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Sustainable Structural Design of Contemporary Tall Buildings of Various Forms

当代多样高层建筑形式的可持续性结构设计

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Abstract

As a building's height increases, the required amount of structural material to resist lateral loads increases drastically. This paper investigates optimal configurations and comparative efficiency between modern structural systems for tall buildings. The intent is to meet design requirements with less structural material in order to save limited resources and construct more sustainable built environments. Tall buildings of various forms, ranging from prismatic to freeform, have been designed with different contemporary structural systems. The structural efficiency of each system, in relation to overall building forms, heights and other important structural configurations, has been studied. Parametric structural models are used to investigate the impacts of various geometric configurations. This study will contribute to providing a useful sustainable structural design guideline for contemporary tall buildings of various forms.

Keywords: Structural Systems, Sustainable Design, Building Forms, Parametric Design

摘要

当建筑物的高度增加时，其相应的承受横向负荷的结构总量也会大幅增加。本文将对现今主要流行的高层结构系统的最优化构造和相对效率进行探讨，尝试挖掘用尽量少的结构材料来达到设计要求的可能性，以创造建造行业的可持续性。无论是棱柱式还是自由式，各种不同形式的高层建筑被配予了当代不同的结构系统。本文对其中各个系统的结构效率和建筑本身的形式、高度以及其他因素间的关系进行了研究，并采用了参数化结构模型研究了不同几何形式对于高层建筑的影响。本文旨在对当今可持续结构设计提供有用参考。

关键词：结构系统、可持续性设计、复杂结构形式、参数化设计

Introduction

Sustainability is one of the most important building design issues today. For tall buildings, which are built with an abundant amount of resources and consume significant amounts of energy, sustainable design is an even more important issue. Selecting an appropriate and efficient structural system for a tall building, through integrative design studies in conjunction with various building systems, is a very important initial step toward sustainable design. Once a particular structural system has been selected, its geometric configuration should be carefully determined because it has a great impact on the system's efficiency.

Lateral shear forces and overturning moments, due to wind loads, significantly influence the structural design of tall buildings. These forces can be carried very efficiently by the primary structural members configured to work in axial actions. When the primary structural members are located over the building's perimeter, the system's efficiency can be maximized. Braced tubes and diagrids are two typical examples that have been developed based on these concepts. Diagrid structures of various

引言

可持续性是当今建筑设计中最重要的课题之一。而高层建筑庞大的耗材耗能使这一课题显得更为重要。如何选择一个合适的高效结构系统并将其整合于整个建筑系统中成为可持续设计至关重要的第一步。当选定某一结构系统后，应该慎重决定其几何构造，因为这将对于系统的效率起到很大影响。

由于风力，横向负荷和倾翻力矩影响着高层建筑的结构设计。这些力可以由主要结构构件的轴向作用来承受。当主要结构部件位于建筑的边缘时，系统的功效为最大。框架筒体结构和斜肋构架结构便是由这个结论产生出的两个典型例子。对于斜肋构架结构，本文研究了其不同方式的整合与角度构造以推导出其比较高功效的几何形态。对于框架筒体结构，本文研究了其不同的列柱间距与支撑构造。加强层结构是当今另一流行的高层结构形式，本文研究了其框架式核心与周边巨型柱之间的优化刚度分布。这些关于框架筒体结构、斜肋构架结构、加强层结构的研究对于棱柱式高层建筑是第一次。

当今建筑领域的多元化让高层建筑不仅限于棱柱式。诸如扭曲式、倾斜式、自由式等复杂的建筑形式相继出现。本课题对于

uniform and varying angle configurations have been studied to determine more efficient geometric configurations. Braced tubes of various column spacings and bracing configurations are studied. Outrigger structures are another prevalently used structural system for today's tall buildings. Optimal stiffness distribution between the core and perimeter mega-columns has been studied for outrigger structures of different heights. These studies with braced tubes, diagrids and outrigger structures have been carried out first for prismatic tall buildings.

Today's pluralism in architecture has produced tall buildings of not only prismatic forms but also more complex forms, such as twisted, tilted and free forms. This paper also studies performance-based structural design options for various complex-shaped tall buildings and investigates more efficient structural solutions to help construct them with less material resources. Parametric structural models have been generated using appropriate computer programs such as Rhino/Grasshopper to investigate the impacts of the variation of important geometric configurations of complex-shaped tall buildings. These include the rate of twist, angle of tilting and degree of fluctuation of free forms. The models have been exported to structural engineering software such as SAP2000 for analyses, design and comparative studies.

The structural design of tall buildings is generally governed by lateral stiffness rather than strength. For the preliminary structural design of each building studied in this paper, stiffness design methodologies have been used to satisfy the maximum lateral displacement requirement of a five hundredth of the building height. The structures studied are assumed to be in Chicago and subjected to wind loads defined by AEI/ASCE Minimum Design Loads for Buildings and Other Structures.

Sustainable Configuration Of Tall Building Structural Systems

Diagrids

The efficiency of a structural system is significantly influenced by its alternative geometric configurations. Therefore, once a system is selected, its detailed configuration should be carefully determined to maximize its structural efficiency and, at the same time, satisfy other non-structural design requirements. Determining geometric configuration is even more important when the diagrid system is used for a tall building because an extremely different structural efficiency can be obtained depending upon alternative diagrid configurations.

- **Diagrids of uniform angles**
  Diagrid structural systems can be configured with diagonals placed at a uniform angle, as is the case with the Hearst Headquarters in New York. The optimal diagrid angle varies depending on the height-to-width aspect ratio of the building. As a diagrid building becomes taller, its optimal diagrid angle becomes steeper, and vice versa for a shorter building, because a taller structure behaves more like a bending beam and a shorter building behaves more like a shear beam. The optimal uniform angles range from 60 to 70 degrees for tall buildings with the height-to-width aspect ratios ranging from about 4 to 10 (Moon et al., 2007).

