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Authors: Dasui Wang, Consultant, ECADI
Lianjin Bao, Chief Engineer, ECADI
Jianlong Zhou, Assistant Chief Engineer, ECADI

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Economical Analysis of the Structural Systems for Supertall Buildings

超高层建筑结构经济性分析

Dasui Wang

Jianlong Zhou

Lianjin Bao

Dasui Wang, Jianlong Zhou & Lianjin Bao

East China Architectural Design & Research Institute Co., Ltd
151 Hankou Road, Shanghai, China, 20002

tel (电话): +86 021 63217420
fax (传真): +86 021 63215908
email (电子邮箱): dasui_wang@ecadi.com;jianlong_zhou@ecadi.com;lianjin_bao@ecadi.com
www.ecadi.com

Dasui Wang graduated from Tongji University. As a consultant for the East China Architectural Design Institute, he currently holds the position as a high-level committee member of the Architectural Society of China, a deputy director of the Ministry of Construction High-Rise Building Review Committee, and an adjunct professor at Tongji University. His main design works include the Oriental Pearl TV Tower, Pudong International Airport and the CCTV main building.

汪大绥毕业于同济大学，华东建筑设计研究院顾问，中国工程设计大师。现任中国建筑学会高层结构委员会副主任，建设部超限高层建筑审查委员会委员，同济大学兼职教授。主要设计作品有东方明珠广播电视塔，浦东国际机场航站楼，CCTV主楼，天津国际金融中心，2010上海世博会世博轴等。

Jianlong Zhou graduated from Tongji University. He is the Chief Engineer of the East China Architectural Design Institute and the Vice Chairman of the Shanghai seismic overrun review of the Committee of Experts. His design works include the Shanghai World Financial Center, the Nanjing Zifeng Tower, Shanghai World Expo Performing Arts Center and the Shanghai South Railway Station.

周建龙毕业于同济大学，华东建筑设计研究院总工程师，上海市抗震超限审查专家委员会副主任委员。主持完成的工程主要有上海环球金融中心、南京紫峰大厦以及2010上海世博会世博演艺中心。 及上海南站等

Lianjin Bao graduated from Tongji University with a Master's Degree. He is the assistant Chief Engineer in the East China Architectural Design Institute and is a member of the Shanghai seismic overrun review of the Committee of Experts. His main projects include the Shanghai Shimao International Plaza, CCTV main building, 2010 Shanghai World Expo Center, etc.

包联进毕业于同济大学，获硕士学位。华东建筑设计研究院总工程师助理，上海市抗震超限审查专家委员会委员。主要作品有上海世茂国际广场，CCTV新主楼，以及2010上海世博会世博中心等。

Abstract

The investments in supertall buildings are huge and the cost of structural materials and construction takes the highest portion. This paper discusses numerous factors that influence the structural construction cost of supertall buildings which includes the shape of the building, the lateral-force-resisting system, and the application of structural materials. In addition, the paper also analyses the role of the construction method and schedule in the construction cost. Lastly, based on several existing and under construction buildings which are around 300-meters-high, preliminary statists and analysis on the amount of steel usage are presented. The cost of structural construction is influenced by a number of factors and needs to balance each other. Therefore, optimized design of the structure is an essential cost reduction process.

Keywords: Building shape; lateral-force-resisting system; mixed structure; steel usage

摘要

超高层建筑投资巨大，结构造价占较大比例。基于超高层建筑结构的受力特点，对影响超高层建筑结构造价的若干因素进行探讨，如建筑体型、结构体系、结构材料等。此外，施工方案和施工周期也间接影响结构造价。最后，对部分已建或在建的300m高度以上超高层建筑的结构用钢量进行初步统计和分析，以期找到一些规律和背景。结构造价受多因素影响，需要相互平衡，合理优化的结构设计是降低结构造价的必由之路。

关键词：建筑体型、抗侧力结构体系、混合结构、用钢量

Overview

In recent years, the construction speed and numbers of supertall buildings are astonishing. According to incomplete statistics, currently, the skyscrapers (500 ft. or 152 m and higher) under construction in China are over 200. The total number of skyscrapers that will be under construction in the next five years is estimated to surpass 800, which is four times the total number of U.S. skyscrapers.

