Title: **Tapered Profile and Structural Design of Supertall Buildings**

Authors: Dasui Wang, Consultant, ECADI
Lianjin Bao, Chief Engineer, ECADI
Jianxing Chen, Chief Engineer Assistant, ECADI
Peng Qian, Senior Engineer, ECADI

Subject: Structural Engineering

Keywords: Seismic
Structure
Supertall
Wind Loads

Publication Date: 2014

Original Publication: CTBUH 2014 Shanghai Conference Proceedings

Paper Type:
1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

Tapered Profile and Structural Design of Supertall Buildings
超高层建筑锥形化体型与结构设计


Dasui Wang


Lianjin Bao


Jianxing Chen


Peng Qian

Dasui Wang, Lianjin Bao, Jianxing Chen & Peng Qian

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
www.ecadi.com

Wang, Dasui (1941–) graduated from Tongji University in 1964. As a Design Master of China and a consultant for East China Architectural Design & Research Institute, he is renowned in the field of engineering design.

汪大绥 (1941—) 1964年毕业于同济大学，中国工程设计大师，华东建筑设计研究总院顾问。

Bao, Lianjin (1971 -) graduated from Tongji University in 1996 with a Master's Degree. He is the deputy Chief Engineer of East China Architectural Design & Research Institute and is an UK Chartered Structural Engineer. He is a member of the Shanghai High-Rise Building Review Committee.

包联进 (1971—) 1996年毕业于同济大学，获硕士学位。华东建筑设计研究总院副总工程师，上海市抗震超限审查专家委员会委员，英国注册结构工程师协会会员。他是上海超限高层建筑审查委员会委员。

Chen, Jianxing (1977 -) graduated from Tongji University in 2006 with a Ph. D. Degree. He is the Chief Engineer Assistant of East China Architectural Design & Research Institute and is an UK Chartered Structural Engineer.

陈建兴 (1977—) 2006年毕业于同济大学，获博士学位，华东建筑设计研究总院总工程师助理，英国注册结构工程师。

Qian, Peng (1980 -) graduated from Tsinghua University in 2006 with a Ph. D. Degree. He is the Senior Engineer of East China Architectural Design & Research Institute. His main projects include Dalian Greenland Center and China Expo Center, etc.

钱鹏 (1980—) 2006年毕业于清华大学，获博士学位，华东建筑设计研究总院高级工程师。主要作品有大连绿地中心以及中国博览会小展厅等。

Abstract

As supertall buildings become higher and higher and its function turns to be more and more comprehensive, huge challenges are brought to the structural design. In this paper, author aims to describe the relation between tapered profile and structural design of supertall buildings from the development of buildings profile. Firstly, tapered profile can reduce wind load, typically for the transverse wind response. Secondly, tapered profile can improve the efficiency of structural lateral system. Furthermore, tapered profile can improve the overall structural stability and stiffness of outer frame. Therefore, tapered profile is not only an outcome of combination of architectural function and structural optimization but also the inevitable trend of supertall buildings development in the future.

Keywords: Supertall Buildings, Tapered Profile, Stiffness of Lateral Resistance System, Wind Load, Overall Stability, Dual Seismic Resistant System

摘要

超高层建筑发展呈现出建筑功能综合化和高度超高化等趋势，这给结构设计带来很大挑战。本文从超高层建筑体型发展锥形化的角度，阐述了锥形体型与结构设计的关系。首先，锥形体型可以充分利用结构材料，减少建筑所受的风荷载，尤其是横风向动力响应。其次，锥形结构布置可提高结构体系的抗侧效率。再次，锥形化结构布置可以改善结构的整体受力性能，如结构整体稳定、外框抗侧刚度等。因此，锥形体型不仅是超高层建筑功能与结构优化相结合的产物，也是今后超高层建筑结构设计发展的必然趋势。

关键词: 超高层建筑; 锥形体型; 结构抗侧刚度; 风荷载; 整体稳定; 双重抗震体系

Background

According to an incomplete statistic, by the end of 2012, 94 supertall buildings over 250 m were completed or under construction in Chinese mainland. From 2013 to 2018, 164 supertall buildings over 250 m are planned to be built there (Ding, J., Wu, H.(et al.) 2014). The main function of supertall buildings has been changed from office use in early times to a comprehensive function combined of office, hotel, apartment and others nowadays. The shape of supertall buildings has transformed from a uniform floor towards a tapered form along the height, which enriches the city's skyline.

In order to meet the requirement of bearing capacity, drift and comfort criteria under lateral load, lateral resistance system has developed from frame-core structure to mega frame-core structure, which can make full use of the structure width and strengthen overturning resistant ability. Tensile force caused by overturning moment in mega column can be balanced by its huge axial force under vertical loads as well.