- **Diagrids of varying angles**
  Appropriately designed uniform angle diagrids are a very efficient structural system for tall buildings. By varying the diagrid angles, the system's efficiency can be further increased. Figure 1 shows examples of a uniform and various varying

复杂形态的高层建筑也进行了基于性能表现的设计研究，并且对低耗材高功效的设计进行了探讨。借助于用Rhino/Grasshopper等适当的软件生成的参数化模型，本课题研究了不同几何构造下的复杂形态高层建筑。其中参数包括：不同的部件扭曲率，不同的倾斜率，还有不同自由形态的波动起伏率。这些模型随后被导入结构工程软件诸如SAP2000中进行相关分析、研究。

决定高层建筑的结构设计往往其侧向刚度，而不是强度。在本文所讨论的每一个例子里，其初始结构设计都采用从刚度设计出发的方法，并且设计效果满足建筑的侧向位移最大不超过建筑高度五个百分点的要求。这些结构研究假设位于芝加哥，他们所承受的风力载荷符合建筑工程学会/美国工程师协会规定的最小建筑载荷。

高层建筑结构系统的可持续性构造

斜肋构架结构

结构系统的功效性很大程度上由它几何构造的可能性决定。因此，当选择一个系统后，该如何具体构造它以让它发挥最大结构功效并让它满足其他非结构方面的设计需要是一个需要慎重推敲的问题。对于斜肋构架结构而言，如何决定它的几何形态构造尤显重要，因为它多样的几何可能性可以使系统具有迥异的结构功效。

- **统一角度的斜肋构架**
  所有斜肋部件可以以相同角度与其他部件连结，比如纽约的赫斯特大厦（Hearst Headquarters）。最优化的斜肋构架角度取决于建筑的高宽比。随着一座建筑物增高，它的最优化斜肋构架角度会越来越陡，反之亦然。这是由于高的建筑物的表现好比为一个弯曲的梁，而矮的建筑物的表现好比为一个剪切梁。当高层建筑物的高宽比范围在4至10时，它统一角度斜肋构造的最优角度在60度到70度之间（Moon et al.，2007）。

- **不同角度的斜肋构架**
  在适当的设计下，统一角度斜肋构架结构会是一个对高层建筑来说功效非常好的系统。如果恰当的改变斜肋部件的角度，系统的功效性可以进一步增强。图1显示了统一角度和不同角度斜肋构架结构的例子。其中建筑物的高宽比约为7。每一座建筑的平面大小为54 x 54米。

- **垂直变化角度的斜肋构架**
  案例1.5为一个垂直变换角度的斜肋构架结构，它斜肋部件的角度越接近地面越陡。这一构造和SOM在首尔的乐天超级塔项目很像。研究显示，当建筑物的高宽比大于7时，采用纵向直变化角度的斜肋构架系统会降低整体耗材。其原因是，斜肋部件在陡的角度能更好的在高建筑物底层抵抗由风力产生的倾覆力矩。

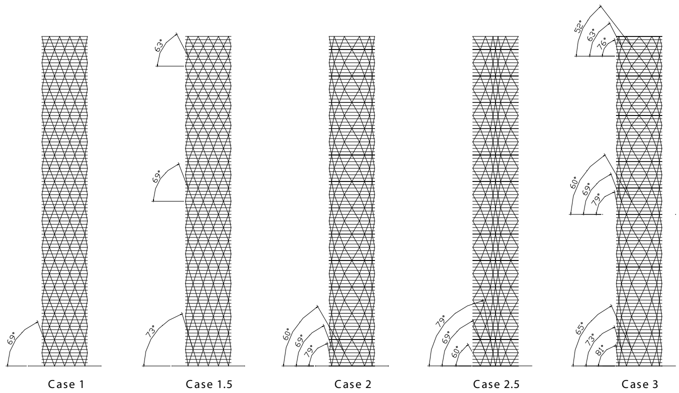

Figure 1. Diagrids of various angle configurations.
图1. 不同角度构成的斜肋构架

angle diagrid structures, the height-to-width aspect ratio of which is about 7. Each building's plan dimensions are 54 x 54 meters.

- **Vertically varying angle diagrids**
  Case 1.5 is an example of vertically varying angle diagrids configured with steeper angle diagonals toward the base. This configuration is similar to that of the Lotte Super Tower design project in Seoul by SOM. Study results suggest that the vertically varying angle configuration uses less structural material than the uniform angle configuration for tall buildings with height-to-width aspect ratios larger than about 7. The reason is diagonals placed at a steeper angle are better at resisting large wind-induced overturning moments at the base of a very tall building.
- **Horizontally varying angle diagrids**
  Diagrids can be configured with steeper angle diagonals toward the building corners, as shown in Case 2, to increase the contribution of diagonals on the web planes (planes parallel to wind) to bending rigidity. Case 2.5 is the reverse case, with shallower angle diagonals toward the building's corners. In this case, the lateral stiffness of the system is substantially decreased. As can be seen in Table 1, the maximum lateral displacement of Case 2 is 72.7 cm, while that of Case 2.5 is 90.1 cm. The amounts of structural steel used for both cases are identical.
- **Combined varying angle diagrids**
  The vertical and horizontal angle variations can be combined to maximize the structural efficiency of diagrids. Case 3 shows the combined angle variation of Cases 1.5 and 2. By combining the vertical and horizontal angle variations, the maximum lateral displacement is reduced by 5.4%. Table 1 summarizes the comparative maximum lateral displacements and steel masses used for the five diagrid structures shown in Figure 1. The difference inmaterial used between the five cases are negligible.

Braced Tubes

The braced tube, developed decades ago, is another very efficient structural system for tall buildings. It carries lateral loads primarily by axial actions of the perimeter columns and braces and is still widely used for today's tall buildings. Structural efficiency of the braced tube is also substantially influenced by the configuration of its perimeter columns and braces. Figure 2 illustrates braced tubes of various column and bracing configurations.

