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Study on Lateral-Load Resisting Efficiency of Mega-Frame Structures Above 450M

450米以上巨型框架结构体系抗侧效率研究

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Abstract

Super high-rise buildings will cost large natural resources and social energy which results in their sustainable development as one of the most important issues including structural design. This paper introduces mega-frame structural system as it is most widely used in practical projects above 450m in China. Different parameters are measured to assess structural performance in resisting lateral load, including column numbers, mega-brace layout and the ratio of core tube area to gross area. Also, the involved parameters of structural design for mega-frame system are to be summarized. This study will contribute to provide structural design suggestions for super high-rise buildings above 450m.

Keywords: Mega-Frame Structural System; Component Layout; Lateral Load-Resisting Efficiency; Structural Economies

摘要

中国超高层建筑的发展一直备受世界的关注，而超高层建筑耗能耗材巨大，使得可持续设计成为结构设计的重要目标之一。本文统计了国内450米以上超高层建筑的结构体系，以应用最为广泛的巨型框架结构体系展开研究，建立参数化模型，研究框架柱数量、巨型支撑布置、核心筒围合面积比例各因素的对抗侧效率的影响，结合巨型框架结构体系的设计要点，可以为450米以上超高层结构设计提供参考。

关键词: 巨型框架结构体系; 构件布局; 抗侧效率; 经济性

Introduction

Super high-rise building has long been the outcome of developing modern city, not only because it dominates a magnificent skyline but also gain important access to achieve sustainable development. By now, China has topped in numbers of tall buildings globally and has eight out of ten world's tallest buildings under construction, which are all above 450m. It predicts that there will be more buildings above 450m of future landmarks in China. Meantime, in consideration of China's complicated terrain and frequent earthquakes, there will be more tough technical issues on designing super high-rise buildings, and one of the key issues is to find a more effective lateral-force resisting system and component layouts.

Figure 1 shows current structural systems applied to buildings above 450m under construction in China and it could be concluded that mega-frame system will be more widely used, given as a newly innovative structural system and its application history in recent years. This paper will focus on the study of factors that co-work in efficiency of resisting lateral loads in mega-frame system, based on building models above 450m.

引言

超高层建筑是现代化城市发展的象征性产物，不仅仅因为它勾勒出了壮观的城市天际线，还因为它是实现城市可持续发展的重要途径之一。目前，中国已经成为全球高层建筑数量排名第一的国家，世界在建的超高层建筑前10位中，国内超高层占据8例，且高度均在450米以上，可以预计在未来几年内，中国超高层建筑中的地标性建筑将普遍超过450米。同时，中国又是地势复杂、地震多发地区，使得超高层建筑的发展需要解决很大技术难题，其中的重点内容之一即找到更高效的抗侧体系和更合理的构件布局。

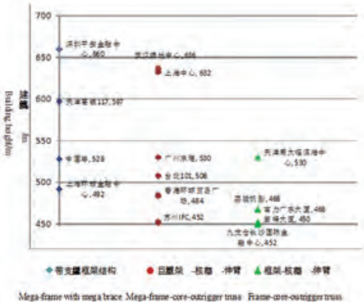


Figure 1. Applied structural systems of supertall buildings above 450m in China(Source: writer)
图1中国450米以上超高层建筑结构体系统计(出自: 作者)

Features of Mega-Frame Structural System

Mega-frame system is featured with large structural stiffness, clear load path, flexible layout and time-saving during construction. Nowadays with the growing height of tall buildings, Mega-frame system has been updated to better suitability. On one side, high-strength material and composite components are widely used in the structure on the background of innovative construction technology and material development, given mega SRC column, mega CFT column, high-strength Steel-Concrete Composite shear wall, etc. Therefore, the traditional mega-frame system is changed to be a more efficient mega-frame hybrid structural system, usually referred to as 'mega-frame system' in short.

On the other side, some newer lateral load-resisting systems are born to get better suitability for building height and load-resisting performance, such as mega-frame with outrigger truss in strengthen-layers and mega-fame with mega brace.

Some of the Key Factors that Work on Lateral-Load Resisting Efficiency in Mega-Frame System

Layout of Mega Columns

The layout of mega-columns could be categorized into two: '8-column-shaped' and '4-column-shaped'.

In essence, different layout of mega-columns all affects the bending stiffness of the outer-frame. We can compare quantitatively the bending stiffness of '8-column-shaped' and '4-column-shaped' layout of mega-columns by using bending stiffness index BRI, which is raised by Taranath in Steel, Concrete, & Composite Design Of Tall Buildings. The BRI is the total moment of inertia of all the building columns about the centroidal axes participating as an integrated system. In Figure 2, we assume the BRI value of '4-column-shaped' layout of mega-columns is 100.Maintaining cross-section area of mega-columns unchanged, so that we can get the BRI value of '8-column-shaped' layout as follows,

$$BRI = 50 + 50\alpha_i^2 , \quad \alpha_i = \frac{b_i}{b}$$

Where,

b_i —Column spacing of a typical mega-column frame

A_i —Axial area of single column

b —Side length of the square

As BRI is proportional to 2th power of a_i, hence the layout of mega-columns has a great influence on lateral load-resisting efficiency of outer-frame. When braces are added to mega-frame, the lateral load-resisting mechanism of brace in flange frame is similar to that of the mega-column, which means bending stiffness contributed by mega-brace changes in the same proportion with BRI. And as the angle of mega-brace changes along with a_i, the contribution of mega-brace to shear stiffness of outer-frame will also change.