Current tapered profile for supertall building scan be classified as followings (see Figure 1):

背景

据不完全统计，截至2012年底，中国大陆已建成和在建的建筑高度超过250m的超高层建筑数量已达94幢。2013-2018年中国计划建成高度250以上的超高层建筑有164幢 (DING, J., WU, H.(et al.) 2014.) 。超高层建筑的主要建筑功能已从早期的单一办公转变为办公、酒店及公寓等综合功能。建筑体型也一改从上而下统一标准层平面的理念，朝着沿建筑高度截面不断变化收缩即锥形化的趋势发展，丰富了城市的天际线。

为了满足水平荷载作用下超高层结构的承载力、变形和舒适度等要求，结构抗侧力体系也从常规的框架核心筒结构体系向巨型框架核心筒结构体系演变。这样可以充分利用建筑物的宽度，提高抗倾覆能力，且巨柱在竖向荷载作用下承担的巨大轴力可平衡倾覆力矩作用下巨柱产生的拉力。

目前的超高层建筑锥形建筑体型大体可分为以下几类 (请见图1) :

1. 平面阶梯式对称收进

典型工程为马来西亚石油双塔大厦。沿建筑高度，建筑平面每隔若干层 (一般在设备转换层) 以建筑平面中心为基准对称收进一次，形成锥形体型。

1. Staged Symmetrical Tapering

Typical project could be referred to PETRONAS Twin Towers in Malaysia. Along the building height, the building plane contracts symmetrically every several floors (usually at transfer story) to form a tapered profile.

2. Staged Non-Symmetrical Tapering

Sears Tower in Chicago, Burj Khalifa Tower in Dubai and Bank of China Tower in Hong Kong are examples of this type. Along the building height, the building plane contracts non-symmetrically every several floors (usually at transfer story)to form a tapered profile.

3. Continuous Tapering

Goldin Finance 117 in Tianjin and John Hancock Tower in Chicago can be referred to for this type. Building tapers gradually as a pyramid and its outer frame columns incline along the height.

4. Regular Geometry Cutting

Taking Shanghai World Financial Center (SWFC) and New York Freedom Tower for example, this profile of building is based on a regular prism. After the shape cutting, a tapered profile is formed.

5. Torsional Tapering

Shanghai Tower is one example of this type. The filleted triangle plane contracts every story with a total rotation of 120 degree along the height.

Satisfying Layout Requirement of Comprehensive Architectural Functions

With the increase of the height of supertall building, architectural function becomes more comprehensive and mixed. Along the height of building, office area is normally set at lower zone of tower; residential area (apartment or hotel) at higher zone. Different functions have different span requirements. For example, office building normally requires 13.5 m (45ft) span, while 9 m (30ft) span for residential area. If the tower plan remains uniform throughout the whole height, it will affect the using efficiency of building space because of the surplus of the building span in the higher zone. If the span of floor keeps unchanged, the beam depth may reduce the clear ceiling height of apartment or hotel.

Furthermore, the elevator shaft area in lower zone of supertall building occupies more than 20-25% of the core area. However, the number of elevator at higher zone is much less than lower zone, thus there will be a considerable reduction in elevator shaft area. If the plan of core tube keeps unchanged, how to make full use of the surplus room may bring problems to architects. Taking Shanghai Jinmao building (see Figure 1(i)) as an example, it is just a matter of expediency to cancel the interior wall of core tube which forms a 30-Story high atrium. Thus the negative impact on building energy consumption and fire protection cannot be ignored.

In addition, supertall building is usually the landmark in a region. From elevation effect or visual perspective of building, standard architectural plan may result in a top-heavy visual effect.

Therefore, tapered profile is an ideal solution to meet different requirements for mixed functions, gradually decreasing elevator shaft and architectural aesthetics of super high-rise building.

Figure 1. Examples of Tapered profile in supertall buildings (Source: ECADI, SOM etc.) (a) Petronas Towers (Kuala Lumper); (b) Sears tower (Chicago); (c) BurjKhalifa Tower (Dubai); (d) Goldin Finance 117 (Tianjin); (e) John Hancock Tower (Chicago); (f) Freedom Tower (New York); (g) SWFC (Shanghai); (h) Shanghai Tower (Shanghai); (i) Jinmao Tower (Shanghai)

图1. 超高层建筑锥形体型示意 (出自: ECADI、SOM等)
(a) 吉隆坡双子塔; (b) 希尔斯大厦 (芝加哥); (c)迪拜塔; (d) 高银金融中心 (天津); (e) 约翰汉考克大楼 (芝加哥); (f) 自由塔 (纽约); (g) 上海环球金融中心; (h) 上海中心 ; (i) 金茂大厦 (上海)

2. 平面阶梯式非对称收进

如希尔斯大厦、迪拜塔以及香港中国银行大厦等。沿建筑高度，建筑平面每隔若干层 (一般在设备转换层) 非对称地局部收进，形成锥形形体。

3. 平面连续收进

如天津高银117大厦和汉考克大厦等，外框柱沿建筑高度均匀倾斜，建筑型体以四棱台形式沿高度逐渐内收，形成锥形体型。

4. 规则几何体切削

如上海环球金融中心、纽约自由塔等，建筑型体以一规则的棱柱体为基准，进行形体切削，最终形成锥形体型。

5. 平面扭转收进

典型工程实例有上海中心，其呈截角三角形状的外幕墙平面沿建筑高度层层内收，且从下到上共旋转120度。

Making Full Use of Structural Materials

For tall building structures, the consumption of structural materials mainly consists of three parts including framed floor system, vertical structural system and lateral resistant system. The first two parts increase linearly with the height of structure and the rest increases non-linearly with height of structure according to the relation between overturning moment and the height of structure.

Under lateral load, supertall building structure can be simplified as a cantilever beam (Wang,D., Zhou, J.& Bao, L. 2012). The minimum overturning moment appears at the top and the maximum at the base (see Figure 2(a)). For tapered tall buildings, the structural material distribution is in accord with the diagram of overturning moment to make full use of materials. The typical engineering examples include Eiffel Tower (see Figure 2(b)) and Oriental Pearl TV tower (see Figure 2(c)).