- **Braced tubes of various column spacings**
  Perimeter column spacing strategies have been studied in this section to improve lateral stiffness of the braced tube system. The height-to-width aspect ratio of each braced tube structure shown in Figure 2 is about 7 and the building's plan dimensions are 54 x 54 meters. Braced tube structural systems are configured with perimeter diagonal braces and vertical columns typically spaced evenly, as is the case with Case 0. In Case 1.1, the column spacing is gradually reduced from 12 m at the middle of each façade plane to 6 m at the building's corners. Between it is 9 m. In Case 1.2, the column spacing is reversed. As the column spacing becomes denser toward the building's corners, the web columns' contribution to the system's bending stiffness increases, and vice versa. Table 2 summarizes the maximum lateral displacements of the braced tubes of various configurations shown in Figure 2.

	Maximum Displacement (cm) 最大位移(厘米)	Maximum Displacement (%) 最大位移(百分比)	Steel Mass only for Diagrids (ton) 单斜肋构架的钢用量(吨)	Steel Mass (%) 钢用量(百分比)
Case 1 例1	76.0	100.0	19,779	100.0
Case 1.5 例1. 5	74.6	98.2	19,612	99.2
Case 2 例2	72.7	95.7	19,891	100.6
Case 2.5 例2. 5	90.1	118.6	19,891	100.6
Case 3 例3	71.9	94.6	19,661	99.4

Table 1. Study results of diagrids shown in Figure 1.
表1. 图1中斜肋构架的研究数据

- **水平变化角度的斜肋构架**
  如案例2，在越接近建筑物的拐角处时，斜肋部件的角度可以相对变陡，这样一来在网状平面上（和风平行的面）的斜肋部件就可以有更强的抗弯刚度。案例2.5是此情况的反例，它的斜肋部件在接近拐角处时角度相对变平，它的侧向刚度因此大大减小。如表1所示，案例2中建筑物的水平方向最大位移为72.7厘米，而案例2.5中则为90.1厘米。在两例中，钢结构耗材总量相同。
- **组合变化角度的斜肋构架**
  垂直方向和水平方向的斜肋部件角度变化可以组合在一起以优化系统的功效。案例3为案例1.5和案例2角度变化的组合。当垂直角度变化和水平角度变化组合在一起后，建筑物的最大侧向位移减少了5.4%。表1总结了图1中五个斜肋构架结构的相对最大横向位移值与钢结构用量，这五个例子中的钢用量近于相等。

框架简体结构

几十年前发明的框架简体结构是另一个功效很高的高层建筑结构系统之一。在这种结构里，侧向负荷大部分是靠周边柱子和支架的轴向动作承受。框架简体结构的功效也随着周边柱子和支架的构造改变而改变。图2显示了不同柱子和支架构造的框架简体结构。

- **不同柱间距的框架简体结构**
  本节研究了如何通过改变柱间距来提高框架简体结构的侧向刚度。在图2中，每一个框架简体结构的高宽比约为7，建筑物的平面大小约为54 x 54米。在典型的框架简体结构中，周边支架和柱子通常都呈等间距排布，如案例0。在案例1.1中，柱间距从立面中段的12米逐渐减少到拐角处的6米。这其中为9米。在例1.2中，柱间距与上述相反。当柱子在拐角处越来越密时，网面上柱子可以更好地发挥其抗弯刚性。越疏则越差。表2总结了图2中各种框架简体结构构造下的最大侧向位移。

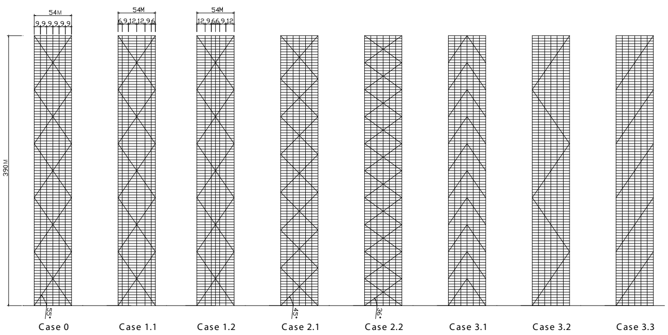

Figure 2. Braced tubes of various configurations.
图2. 不同形式的框架简体

- **Braced tubes of different diagonal angles**
  An angle of about 35 degrees produces the maximum shear rigidity for braced tubes (Moon, 2010). Therefore, diagonal member sizes can be smaller as the diagonal angle nears 35 degrees. However, smaller member sizes at each level do not guarantee that the least amount of material is used overall. While the diagonal member sizes become smaller as the angle nears 35 degrees, the total length of all diagonals decreases as the angle becomes steeper. Cases 0, 2.1 and 2.2 are designed with braces placed at angles of 55, 45 and 36 degrees, respectively. When the overall amount of structural steel used is almost identical in these three cases, the lateral stiffness of each structure, with diagonal braces placed at substantially different angles, is also very similar.

- **Braced tubes of different brace shapes**
  In addition to X-braces used for Case 0, other types of braces are also used for tall building structures, as can be seen in Cases 3.1, 3.2 and 3.3. When the same amount of structural material is used, the case of X braces that are continuously connected over the entire building height, provides the greatest lateral stiffness among the four cases. The structural performances of Case 3.1 with chevron bracings and Case 3.2 with alternate direction single diagonal braces are not much different. The lateral stiffness of Case 3.3 with single direction single diagonal braces is substantially smaller than that of the other three cases.

Outrigger Structures

The outrigger system is another prevalent structural system for today's tall buildings. Structural efficiency of outrigger structures depends on the number and locations of outrigger trusses. These were studied and presented by many, including Smith and Coull (1991). This section investigates optimal lateral stiffness distribution between the braced core and perimeter mega-columns of outrigger structures.

- **Optimal stiffness distribution**
  Tall buildings of 60, 80 and 100 stories have been designed with steel outrigger structures as shown in Figure 3. The height-to-width aspect ratios of the 60-, 80- and 100-story outrigger structures are about 6, 8 and 10, respectively. The building's plan dimensions are 36 x 36 meters and its typical story height is 3.9 meters. Braced cores of 18 x 18 meters are located at the center. Double story height outrigger trusses are located at every 20 stories.

