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Development of Innovative Structures for Supertall and Unique Towers

超高层建筑的创新结构发展


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John Viise先生为高层建筑及特殊用途结构提供了结构工程服务。Viise先生负责设计的工程项目包括与福斯特建筑事务所合作的位于阿布扎比的中央市场重建项目，以及与AS+GG合作的天津万通中心办公楼项目。Viise先生曾负责设计的工程项目包括迪拜塔、芝加哥特朗普国际酒店大厦和广州珠江城大厦。

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赵延彤博士所参加设计的高层建筑工程项目遍及世界各地，在超高层建筑结构分析与设计方面具有技术专长。工程项目包括48 层的芝加哥君悦中心大厦、马德里卡哈大厦、迪拜指标大厦、莫斯科的俄罗斯大厦和上海金茂大厦的结构设计。

Robert Halvorson, the founding Principal of Halvorson and Partners. He began his career at SOM and became a Partner in 1985. He was also the Partner in Charge of the structural group during the design of the Jin Mao Tower. He led H+P's designs for the Index Building in Dubai, Central Market Towers in Abu Dhabi and the re-constructible UAE Pavilion at Expo 2010 in Shanghai.

Robert Halvorson 先生是H+P建筑结构事务所的创始人。1975年他的职业生涯始于SOM建筑事务所，1985年成为SOM合伙人。在设计上海金茂大厦期间，他担任结构工程总监。他领导H+P参与设计的项目包括迪拜指标大厦、阿布扎比中央市场大厦、以及2010年上海世博会阿联酋展馆。

Abstract

As tall buildings grow to greater heights and strive to incorporate more unique forms, clarity in the development of the structural system at conceptual design is essential. These types of projects must be rooted in fundamental principles, including sound wind and seismic engineering. With the critical groundwork laid in the preliminary design phases, the power of the latest in digital design tools and strategically implemented newer construction technology can be channeled to optimize what has already been deemed to be a viable structural base scheme. This paper will highlight a select number of recent tower projects which illustrate these assertions. Objectives are to share the intentions, process and benefits of collaborative conceptual development for structural systems for supertall and unique towers; highlight newer technologies which are being implemented into current tall building structural systems.

Keywords: Aerodynamic Shaping, Damper, Elasto-Plastic, Epr, Mega-Structure, PBD

摘要

随着高层建筑高度越来越高、造型越来越独特，在概念设计中清晰的结构体系开发是十分必要的。这些结构体系必须基于力学基本原理，包括风工程和地震工程。只有在最初设计阶段打下坚实的基础，才能充分发挥最新计算工具及施工技术的作用，从而达到结构体系的最优化设计。本文将对几座超高层独特建筑项目进行概述。目标是介绍超高层独特建筑结构体系概念的开发及目前最新技术在高层建筑结构体系中的运用。

关键词：空气动力造型，阻尼器，弹塑性，专家审查（EPR），巨型结构，性能化设计（PBD）

Tall Building Conceptual Design

In an effort to keep up with tighter, more ambitious design schedules, modern tall building design is finding itself more and more dependent on the very latest innovations in design software and advances in construction technologies. Building forms and project scales once considered too aggressive or unusual for further consideration are quickly – and without much forethought – finding their way through preliminary analysis and sizing. Though the desire by all concerned (clients, architects, and engineers) to realize visionary architecture is unquestionable, it is the duty of structural engineers to keep in check this initial enthusiasm to ensure a measured approach is followed. If engineering firms succumb to the temptation of what at first appears to be the increased efficiency of the computers, there is a real danger that limiting resources of finances and manpower may be squandered on early flawed structural concepts. Additionally, systems developed in this manner have the potential to leave others in the design team, as well as clients, forced to work around a contrived system as projects proceed. The question is not about forgoing the use of the latest in computer software and

高层建筑概念设计

为了满足加快设计进度的迫切需要，现代高层建筑设计越来越依赖于最新的设计软件及先进的施工技术。曾经被认为太大或太过分的建筑造型及项目规模，未经过深思熟虑，很快地进入到初步计算机分析并确定结构尺寸。虽然业主、建筑师及工程师各方都希望尽快完成建筑设计，但是结构工程师有责任对最初的设计进行把关以确保结构的合理可靠。如果工程设计单位太依赖于似乎高效的计算机技术，那么很可能出现由于最初结构概念的缺陷而造成人力物力资源的浪费。此外，以这种方式开发的结构体系可能会迫使设计团队及业主围绕该人为的体系而展开工作。现在的问题不是要放弃使用最新的计算机软件及技术，而是在何时应将最初的结构概念转移到计算机上进行分析。