Tapered profile structural system is a kind of biomimetic behavior as well. In the nature, the diameter of bamboo nodes decreases steadily with the height (see Figure 3). Its manner perfectly adapts to lateral load (Sarkisan, M., 2012), so bamboo's growth principle can be applicable to supertall buildings and other cantilever structures.

Reducing Wind Load

The wind load increases exponentially with the height. When the height of a tall building exceeds 250m, the wind load will normally dominate the structural design. The overturning moment caused by the wind in upper zone of buildings will occupy large percentage of total overturning moment at the base. Rational building form or profile can reduce the wind load, and is beneficial to the aerodynamic response and the mitigation to correlated vortex shedding in a slender high-rise building.

Along-Wind Force

For a determined terrain roughness, the wind speed increases exponentially up the height of the supertall building. In a tapered building, as the width in the along-wind direction decreases form bottom to top, the upper windage area is decreased. As a result, the point of action of wind load resultant is lowered, and along-wind load is reduced, furthermore overturning moment decreases accordingly (Galsworthy, J. (et al.) 2012).

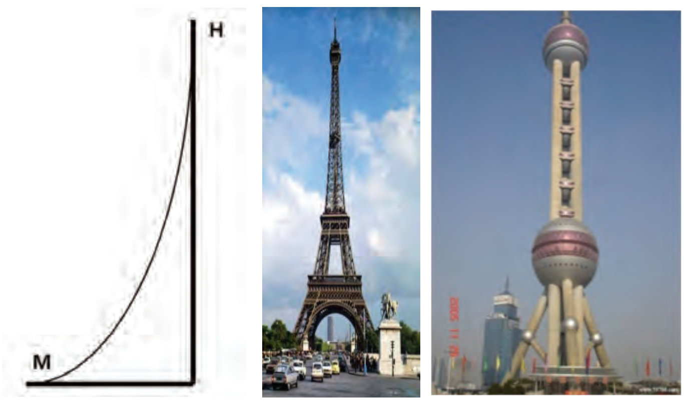

Figure 2. Bending moment diagram of cantilever and its engineering examples (Source:ECADI)
(a) Bending moment diagram of cantilever; (b) Eiffel Tower; (c) Oriental Pearl TV Tower
图2. 悬臂结构的弯矩图与工程实例 (出自: ECADI)
(a) 悬臂结构弯矩图; (b) 埃菲尔铁塔; (c) 东方明珠电视塔

适应建筑综合功能布置要求

随着超高层建筑高度的不断增加，建筑功能也朝着综合化和混合化的趋势发展。沿着塔楼高度，办公类建筑一般布置在塔楼低区，居住类建筑 (公寓或酒店) 布置在塔楼高区。不同类别的建筑功能有不同的进深要求，如办公建筑一般需要13.5米 (45英尺) 的进深，而居住类建筑往往只要9米 (30英尺) 的进深即可。如果塔楼平面在整个高度内保持不变，则高区的建筑进深有些富余，从而影响建筑空间的使用效率。此外，如果保持楼面跨度不变，则结构梁高的要求将降低公寓或酒店的净高。

其次，在超高层建筑中塔楼低区所有电梯井道的面积所占核心筒包围面积往往超过20-25%。在塔楼高区，电梯数量大幅减少，电梯井道所占面积也相应减少。对建筑师来说，如果保持核心筒平面不变，则高区电梯井道取消后的建筑空间利用往往是很棘手的课题。如上海金茂大厦酒店区核心筒内墙取消后 (请见图1(i))，形成了贯穿30多层高的中庭，当然，这仅仅是权宜之计。超大空间对建筑能耗和建筑消防的负面影响不可忽视。

另外，超高层建筑往往是一个地区或城市的地标，从建筑立面效果或者视觉透视的关系来说，如果建筑平面自下而上采用相同的平面尺寸，则会使建筑物产生头重脚轻的视觉效果。

因此，结合超高层建筑上下区有着不同的功能需求以及建筑审美的要求，逐层减小的电梯井道空间，楼层平面沿高度不断内收形成锥形化的体型，是一个理想的解决方案。

充分利用结构材料

在超高层建筑结构中，材料用量主要由楼盖、竖向结构以及抗侧力结构三部分组成，其中楼盖和竖向结构材料用量与结构高度成线性比例增加。超高层建筑水平荷载作用下倾覆力矩与高度的关系表明，结构抗侧力结构材料的用量会随着建筑高度呈非线性急剧增加。

超高层建筑结构可以简化为一悬臂梁 (WANG,D., ZHOU, J.& BAO, L. 2012.) 。在水平荷载作用下，结构倾覆力矩在顶部最小，在底部最大，如图2(a) 所示。在水平荷载作用下，锥形内收体型的高层建筑结构材料分布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 (见图2(b)) 和东方明珠电视塔 (见图2(c)) 。

锥形体的结构也呈现出仿生学的特性。在自然界中，毛竹的竹节直径沿高度不断减小 (见图3) 。毛竹的这种体形极好地适应了作用于其上的侧向荷载承载力要求 (SARKISIAN, M., 2012.) 。其生长原理同样适用于超高层建筑以及其它悬臂类结构。