There is no unanimous conclusion about the influence of mega-column layout on bending stiffness of mega-frame system with outrigger trusses. Therefore, this paper sets up a 450m model (case 1) under the condition of earthquake intensity level 8 and the height-to-

下图1对国内已建及在建450米以上超高层建筑的结构体系进行统计，可以看出，巨型框架结构体系作为近年来广泛应用的创新型结构体系，具有极大的发展前景。本课题以450米以上巨型框架结构体系为例，对影响巨型框架体系抗侧效率的几个因素展开研究，以期对巨型框架体系的选型提供参考。

	结构高度 /m Structural height/m	结构高宽比 height-to-width aspect ratio	底层核心筒围合面积 Bottom core tube area	典型平面布置 Typical layout of mega column	加强层 Strengthen-layer	巨型支撑 Mega brace
深圳平安金融中心 Pin An Finance center	540	7.4	19.5%		7 道带状桁架 4 道伸臂桁架 7 belt trusses, 4 outrigger trusses	单向 One way
上海中心 Shanghai tower	580	7.0	16.4%		8 道带状桁架 6 道伸臂桁架 8 belt trusses, 6 outrigger trusses	无 none
高银 117 Goldin 117	584	9.5	32%		8 道带状桁架 8 belt trusses,	双向 Two way
广州东塔 Guangzhou Chow Tai Fook Center	518	8.4	27%		6 道带状桁架 4 道伸臂桁架 6 belt trusses, 4 outrigger trusses	无 none
中国尊 Zhongguo Zun	528	13.4	32%		8 道带状桁架 8 belt trusses	双向 Two way
上海环球金融中心 Shanghai world finance center	492	8.5	25%		7 道带状桁架 3 道伸臂桁架 7 belt trusses, 3 outrigger trusses	单向 One way
苏州 IFC Suzhou IFC tower	450/419	7.4	34%		6 道带状桁架 4 道伸臂桁架 6 belt trusses, 4 outrigger trusses	无 none

Table 1. Engineering practice research (Source: writer)
表1. 工程案例调研 (出自: 作者)

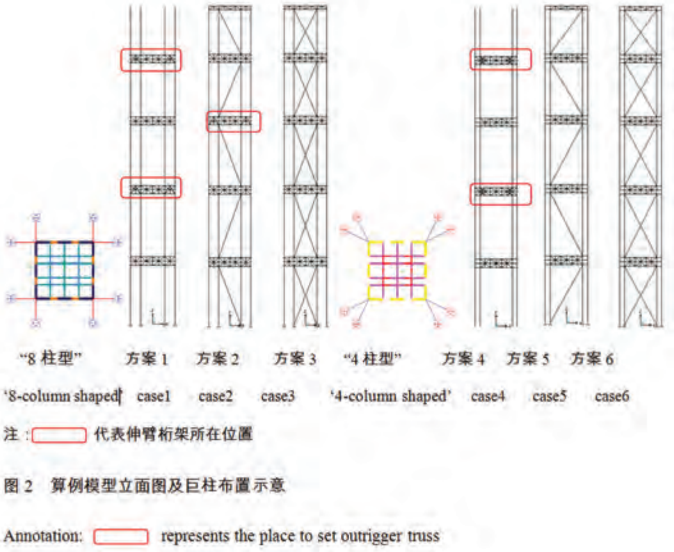


Figure 2. Layout of mega-columns (Source: writer)
图2巨型柱平面布置 (出自: 作者)

width aspect ratio for each model is 7.5. And sets up another 3 models by deleting outrigger truss, adding mega-brace and changing column spacing (case 2-4) to compare how layouts of mega-column affect bending stiffness of different Mega-frame system. Models are shown in Figure 3, $\boldsymbol{a_i}$ of case 1 is 0.53, $\boldsymbol{a_i}$ of case 2 is 0.77.

Comparison of every case is based on the premise of structural roof displacement meeting code requirements, and the section size of lateral load-resisting steel members is determined on the premise of meeting capacity and stability requirement. Basic elastic indexes are shown in Table 2, bending stiffness of case 1 is almost the same as case 3, while case 2 is 14% less than case 4, which is very close to the difference between BRI. So layout of mega-column has little impact on lateral load-resisting efficiency of outrigger trusses, but has great impact on that of the mega-brace.

Also, we can see that layout of mega-column has great influence on shear stiffness of brace from outer-frame shear ratio. But shear stiffness of mega-frame with outrigger trusses is weak, so that the influence of mega-column layout is negligible.