为了保持领先地位，H+P不断探索最新的数字设计技术，适当应用并充分发挥其高效率（见图1）。当数字设计工具如参数化建模用于高层建筑设计时，H+P合理确定输入规则及约束条件，以确保计算机模型准确反映基本设计问题。计算机仅用来对结构进行微调，而非完全用来解决结构问题。这样的设计方式能将经验丰富的工程师的专业技能与计算机建模的高速度充

technologies, rather it is at which point the initial concept should be turned over to the computer analysis.

In order to remain at the forefront of field, it is important to invest in the latest digital design tools and strives to apply them appropriately to best take advantage of the increased efficiency they offer (see Figure 1). To this end, when digital design tools like parametric modeling are utilized for tall building design, we stress the thoughtful determination of input rules and constraints to ensure that computer modeling is answering the fundamental design issues at hand. Rather than completely "driving" the solution, the computer is reserved for "fine-tuning." Approaching design in this manner takes full advantage of the combined expertise of seasoned engineers and the speed offered through computer modeling.

The following selected projects are examples of projects where Halvorson + Partners (H+P) personnel have applied their experience to develop design concepts based on fundamental tall building design principles. Additionally, some of the selected projects also demonstrate how to apply newer technologies to enhance the behavior and response of building systems based on the unique loading constraints of the particular project.

Opportunities To Express Clear Structural Systems (Russia Tower)

The Russia Tower, designed by H+P in conjunction with Foster + Partners out of London (see Figure 2), offered an opportunity to directly express a number of fundamental tall building structural design principles in the design. The following structural system principles were expressed in the building's architecture:

- gravity loads spread out over a broad base
- lateral loads carried on the same elements utilized to support gravity loads and with minimized premium over sizing required to support gravity loads
- majority load supported as direct axial force with minimal bending
- material and component characteristics evaluated and used cost-effectively (i.e., concrete in compression, steel in tension)

Tall building design principles applied in this context lead to the development of an innovative braced spine system where gravity load is spread (principle 1), column and wall gravity elements also resist lateral loads (principle 2), the core is braced primarily by the axial stiffening effect of diagonal brace/columns (principle 3), and steel is utilized for the main bracing/column elements while concrete is used to frame the interior core area (principle 4). Although sophisticated non-linear analysis was eventually conducted, the essence of the system drew from the experience and intuition of senior staff. Only cursory analysis was conducted prior to drafting the range of possible structural system options discussed with Foster + Partners for development.

Applied Aerodynamic Shaping And Structural Layout (Wuhan Greenland Center)

Moving to August 2010, Adrian Smith and Gordon Gill Architecture (AS+GG) approached H+P to participate in the competition for a new tower project for the Shanghai Greenland Group in Wuhan (now the Wuhan Greenland Centre, see Figure 3). In this case, aerodynamic shaping and layout of this 606m mixed-use tower (2nd tallest in China when completed) took advantage of low seismicity of the site (GB

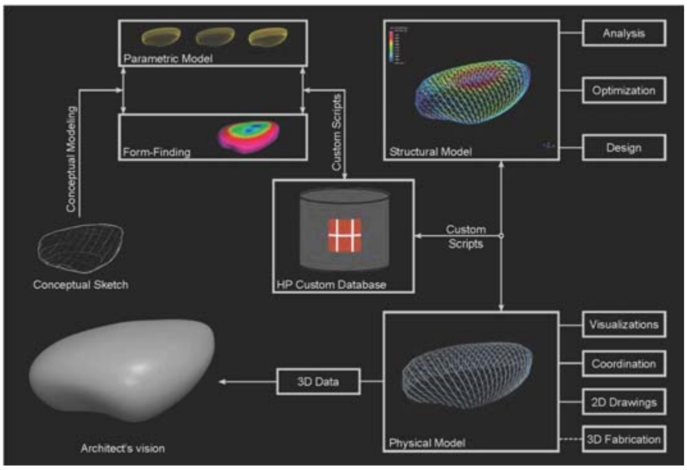

Figure 1. H+P Workflow Diagram with Digital Design Tools (Source: H+P)
图1. H+P用数字设计工具工作流程图 （H+P）