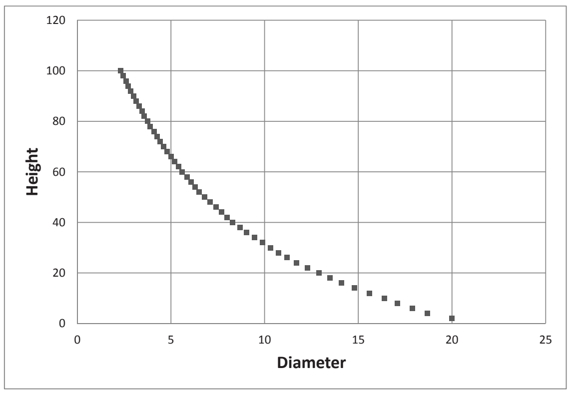

Figure 3. Relation between the height and diameter of bamboo (Source: Designing tall buildings)
图3. 竹子高度与直径的关系 (出自: Designing super buildings)

Cross Wind Load

As the aspect ratio of a supertall building is greater than 6, the cross wind load should be taken into consideration. For supertall buildings, the main aim is to reduce the cross wind resonant response due to vortex shedding. The key parameter is the natural frequency of the vortex shedding (f)which could be calculated with the following formula. The natural frequency of the vortex shedding f is a function of the shape of the building (St), the building width (B), and the wind speed (U).

$$f = \frac{S_t U}{B}$$

Where:

S_t stands for Strouhal number, which is a constant for a given cross section and approximately equals to 0.2 for a circular section, 0.10 to 0.16 for rectangular sections.

U stands for the wind speed at a certain height of a building.

B stands for the width at a certain height of a building.

When the vortex shedding frequency f approaches a natural vibration frequency of the building fB, large responses can occur. The variation of the size or shape of cross section along the height of a building could affect the value of Stor B, which could disturb the organization of the vortices, in order to reduce the cross wind load. Hence, compared to prismatic form, tapered profile could not only reduce cross wind load, but also improve the perceptible acceleration at the top.

Improving Structural Lateral Resistant Stiffness

The optimization of the shape of super high-rise buildings can be achieved by structure shape-finding (Stromberg, L.,Baker, W. F. (et al.) 2011.). For super high-rise structures, lateral load is the main factor in design, so its shape-finding can be done like the following. Under uniform lateral load, shape finding starts from an initial shape (a cylinder, for example) which is iteratively modified through the optimization process until the best shape for the minimum drift at the top of the overall building (or the maximum lateral resistance stiffness) is found. In the example shown in the Figure 4, the geometry is parametrically controlled by the radii of the floor plates at various elevations. The height of the building, the base diameter and the overall internal volume remain unchanged.

Figure 4 shows the structure shape-finding process of a cylinder. The shape of the structure becomes a cone from a cylinder after several iterations. The genetic algorithm is also suitable for similar cases. As Figure 5 shows, after several generations of mutation and heredity, the same form and result are worked out (Goldberg, D.E. 1989.). The two examples above show that as to the super high-rise buildings that are mainly under lateral load, when keeping the volume of the building unchanged, cone shape has the biggest lateral-resistance efficiency (stiffness).

For tapered-shaped supertall buildings, if the framing column is slightly tilted, the lateral drift of the frame can be reduced. More levels can be erected with a tapered form than a rectangle form. Based on a simplified analysis of a tower with 32 stories high, it is divided into three groups as no slope, half slope from the middle, and an entire slope from the top (see Figure 6). When the exterior columns have a inclination of 8%, the 32-floor frame will have a lateral displacement reduced by 50% (Lin, T. & Stotesbury, S.D. 1992).

减少风荷载

随着建筑高度增加，风荷载呈现指数级增长。当建筑高度超过250米时，风荷载一般是超高层建筑中主要的水平控制荷载。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。合理的建筑体型可有效减小风荷载效应，具有更好的空气动力学特性，特别是降低高宽比较大的建筑物的横风向作用。

顺风向风荷载

当场地粗糙度一定时，顺风向水平风荷载随建筑物高度呈指数级增加。在上小下大的锥形立面中，建筑迎风面宽度逐渐缩小，这就减小了建筑上半部受风面积，降低了建筑的立面形心高度，从而使风荷载的合力作用点下降，并且可显著减小顺风向的风荷载以及风荷载导致的倾覆弯矩 (GALSWORTHY, J. (et al.) 2012.) 。

横风向风荷载

当超高层建筑高宽比大于6时，结构变得较为细柔，其所受的横风向作用不容忽视。超高层建筑空气动力学优化重点是降低与横向风振有关的动力荷载与响应。影响横风向共振的主要参数为漩涡脱落的频率f。

$$f = \frac{S_t U}{B}$$

式中St为斯托罗哈数，对矩形截面为0.12，圆形截面为0.2，倒圆角的矩形平面为0.16;

U为建筑物某高度处的风速;

B为建筑物某高度处的特征宽度。

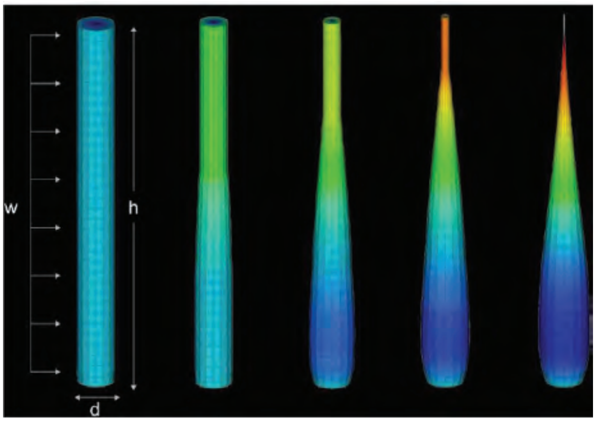

Figure 4. Shape-finding of a high-rise building (Source: Stromberg, L.,Baker, W. F.)
图4. 圆柱形高层建筑结构找形 (出自: Stromberg, L., Baker, W. F.)