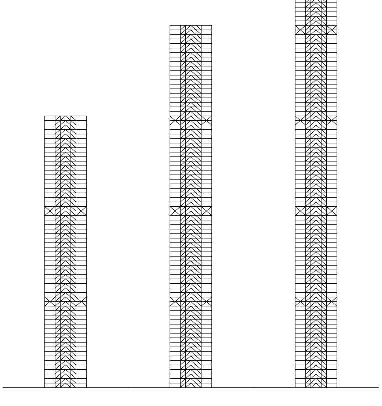

Figure 3. 60-, 80- and 100-story outrigger structures.
图3. 60、80及100层高的加强层结构

	Case 0 例0	Case 1.1 例 1.1	Case 1.2 例 1.2	Case 2.1 例 2.1	Case 2.2 例 2.2	Case 3.1 例 3.1	Case 3.2 例 3.2	Case 3.3 例 3.3
Maximum Lateral Displacement (cm) 最大侧向位移（厘米）	76.0	73.4	78.2	75.9	75.8	77.8	78.4	82.2

Table 2. Maximum lateral displacements of braced tubes shown in Figure 2.
表2. 图2中框架筒体的的最大侧向位移

Stiffness Distribution b/w Core and Mega-Col 核心和巨型柱之间的刚度分布比例				
		3:7	4:6	5:5
Structural Steel Use in % 结构钢用量百分比	60-Story Outrigger Structures 60层高加强层结构	101.8%	100.0%	101.5%
	80-Story Outrigger Structures 80层高加强层结构	100.9%	100.0%	104.5%
	100-Story Outrigger Structures 100层高加强层结构	95.2%	100.0%	105.6%

Table 3. Structural steel use comparison for the outrigger structures with different stiffness distribution ratios between the braced core and perimeter mega-columns.
表3. 框架式核心和周边巨型柱之间不同的刚度分布比例及其构成的加强层结构的钢用量对比

- 不同支架角度的框架筒体结构
  35°的支架角度可以使框架筒体产生最大的抗剪刚度（Moon，2010）。因此，在角度接近35°时，斜支架部件的尺寸可以相对减小。但是，如此每一层都用小尺寸部件也不能保证整体结构耗材减少。虽然斜支架部件在越接近35°越来越小，但是当角度变大时，斜支架部件的总长度会变小。案例0、2.1和2.2 中，斜支架部件分别放在55°、45°和36°。在这些情况里，钢材料的耗材总量几乎相同，它们的侧向刚度也几乎相同，即使它们的斜支架部件放置角度不同。

- 不同支撑形状的支撑筒体结构
  除案例0中的X形支架外，其他不同种类的支撑也可以被运用于高层结构里，就像案例3.1、3.2、3.3显示的那样。当结构的耗材量相同时，覆盖整幢建筑物高度的X形支撑可以形成最大的侧向刚度。例3.1中的V形支撑和例3.2中的变向单向斜支撑在结构表现上没有很大区别。例3.3中的单向斜支撑的侧向刚度比其他三个例子要小很多。

加强层结构

加强层结构是现今主要流行的另一种高层结构体系。加强层结构的功效是由加强层桁架的数量和位置决定的--这曾被包括史密斯和库尔(1991)在内的许多人研究和表述过。本节将探讨加强层结构中框架式核心与周边巨型柱之间的优化侧向刚度分布。

- 优化刚度分布
  图3示意由钢结构加强层组成的60、80和100层的高楼。这些60、80 和100层高的加强层结构的高宽比分别是6、8和10。楼层平面的大小为36米x36米，典型的层高为3.9米。18米x18米的带支撑的核心筒位于中央，每20层置有双层高的加强层桁架。

研究表明，带支撑的核心筒与周边巨型柱之间的抗弯刚度分布比例为3：7、3：6和5：5。这些刚度比例是由两种不同结构的模型得出的：一个是只含有带支撑的核心筒的局部模型；另一个带有整个加强层系统，包括通过加强层桁架连接到带支撑的核心筒的巨型柱。表3中总结对比了三种不同高度加强层的结构钢用量，列举了满足相同侧向位移条件的三种不同刚度分布比例。对于60和80层高的加强层结构，比例为4：6的刚度分布为最优化设计；对于100层高的则是3:7。不同刚度分布比例由建筑高度的增加影响越发明显。

The studied bending stiffness distribution ratios, between the braced core and perimeter mega-columns, are 3:7, 4:6 and 5:5. These stiffness ratios are based on the two different structural models: a partial model only with the braced core and an entire outrigger system model including mega-columns, connected to the braced core through outrigger trusses. Table 3 summarizes the comparative structural steel use for the three different heights of outrigger structures with the three different stiffness distribution cases to satisfy the same target lateral displacement requirement. For the 60- and 80-story outrigger structures, a stiffness distribution ratio of 4:6 produces the most efficient design, while for the 100-story outrigger structure it is 3.7. The impact of different stiffness distribution becomes greater as the building height increases.

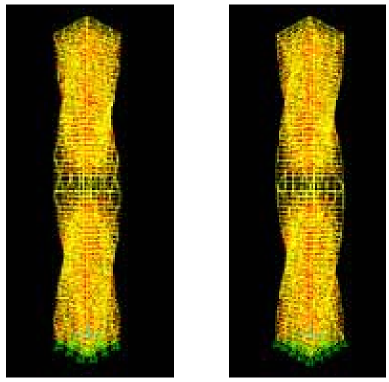

Figure 4-1. Examples of 60-story twisted diagrid (left) and braced tube (right) structures.
图4-1. 60层高的扭曲状斜肋构架和框架筒体结构

Twisted Tall Buildings

Twisted forms are often employed for today's tall buildings, with the Shanghai Tower in Shanghai and Infinity Tower in Dubai as cases in point. This section studies various structural system design options for twisted tall buildings and their performance. Twisted tall buildings of 60, 80 and 100 stories have been designed with diagrids, braced tubes and outrigger systems. The height-to-width aspect ratios of these buildings range from about 6 to 10. The studied buildings' typical plan dimensions are 36 x 36 meters with 18 x 18-meter gravity cores for braced tubes and diagrids, and braced cores for outrigger structures. The rates of twist studied range from 1 to 3 degrees per floor.