分结合起来。

在以下实例中，H+P根据高层建筑结构基本设计原理，将其经验应用于概念设计。其中有些项目还展示了H+P如何根据不同项目的各具特色的限制条件，使用最新技术来提高结构体系的整体性能。

表达清晰结构体系的机会（俄罗斯大厦）

俄罗斯大厦由H+P与英国福斯特建筑事务所共同合作设计（见图2）。该项目的设计提供了直接表达高层建筑结构设计原则的机会。建筑设计遵循了以下基本原则：

- 重力荷载在结构底部向外扩展
- 利用同一构件承受重力和侧向倾覆力，从而使构件尺寸达到最小
- 主要荷载由轴向构件承受，尽量减小构件受弯
- 根据受力特征选用高效材料（如，混凝土易抗压、钢材易受拉）

遵循以上高层建筑设计原则，产生了创新性的支撑脊柱结构体系。该体系中，重力荷载在底部向外扩展（原则1），柱和墙同时承受重力和侧向力（原则2），核心筒主要由轴向受力的斜柱进行支撑（原则3），钢材主要用于受拉支撑，而混凝土则用于受压核心墙（原则4）。尽管最终进行了非线性结构分析，但是

Figure 2. Russia Tower Rendering (Source: Foster + Partners)
图2. 俄罗斯大厦效果图（由福斯特建筑事务所提供）

Figure 3. Wuhan Greenland Center Competition Rendering (Source: Adrian Smith + Gordon Gill Architecture)
图3. 武汉绿地中心竞赛方案效果图（由AS+GG提供）

seismic intensity 6, the lowest) and minimal basic design wind pressure of 0.350 kN/m2. Though the absolute height of this structure placed it firmly in the "wind controlled" category, it was quickly recognized that the relatively mild wind climate and low seismicity of the site would allow them to push the boundaries of height and slenderness of structure through sophisticated wind engineering and aerodynamic shaping.

Coupled with the standard guiding principles of tall building design, this project is a prime example of how design intuition could work in conjunction with an understanding of current wind engineering research and newer technology to maximize performance of a proposed structural system. H+P worked with Rowan Williams Davies and Irwin Inc. (RWDI) consulting engineers out of Guelph, Ontario, Canada to identify effective aerodynamic shaping measures that could be pursued in the design to minimize the building response and mitigate loading effects on the building due to wind (see Figure 4). The aerodynamic shaping features incorporated into the massing for the design competition included: orientation of the building on the site to reduce drag, tapering tower form, rounding of corners of the building, and vented corner screen walls.

In addition to aerodynamic shaping studies of the overall form, the layout pattern of the mega-columns in the core linked to mega-column system on the floor plate shape could have a significant impact on the performance of the system (particularly in a case such as this, where design is definitely wind-controlled). Studies demonstrated that the triangular floor plate layout of mega-columns was the least sensitive to the orientation of the building to prevailing wind direction (see Figure 5), consequently a mega-column layout working within the constraints of the floor plate shape was pursued for the structural system.

Engaging Mega-Structure Behavior (One Dubai)

On another supertall tower design project in Dubai, One Dubai Tower, H+P collaborated with AS+GG again to develop a design concept for a mega-structure comprised of three towers of varying heights, linked elegantly by slender sky-bridges (see Figure 6). Again, the initial system layout for each tower was developed utilizing sound tall building design principles but in this project's case, the architects and engineers worked closely to develop a strategy to take full advantage of the bridges linking the towers in order to optimize the structural

该体系的精华是通过结构工程师丰富的经验和直觉而产生的。在与福斯特事务所探讨各种结构体系方案之前，仅进行了粗略的结构分析。

应用空气动力造型及结构布置（武汉绿地中心）

2010年8月H+P与美国AS+GG建筑事务所合作，参加了上海绿地集团在武汉的新大厦项目方案竞赛（即现在的武汉绿地中心，见图3）。在该项目中，606米高的综合用途大厦（中国第二高楼）空气动力造型及布局充分利用了场地低地震（地震烈度6）和低风压（最低基本设计风压值为0.350 kN/m2）的特点。虽然该高度的建筑属于风控制类型，H+P很快意识到项目场地相对温和的风气候及低地震区将允许他们通过先进的风工程及空气动力造型，来提高建筑高度、实现较大的高细比。

