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Design of Sustainable Asian Supertall Buildings for Wind

考虑风效应的亚洲超高层建筑可持续设计

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Abstract

This paper describes case studies of supertall Asian buildings, focusing on the impacts of wind and other climatic factors on their design. The aerodynamic shape of supertall buildings is critical in avoiding excessive wind loads and building motions as well as increasing the viability of natural ventilation and daylighting strategies, thereby reducing the cost of the structural systems and the building's carbon footprint. Efficiency can be improved through use of supplementary damping systems to dissipate the energy in the building motions. Historical climatic records at heights above 300 meters for supertall buildings are sparse, however, recently developed regional atmospheric modeling software combined with large databases of archived re-analysis results from the weather forecasting community now help to shed more light on upper-level climatic conditions.

Keywords: Climate, Wind Load, Structural Damping, Natural Ventilation, Vortex Shedding

摘要

本文主要讨论风和其它气候因素对部分亚洲超高层建筑设计的影响。超高层建筑的空气动力外形对于避免过大的风荷载和风致振动至关重要，因而对减少结构体系造价和建筑碳排放量有着举足轻重的作用。当然效率还可以通过附加的阻尼系统消能得到提高。在超高层建筑设计中考虑气候因素最具挑战性的问题之一是超过300米高度的历史气候资料事实上非常有限。近期发展起来的区域大气建模软件对此提供了有希望的解决途径，该方法结合了大量来自气象预报领域的数据库并结合大气物理模型重分析的结果，有助于了解高层的气候环境。

关键词：风气候、风荷载、结构阻尼、自然通风、漩涡脱落

Introduction

The sustainability of supertall buildings is a laudable goal and general enough in its statement to allow interpretation within all areas of tall building design. From a wind engineering viewpoint, the design of sustainable super tall buildings translates in one sense to efficiency and in another to long-term performance or durability. Design efficiencies related to good consideration of wind – form, structure, material – result in lower initial costs and carbon footprint. Long term performance as it relates to occupant comfort and enjoyment and durability of building components including the curtain wall are each driven in large part by wind-induced motions of a given building as well as the internal thermal conditions maintained by ventilation: be it delivered by natural ventilation or building mechanical systems. Wind engineering for tall buildings requires examination of a number of variables including the local climate and the exposure of a building, the architecture and its susceptibility to different wind loading phenomena, the structural system and how its key parameters affect loading and performance. Further, appreciation of the wind climate around the building can lead to a higher viability of natural ventilation: this is

引言

超高层建筑的可持续性是一个有价值的目标并且可用于诠释所有的高层建筑设计。从风工程角度来看，超高层建筑的可持续设计意味着两方面内容：其一是设计的效率；其二是长期的使用性能和耐久性。设计的效率包括考虑风效应的建筑外形优化、结构体系优化、材料选择与用量优化等，并由此降低基本造价及碳排放量。长期的使用性能和耐久性涉及居住者的使用舒适度和包括幕墙在内的建筑构件的耐久性，这些在很大程度上取决于建筑物的风致振动和建筑物内部长期的热力学状态，建筑物内部的热力学状态取决于通风空调系统，即采用自然通风或机械通风。高层建筑风工程要求考虑很多影响因素，包括地区性气候和建筑物周边的地貌、建筑外形及其对不同风荷载现象的敏感度、结构系统和其关键参数对荷载和性能的影响等等。建筑物周围适合的风气候有助于增加自然通风设计的可行性，从而可作为建筑外型设计中值得考虑的内容。重要的是在评估一栋建筑物优劣的指标中应反映住户的满意程度和极端情况下的使用功能。本文针对CTBUH定义的300米以上超高层建筑考察了风工程应用的成功例子，并讨论了与其相关的自然通风问题。

a component that can be designed through building form. Ultimately, it is important that the criteria against which a given building is judged includes sensitivity to the owner's wishes and the ultimate occupants of the completed building. The present paper examines good wind engineering practice and a discussion of natural ventilation as it relates to tall buildings with some examples specific to supertall buildings, following the CTBUH definition of greater than 300m in height.

The Nature of Wind for Supertall Building Design

Most meteorological data for building design comes from airport measurements at 10m above grade. In the case of supertall buildings, exclusive use of this data is inappropriate for design because the increase of wind speed with elevation does not necessarily follow building code models. While such models have been largely validated for building heights up to about 300m, wind speeds beyond this height can be significantly more variable (Irwin, 2006). Above 300m, wind flow properties in storms generally follow the engineering model of strong winds in the atmospheric boundary layer associate with synoptic storm systems such as described in ESDU (1982, 1983). However, depending on region, strong winds may also be due to one of a number of different storm types with profiles as indicated in Figure 1. The wind speed profiles (nominal mean values) shown in Figure 1 were determined from various studies of individual storms using Weather Research Forecasting (WRF) tools applied in wind climate studies by RWDI.

