢板剪力墙; 水平力作用下的Mises应力

References (参考书目):

Fan, Z., Liu,X. & Huang, Y. **The Latest Progress in Design and Research of Shear Wall Super High-Rise Building** [J], Building structure, 2011.04;

Fan, Z., et. al. **Design and Construction Simulation of Steel Plate Shear Wall** [J], Construction Technology, 2012.09;

GB 50017-2003. **Code for Design of Steel Structure** [S].

Nie J., et. al. **Analysis of Lateral Bearing Capacity of Shear Wall Stiffening Plate with Opening**[J],Journal of Building Structures, 2013.07;

NIE J., et. al. **Experimental Research on Seismic Behavior of Steel Plate Shear Wall** [J], Journal of Building Structures, 2013.01;