基于高层建筑设计的基本原则，H+P将设计直觉与风工程研究及最新的技术结合，力求开发性能最优化的结构体系。H+P在加拿大RWDI风工程顾问公司的协助下，确定了有效的空气动力造型，从而减小风压对建筑的作用及降低结构反映（见图4）。与建筑体量相结合的空气动力造型特征包括：减小风作用的建筑朝向，逐渐变细的塔楼造型，呈圆形的建筑转角，及开孔的转角幕墙等等。

除了整体外形的空气动力造型研究，核心筒内外巨型柱的布置形式对结构体系性能将产生很大的影响（特别是由风控制设计的结构）。H+P的研究显示三角形楼面布置的巨型柱对建筑朝向的敏感度最小（见图5）。因此，在结构体系设计中，巨型柱的布局与楼面形状协调一致。

巨型结构设计（迪拜1号大厦）

另外一个位于迪拜的超高层设计项目为迪拜1号大厦，其中包括三座不同高度的塔楼，并由优美的天桥在不同的位置将塔楼连在一起。H+P与AS+GG再次合作为该巨型结构提供了概念设计方案（见图6）。 最初的结构体系为三个相互独立的结构，不过就本项目的设计，H+P与AS+GG密切合作充分利用连接塔楼的天桥以优化

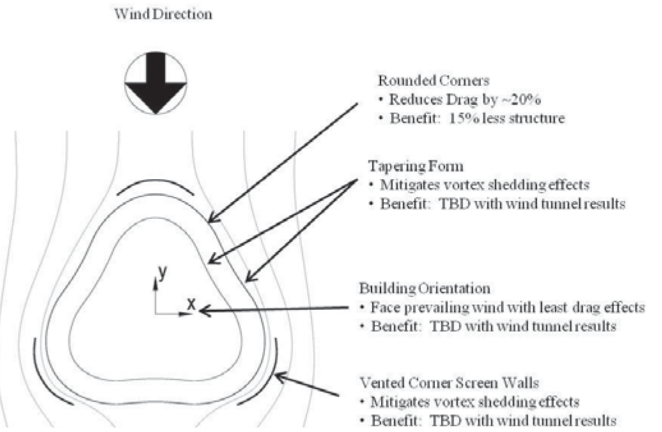

Figure 4. Wuhan Greenland Center Competition Aerodynamic Shaping (Source: H+P)
图4. 武汉绿地中心竞赛方案空气动力造型（H+P）

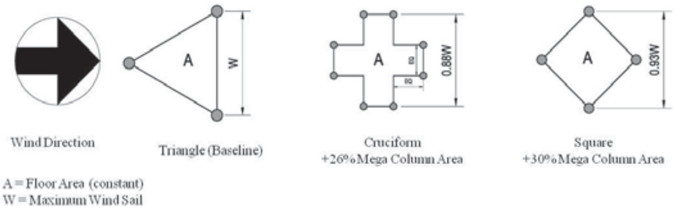

Figure 5. Wuhan Greenland Center Competition Mega-Column Layout (Source: H+P)
图5. 武汉绿地中心竞赛方案巨型柱布置图（H+P）

Figure 6. One Dubai Rendering (Source: Adrian Smith + Gordon Gill Architecture)
图6. 迪拜1号大厦效果图（由AS+GG提供）

performance of the system. The initial structural system designs were developed with detailed oversight of experienced tall building engineers, which allowed adaptations to the design (such as dramatic height increases) to occur without total re-work of the design concept.

In the competition phase, the tallest tower T1 reached a maximum height of 686m (T2-525m and T3-445m). Initially, the bridges were allowed to function as slender links that could transfer shear between the towers by pushing and pulling on adjacent towers. This type of linkage, although it transferred no global over-turning moment directly between towers, had a benefit in that it linked together three structures with varied dynamic properties and, as a result, tended to dampen out the dynamic responses of the entire structural system. After AS+GG was contracted to begin work on the project, the tower heights began to increase in response to the client's requests. Eventually Tower T1 height increased to 1008m (T2-874m and T3-685m) (see Figure 7).

Although the base dimension of the towers increased from 64m (Scheme 1) to a base dimension of 75m (Schemes 3A and 3B), it was determined that the enlarged base dimension along with upsized tower system elements alone could not improve stiffness enough to meet the greater loading requirements of the taller tower scheme. In order to meet these demands, it was concluded the nature of the bridge linkages needed to be altered, such that global overturning moments, not just shears, could be transferred directly through the bridges between the towers to produce true mega-structure behavior of the linked system.