Local climate varies widely from region to region. Strong winds for structural design for a large number of cities, including Shanghai, are governed by typhoons. In mid-latitude regions, design winds are generally associated with large scale synoptic low pressure systems. In the Red Sea and Arabian Gulf regions, seasonal Shamal from the North and Aziab winds associated with dust storms have a major influence on design. In equatorial regions, winds associated with thunderstorm cells dominate the strong wind climate. This last case poses a particular challenge to wind engineers as there are a number of different types of thunderstorm outflows ranging from gust fronts to small scale but intense microbursts, all of which have poorly understood wind profiles.

Beyond strong winds, local influences such as topography and large bodies of water affect the near surface or boundary layer winds due to the differential diurnal impacts of temperature. These influences manifest as a sea-breeze/land-breeze effect, where by the temperatures over the land rise more quickly than over the sea during the day, which will tend to drive the winds more inland during the day, with the reverse occurring at night. A similar effect between mountains and lowlands resulting in downslope winds which in extreme cases can be quite strong due to funneling around and between significant topography. These diurnal winds can result in vertical wind circulations over the height of the tallest buildings contemplated today and are clearly important considerations in design.

Weather Research Forecast Modeling

Meteorologists apply numerical methods combined with site observations to forecast weather. The same techniques can be applied in a hind-cast model to analyze historical data over a range of scales as depicted in Figure 2. Scales ranging from distances consistent with global or continental weather pattern to local distances affected by hydrology, vegetation, topography and levels of urbanization can be accounted for by applying increasing levels of sophistication and inputs. The Weather Research and Forecast Model (WRF) is a publically

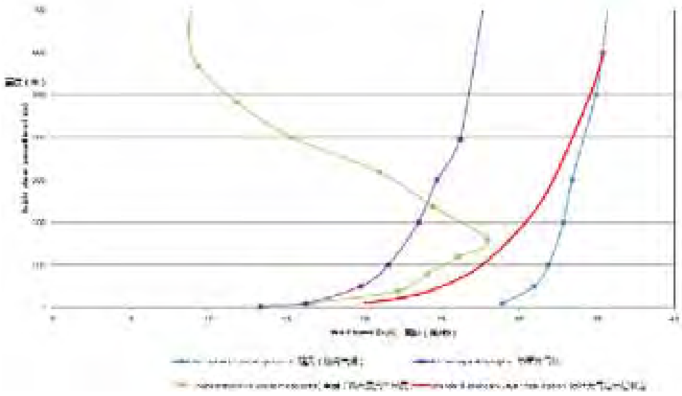

Figure 1. Wind speed profiles from various storm events
图1. 不同风暴的风速剖面

超高层建筑设计中的风特性

大多数用于建筑设计的气象数据来自于机场上10米高度处的近地风测量。对超高层建筑的情况，仅依据此数据进行设计并不完全合理，因为风速随高度的增加不一定与建筑规范给出的风剖面一致。虽然该风剖面在300米以下得到过大量验证，但超过该高度后则存在很大的变数（Irwin，2006）。300米以上的风暴特性一般符合天气尺度强风的工程模型，如工程科学数据库（ESDU 1982，1983）中所述。然而在不同地区，强风也可能是由多种不同类型的风暴引起，其风剖面会有很大不同，如图1所示。

不同地区的局部气候会有很大差别。对包括上海在内的许多城市，其主导结构设计的强风由台风控制。在中纬度地区，设计风速一般与大尺度低压系统有关。在红海和阿拉伯湾地区，来自北方的季节性夏马风和阿齐阿勃风与沙尘暴同时出现将对设计产生重大影响。在赤道地区，与雷暴云泡相伴的风决定了强风气候。雷暴强风情况对风工程师是一个特殊的挑战。雷暴风的外流有多种不同形态，包括阵风峰面到强烈的小尺度微暴气流，而目前对与此相应的风剖面还知之甚少。

除强风之外，由于温度的昼夜变化，地形地貌和大体量的水体等地区性因素也会对近地或边界层风产生影响。这些影响可具体表现为海陆风效应：白天时陆地温度上升较洋面快，驱使风往内陆吹；而夜间时则情况相反。类似的影响在山脉和低地间会产生下坡风。在某种极端情况下，由于周围地貌产生的狭道效应或较大的地势差会使下坡风风速非常之大。这些昼夜变化的风会导致在现今规划的最高建筑物上沿其高度方向出现竖向风环流，是设计中需要认真考虑的课题。