Due to massive stories, large floor plans, and long construction periods, supertall buildings are huge investments. For supertall buildings, the ratio of structure cost to the total cost is as high as 30% to 35%. Therefore, reducing the structure costs can significantly save the financial investment of the project. Reducing the amount of material can reduce carbon emissions, which helps achieve the goals of green building and make the construction development sustainable. Based on a structural design standpoint, this article will identify the main factors that affect the cost of buildings.

概述

近几年来，中国超高层建筑的建设数量与速度惊人。据不完全统计，中国目前正在兴建的摩天大楼（500英尺或152m高度以上）总数超过200幢，未来5年中国的摩天大楼总数将超过800幢，是目前美国摩天大楼总数的4倍。

超高层建筑由于楼层数多、建筑面积超大、施工周期长，因此需要巨大投资。对超高层建筑而言，结构造价占总造价比例高达30%~35%。因此，降低结构造价对节约工程投资意义重大。同时，减少结构材料用量可降低碳排量，有助于实现绿色建筑和建筑可持续的发展目标。本文从结构设计的角度，对影响超高层建筑结构造价的主要因素进行探讨。

结构造价相关因素

结构造价可以用直接经济指标或间接经济指标来衡量。直接经济指标一般采用结构造价百分比、单位面积结构综合造价或者单位面积材料用量。鉴于超高层建筑具有施工周期长、投资回收慢、竖向构件面积大等特点，也可用间接经济指标来补充衡量，如竖向构件占楼层面积比、施工可建性、社会效应等。限于篇幅关系，本文主

Factors Affecting Structural Cost

The cost of the structures of the building can be measured with direct and indirect economic indicators. Generally, the direct economic indicators use the percentage of structural cost to total building cost or the material usage per unit area. Based on the characteristics of long construction time, slow return of investments, and large vertical components, indirect economic factors can also affect the total cost of the building such as the ratio of vertical component to the total floor area, construction method or constructability and social environmental impact to its vicinity. Limited to the length of the paper, this article will mainly focus on the direct economic indicators and the construction method or constructability to discuss building structural economics.

Due to the structural resistant systems and unique construction characteristics of supertall buildings, factors including building shape, lateral resistance systems, structural materials, and construction time will affect the structural cost most and will be discussed in detail.

Building Shape

Height to width ratio, variations of the building façade, and the shape of the plan are the main stereotypes that have an impact on the economic efficiency of the structure system for supertall buildings.

Height to Width Ratio

Supertall buildings can be under other conditions simultaneously. Under wind loads, the basement overturning moment is proportional to the square of the height of the building and the lateral displacement of the top of the building is proportional to the fourth power of its height. Compared to high-rise buildings, the height of the supertall building increases ten multiple times while the width of the building only increases several times at most, thus the ratio of height to width will be greater. Therefore, limiting the displacement at the top of building and reducing people's awareness of the building movement becomes a challenge. In order to increase the resistance to horizontal force and lateral displacement in supertall buildings, the most effective way is to increase the width of the building.

The height to width ratio of supertall buildings also significantly affects the wind load in the cross-wind direction. Some slender supertall buildings, for example (see Figure 1), has a main structure height of about 167 m with an original exterior design dimensions of 16.8 m × 16.8 m, then the height to width ratio of the structure is about ten. Based on the model of wind tunnel tests, it shows that the base moment in a cross-wind direction is about three times of that in downwind, thus the cross-wind effect is very obvious. To optimize the design, the size is increased to 18.0 m x 18.0 m, then the structural height to width ratio decreases to nine and this reduces the base moment by 50%. Thus, the structural height to width ratio is the most critical factor in the optimization of building shape.