Scheme 3A (Mega-braced scheme) was determined to produced an effective linkage system but that an inherent challenge of the system was the design of long slender concentric brace elements. A comprehensive non-linear buckling analysis determined that long-term gravity and temperature effects significantly impacted the design of the elements. As a result, a system of lock-up devices, dampers, and climate control measures were considered in the design of the braces in order to minimize the loading due to these effects. The final designed struts proved to be extremely effective, increasing stiffness of the system by almost 70% from the unlinked tower system and by approximately 55% from an unaltered bridge stiffness scheme.

In the final analysis, although Scheme 3A resulted in an efficient design, it was concluded that it represented a significant departure from the competition scheme aesthetics. As a result, a more nuanced

整个结构体系的性能。由于最初的结构体系设计是在经验丰富的高层建筑工程师的指导下进行，使得可对设计做适应的修改（如建筑高度显著增加）而无需全部返工。

在方案竞赛阶段，最高的塔楼T1 最大高度为686米（T2为525米、T3为445米）。细长天桥的作用是通过推拉相邻塔楼来传递塔楼之间的剪力。虽然这种连接不能直接传递塔楼间的整体倾覆力矩，但将三个具有不同动态特征的塔楼结构连在一起，从而减小整个结构体系的动态反应。在AS+GG签署项目合同开始工作之后，业主又提出了增加塔楼高度的要求。最终塔楼T1高度增至1008米（T2为874米、T3为685米）（见图 7）。

尽管塔楼的底部宽度从64米（方案1）增至75米（方案3A和3B），但H+P确定仅利用增加的底部宽度，结构刚度仍不能达到由于塔楼高度增加而产生的较大荷载的要求。因此，H+P决定采用不同类型的天桥连接，使其不仅传递相邻塔楼之间的剪力，也可直接传递整体倾覆力矩，从而形成真正的连体巨型结构体系。

H+P确定方案3A（巨型支撑方案）可产生有效的连接体系，但问题在于细长支撑构件的设计。对整体结构进行的非线性稳定分析，表明重力荷载和温度变形会对构件设计产生极大的影响。因此，为了减小由此产生的荷载影响，在支撑设计中考虑设置锁定设备、阻尼器及温度控制措施。最终设计的支撑结构非常有效，整体刚度比无天桥连接体系增加近70%，比原天桥连接体系增加近55%。

在最终的分析中，尽管方案3A是一个有效的设计，但AS+GG认为该方案与竞赛方案的美观相距甚远。因此，H+P与AS+GG共同研究更为细致的加强连接天桥结构。通过对不同支撑桁架高度的研究得出，方案3B（支撑桁架连桥方案）可以提供足够的塔楼连接。方案3B在支撑桁架之间设置一个短支撑使加强连接。最终的连接方案，使得支撑桁架连桥可在塔楼之间传递达25%的整体倾覆力矩(见图8）。

应用新技术减小运动知觉（芝加哥伊利森大厦）

对于一些细高的高层建筑，即使结构设计遵循基本原则，在风荷载作用下仍会产生很大的动态反映。新科技可提供最具成本效益的方法来控制建筑的摇摆运动幅度的问题。一般来说，水平加速度的变化与广义质量及阻尼平方根成反比例，而与结构的刚度和周期关系不很明显。因此，通常减小建筑加速度的最经济有效的方法是重新布置结构构件，使广义质量达到最大。如果不能有效的减小加速度，采用建筑阻尼器是比较有效的方法。