As lateral load-resisting efficiency is connected with economy directly, here set up models under the condition of earthquake intensity level 7 in the same way, which is wind load control. Compared with models in earthquake intensity level 8, here calculate the percentage of steel consumption of the main lateral load-resisting steel members, as is shown in Figure 4.

As is shown, '4-column-shaped' layout of mega-column can reduce steel consumption of mega-frame system significantly. In earthquake intensity level 7, no matter how the layout of mega-column is, steel consumption of braced mega-frame system is smaller than that of the mega-frame with outrigger trusses. As structural design in earthquake intensity level 7 is controlled by rigidity-to-gravity ratio, so that braced mega-frames become very effective and steel-saving in increasing lateral stiffness. In earthquake intensity level 8, structural design is controlled by shear-weight ratio and story drifts. While adding outrigger or mega-brace can both decrease story drifts significantly, the steel consumption of mega-brace can be very large to satisfy strength capacity and stability, if it is set to cross many stories

Mega Brace Angle

For braced mega-frame system, mega brace in web frame provide most of the shear stiffness for outer frame, while mega brace and column of flange frame provide bending stiffness under unidirectional horizontal loading (Figure 5). From simplified model of braced frame, we can get the shear stiffness of web frame and bending stiffness of flange frame as follows:

$$V = D_T\gamma = (A_d E_d \sin 2\theta \cos\theta)\gamma$$

$$M = K_T\chi = A_c E_c \frac{b^2}{2}(1+\frac{A_d}{A_c}\frac{E_d}{E_c}\sin^3\theta)\chi$$

Where,

$\boldsymbol{D_T}$ —equivalent shear stiffness

$\boldsymbol{K_T}$ —equivalent bending stiffness

$\boldsymbol{b}$ —Column spacing

巨型框架结构体系特点

巨型框架结构体系具有整体刚度大、传力路径明确、布置灵活、施工进度快等特点。随着建筑高度的不断上升，对巨型框架结构体系的适用性也提出了更高的要求。一方面，由于施工工艺和建筑材料的不断发展，高强材料和组合构件在巨型框架结构中得到广泛推崇，如巨型SRC柱、巨型CFT柱、高强混凝土钢板组合剪力墙等，在此基础上形成了高效的巨型框架混合结构体系(简称"巨型框架结构体系")。另一方面，巨型框架结构从体系上衍生出新的抗侧力体系，如带伸臂加强层的巨型框架结构体系和带支撑的巨型框架结构体系，使这一体系的抗侧效率大大提高。

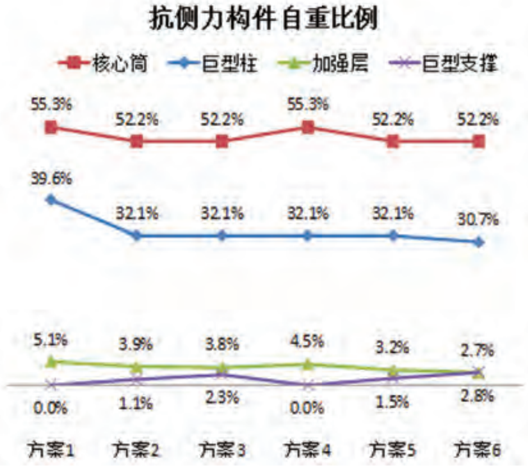
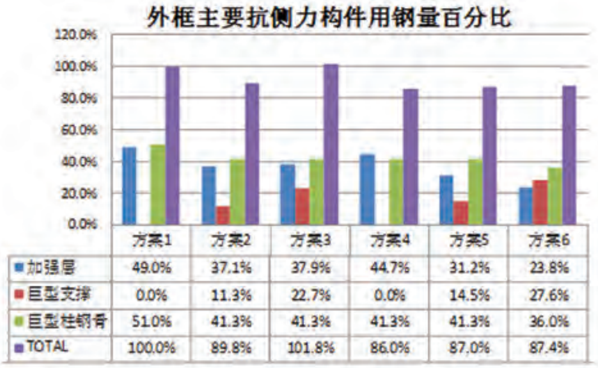


Figure 3. Vertical view of comparison cases and layout of mega-column (Source: writer)
图3比选方案立面图及巨柱布置示意 (出自: 作者)

	周期/s Period/s		侧向刚度（%） Lateral stiffness (%)	风荷载下顶点侧移/mm Vertex lateral displacement under wind load/mm		位移差/mm Displacement difference/mm	最大层间位移角（地震） Max story drift(under earthquake)
	平动 Translation	扭转 Torsion		X向 X-direction	Y向 Y-direction		
方案1 Case-1	7.16	4.12	100.0%	352	339	13	1/504
方案2 Case-2	7.27	3.63	92.4%	382	373	9	1/529
方案3 Case-3	7.20	3.37	95.0%	371	366	5	1/535
方案4 Case-4	7.08	4.12	97.1%	362	348	14	1/508
方案5 Case-5	7.13	3.48	98.1%	359	355	4	1/548
方案6 Case-6	6.80	3.12	106.3%	330	327	3	1/615