Twisted diagrids and braced tubes

Both the diagrids and braced tubes are very efficient structural systems for tall buildings of more conventional shapes, such as rectangular box form towers. If these structural systems were employed for twisting tall buildings, the systems' lateral stiffness decreases as the rate of twist increases. Figure 4-1 illustrates examples of 60-story twisted diagrid and braced tube structures. The stiffness reduction of braced tubes, composed of verticals and diagonals, is much more sensitive to the rate of twist compared to that of diagrids, composed of only diagonals. This sensitivity becomes accelerated as the building height increases. Figure 5 clearly shows this phenomenon with the maximum lateral displacements of twisted diagrids and braced tubes of various heights and rates of twist. For both the diagrids and the braced tubes, the member sizes determined for the straight structures using stiffness based design methodologies are also used for the twisted structures, in order to investigate comparative structural efficiency.

Twisted outrigger structures

The outrigger tower of 60 stories has been twisted with two different rates, as shown in Figure 4-2. The first case twists the tower by 1.5 degrees per floor, which results in a total turn of 90 degrees. The result is that the mega-columns on the building perimeter wrap around the building spirally. Therefore, the position of the mega-columns on the flange planes (i.e., planes perpendicular to wind) at the base changes to those on the web planes at the top, which decreases the lateral stiffness of the system. The second case twists the tower by 3 degrees per floor, which results in a total turn of 180 degrees. In this case, the position of the mega-columns on the flange planes at the base changes to those on the web planes at mid-height, and finally to those on the opposite flange planes at the top. This geometric configuration forces the structure to behave more like a cantilever beam without outriggers, compared to typical outrigger structures in which curvature reversals occur around the outrigger truss levels. As a result, this increased rate of twist further decreases the lateral stiffness of the system. Figure 6 summarizes lateral displacement profiles of the

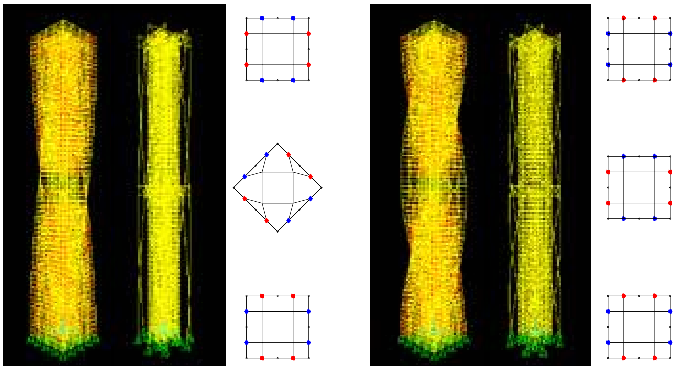

Figure 4-2. 60-story twisted outrigger structures with rates of twist of 1.5 and 3 degrees per floor.
图4-2. 每层楼扭转 1.5度和3度的60层高的加强层结构

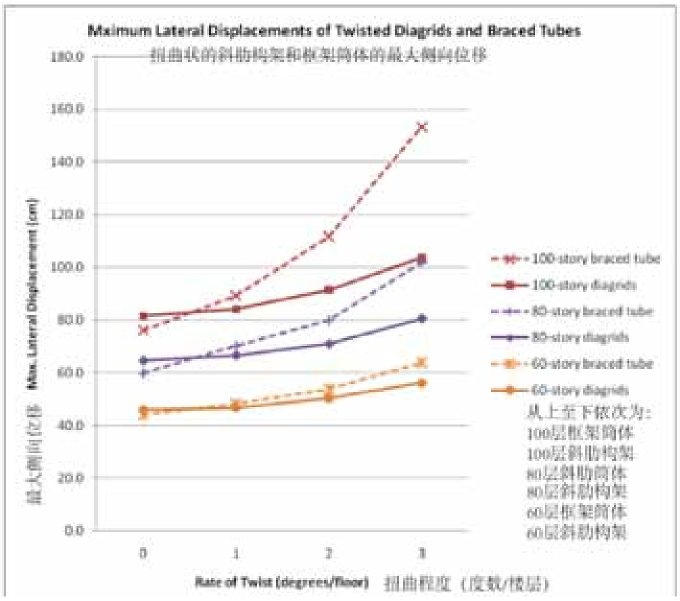

Figure 5. Maximum lateral displacements of twisted diagrids and braced tubes.
图5. 扭曲状的斜肋构架和框架筒体的最大侧向位移

扭曲状高层建筑

现今有许多高层建筑采用扭曲状的外形设计，例如上海的上海中心大厦和迪拜的无限塔。本节研究了针对扭曲状高层建筑及其性能所做出的不同的结构系统设计方案。60、80和100层高的扭曲状高层建筑已采用斜肋构架、框架筒体和加强层结构。这些建筑高宽比范围在6到10之间。研究的建筑平面大小一般是36米x36米，核心18米x18米--框架筒体和斜肋构架结构采用重力核心，而加强层结构则采用框架式核心。扭转的角度每层在1至3度之间。

Lateral displacements du to Gravity 重力导致的侧向位移				
Floor Offset 楼层偏置	Tilted Angle (degrees) 倾斜角度(度)	Braced Tubes 框架筒体	Diagrids 斜肋构架	Outrigger Systems 加强层系统
0 Fl Offset 0楼层偏置	4	42.2	39.3	38.6
12 Fl Offset 12楼层偏置	9	53.7	55.1	42.7
16 Fl Offset 16楼层偏置	7	58.1	59.4	52.0
20 Fl Offset 20楼层偏置	13	59.7	62.5	53.9

Table 4. Gravity-induced maximum lateral displacements of tilted structures shown in Figure 7-1, 7-2 and 7-3
表4. 图7.1、7.2和7.3中倾斜式的结构中重力导致的最大侧向位移