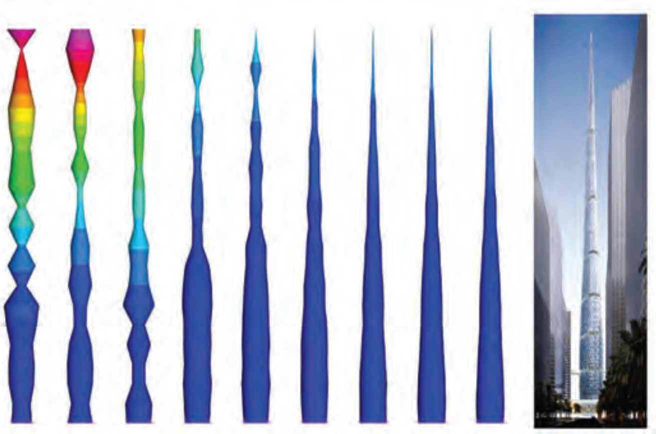

Figure 5. Shape-finding of a high-rise building using genetic algorithms (Source: Stromberg, L.,Baker, W. F. (et al.) 2011.)
图5. 使用遗传算法的圆柱形高层建筑结构找形 (出自: Stromberg, L., Baker, W. F. (et al.) 2011)

Improving the Overall Structural Stability

The tapered-shape building has a different gravity distribution from the non-tapered building (see Figure 7). For the non-tapered building, the gravity distribution remains almost uniform along the elevation of the building. However, for the tapered-shape building, the gravity decreases linearly with the level of the building. The tapered-shape building seems to be more stable since it has a lower gravity center.

To keep the overall stability of the super high-rise building, the P-delta effect shall be small enough to prevent the instability or collapse arisen by the lateral load, such as wind load and earthquake load. Generally, the P-delta effect should be less than 20% when the structural stiffness reduces 50 percent, which means the critical buckling coefficient λcr for the structure on the gravity load will be 10 at least.

Under the gravity load, λcr can be expressed by the following formulas.

For the non-tapered shape structure,

$$\lambda_{cr} = \frac{EI\pi^2}{4H^2}\frac{1}{\frac{1}{3}\sum_{i=1}^{n}G_i} \quad (\text{when} q_2 = q_1)$$

For the tapered-shape structure,

$$\lambda_{cr} = \frac{EI\pi^2}{4H^2}\frac{1}{\frac{5}{18}\sum_{i=1}^{n}G_i} \quad (\text{when} q_2 = 0.5q_1)$$

$$\lambda_{cr} = \frac{EI\pi^2}{4H^2}\frac{1}{\frac{1}{6}\sum_{i=1}^{n}G_i} \quad (\text{when} q_2 = 0)$$

Where EI is the lateral resistant stiffness of the structure, and H is the height of the structure, and $\sum^{n}_{(i=1)}G_i$ is the whole weight of the structure.

In the design of high-rise building, the ratio of stiffness-to-weight KD is used to control the overall stability, which

$$K_D = \frac{EI\pi^2}{H^2\sum_{i=1}^{n}G_i}$$

To keep the overall stability of the high-rise building, KD will be 1.352, 1.127 and 0.676 for q2=q1, q2=0.5, q1 and q2=0 respectively.

The above analysis shows that the tapered-shape structure has lower request of the ratio of stiffness-to-weight, which means the tapered-shape can improve the overall structural stability. Assuming the same height and the same weight of the structure, the larger the tilt angle of the tapered shape is, the lower is the request ratio of rigidity-to-gravity will be, even up to 50% lower.

Increasing the Shear Force Carried by Outer Frame

Chinese code for seismic design requires two seismic resistant systems in supertall buildings. In the frame-core structure, outer frame is required to have enough lateral resistant stiffness and the maximum ratio of story shear force carried by frame to total base shear force under seismic load should be more than 10%. As the shear stiffness of mega frame is small, it is difficult to meet this requirement for mega-frame-core structure. As a result, if the outer frame column is inclined

当风荷载的漩涡脱落频率f与建筑物某一阶自振频率fB接近时，则易产生横风向共振。如果建筑的截面形状或尺寸随高度逐渐变化，则会引起斯托罗哈数St或特征宽度B产生相应的变化，从而干扰了沿楼高方向的漩涡脱落的一致性，达到减小横风向风荷载的效果。由此可见，与传统棱形体型的建筑相比，锥形体型不仅能有效降低建筑所受的横风向作用，而且也可以改善建筑物顶部的舒适度。

提高结构抗侧刚度

超高层建筑体型的优化，可以通过结构找形的方法来实现 (Stromberg, L., Baker, W. F. (et al.) 2011.) 。由于水平荷载作用成为超高层结构设计的主控制因素，因此对于超高层建筑的找形可以通过如下方法进行。在给定的水平荷载作用下，通过假定一个初始形体，(见图4) 比如说是一个圆柱体，以各层楼面的的直径为变量，在整个建筑物的体积和高度不变和底层直径保持不变的情况下，求解整个建筑物顶点水平位移最小 (或抗侧刚度最大) 的最优化解来实现。