Table 2. Stiffness and deformation indexes of Cae1-6 (Source: writer)
表2方案1-6刚度及变形指标 (出自: 作者)



	方案1	方案2	方案3	方案4	方案5	方案6
■加强层	49.0%	37.1%	37.9%	44.7%	31.2%	23.8%
■巨型支撑	0.0%	11.3%	22.7%	0.0%	14.5%	27.6%
■巨型柱钢骨	51.0%	41.3%	41.3%	41.3%	41.3%	36.0%
■TOTAL	100.0%	89.8%	101.8%	86.0%	87.0%	87.4%

Figure 4. Outer-frame steel consumption of different cases under different loads (Source: writer)
图4不同荷载工况下各方案外框用钢量对比 (出自: 作者)

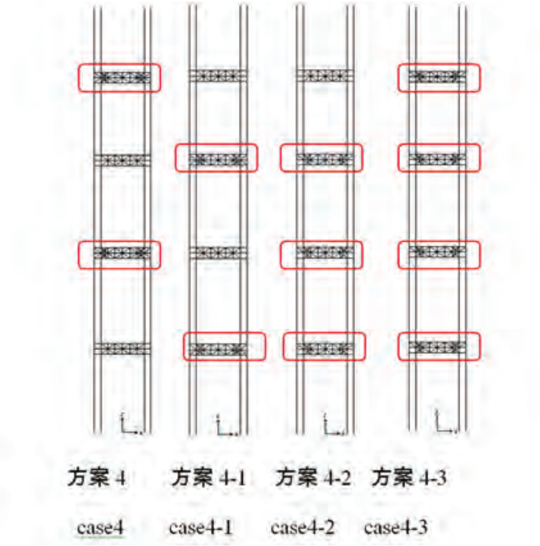


Figure 5. Force diagram of braced-frame (Source: writer)
图5支撑框架受力示意 (出自: 作者)

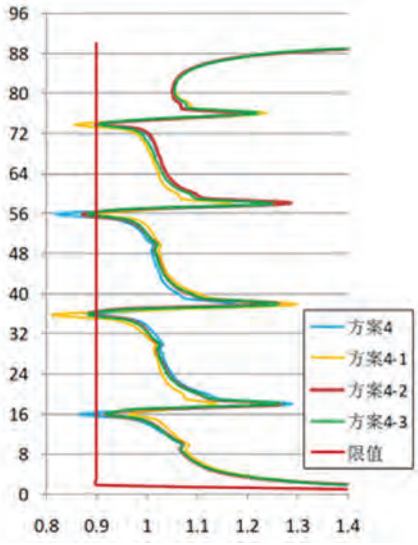


Figure 6. Comparison of lateral rigidity ratio of each case in figure 5 (Source: writer)
图6 图5各方案楼层侧向刚度比 (出自: 作者)

A_C —Axial area of single column

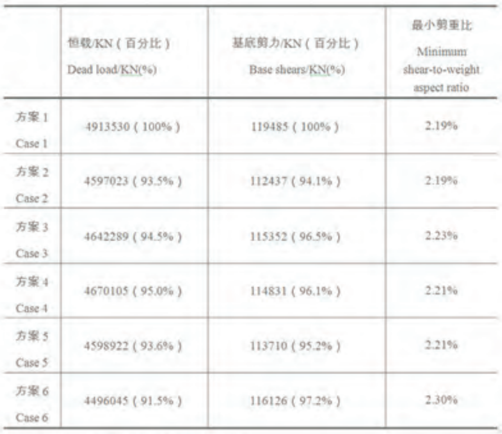
A_D —Axial area of single brace

E_C —elastic modulus of column material

E_D —elastic modulus of brace material

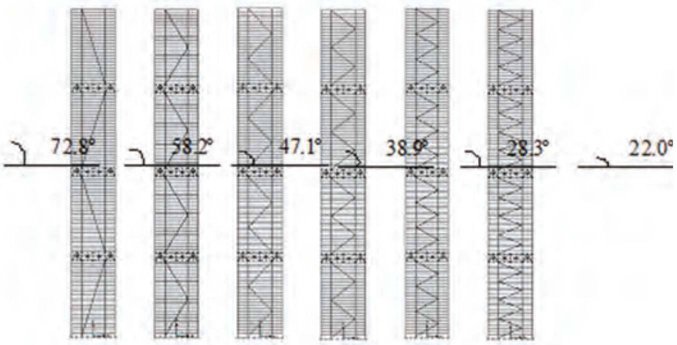
Mega brace angle affects the ratio of axial stiffness of mega column and brace, which is also an important factor of structure lateral stiffness. To make sure the optimistic angle of mega brace, this chapter takes height-width ratio of 7.5 as an example, and set up 6 models for comparison with mega braces of different number and different angle, as shown in Figure 6. Table 3 lists the period, lateral displacement and steel consumption. Figure 7 shows the relation curve of brace angle and story drift and Figure 8 shows the relation curve of brace angle and shear force proportion that outer frame undertakes.