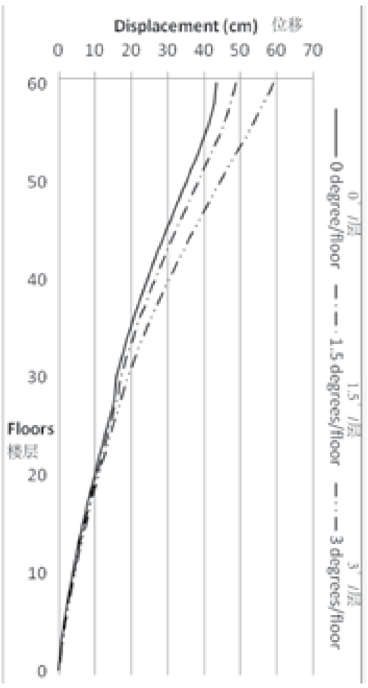

Figure 6. Lateral displacement profiles of 60-story twisted outrigger structures.
图6. 60层高的扭曲状的加强层的侧向位移图

60-story twisted outrigger structures . Similar studies were conducted with 90-story twisted outrigger structures and it was found that their overall structural performance characteristics were similar to those obtained in the 60-story twisted outrigger studies.

Tilted Tall Buildings

Employing tilted forms in tall buildings is a relatively new architectural phenomenon, with the Gate of Europe Towers in Madrid and the Veer Towers in Las Vegas as cases in point. This section studies structural system design options for tilted tall buildings and their performance. The 60-story tall building has now been tilted with various offsets and designed with diagrid, braced tube and outrigger structural systems. Tilted towers are deformed laterally not only by wind but also by gravity loads, due to their eccentricity. Figures 7-1, 7-2 and 7-3 illustrate tilted braced tubes, diagrids and outrigger structures, respectively. The first cases are the straight towers without tilting. The second cases are continuously tilted cases with a tilt angle of 4 degrees. The third, fourth and fifth cases, with offsets of 12, 16 and 20 floors, result in tilted angles of 7, 9 and 13 degrees, respectively.

扭曲状斜肋构架及框架筒体

斜肋构架及框架筒体是高层建筑中较传统外形（如长方体盒状塔楼）更有效的结构体系。如果这些结构体系被用于扭曲状的高层建筑，系统的侧向刚度将由弯曲角度的上升而减小。图4-1中例举了60层高的扭曲斜肋构架和框架筒体结构。从所减少的刚度来看，相比由对角线组成的斜肋构架，由竖直和对角线组成的框架筒体对于扭转的角度更加灵敏。 这种灵敏度由建筑高度的提升而增强。图5清楚地说明了这种现象，展示由不同高度和扭转角度构成的有着最大侧向位移的扭曲斜肋构架和框架筒体。对于斜肋构架和框架筒体，为探究相对的结构效能，在竖直建筑中以刚度为基础设计的构件尺寸也被用于扭曲状的结构。

扭曲状加强层结构

图4-2展示了由两种扭转角度所生成的60层高的加强层建筑。第一个例子中每层楼旋转1.5度，总共加起来旋转90度，致使楼周边的巨型柱呈旋转状分布。这样巨型柱的位置由底部翼缘平面(与风向垂直的平面)向上方网状平面变化,从而减小了系统的抗弯刚度。第二个例子中每层楼旋转3度,总共加起来旋转180度。在这种情况下，巨型柱的位置由底部翼缘平面向上变化，在高度的一半转换到网状平面上，最后在顶部到相反方向的翼缘平面上。比之其曲率在加强层桁架层变化的一般的加强层结构，这种几何分布致使结构的性能更像没有加强层的悬挑梁。结果表明扭转角度的提升减小了系统的侧向刚度。图6为60层高加强层结构的侧向位移的曲线图。之前人们曾对90层高的加强层结构进行此类研究，发现它们整体的结构性能与60层高加强层的相似。

倾斜式的高层建筑

高层建筑采用倾斜式的外形是一个比较新的现象，像马德里的欧罗巴门塔和拉斯维加斯的维尔酒店双塔就是这样的例子。本节探讨了针对倾斜式高层建筑及其性能所做出的结构系统设计方案。现在60层的高楼在不同位置倾斜，分别由斜肋构架、框架筒体及加强层结构系统构成。倾斜的高楼不但由风力影响，而且根据重心的偏移程度受重力作用在侧向形变。图7—1，7—2和7—3分别示意斜肋构架、框架筒体及加强层结构。每张图中第一个是没有倾斜的竖直高楼；第二个连续呈4度角倾斜；第三、四、五个分别在12、16和20层倾斜，倾斜的角度为7度、9度和13度。

倾斜式的框架筒体和斜肋构架

倾斜式的框架筒体和斜肋构架在风力作用下的侧向刚度与竖直的框架筒体和斜肋构架相似，毋庸考虑倾斜角度的变化。图8归纳了倾斜式结构在风力影响的侧向位移。表4显示倾斜式的框架筒体和斜肋构架最初的侧向位移受重力影响非常显著。当倾斜的角度增大时，在重力作用下的侧向位移比由风力导致的要更大。但是如果在施工过程中严格规划，由重力影响的形变可以被有效地控制住。

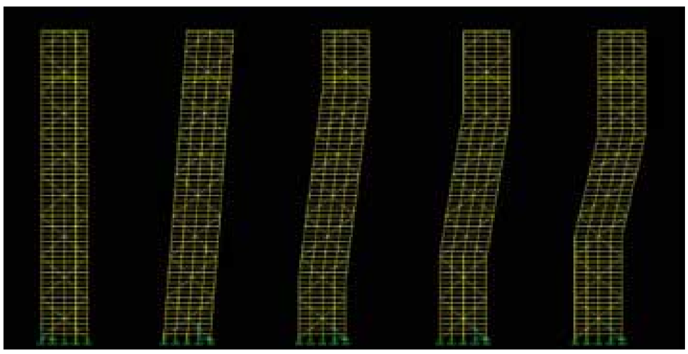

Figure 7-1. 60-story tilted braced tubes (elevation view).
图7-1. 60层高的倾斜式框架筒体（立面视图）