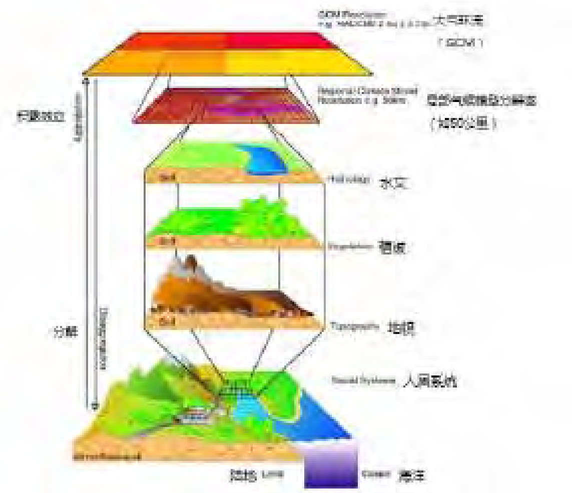

Figure 2. Levels of local climate influences studies using Weather Research Forecasting (WRF) Model
图2. 利用天气研究预报模型（WRF模型）得到的当地气候的影响

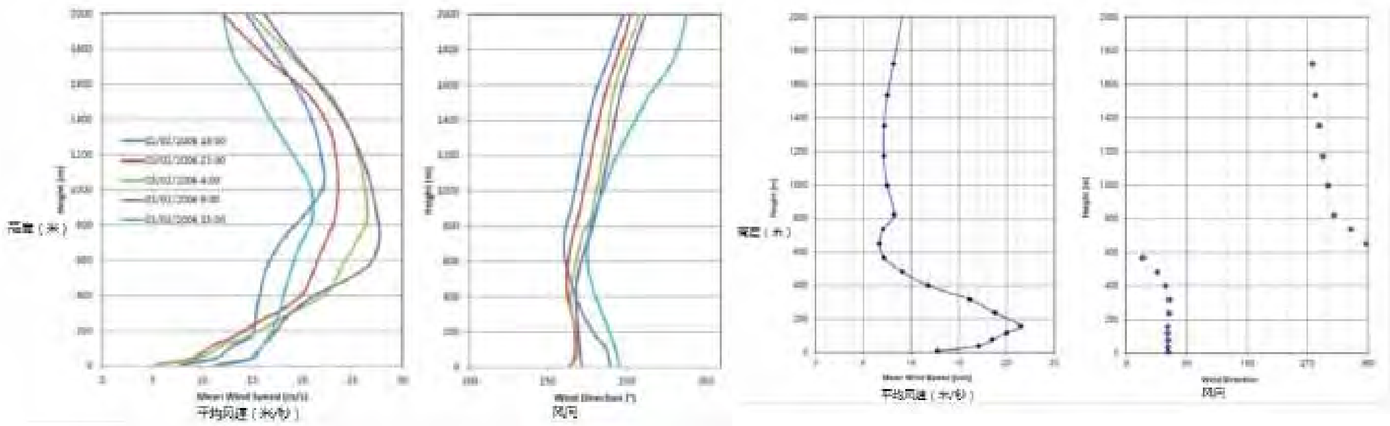

Figure 3. a) WRF Modeling of an Aziab wind storm in Saudi Arabia, (b) WRF Modeling of a thunderstorm outflow
图3. a) WRF模型模拟的一个在沙特阿拉伯的阿齐阿勃风（Aziab），(b)WRF模型模拟的雷暴外流

available software and framework developed as a collaborative partnership, principally among the NCAR, the National Oceanic and Atmospheric Administration (NOAA), the National Centers for Environmental Prediction (NCEP), the Forecast Systems Laboratory (FSL), the Air Force Weather Agency (AFWA), the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration (FAA). WRF is a limited-area, non-hydrostatic, terrain-following sigma-coordinate model designed to simulate or predict atmospheric circulation on scales ranging from hundreds of meters through to thousands of kilometers. WRF allows the ability to conduct simulations reflecting either real data or idealized configurations.