图4给出了圆柱形结构找形的一个演变过程，结构的外形从一个圆柱形经过若干次迭代之后变成了一个圆锥体。类似的问题，可采用遗传算法进行优化，如图5所示。经过多代的遗传与变异后，得到了相同的优化结果 (Goldberg, D.E. 1989.) 。上述这两个例子说明，在以水平荷载作用为主的超高层建筑中，保持建筑的体积不变，锥形化体型有着最大的抗侧效率 (刚度) 。

在锥形体型的超高层建筑中，外框架柱略微向内倾斜，可以减少框架的侧移。这样，在相同的体积下，锥形框架可以比矩形框架建造得更高。用简化计算模型对某32层的高层建筑进行研究 (LIN, T. & STOTESBURY, S.D. 1992.) ，分为非倾斜、倾斜高度为1/2高度和全高倾斜三种情况 (请见图6) 。研究结果显示，当外柱的斜率为8%时，可使框架的侧向位移减小50%。

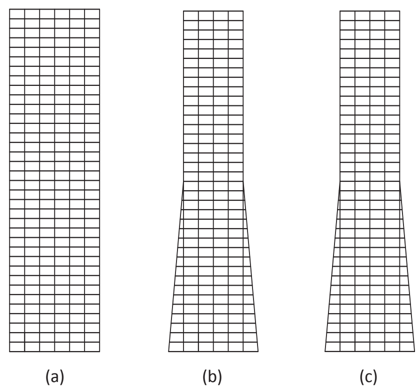

Figure 6. Comparison of lateral-resistance stiffness of frames with different slope (Source: ECADI)
(a) None slope; (b) Half slope from middle; (c) Entire slope from the top
图6. 倾斜框架抗侧刚度对比 (出自: ECADI)
(a) 不倾斜; (b) 1/2高度倾斜; (c) 全高倾斜

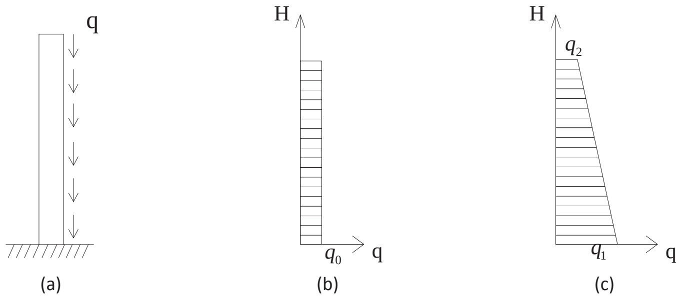

Figure 7. Gravity distribution along the elevation of the high-rise building (Source: ECADI)
(a) Model of high-rise building; (b) Non-tapered building; (c) Tapered-shape building
图7. 建筑物重力荷载沿高度分布 (出自: ECADI)
(a) 超高层建筑模型; (b) 传统非锥形化模型; (c) 锥形化建筑模型

towards inside, horizontal component of axial force in the column can counterbalance part of story shear force caused by horizontal load.

Figure 8 shows the elevation of Goldin Finance 117 Tower, mega-truss tube is used as the outer frame, four mega columns are set at four corners. In each elevation, the inclination θ of the mega column to vertical is 0.882 degree.

One corner column at the bottom of the building is studied for the composition of horizontal shear force under horizontal earthquake loads. As shown in Figure 9, P and Virepresent respectively the axial force and shear force at the cross section of the member; Vt represents the shear force at the horizontal section of the member, whose value could be calculated as the following,

$$V = P \ \sin\theta + V \cdot \cos\theta$$

P·sinθ is the projection of axial force in horizontal direction.

Analysis result shows that the shear force contributed by the axial force of inclined column occupies 23%-31% of the total shear force under the horizontal earthquake load. It proves that the inclined columns can improves the shear capacity of the outer frame.

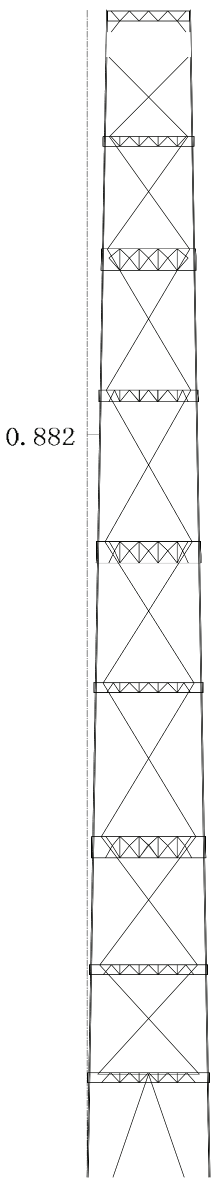

Figure 8. Elevation of outer frame of Goldin Finance 117 Tower (Source: ECADI)
图8. 天津高银117大厦外框结构的立面图 (出自: ECADI)

提高结构整体稳定性

锥形化建筑的重力分布不同于普通建筑 (如图7所示) 。对普通高层建筑，重力分布沿高度接近均匀分布，对锥形化体型建筑，重力分布随高度增加逐渐减小。锥形化体型建筑的重心较低，看起来具有更好地稳定性。