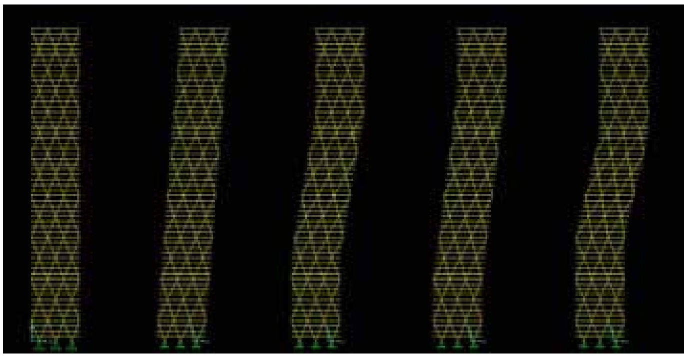

Figure 7-2. 60-story tilted diagrids (elevation view).
图7-2. 60层高的倾斜式斜肋构架（立面视图）

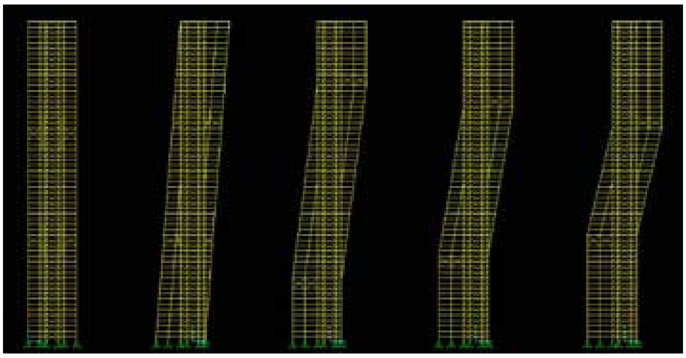

Figure 7-3. 60-story tilted outrigger structures (section view at outrigger truss plane).
图7-3. 60层高的加强层结构（加强层桁架剖面视图）

Tilted braced tubes and diagrids

Lateral stiffness of the tilted braced tubes and diagrids against wind loads is similar to that of the straight braced tube and diagrid structures, regardless of the changes of the tilted angles. Figure 8 summarizes wind-induced maximum lateral displacements of the tilted structures. Initial lateral displacements of the tilted braced tubes and diagrids, due to gravity loads, are significant as can be seen in Table 4. These gravity-induced lateral displacements, which are even larger than the wind-induced displacements, become greater as the angle of tilt increases. However, gravity-induced deformations can be managed substantially during the construction process if they are carefully planned.

Tilted outrigger structures

Lateral deformations, caused by wind loads, are reduced in tilted outrigger structures. Wind-induced maximum lateral deformation values obtained by structural analyses are 47.8, 37.9, 34.6, 33.6 and 34.6 cm for the straight and four tilted outrigger structures as shown in Figure 7-3. Increased lateral stiffness of the outrigger system in tilted towers is a result of triangulation by the major structural components – braced core, outrigger trusses and mega-columns - by tilting the tower, as can be seen in Figure 7-3. Gravity-induced lateral deformations are also relatively small in tilted outrigger structures, compared to those in tilted braced tubes or diagrids.

Freeform Tall Buildings

As a building's form becomes more irregular, finding an appropriate structural system for better performance and constructability is essential to successfully carry out the project. Freeform structures, defined by polygons other than triangles, can be easily distorted. Triangular units of diagrids are not only structurally very efficient for tall buildings but are also more appropriate to define any freeform shape without distortion. This section studies structural performance of diagrid structural systems employed for freeform towers. Free forms in this study have been generated by combining various sine curves. The primary variable of the free forms is their deviation from the original rectangular box form. The degree of deviation is measured as the maximum distance deviated from the original rectangular box form. The rectangular box form diagrid building's typical plan dimensions are 36 x 36 meters with an 18 x 18-meter core at the center. Figure 9 shows three 60-story freeform diagrid structures with the maximum deviation distances of +/- 1.5, 3 and 4.5 meters. The gross area of each building remains the same regardless of the different degrees of deviation.

The lateral displacement of the structure becomes larger as the freeform shape deviates more from its original rectangular box form. The maximum lateral displacements of the first, second and third cases

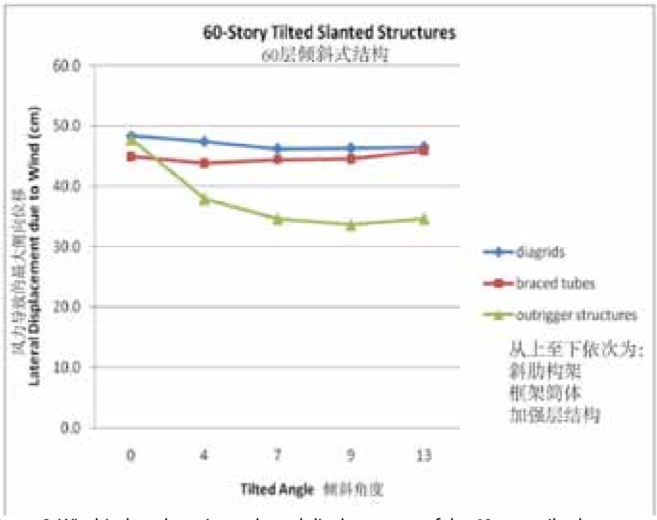

Figure 8. Wind-induced maximum lateral displacements of the 60-story tilted structures shown in Figures 7-1, 7-2 and 7-3.
图8. 图7-1、7-2和7-3中60层倾斜式结构中风力导致的最大侧向位移

倾斜式的加强层结构

在倾斜式的加强层结构中，受风力影响所产生的侧向形变会有所减小。当对图7—3中竖直和四种倾斜形式的加强层结构进行结构分析，结果显示它们由风力产生的最大侧向形变大小分别为47.8、 37.9、34.6、33.6和34.6厘米。图7—3显示，当高楼倾斜时，呈三角形状的结构构件--框架筒体、加强层桁架及巨型柱--提升了倾斜式高楼中加强层系统的侧向刚度。与框架筒体和斜助构架相比，受重力影响的侧向形变在加强层结构中并不明显。