为了最大限度地提高效率，阻尼器通常安装在结构上部。按照经

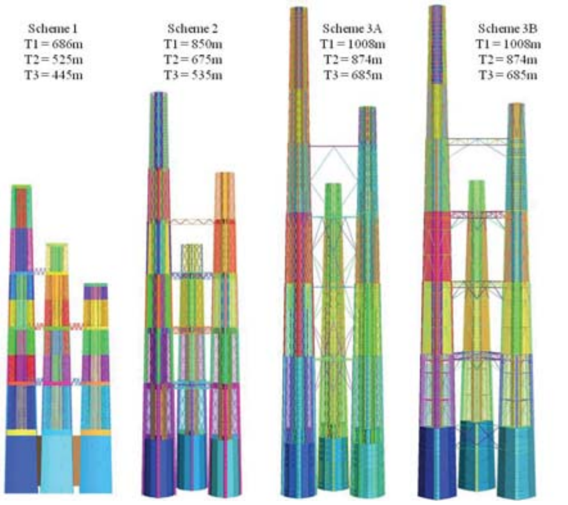

Figure 7. One Dubai Height History (Source: H+P)
图7. 迪拜1号大厦高度变化过程（H+P）

approach to stiffening up the bridge linkages was developed. Scheme 3B (Strutted Bridge scheme) was the result of a number of studies with varied strutted bridge depths reviewed in order to achieve a sufficient tower linkage for the increased height. Scheme 3B included a shorter brace below the bridge trusses used to stiffen the bridge linkages. In the final linked condition, the strutted bridge linkages were able to achieve up to 25% global over-turning linkage between towers (see Figure 8).

Newer Technologies Applied To Minimize Motion Perception Issues (Elysian Tower)

In some slender tower situations, dynamic response of the building due to wind loading can be significant even when sound principles are utilized to lay out the structural system. In these cases newer technologies may offer the most cost-effective means by which motion perception issues can be controlled. Generally, horizontal accelerations vary inversely proportional to generalized mass, vary inversely proportional to the square root of damping, and, less significantly, are correlated to the stiffness and period of the structure. As a result, often the most cost-effective way to reduce building accelerations is by re-proportioning building elements to maximize generalized mass. If this cannot be achieved in a cost-effective manner, a more efficient way to meet acceleration limits may be to incorporate a building damper.

In order to maximize the efficiency of the devices, dampers are often located in the upper portions of structures. Damper sizes, as a rule of thumb, are about 2% the size of the Generalized Mass of the building and can take on many different forms. A few different types of building dampers are: (1) Sliding Mass, (2) Pendulum, (3) Sloshing Tank, and (4) Liquid Column (see Figure 9). H+P has incorporated damping devices into two high-rise buildings in Chicago. The Elysian Tower (designed in conjunction with Lucien Lagrange Architects) and 50 East Chestnut (a collaboration with Solomn Cordwell Buenz & Associates, Inc.) are the only two buildings in Chicago which utilize Sloshing Tank Damper devices at their tops to control accelerations. In the future, with the emphasis on green architecture and sustainable design, it is anticipated that this type of technology will become more prevalent given the focus on using less material to meet performance criteria limits. Damping devices by definition minimize the amount of required structure and allows for designers to stay at the forefront of cost-effective damper design implementation to tall building designs.

New Technologies Applied To Minimize Rare Level Seismic Damage (Vantone Center)

Supertall building design projects in China usually require Performance Based Design (PBD) including non-linear time history analysis to demonstrate acceptable building response under prescribed rare level earthquake loadings. During this Elasto-Plastic analysis, conducted and presented for Expert Panel Review (EPR), component performance is recorded and compared against performance objectives specified by Chinese Code. Traditionally system designs incorporate strengthened zones at critical locations in the structure along with secondary structural frames to provide ductility and robustness under rare level seismic events. In most cases satisfactory conceptual design can be achieved drawing on the design experience of engineers well-versed in tall building design in higher seismic regions. Recently H+P has begun investigating the use of supplemental damping systems to not only achieve performance objectives efficiently but to also minimize

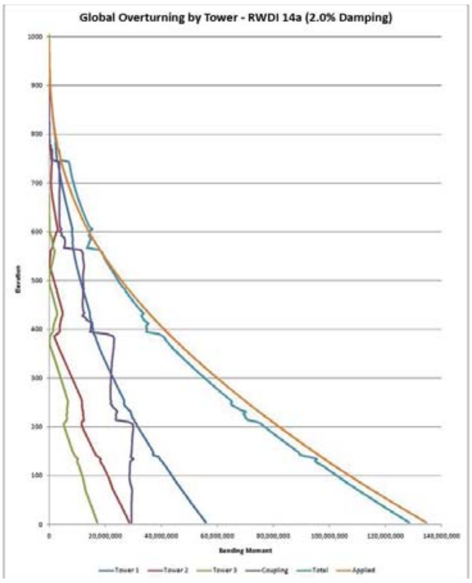

Figure 8. One Dubai Global Overturning Diagram (Source: H+P)
图8. 迪拜1号大厦整体倾覆力矩图（H+P）