Cone-Shaped Buildings

When constructing cone-shaped facades with continuous reductions of cross-sections along the height, on one hand, it can go through the cross section along the contracted height which can significantly reduce the vortex shedding wind loads and cross wind effects. On the other hand, it could increase the efficiency of the structure to resist horizontal forces. These two effects are reflected in the following two aspects:

- Effectively resistant to the overturning moment
  Under the horizontal loads, the cone-shaped supertall building could fully take advantage of its structural ability to withstand

Figure 1. Test Elevator tower (Source: Bao lianji)
图1. 某电梯试验塔（出自：Bao lianjin）

要从直接经济指标以及施工可建性角度来探讨结构的经济性。

针对超高层建筑的结构受力和施工特点，以下就建筑体型、抗侧力结构体系、结构材料以及施工周期等对影响结构造价的若干因素进行重点分析。

建筑体型

影响结构经济性的超高层建筑体型主要包括高宽比、建筑立面变化以及平面形状等。

高宽比

超高层建筑在其他条件相同时，在风荷载作用下，建筑物基底倾覆力矩与建筑高度的平方成正比，而建筑物顶部的侧向位移与其高度的四次方成正比。与多高层建筑相比，超高层建筑高度增加几十倍，但房屋的进深（宽度）最多增加几倍，其高宽比就愈大，位移控制以及顶部舒适度就会成为主要问题。因此，为了增大超高层建筑抵抗水平力和侧移的能力，增加建筑的有效宽度是最有效的方法。

超高层建筑物的高宽比也显著影响横风向的风荷载。以某细柔的超高层建筑为例（见图1），其主体结构高度约为167m，平面呈正方形，原方案设计的外形尺寸为16.8m×16.8m，结构的高宽比约为10。基于该模型的风洞试验表明，其横风向的基底弯矩约为顺风向的3倍，横风向效应非常明显。优化方案将建筑平面尺寸调整为18.0m×18.0m的正方形，结构高宽比减小为9，基底弯矩减小幅度为50%。结构高宽比在建筑体型的优化过程中是最关键的因素。

锥形化体型

建筑立面锥形化内收的体型，一方面通过截面沿高度不断收缩，可显著减小风荷载作用下的漩涡脱落和横风向效应，另一方面可提高结构抵抗水平力的效率，体现在以下两个方面：

- 有效抵抗倾覆力矩
  在水平荷载作用下，锥形内收体型的高层建筑其倾覆力矩基本符合其倾覆力矩的分布规律，结构材料的效能可以得到充分发挥，比较典型的工程实例有埃菲尔铁塔(请见图2(a))和东方明珠电视台(请见图2(b))。
- 提高结构抗侧力刚度
  锥形化体型的超高层建筑，外框架柱略微倾斜，可以减少框架的侧移。用简化计算对三个高为16，32和40层的三开间建筑物进行研究，倾斜部分的高度分别为1/2高度和全高（请见图3）。研究结果显示，40层框架的相对侧移减小得最多，因为其高宽比最大。当外柱的斜率为8%时，可

Figure 2. Examples of cone-shaped supertall buildings. (a) Eiffel Tower, (b) Oriental Pearl TV Tower (Source: Bao Lianjin)
图1. 锥形体型工程案例，(a) 埃菲尔铁塔，(b) 东方明珠电视塔（出自：Bao lianjin）

the overturning moment thus the strength of the structural material could be effectively used. The typical examples of this shape are the Eiffel Tower (see Figure 2a) and the Oriental Pearl TV Tower (see Figure 2b).

- Increase structural stiffness against lateral force
  For cone-shaped supertall buildings, if the framing column is slightly tilted, the lateral displacement of the framework could be reduced. Based on a simplified analysis of three buildings that is 16, 32 and 40-story tall, each has three bays and is cone-shaped. They are divided into three groups as no slope, half slope from the middle, and an entire slope from the top (see Figure 3). The relative lateral displacement of the 40-story building is found to decrease the most due to its greatest height to width ratio. Quantitatively, when the exterior columns have a slope of 8%, the 40-layer framework will have a lateral displacement reduced by 50% (Source: T. Y. Lin & SD Sri Lanka Taiwan Si Boli, 1992).