超高层结构的稳定性设计主要控制在风荷载或水平地震作用下，重力荷载产生的二阶效应不致过大，以免引起结构的失稳或倒塌。在结构刚度折减50%的情况下，重力二阶效应需控制在20%，也就是说在重力荷载作用下，结构的第一屈曲临界荷载系数λcr应至少大于10。

在重力荷载作用下，超高层结构第一阶屈曲的临界荷载系数λcr可由下式表示。

对沿高度不变的体型为

$$\lambda_{cr} = \frac{EI\pi^2}{4H^2}\frac{1}{\frac{1}{3}\sum_{i=1}^{n}G_i} \quad (\text{when}\, q_2=q_1)$$

对沿高度不变的体型为

$$\lambda_{cr} = \frac{EI\pi^2}{4H^2}\frac{1}{\frac{5}{18}\sum_{i=1}^{n}G_i} \quad (\text{when}\, q_2=0.5q_1)$$

$$\lambda_{cr} = \frac{EI\pi^2}{4H^2}\frac{1}{\frac{1}{6}\sum_{i=1}^{n}G_i} \quad (\text{when}\, q_2=0)$$

其中EI为结构整体抗侧刚度、H为结构刚度，∑_(i=1)^n G_i 为结构总重力荷载。

在超高层结构设计中，采用刚度和重力荷载的比值的系数，即刚重比

$$K_D=\frac{EI\pi^2}{H^2\sum_{i=1}^{n}G_i}$$

来控制结构的整体稳定性。为保证结构的整体稳定性，对沿高度不变的体型，KD=1.352; 对锥形化体型，当顶层重量为底层的一半时，KD=1.127，当重力荷载沿高度分布为三角形时，KD=0.676。

上述分析表明，锥形化体型的结构对刚重比的要求降低了，即锥形化提高了结构整体稳定性。对同样高度、同样总重量的结构，锥形化的倾斜角度越大，对刚重比要求越低，最多可以低50%。

Figure 9. Force diagram of inclined column (Source: ECADI)
图9. 斜柱受力示意图 (出自: ECADI)

However, coins have two sides. The example above shows that the inclination of mega column towards inside could bring the horizontal component of axial force which is favorable for lateral resistance. On the contrary, the inclination of mega column towards outside could be unfavorable. Figure 10 shows the 3D view and top view of the outer frame structure of Tianxi Tower in Nanning. 8 columns with an inclination towards outside are arranged at the lower zone. The maximal inclination of column to vertical is 6.7 degree. The horizontal component (4153 kN) of axial force in the tilted column occupies 28% of the whole story shear force, whereas the inclination of columns towards outside could cause shear force in the same direction of the lateral load which increase the shear force resisted by core.

In summary, due to the inclination of columns towards inside, the tapered tall building could strengthen the lateral stiffness of outer frame, increase the shear force carried by outer frame and improve the second seismic resistant system. On the contrary, the inclination of frame columns towards inside, which makes a reverse tapered building, could reduce the structural stiffness of outer frame and is unfavorable to the lateral resistance of the whole structure.

Conclusion

Reduction of the plan shape/area of the tower up the height or tapered profile is of significant benefit to architectural functions and structural design in super high-rise buildings. At the same time, a series of problems are brought up and need to be balanced and rethought out.

1. Not only the requirement of the mixed-use functions can be met, but also the structural material is made full use of. And the wind load upon the building can be reduced effectively.
2. Both the stiffness of lateral resisting system and overall stability are improved significantly. As a result, the P-Δ effect is reduced under lateral loads.
3. In the frame core system, inclined columns due to tapered profile can add the shear forces of the outer frame, which guarantees the second seismic resisting system.
4. In some cases, it is impractical that the footprint of the tower is oversized or more levels are needed to erect.
5. Without uniform level up the height in a tapered profile building, the elevation, façade details, formwork system and erection technology will be more complicated. Accordingly, the construction period will be expanded and cost will be added.

提高外框承担剪力

中国抗震规范要求高层建筑需具备二道抗震防线。对于框架核心筒体系来说，要求外部框架具备足够的抗侧刚度，使它所分担的楼层地震剪力最大值不应小于结构底部总地震剪力的10%。由于巨柱框架的抗剪刚度很小，对于大多数的巨型框架—核心筒结构体系来说10%的剪力承担比例是难以满足的。为此，可以将外部框架柱向内倾斜一定的角度，柱轴压力 (轴拉力) 产生的水平分力可以部分抵消水平荷载产生的楼层水平剪力。

图8给出了天津高银117大厦外框结构的立面图，外框结构采用巨型桁架筒，四根巨柱位于结构平面的四个角部，在每一个立面内倾斜角度θ为0.882度。

以其底层的一根角柱为对象，研究其在水平地震荷载作用下构件截面水平剪力的组成。图9为该斜柱的受力示意图。P和Vi (i=x或y，表示方向) 为杆件横截面所受的轴力和剪力，Vt表示杆件所受水平截面上的总剪力值，它的大小可以表示为:

$$V = P\ \sin\theta + V\cdot\cos\theta$$

其中P·sinθ为轴力对水平剪力的贡献量。

分析结果表明，底层柱在水平地震作用下，由于柱子倾斜提供的水平剪力约占总水平剪力值的23%~31%，这说明巨柱轴力的水平分量对楼层水平剪力的影响是客观存在的。

但巨柱轴力的水平分量对楼层水平剪力的影响是双面的。上述例子说明了巨柱向内倾斜，巨柱轴力的水平分量对抵抗水平力有利; 反之，巨柱向外倾斜，巨柱轴力的水平分量对楼层剪力不利。图10给出了南宁天玺大厦外框结构的三维示意图和俯视图，底部共有8根向外倾斜的柱子，在Y方向向外最大倾斜6.7度。通过计算分析可以得到斜柱轴力产生的水平分量 (4153千牛) 占整个楼层水平力 (14732千牛) 可达28%。外倾斜柱为塔楼结构提供负向剪力，与外部水平荷载叠加，反而使核心筒承担更多的水平剪力。