It can be concluded that generally when the mega brace angle is around 47º, the outer frame and core wall can form the optimistic stiffness distribution which lead to smallest story drift and the greatest extent that the outer frame undertakes seismic shear force. From the economic aspect, the steel consumption of mega brace is gradually reducing with the angle increasing, but when the angle is larger than



	恒载/KN（百分比） Dead load/KN(%)	基底剪力/KN（百分比） Base shears/KN(%)	最小剪重比 Minimum shear-to-weight aspect ratio
方案 1 Case 1	4913530（100%）	119485（100%）	2.19%
方案 2 Case 2	4597023（93.5%）	112437（94.1%）	2.19%
方案 3 Case 3	4642289（94.5%）	115352（96.5%）	2.23%
方案 4 Case 4	4670105（95.0%）	114831（96.1%）	2.21%
方案 5 Case 5	4598922（93.6%）	113710（95.2%）	2.21%
方案 6 Case 6	4496045（91.5%）	116126（97.2%）	2.30%

Table 3. The dead weight, base shear and shear-to-weight aspect ratio of case 1-6
表3 方案1-6自重、基底剪力及剪重比统计



Firgure 7. Angles of Mega Brace (Source: writer)
图7巨型支撑的布置角度 (出自: 作者)

表1对当前国内采用巨型框架体系的典型工程进行了统计，可以看出影响该体系抗侧效率的几个关键点。其中，结构高宽比和核心筒围合面积比例的确定是控制整体刚度的重要指标，外框主要抗侧力构件的布局设计是方案优化的主要内容。由此，下文将针对这几个关键点展开研究。

影响巨型框架体系抗侧效率的几个关键点

巨型柱的平面布置

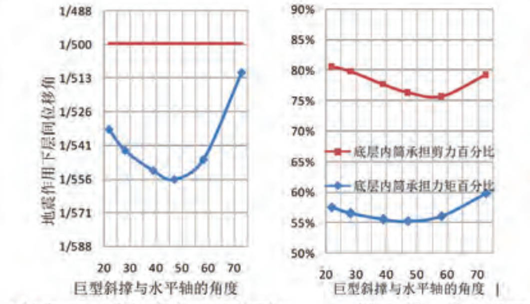
450m以上的巨型柱布置可以分为“4”柱型和“8”柱型两类。

不同柱平面布置从本质上是影响了外框的弯曲刚度，采用塔拉纳特在专著《高层建筑钢-混凝土组合结构设计》中提出的弯曲刚度指数BRI，可以对“4”柱型和“8”柱型的弯曲刚度进行量化的比较。BRI的定义为: 建筑物底层所有立柱截面围绕自身为整体的重心轴旋转，所得截面惯性矩的相对值。其中以图2中“4”柱型布置形式下的BRI值为100，在保持平面巨型柱截面积之和相等的前提下，得到“8”柱型布置下的BRI值为:

$$BRI = 50 + 50\alpha_i^2 , \quad \alpha_i = \frac{b_i}{b}$$

式中:

b_i —同一榀框架巨型柱的柱距



a) Maximum story drift under frequent earthquake

b)Internal force of core bottom

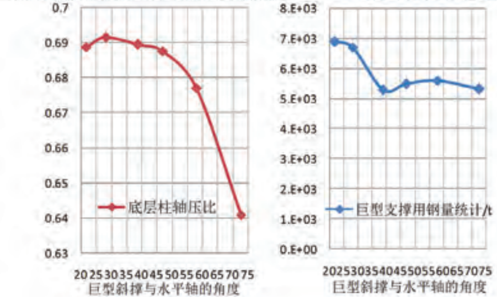


Figure 8. Relative index comparison under different brace angles (Source: writer)
图8. 不同支撑布置角度下相关指标对比 (出自: 作者)

40º, the total length of brace is reducing so that the steel consumption shows no evident change.

The increase of height-width ratio greatly influences the structure bending stiffness, so mega brace optimistic angle also increases. In the mean time, A_D / A_C is related to the brace angle. When the height-width ratio is increasing, the sectional area of mega column will increase much more quickly than that of mega brace, which weakens the influence of brace angle on bending stiffness. Therefore, when the height-width ratio is increasing, the mega brace angle change will mainly affect the proportion of shear force that outer frame undertakes.

The Ratio of Core Tube Area to Gross Area

Core tube is the main source of gravity and lateral stiffness, having a direct influence on seismic force, structure stiffness and the internal force distribution between outer frame and core tube, etc.

In order to compare the influence of percentage of area enclosed by core tube to lateral stiffness of different outer frame systems, a series of mega frame system which are 450m tall and the depth-width ratio is 7.5 are settled under 8 degree seismic region. The ratio of core tube area to gross area is set as 20%, 24%, 28%, 32% and 36% to compare the lateral stiffness of these two different outer frame systems in mega frame.

The percentage of story shear and overturning moment partook by outer frame under statistic different ratio of core tube area to gross area is showed in Table 4. It can be claimed that the percentage of shear force and overturning moment stood by mega frame including two-way bracing is generally bigger than 30% and 40%, respectively. When the core tube area to gross area is less than 28%, the capacity of standing overturning moment of these two mega frame systems is comparable to each other.