Shapes against Wind

When the height of a building is more than 150 m, wind load is the main load that causes the horizontal displacement for supertall buildings. The selection of a reasonable shape for the building can effectively reduce the wind load effect. It is especially true for buildings with high height to width ratios because it will reduce the cross-wind effect drastically.

- "Unloading Wind" Shapes
  As the building height increases, the wind load will increase exponentially. The overturning moment caused by high wind loads at the top of the building will account for a larger proportion of the total overturning moment at the base. Creating opening holes in the higher part of the building façade and reducing the area of the windward side of the building will effectively reduce wind loads and overturning moments at the base, as shown in Figure 4.

- Twisted Shapes
  To reduce wind load caused by cross-wind effects and increase resident comfort at the top of the building, a twisted vertical facade is a very effective method. Moderate twisted vertical façades could reduce the correlation between the vortex shedding and the torsion degree of the building, hence reducing the cross-wind dynamic responses. The great

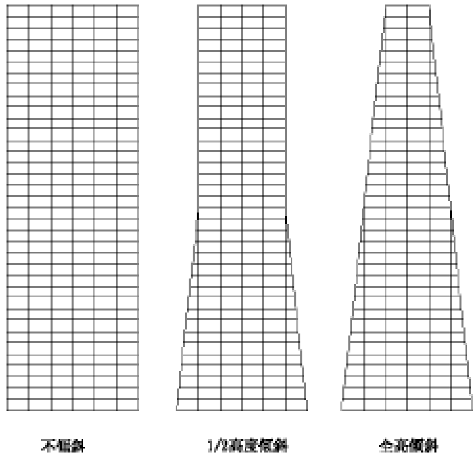

Figure 3. Cone-shaped framework. (a) None slope, (b) Half slope from middle, (c) All the way slope from top (Source: Bao lianjin)
图3. 锥形框架,(a)不倾斜,(b)1/2高度倾斜,(c)全高倾斜（出自：Bao lianjin ）

使40层框架的侧向位移减小50%（文献:林同炎& SD斯多台斯伯利，1992）。

抗风体型

当建筑高度超过150m时，风荷载一般是超高层建筑主要的水平控制荷载。合理的建筑体型可有效减小风荷载效应，特别是降低高宽比较大的建筑物的横风向作用。

- “卸风”体型
  随建筑高度增加，风荷载呈现指数级增长。建筑物顶部和高区风荷载所引起的倾覆力矩占基底总倾覆力矩的比例较大。在建筑物高区立面开设一些洞口，减小迎风面面积，对减小基底风荷载以及倾覆力矩作用非常明显，如图4所示。

- 扭转体型
  对横风向引起的风荷载以及顶部舒适度控制，采用沿高度不断扭转的建筑体型则是非常有效的方式。适度增加建筑物的扭转程度可使涡漩脱落之间的相关性减少，降低横风向动力响应。例如芝加哥螺旋塔（请见图5(a)）的扭转体型使顶部加速度减少了约80%。又如上海中心大厦（请见图5(b)）采用扭转120°的体型，与传统规则不扭转的箱体体型相比，风荷载作用降低达60%。初步估算表明，上海中心大厦优化后的建筑体型可节省结构造价6000万美元。

Figure4. Examples of punched façade supertall buildings. (a) Shanghai World Financial Center, (b) Dalian Tower (Source: Bao lianjin)
图4. 立面开孔实例,(a)上海环球金融中心,(b)大连绿地中心（出自：Bao lian-jin）

example is the Chicago Spire (see Figure 5a) which twists the body to make the top wind acceleration decrease by about 80%. Another example is the Shanghai Tower (see Figure 5b), which the body of the building is twisted 120°. Compared to traditional high-rise buildings without a twisting body shape, the wind loads are reduced by 60%. A preliminary estimate shows that the optimized Shanghai Tower has saved sixty million dollars in structural costs.