自由式高层建筑

对于有着不规则外形的建筑，找到性能更好且易于建造的合适的结构系统非常重要。自由式的结构——由多边形和三角形组成——非常容易形变。在高层建筑中，三角形单元组成的斜肋构架不但结构非常高效，而且便于形成自由式的外形并使其不形变。本节研究了斜肋构架在自由式建筑中的结构性能，其中自由式的外形由合并多种正弦曲线所得出。自由式形式基本的变量为它们偏离原有长方体盒状形式的尺度，这可以通过测量偏离长方体盒状形式最大的距离而得出。斜肋构架组成的盒形建筑典型的平面大小为36米x36米，有18米x18米的核心位于中央。图9展示了三座60层高的自由式斜肋构架结构，它们最大偏离的距离的绝对值分别为1.5、3和4.5。尽管这三座建筑偏离的尺度不同，它们每层楼的建筑面积是相同的。

当自由式的形式与原有长方盒外形偏离程度越大时，结构的侧向位移也就越大。图中第一、二、三个最大的侧向位移分别是52.2、58.0和69.0厘米，而棱柱式的高楼则是46.6厘米。与扭曲式斜

are 52.2, 58.0 and 69.0 cm, respectively, compared to 46.6 cm in the case of the prismatic tower. Similar to the cases of twisted diagrids, this stiffness reduction is again very much related to the changes of the diagrid angle caused by free-forming the tower. The prismatic tower of the first design is configured with diagonals placed at an angle close to the optimal. As the degree of fluctuation of free form increases, the diagrid angle deviates more from its original near-optimal condition, and, consequently, lateral stiffness of the diagrid system is substantially reduced.

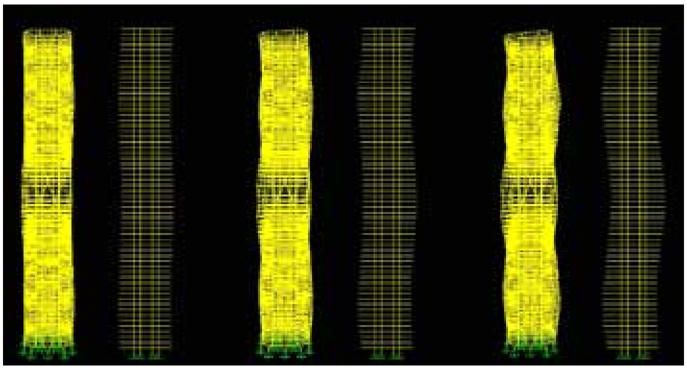

Figure 9. 60-story freeform diagrids (3D and section views) with the maximum deviation distances of +/- 1.5 m, 3 m and 4.5 m from the rectangular box form diagrids.
图9. 与盒状外形最大偏离位移绝对值为1.5米、3米和4.5米的60层自由式斜肋构架(3维和剖面视图)

肋构架相似，自由式高楼中所减少的刚度与斜肋构架角度的变化相关。第一个方案中的棱柱式高楼采用了近于优化的角度的斜肋构架。当自由式的外形起伏程度增大，斜肋构架角度将更加偏离原本近于优化的条件，结果是斜肋构架系统的侧向刚度明显减弱了。

Conclusions

Tall buildings have become a worldwide architectural phenomenon and require a significant amount of resources because of their enormous scale. This paper presented sustainable structural design guidelines for contemporary tall buildings of various forms. The efficiency of a particular structural system selected for a tall building is substantially influenced by its detailed configurations. This paper studied diagrids, braced tubes and outrigger structures of various geometric configurations and stiffness distributions.

As a building's form becomes more complicated, finding an appropriate structural system and configuration for better performance and constructability is essential for successful execution of the project. The studies presented in this paper have been primarily about the static responses of tall structures due to wind loads. With regard to the across-wind directional dynamic responses due to vortex shedding, it should be noted that complex-shaped tall buildings generally perform better. This is because they can mitigate wind-induced vibrations by disturbing the formation of organized alternating vortexes. Considering that vortex-shedding-induced lock-in phenomenon often produces the most critical structural design condition for tall buildings, complex building forms' structural contribution can be significant.

Structural performance substantially influences the design of tall buildings, while the most efficient structural solution may not best support other building systems. Therefore, not only structural but also architectural characteristics, constructability and other aspects should be studied holistically to select the most appropriate structural system and its configuration for tall buildings. Considering the many tall buildings being proposed all over the world, the importance of studies on sustainable design strategies for tall buildings cannot be overemphasized in regards to saving our limited resources.

结论

高层建筑现今已在全球普及,由于它们建造的规模庞大,所消耗的能源也非常多。本文为当今多样的高层建筑形式提供了可持续结构设计的纲领。每个高层结构系统的效率极大程度上是由它细部的构造决定的。本文研究了斜肋构架、框架筒体和加强层结构不同的几何构成和刚度分布。

当建筑的外形变得越发复杂时，为使项目顺利地执行，采用高效且适宜建造的结构系统及其形态至关重要。本文所做的研究主要针对高层建筑在风力影响下的静态反应。值得注意的是，对于旋涡脱落引致的横风向动力反应，有着复杂外形的高层建筑结构一般更加高效，这是因为它们可以干扰规则交替旋涡的形成，从而削减风力振动。 考虑到旋涡脱落导致的锁定现象是高层结构设计中最主要的制约条件，复杂的建筑外形在结构上的贡献很大。

结构的性能很大程度上影响着高层建筑的设计，但一个高效的结构系统并不一定适用于另一个建筑的系统。因此，当为高层建筑选择最适用的结构系统和形态时，除了结构本身，还需要全面考虑建筑的特性、可建造性及其他方面的问题。考虑到现下全球有众多在规划中的高层建筑，为了节省我们有限的资源，研究其可持续性的设计策略至关重要。

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