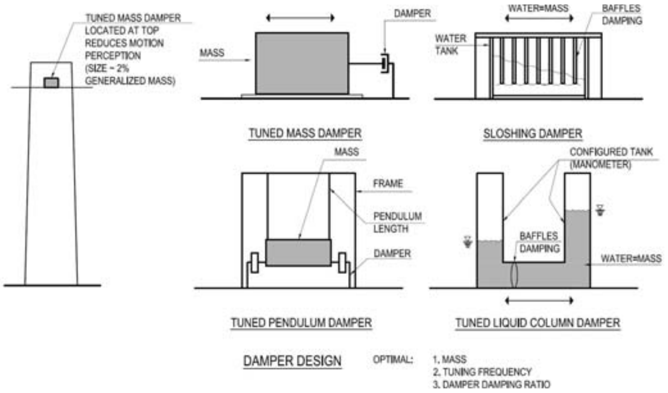

Figure 9. Damper Design Principles (Source: H+P)
图9. 阻尼器设计原理（H+P）

验，阻尼器的质量约为建筑广义质量的2%，且可以采取不同的形式。建筑阻尼器的几种不同类型包括：（1）滑动体，（2）钟摆，（3）液体柱，及（4）充液箱（见图9）。H+P设计的位于芝加哥的两座高层建筑分别安装了阻尼器。伊利森大厦 （与 Lucien Lagrange 建筑事务所合作项目）和 50东板栗公寓（与 SCB 建筑事务所合作项目）是芝加哥仅有在其顶部使用了充液箱阻尼器装置来控制加速度的两座建筑（见图10）。将来，在强调绿色建筑与可持续性设计中，H+P预期为了节省材料，并满足性能化设计的要求，使用这种技术将会更加普遍。阻尼装置可以大大减少所需的结构材料用量。因此，H+P将致力于在高层建筑设计中，率先采用经济有效的阻尼器。

应用新技术减少罕遇地震破坏（天津万通中心）

中国的超高建筑设计项目往往要求进行性能化设计(PBD)，包括非线性时程分析以确保建筑在罕遇地震下的结构反映满足规范的要求。在进行弹塑性分析时，作为专家审查（EPR）报告的一部分，结构性能应达到规范规定的性能目标。通常，结构体系设计在关键部位设置加强区，同时设置框架作为二道防线，使得在罕遇地震作用下，确保结构的延性和安全可靠。在多数情况下，凭借工程师在高层建筑抗震设计方面的丰富经验， 可以做出令人满意的概念设计。近来，H+P开始研究采用附加阻尼系统，它既能有效达到性能目标，又可减少在罕遇地震下的结构耗能和建筑破坏。

H+P 与AS+GG合作共同设计了185米高的天津万通中心。H+P考虑在该办公楼上设置锁定装置（该阻尼器在风荷载及多遇地震作用

the amount of dissipated energy by the structure and therefore the damage to the base building structure for rare seismic events.

For the Vantone Center in Tianjin (designed in collaboration with AS+GG) lock-up devices (essentially fused dampers which behave rigidly under design level wind and seismic loading) were investigated for an approximately 185m composite tube-frame office tower. The structural system of the tower consists of a reinforced concrete core linked to composite concrete filled tube perimeter columns through a system of steel outrigger trusses at one double story height mechanical level. Steel belt trusses utilized at this same level link perimeter columns together (see Figure 10). A dual system steel perimeter frame provides a second line of defense to resist seismic loads.

H+P worked with Taylor Devices Inc. out of North Tonawanda, New York to establish damper lock-up device designs at isolated locations (4 outrigger diagonal locations) which allow these elements to respond rigidly at low level forces (frequent earthquake and 100 year wind loads) to ensure inter-story drift limits are met and to engage at rare level earthquake loads to dampen out higher loading. Utilizing appropriate damper designs, it was demonstrated that the overall energy absorbed by the structural system of the building (a measure of overall structure damage) could be significantly reduced by incorporating even a small number of isolated lock-up devices. The reduction of energy absorbed by the structure is due to two effects: (1) lengthening of the period of the system, and (2) a greater portion of the energy being absorbed by the isolated dampers on these specific elements (see Figure 11). The diagrams demonstrate that energy dissipated by the structure when dampers were utilized (considering one governing rare seismic event) is approximately 50% of the base case when no dampers are employed. This study implies that significantly less damage may occur and less subsequent repair work may be required to restore a building to its full design integrity level after a rare earthquake when dampers are utilized. Design of the dampers is established to ensure the building can still meet the inter-story drift criteria for rare earthquake loading, thereby capping the amount the building could "softened up".