- Other measures
  For supertall buildings, other optimizing building plan methods such as using streamline plans, passivation of building corners, setting the size of the flow troughs, and using a gradual retreat facade along the height of the building can effectively reduce the cross-wind effects of the wind load to bring significant economic benefits.

Structural Systems

Lateral Force Resistance Structural System

For supertall buildings, the relationship of the load and overturning moment versus the building height indicates that the increase of material usage and construction cost is non-linearly proportional to the height. Therefore, improving the efficiency of the structural system against the lateral force is an effective way to reduce structural cost. Structural efficiency (MARK, S. et al 2006) refers to the percentage of the lateral displacement caused by the column shortening and elongation to the total lateral displacement. The total lateral displacement in structure is composed of the displacements caused by shear deformation, bending, and column elongation and shortening. For The Willis (Sears) Tower, the preliminary design of the framed tube structural system had only 61% efficiency. Its framework is optimized by using dense internal columns and deep beams to form a beam tube system and the efficiency reached 78%, which is closer to the target value of 80%, while effectively reducing the structural cost. For the Jinmao Tower, its lateral resistant system is composed of a core tube framed with strong pillars by truss beams. Its efficiency is 70% which is better than the frame tube system and is roughly equal to the efficiency of the beam tube. On the contrary, the structural efficiency value for traditional framework of the structure is 15% to 20% since the lateral displacement is mainly caused by the bending of the beam column, of which the lateral force resistance system is inefficient.

Floor Systems

For supertall buildings, the structural height of the floor system has a great influence on structural cost. If a 60-story building, for example, has each of its floor structure thickness increase up to 30 cm, the total height of the structure will have an increase of 18 m, thus wind and seismic effects will be greatly increased as well. The cost of elevators, building facade systems, and other electrical and mechanical facilities should be increased accordingly as well. In addition, the floor span is also the main factor that will affect the load-bearing structural material usage. By reducing the norminal floor structural height, the cost for the supertall building structures could be reduced accordingly.

Structural Materials

Among the total cost of the structure of supertall buildings, material cost accounts for about 50% of the cost while the other 50% of the indirect costs are generated by the labor and equipment required for field installation. Excluding the type and quantity of the materials, then

Figure 5. Examples of twisted-shaped supertall buildings. (a) The Chicago Spire (Source: RWDI), (b) Shanghai Center/Tower (Source: Gensler)
图5. 扭转体型工程案例，(a)芝加哥螺旋塔（出自：RWDI）(b) 上海中心大厦（出自：Gensler）

- 其他措施
  超高层建筑采用流线形平面、建筑角部钝化、沿高度逐步退台以及立面设置导流槽等体型优化措施均可以有效降低风荷载横风作用，从而取得可观经济效益。

结构体系

抗侧力结构体系

超高层建筑水平荷载作用下倾覆力矩与高度的关系表明，结构材料用量随建筑高度非线性急剧增加。因此，提高抗侧力结构体系的效率是降低结构造价的有效途径之一。结构效率（MARK, S. et al. 2006.）是指柱缩短和拉伸引起的侧向位移占结构总侧移的比例。结构总侧移包括剪切变形、弯曲变形以及柱拉伸和缩短引起的变形。西尔斯大厦初步设计方案采用框筒结构体系，只有61%的效率值，后来通过引进建筑内部密柱深梁的框架形成束筒体系，其效率值达到78%，接近达到80%的目标值，从而有效降低了结构造价。金茂大厦采用巨柱伸臂的抗侧力结构体系，其效率值为70%，优于框筒体系，与束筒的效率基本相当。反之，普通框架结构的结构效率值为15%~20%左右，侧向位移主要由梁柱的弯曲变形引起，抗侧力体系效率很低。

楼盖体系

超高层建筑中楼盖体系的结构高度对结构造价也有很大影响。以60层建筑为例，每层楼盖结构厚度增加30cm，累积起来结构的总高度就增加了18m，风荷载和地震作用就会大大增加。并且，电梯、立面围护系统以及其他机电设施的造价都要相应增加。此外，楼盖跨度也是影响承重结构材料用量的主要因素。降低标准层楼盖结构高度，可间接提高超高层建筑结构的经济性。