At the different of ratio of core tube area to gross area, Figure 9 shows the steel weight of lateral force resisting component of external frame in different model. It can be found that when the ratio of core tube area to gross area is less than 24%, mega frame including two-way bracing would have significant economic advantages. With the ratio of height to width increasing, this advantage will be more significant.

$\boldsymbol{A_i}$—单根立柱的轴向面积

$\boldsymbol{b}$—正方形平面边长

由于BRI与$\boldsymbol{a_i}$的2次方成正比，因此从外框抗弯的角度，巨型柱布置对外框的抗侧效率影响是很大的。巨型框架设置支撑以后，翼缘框架中支撑参与结构抗弯的机理和巨型柱是一样的，所以BRI变化后，巨型支撑贡献的弯曲刚度也按同样的比例改变。并且，$\boldsymbol{a_i}$的改变也引起巨型支撑布置角度的改变，从而影响巨型支撑对外框剪切刚度的贡献。

对于设置伸臂桁架的巨型框架体系，巨型柱布置对外框弯曲刚度的影响没有统一的定论，基于此，本课题建立某8度区450m、结构高宽比为7.5的算例模型 (方案1)，通过删除伸臂构件、设置巨型支撑、移动柱距等方式得到其他对比方案 (方案2-4)，比较不同巨型柱平面布局对巨型框架两种外框体系弯曲刚度的影响，比选方案示意见图3所示。其中。布局1的$\boldsymbol{a_i}$为0.53，布局2 的$\boldsymbol{a_i}$为0.77。

各模型的比选以结构整体侧移满足规范要求为前提，外框主要抗侧力钢构件以满足承载力和稳定性要求确定构件尺寸。表2对各模型的基本弹性指标进行了统计。可以看出，对于同样的外框体系，方案1和方案3的外框弯曲刚度几乎没有区别，方案2和方案4相差了14%，与对应的BRI值之差十分接近，因此，巨型柱布置对伸臂桁架的抗侧效率没有太大影响，但对巨型支撑的抗侧效率影响很大，巨型支撑的弯曲刚度随BRI值的变化同比例的改变。

表中，由各方案外框承担楼层剪力百分比可以看出，巨型柱布置对支撑的剪切刚度影响也很大，而带伸臂桁架的巨型外框剪切刚度很弱，受巨型柱平面布置的影响也可以忽略。

由于抗侧效率和经济性直接相关，按图3对应的方案编号，按同样的建模方法增加7度区 (风荷载控制) 下的分析模型。结合已建的8度区 (地震控制) 模型，比较不同荷载工况下各方案外框主要抗侧力构件用钢量的大小，如图4所示，其中各荷载工况均以方案1总用钢量为对比参数，计算其他方案用钢量所占百分比。

总体上，"4柱"型的巨型柱平面布置可以显著降低巨型框架体系的外框用钢量。7度区结构受刚重比控制，而巨型支撑对提高整体刚度的效率很高，无论巨型柱采用何种布置形式，带支撑的巨型框架体系外框用钢量总是小于带伸臂加强层的巨型框架体系;8度区结构受剪重比和层间位移角控制，设置伸臂桁架或外框设置巨型支撑均能有效控制结构侧移，而巨型支撑跨越较多楼层，在满足承载力和稳定性要求的前提下截面尺寸较大，经济性不明显。

巨型支撑的布置角度

对于带支撑的巨型框架体系，单方向的水平荷载作用下，腹板框架的巨型支撑为外框提供主要剪切刚度，翼缘框架的巨型支撑和巨型柱为外框提供弯曲刚度 (图5所示)，由支撑框架的简化模型得到腹板框架的剪切刚度和翼缘框架的弯曲刚度分别为:

$$V = D_T\gamma = (A_d E_d \sin 2\theta \cos\theta)\gamma$$

$$M = K_T\chi = A_c E_c \frac{b^2}{2}(1 + \frac{A_d}{A_c}\frac{E_d}{E_c}\sin^3\theta)\chi$$

式中:

$\boldsymbol{D_T}$—等效剪切刚度，

$\boldsymbol{K_T}$—等效弯曲刚度

Related Factors That Affect Lateral-Load Resisting Efficiency

Architectural Shape

To avoid influence of architectural shape on structural performance, this study uses models with rectangular plane layout which doesn't change along the elevation. However, in actual project, supertall architectural shape is usually complicated which has direct impact on determination of structure case and lateral efficiency.