从上面的分析可以看到，锥形化的超高层建筑由于外框柱内倾可以提高外框的抗侧刚度，增加外框分担的剪力和第二道防线的能力; 反之，对于倒锥形建筑，外框柱的外倾会反而会降低外框结构刚度，对整个结构的抗侧产生不利的作用。

结论

在超高层建筑中，锥形建筑体型给建筑功能和结构设计带来了很多好处，也提出了一些新问题，需要在今后的设计中进一步平衡和综合考虑。

1. 不仅是超高层建筑功能综合化的合理选择，而且充分利用结构材料，同时显著减少了对超高层建筑结构设计起主要控制荷载的风荷载。
2. 可显著提高超高层结构整体抗侧刚度和稳定性，减少侧向荷载作用下的P-△效应。
3. 对于框架核心筒体系，适应锥形体型的倾斜外框架柱可有效提高外框架承担的楼层剪力，从而提升外框作为结构抗震第二道防线的作用。
4. 在建筑规划规定的前提下，建筑基底占地面积要求太大较不实际，或需要建造更多楼层得到足够的楼层面积。
5. 对于锥形结构，由于无统一标准楼层，建筑立面、幕墙构造、模板工程以及施工建造技术等更加复杂多变，施工周期和造价相应增加。

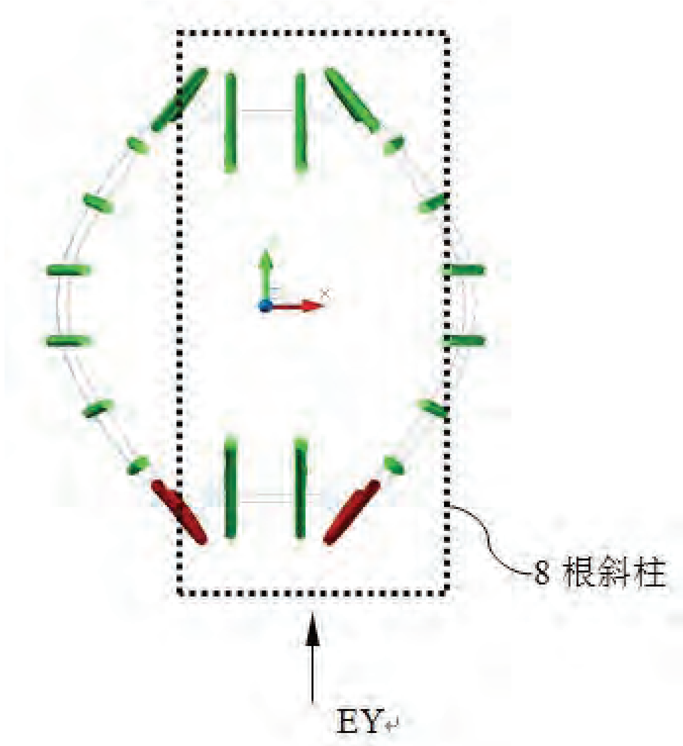

Figure 10. 3D view and top view of the outer frame structure of Tianxi Tower in Nanning (Source: ECADI)
(a) 3D view of the outer frame; (b) top view of the outer frame
图10. 南宁天玺大厦外框结构的三维示意图和俯视图 (出自: ECADI)
(a) 外框结构三维示意图; (b) 外框结构俯视图

References (参考书目):

Ding, J., Wu, H.(et al.) 2014. "**Current Situation and Discussion of Structural Design for Super High-Rise Buildings Above 250M in China**." Journal of buildings structures, Vol.35, No.3:1-7

Galsworthy, J. (et al.) 2012. "**Design of Sustainable Asian Super Tall Buildings for Wind**", Proceedings of the CTBUH 9th World Congress. 408-416. Chicago: Council on Supertall buildings and Urban Habitat

Goldberg, D.E. 1989. **Genetic Algorithms in Search, Optimization, and Machine Learning**. Indiana: Addison Wesley Longman.

Lin, T. & Stotesbury, S.D. 1992. **Structural Concepts and Systems**. Beijing: China Architecture and Building Press.

Sarkisan, M., 2012. **Designing Tall Buildings** .New York and London: Taylor&Francis Group.

Stromberg, L.,Baker, W. F. (et al.) 2011. "**A New Frontier in Modern Architecture : Optimal Structural Topologies**", International Association for Shell and Spatial Structures.

Wang,D., Zhou, J.& Bao, L. 2012. "**Economical Analysis of the Structural Systems for Supertall Buildings**", Proceedings of the CTBUH 9th World Congress. 788-794. Chicago: Council on Supertall buildings and Urban Habitat