结构材料

在超高层建筑的结构总造价中，结构材料直接费约占50%左右，而另外50%为现场安装所需劳动力和设备产生的间接费用。因此，结构材料的选用除了考虑材料用量，还应考虑材料的施工特点、材料供应、价格波动、施工现场条件、人力以及技术管理状况等。

钢-混凝土混合结构是在同一结构体系中，钢与钢筋混凝土两类结构的构件并用，充分利用两类结构的优点，弥补二者的缺点，相互取长补短，使用材料总消耗量降低的同时还减少了间接费用，从而取得更好的经济效果。比如混合结构施工时外框梁柱中的钢骨可以先形成骨架，为钢筋混凝土模板体系提供支撑；采用

the construction methods, material availability, material price volatility, construction site conditions, and human and technical management for the selection of materials should also be considered.

A steel-concrete hybrid structure is a structural system with the components of steel and reinforced concrete structures which takes full advantage of the two types of structural materials. This makes up for the shortcomings of each material and complement each other. The reduced material consumption also lessens indirect costs and hence achieves better economic results. During the construction of hybrid structures, the steel frame could be used as a skeleton to support the reinforced concrete formwork system. For steel beam composite floors, the steel sheeting can be used as forms which can greatly reduce the usage and cost of formwork and scaffolding.

According to incomplete statistics, 24% of the 100 tallest buildings in the world are steel structures and the rest are of steel-concrete composite structures. By contrast, steel structural systems account for 57% before 1990. In recent years, the supertall buildings in China, such as the Jinmao Tower, Shanghai World Financial Center, the Shanghai Tower (still under construction), Tianjin 117 Building, etc., are all steel-concrete composite structures.

Construction Period

Due to the large floor plan and massive stories, the construction period of supertall buildings is fairly long. Shortening the construction period can put the building to use earlier, which increases rental income, so the owners can obtain a return on their investments quicker and shorten the payment time. Therefore, accelerating the construction speed and shortening the construction period are other means to increase economic efficiency within structures. The Tianjin Tower, for example, illustrates a close relationship between the shortening of the construction period and the selected structural systems.

The Tianjin Tower office building, 75 stories about the ground, has a building height of 336.9 meters (see Figure 6).The structural system of the Tower includes a CFST (Concrete-Filled Steel Tubular) column frame, a core Steel Plate Shear Wall system (SPSW), and it is framed with strong pillars and deep beams for a lateral force resistance system. In the original design, the framing columns bear all of the vertical loads and the SPSW does not bear any of the vertical loads. The installation of the SPSW after the completion of the main structure will delay construction. This method causes the construction period to be extended for six months and not be able to meet the owner's expectations. By optimizing the design of the SPSW design and adjustment of the construction sequence, the method of delaying SPSW construction is used after the completion of fifteen floors of the main structure. The first layer of the SPSW construction initiates when the concrete for the sixteenth story begins to pour. To prevent SPSW buckling under vertical loads, the plate thickness of the SPSW must be thickened and strengthened by vertical stiffeners. The increased usage of steel is about 500 tons, which is equivalent to the cost of about six million RMB. However, the construction period is shortened by almost six months, saving ten millions of RMB in interest alone (MARK SARKISIAN & DASUI WANG, 2011). Not only did it reduce the total investment cost of the project, it also met the owner's scheduling requirements.