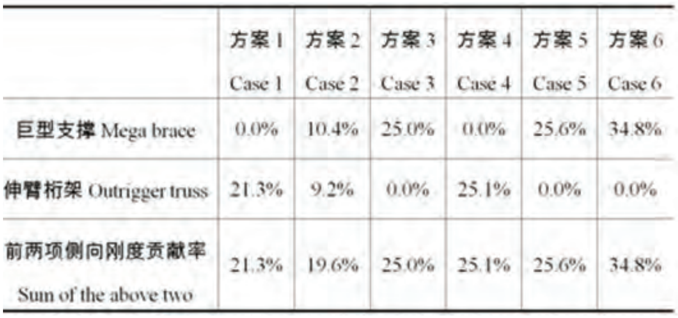
Architectural shape of conical adduction is usually most applicable to supertall building. On one hand, with plane size gradually reducing, vortex shedding and across-wind effect can be greatly reduced; on the other hand, seismic load reduces with self-weight reducing. Meantime, conical system can increase lateral effectiveness and imagine conical system as a vertical outrigger beam, conical shape is similar to the moment distribution of outrigger beam so that the section and material are used to the greatest extend. For mega frame system, with mega column slightly inclined, not only story drift reduces, but the outer frame can also undertake more shear force. (Wang et al, 2012)

With building height increasing, wind force is exponentially growing. As overturning moment brought about by wind force at the top of the building occupy a relatively large proportion of base moment, it is hard to resist wind force simply by optimizing structure system. Sometimes architectural shape optimization can get a better effect. For example, the Shanghai Tower adopts a triangle plane with an arc angle. With the torsional shape and a gap winding up, the across-wind dynamic response is greatly reduced and then the component size is optimized and the structure weight is decreased.

Structural Material

A general development tendency of mega frame is to use concrete material with high strength and high performance and composite component made of high-performance material, like mega SRC column, mega CFT column, CCFT column, steel plate shear wall with high-strength concrete etc.

Analysis shows that when concrete strength grade changes from C40 to C80, construction cost increases about 50%, and for structures mainly in compression, their capacity can increase about 80%. Therefore, concrete strength grade improvement is a effective way to decrease structure weight, especially for supertall building and large-span structure.



	方案1 Case 1	方案2 Case 2	方案3 Case 3	方案4 Case 4	方案5 Case 5	方案6 Case 6
巨型支撑 Mega brace	0.0%	10.4%	25.0%	0.0%	25.6%	34.8%
伸臂桁架 Outrigger truss	21.3%	9.2%	0.0%	25.1%	0.0%	0.0%
前两项侧向刚度贡献率 Sum of the above two	21.3%	19.6%	25.0%	25.1%	25.6%	34.8%

Annotation: "the average shears of each stories the core tube bear" does not include the strengthen-layers and the neighboring stories.

Table 4. Statistics about the proportion of the contribution to lateral stiffness of mega braces and outrigger trusses. (Source: writer)

注: 其中"核心筒承担各层剪力平均值"中"各层"不包括加强层及上下各层。

表4 巨型支撑与伸臂桁架对侧向刚度贡献率统计（出自: 作者）

b —柱距

A_C—单根立柱的轴向面积，

A_D—单根支撑的轴向面积

E_C—单根立柱的弹性模量，

E_D—支撑材料的弹性模量

巨型支撑的设置角度反映了巨型柱和巨型支撑的轴向刚度比，是影响结构侧向刚度的重要因素。为确定巨型框架体系的最佳支撑设置角度，本节以结构高宽比为7.5为例，按每区设置不同数量的巨型支撑对应不同的布置角度建立对比模型6组，如图6所示。下表3统计了各模型的周期、侧移、用钢量指标，图7为支撑设置角度与层间位移角的关系曲线，图8为支撑设置角度与外框承担剪力百分比关系曲线。

可以看出，从整体角度，巨型支撑的设置角度在47º左右，外框和内筒可形成最为合理的刚度分布，层间位移角达到最小，外框最大程度地承担楼层剪力; 从经济性角度，巨型支撑用钢量随设置角度的增大而减小，设置角度大于40º时，由于角度增大，支撑总长度减小，支撑总用钢量无显著变化。

结构高宽比增大以后，结构受弯曲刚度的影响更大，因此巨型支撑的合理布置角度也会相应增大，但同时考虑到，A_D/A_C 和支撑角度是关联的，高宽比增大后，巨型柱截面积的增幅将显著大于巨型支撑，导致支撑角度对弯曲刚度的影响会削弱，因而高宽比增大后，巨型支撑布置角度的影响将主要体现在提高外框分担剪力的能力上。

核心筒围合面积比例

核心筒作为结构自重和侧向刚度的主要来源，对地震作用大小、结构整体刚度、外框与内筒的内力分配都有直接的影响。

为了比较不同核心筒围合面积比例对巨型框架不同外框体系抗侧效率的影响，下面建立8度区荷载工况下，结构高度为450m，高宽比为7.5的巨型框架模型，分别改变核心筒围合面积比例为20%、24%、38%、32%和36%，对比巨型框架两种外框体系的抗侧效率。

表4统计了不同核心筒围合面积比例下的外框分担楼层剪力和倾覆力矩百分比，可以看出带双向支撑的巨型框架承担结构剪力百分比一般大于30%，承担楼层倾覆力矩百分比一般大于40%，核心筒围合面积比例小于28%以后，巨型框架两种外框体系承担楼层倾覆力矩的能力比较接近。

图9统计了不同核心筒围合面积比例下各模型外框主抗侧力构件的用钢量，可知核心筒围合面积比例小于24%以后，带双向支撑的巨型框架结构体系具有显著的经济优势。随着高宽比的增大，这一优势将更加显著。