Conclusion

Today's world of supertall building design demands a re-focusing on the value of conceptual design, prior to the initiation of computer modeling. The advent of powerful computing tools and tight schedule demands tempt structural engineers to jump into computer modeling prior to thoughtfully considering the problem at hand, but engineers should resist skipping this vital step. Thoughtful consideration of structural systems during conceptual design allows digital design tools and new technology to be incorporated with clarity into a structural system. This manner of working often takes more time, but it is also only through this process that truly great architecture and structural design can be realized.

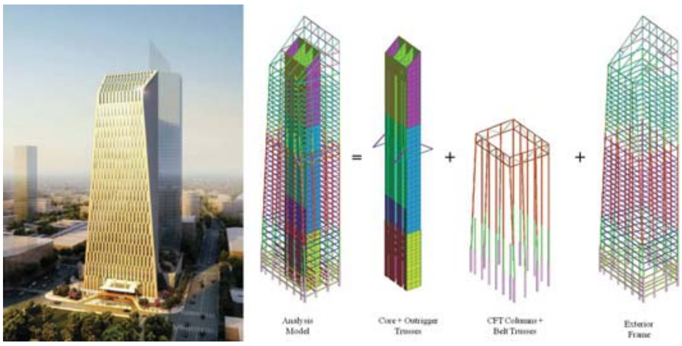

Figure 10. Vantone Center Rendering and Structural System (Source: Adrian Smith + Gordon Gill Architecture and H+P)
图10. 万通中心效果图及结构体系（AS+GG 和H+P）

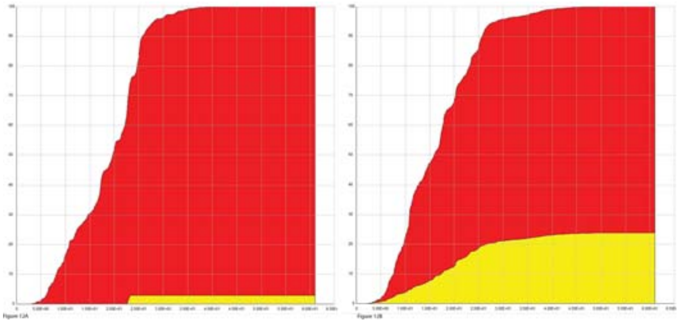

Figure 11. Vantone Center System Energy Dissipation Diagrams with and w/o Dampers (Source: H+P)
图11. 万通中心系统耗能图（带阻尼器与不带阻尼器）（H+P）

下保持刚性）。主楼的结构体系由钢筋混凝土核心筒通过在设备层的伸臂桁架与钢管混凝土外围柱相连接所组成。同一层的外围柱使用钢腰桁架连接起来（见图10）。这个双层钢架体系中，外围框架对于抵抗地震荷载起到了二道防线的作用。

H+P与美国泰勒设备公司合作在4个伸臂桁架支撑处设置阻尼器锁定装置，在多遇地震和风荷载下保持刚性，在罕遇地震下发挥其阻尼作用。在设计中，H+P确定即使设置少量的锁定装置就可以大幅降低建筑结构体系的耗能（总体结构的损坏程度）。结构耗能的减少是由于：（1）结构周期的延长，和（2） 大部分能量被阻尼器所吸收（见图11）。图中表明使用阻尼器时结构所耗散的能量约为不使用阻尼器时所耗散能量的50%。该研究表明使用阻尼器时，可极大降低罕遇地震造成的破坏，并可进行随后的修复工作以将建筑恢复至设计时的完好状态。阻尼器的设计可以确保建筑在罕遇地震的作用下，仍然能满足层间位移的标准要求，从而限定建筑结构的柔软程度。

结论

对于超高层建筑设计，在开始进行计算机建模之前，需要注重概念设计。强大的计算工具和紧迫的设计进度要求使得结构工程师很容易对手头上的问题没有经过周到的考虑就直接进入计算机建模，不过工程师最好不要跳过这关键的一步。在概念设计阶段对结构体系进行认真考量使得工程师可结合数字设计工具和新科技来设计清晰的结构体系。 这样的工作方式通常会花较多的时间，但只有通过这个过程才能实现真正完美的建筑和结构设计。

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