Figure 6. Tianjin Tower (Source: Bao lianjin)
图6. 天津津塔（出自：Bao lianjin）

钢梁组合楼盖，压型钢板可以作为模板，这样可以大大减少模板和脚手架的用量和费用。

据不完全统计，目前100幢最高的超高层建筑中，纯钢结构只占了24%，其他均为钢-混凝土混合结构，而在1990年前纯钢结构比例高达57%。近年来国内建成的超高层建筑，如金茂大厦、上海环球金融中心以及在建的上海中心大厦、天津117大厦等均采用了钢与混凝土混合结构。

施工周期

超高层建筑由于建筑面积大，楼层数多，施工周期普遍较长。缩短施工周期意味着建筑可提前投入使用，增加租金收入，业主可尽早获取投资回报，缩短还贷时间。因此，加快施工速度、缩短施工周期也是提高结构经济性的方式之一。本文以天津津塔项目为例，说明施工周期的缩短与结构体系选择的密切关系。

天津津塔为办公建筑，地上75层，建筑高度为336.9m（如图6所示）。塔楼结构体系由“钢管混凝土柱框架＋核心钢板剪力墙体系（SPSW）＋外伸刚臂抗侧力体系”组成。原设计中竖向荷载全部由框架柱承担，SPSW不承担竖向荷载，导致SPSW需在主体结构封顶后延迟安装。该方案使施工周期延长6个月，不能满足业主预期要求。优化设计对SPSW施工顺序进行了调整，采用SPSW延迟主体结构15层，即主体结构混凝土浇捣到16层后，开始第1层SPSW。为了防止SPSW在竖向荷载作用下发生屈曲，对部分钢板剪力墙钢板厚度进行了加厚并采用竖向加劲肋进行加强。钢板剪力墙及加劲肋方案仅比原设计方案增加用钢量500吨，增加费用约为600万元，却使得项目施工周期缩短近六个月，光利息一项就可以节约上千万元(MARK SARKISIAN & DASUI WANG, 2011)，降低了工程的总投资费用，很好的满足业主工期要求。

超高层混合结构用钢量分析

图7给出了目前中国建成或在建的部分超高层建筑的结构用钢量指标（图中圆点，单位面积用钢量，不包含钢筋用量）。这些超高层建筑高度在300m及以上，主要用于办公、酒店或公寓等用途。基于目前国内超高层建筑90%以上选用混合结构体系的现状，本文用钢量分析选取以钢-混凝土混合结构类型为主。作为

Analysis of the Structural Steel Consumption in Supertall Buildings

Figure 7 illustrates the steel consumption of supertall buildings that completed or under construction in China (Shown as dots; the steel weight excludes the weight of reinforcement per unit area of the building). These supertall buildings, with height of 300m and above, are mainly used for offices, hotels, or apartment. Since over 90% of current supertall buildings in China are of a steel and reinforced concrete hybrid structure, the data used in this article are mainly gathered from this type of buildings. In comparison, figure 7 also illustrates the steel consumption of supertall building in North America with similar heights (shown as triangles). However, unlike the hybrid structures in China, the structures in North America are all built with steel.

Studying these data by using statistical methods, such conclusions can be drawn:

The steel consumption per unit area is dispersed wildly and ranges from 100kg/m2 to 250kg/m2. This distribution index is closely related to the height of the building, the height to width ratio, and the type of lateral force resistant system utilized. Similar to the foregoing analysis, the higher the building is, the greater the height to width ratio, the more steel will be required based on unit area of the building. The efficiency of the structural system also directly affects the structural steel usage, such as that less steel is required in the system of core tube combined with surrounding frames and also in the system of biased grid structures.

According to the statistics of limited data, the steel usage of frame columns (pillars) and outrigger and ring trusses account for 30% and 15% of the total structure steel consumption, respectively. The shape of the column and the steel consumption of column within the frame have one of the greatest impacts on total steel usage.

The amount of steel usage for supertall building greatly varies in different regions, which indicates that wind and seismic loads are major factors that affect the amount of structural steel used. Generally, wind loads are much higher in coastal areas, so the steel usage of supertall buildings in Shanghai is much higher than those in inland cities such as Wuhan, Chongqi and Wuxi. A high usage of steel is found in Tianjing and Beijing because these cities are within high seismic load zones.