影响抗侧效率的其他因素

建筑造型

本课题为避免建筑造型对结构受力的影响，研究一律采用平面为矩形、平面尺寸通高不变的算例模型，但实际工程项目中，超高层建筑的造型往往比较复杂，而建筑造型的确定对结构方案的确定以及抗侧效率都有直接的影响。

锥形内收的建筑造型往往是最适用于超高层建筑的造型，一方面通过平面尺寸沿高度的不断缩进，可显著减小风荷载作用下的漩

Adoption of composite column with high-performance material, on one hand, can reduce component size and self-weight, among which mega CFT column can reduce steel consumption to the greatest extent; on the other hand, it can greatly enhance structure capacity, but good ductility and hysteretic behavior of mega column should be guaranteed. (Ding et al, 2011)

Axial compression ratio of shear wall is a controlling index of overall core height. Considering certain requirements of ductility, concrete grade should be limited to C60. So to fill steel plate in reinforcing concrete wall to form composite steel plate shear wall becomes the most effective way to control section size not to be too thick. And at the same time, it raises structural overall rigidity, shear capacity and ductility. So it is the most preferable practice for strengthen zone at the core bottom.

Conclusion

When the structure height is higher than 450 m, it is most proper to use mega frame structure system with strengthen-layers or mega braces, considering the improving of lateral-force resisting efficiency. The one with mega braces is more suitable for the tall building with bigger height-to-width aspect ratio, such as Goldin 117 Building with a height-to-width aspect ratio as big as 9.5. While allowing the core tube to occupy a relatively small plane area so that the space utilization is well improved, the target to have a sustainable development on vertical space of the building can be realized.

From the aspect of economy, when the mega columns are laid on the corner, mega frame with two-way mega braces can play most economically. In practical engineering, since the architectural appearance and functions should be taken into account as well, it differs from different projects to determine which shall be the most economic. Anyway, efficient lateral-force resisting system and reasonable element layout are the key points to reduce the cost of a structure.

涡脱落和横风向效应，另一方面通过减轻自重减小地震荷载作用。同时，锥形体系可提高结构抵抗水平力的效率，将锥形体系想象成竖放的悬臂梁，锥形内收的体型与悬臂梁倾覆力矩的分布相吻合，可最大程度地利用截面和材料。对于巨型框架体系，通过巨型柱略微倾斜，既可以减小结构侧移，又可以显著提高外框承担剪力。

随建筑高度增加，风荷载以指数级增长。建筑物顶部的风荷载引起的倾覆力矩占基底倾覆力矩的比例较大，单纯依靠结构体系的优化是比较困难的，有时在建筑造型上的创新能带来事半功倍的效果。如上海中心大厦采用带弧形转角的三角形平面，通过建筑造型的扭转、以及沿转角蜿蜒而上的缺口，最大程度地减小了横风向动力响应，从而优化构件尺寸，减轻了结构自重。

结构材料

巨型框架体系发展的一个普遍趋势即采用高强高性能混凝土材料和由高性能材料组成的组合构件，如巨型型钢混凝土柱、巨型钢管混凝土柱、约束钢管混凝土柱、高强混凝土钢板组合剪力墙等。

资料分析表明，混凝土强度等级从C40提高到C80时，造价约增加50%，而在以受压为主的结构中，其承载力可提高80%左右。因此，提高混凝土的强度等级是减轻结构自重，特别是超高层建筑及大跨度结构自重的有效途径。

采用高性能材料的组合柱截面，一方面大大减小构件尺寸，减轻自重，其中巨柱采用钢管混凝土形式可最大程度降低用钢量; 另一方面在大大提高结构承载力的同时，要保证巨型柱良好的延性和滞回性能，实验和震害记录表明，实腹式钢骨混凝土柱具有较好的抗震性能。

剪力墙轴压比是核心筒全高的控制性指标。考虑一定的延性要求，混凝土材料等级被控制在C60，因此在核心筒普通钢筋混凝土墙肢内嵌入钢板形成组合钢板剪力墙的这种构造选型成为了控制截面尺寸、不致剪力墙过厚最为有效的方式，同时提高了结构整体刚度、抗剪及延性等性能，因此是地震区核心筒底部加强区普遍选取的构件选型。

结语

结构高度大于450m时，从抗侧效率出发，带伸臂加强层的巨型框架体系和带支撑的巨型框架体系仍是最适用的结构体系。其中，带支撑的巨型框架适用于高宽比更大的超高层建筑，例如结构高宽比达到9.5的高银117大厦，同时又可以保证核心筒占据较小的平面围合面积，提高空间利用率，有利于实现超高层建筑在垂直空间上的可持续发展。

从经济性角度，当巨型柱布置于平面角点位置时，带双向支撑的巨型框架表现出最佳经济性。实际工程还应考虑建筑造型及功能要求，最具经济性的结构体系依据具体工程而异，但可以看出，高效的抗侧力体系和合理的构件布局是降低结构造价的关键。

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