Supertall buildings in China use a hybrid structure of steel and reinforced concrete rather than the pure steel structures that are used in North America. However, the steel usage of buildings in China is close to or even higher than that in North America. This is because there are stricter requirements in Chinese Building Codes such as the limitation of horizontal displacement in structures, the percentage of seismic load that frames bear, and the ratio of base shear to the total weight. In addition, high strength steel is rarely used in China, which contributes as one of the reasons for the high consumption of steel.

Conclusion and Recommendations

Structural cost of supertall buildings accounts for a large proportion of the total investment. In order to achieve a successful economic structure, then multiple optimizing design factors, such as building plan, structural systems, and the selection of materials and construction methods, should be considered starting from concept design.

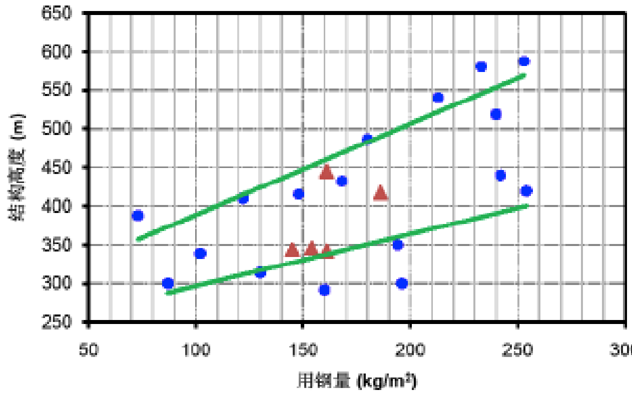

Figure 7. Steel consumption of hybrid structure (Source: Bao lianjin)
图7. 混合结构用钢量统计（出自：Bao lianjin）

对比，图中也给出了北美相近高度的超高层纯钢结构用钢量（图中三角形）指标。

由表中统计结果比较分析，本文得出以下一些结论：

单位面积用钢量指标分布较为分散，从100kg/m2至250kg/m2不等，与建筑高度、结构高宽比以及抗侧力结构体系密切相关。如前文分析，建筑高度越高，结构高宽比越大，单位面积结构用钢量越大。结构体系的效率高低也直接影响结构用钢量指标，如采用支撑筒外框或斜交网格结构其用钢量相对较低。

根据部分统计结果，框架柱（巨柱）、伸臂桁架和环带桁架用钢量占结构总用钢量比例分别为30%和15%左右。框架柱型钢含钢率、巨柱的截面形式是影响钢结构用钢量最关键指标之一。

不同地域的超高层建筑用钢量差异较大，这说明风荷载或地震等水平荷载也是影响结构用钢量的主要因素。沿海城市风荷载普遍较大，武汉、重庆、无锡等区域用钢量为低值，北京、天津和上海等用钢量为高值。

与北美纯钢结构用钢量相比显示，中国混合结构的型钢用钢量接近或高于其钢结构用钢量。这与我国规范体系的结构设计指标控制过于严格相关，如结构位移、外框承担地震水平力比值以及基底剪重比等。另外，高强钢应用较少，也是造成用钢量偏高的原因之一。

结论和建议

结构造价占超高层建筑总投资比例较大，在结构设计中应从概念设计出发，从建筑体型、结构体系、材料和施工方案等多方面综合考虑以提高结构经济性。

在满足建筑规划、功能的前提下，建筑形体的优化对结构的经济性往往起到事半功倍的作用。

应重视风洞试验技术在超高层建筑结构设计的应用。目前国内结构设计“重震轻风”的倾向宜得到纠正。对复杂体型的建筑，风洞试验技术是确定风荷载的主要依据，尤其是确定横风向荷载和效应。

Without compromising the requirements of architecture and building function, the optimization of the building plan is the most important factor in saving the total cost of supertall buildings.

More emphasis should be focused on the application of wind tunnel technology in the structural design for supertall buildings. The trend of the "focus on seismic loads while neglecting wind effects" should be rectified while both loading conditions should be analyzed equally. Wind tunnel tests should be applied to determine the effects of horizontal wind loads, which is especially true for supertall buildings with complex façades.

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