Application of WRF to Supertall Buildings WRF

RWDI has executed the WRF model, over a nested model domain centered on several supertall buildings including the Burj Khalifa (Qiu et. al., 2005). Studies have included simulation of specific historical storms to investigate the character of Shamal wind storms at altitudes greater than 800m above ground. Recently, with improvements in the Global Circulation Database, RWDI studies have included full simulations over 10+ years to develop meaningful statistical data for analysis of not only storms but also common prevailing and diurnal winds. Examples from a recent study are shown in Figure 3a and 3b. Figure 3a presents the development of an Aziab dust storm while Figure 3b presents a thunderstorm event in the vicinity of the tower. While wind speeds in these particular storms did not approach the design wind speed, the profile and wind direction with height reveal significant variation from generally assumed storm profiles

RWDI's application of WRF modeling has focused on storms where surface data (i.e. 10m elevation anemometer data available from meteorological stations) alone does not reveal the full characteristics with height, particularly those storm characteristics where a portion of a building may be exposed to higher than expected wind speeds. Where available, balloon data have also been analyzed in parallel to give confidence in the WRF modeling. To date, studies have largely validated established practice including ESDU profiles and in some cases indicated established practice may be conservative. However, RWDI has not recommended reduced design wind speed profiles with height. This is due to the uncertainties in the modeling within WRF including turbulence and uncertainties with the input data. Use of this technology in wind engineering studies is in its relative infancy and has acknowledged limitations. However, the technology clearly has potential for application to design of supertall buildings - both for the

气象研究预测模型

气象学家采用各种数值方法结合实地观测来预报天气。同样的技术可用于后报模型以分析某种尺度范围的历史气候数据，如图2所示。通过增加精度和输入数据量，可以使考虑的尺度涵盖从全球或洲际天气尺度到受水文地理、植被、地形和城市化程度影响的局部地区性尺度。气象研究和预测模型（WRF）是一个对公众开放的软件和研发框架，主要由美国国家大气研究中心（NCAR）、美国国家海洋和大气管理局（NOAA）、美国国家环境预报中心（NCEP）、美国预报系统实验室（FSL）、美国空军气象局（AFWA）、美国海军实验室、俄克拉荷马大学和美国联邦航空管理局（FAA）等多方合作开发的。气象研究和预测模型（WRF）是一个有限区域的、非流体静力的、地形跟随的σ坐标模型，用于模拟或预测从几百米到几千公里内的中尺度大气环流。WRF具有模拟反映真实数据或理想情况的能力。

WRF模型在超高层建筑中的应用

RWDI以建筑物为建模中心，对包括迪拜哈利法塔在内的几栋超高层建筑采用WRF模型对部分历史记录的风暴进行了模拟分析（Qiu等，2005），以确定800米以上的夏马风暴特性。近年来，随着全球环流数据库的进一步完善，RWDI的分析已包括10年以上的完整模拟，不但可以对风暴,而且可以对常遇盛行风和日变风进行有统计意义的数据分析。图3a和 3b所示为最近的研究实例。图3a展示了阿齐阿勃沙尘暴的发展，图3b展示了塔楼附近的雷暴过程。虽然在这些风暴中，风速并没有达到设计风速，但风速风向随高度的变化表明与一般假设的风暴剖面有很大不同。

RWDI在WRF模型应用方面主要着重于研究那些近地风数据（即气象站10米高度的记录）中不能反映随高度变化特性的风暴，特别是有可能使建筑某一部分受到超过预期风速的那些风暴。研究中还同时分析现有的探空气球数据，以增加WRF模型分析结果的可信度。目前，这些研究在很大程度上验证了工程实践中业已确定的方法，包括ESDU的风剖面，但在某些情况下发现这些确定的方法可能偏于保守。但考虑到紊流的WRF模型中的不确定因素和输入数据中的不确定因素，RWDI并不建议降低沿高度的设计风速。上述技术目前尚未完全成熟，还存在一些公认的局限性。尽管如此，这项技术已清晰地展现了在超高层建筑应用领域的潜力。

考虑风效应的建筑外形设计

由于高层建筑的高度与增强的高层风速，风荷载及其效应对整个结构抗侧体系和基础抗倾覆设计的至关重要性在高层建筑设计领域中已是众所周知。仅就静力荷载而言，高层建筑的基底倾覆力矩与建筑顶部风速的平方成正比，也与建筑高度的平方成正比。

structural design and mechanical design including stack effect and ventilation.

Design of the Building Form for Wind

The tall building design community is generally aware that wind loading and its effects dominate the design of the overall lateral structural system and overturning resistance of the foundation. This is due primarily to the height of tall buildings and the increase in wind speed at the top of a building as explained in the previous section. Looking just at the static load, the overturning force at the base of a tall building is proportional to the square of velocity at the top of the building and is also proportional to the square of the height. Additionally, the structural systems of tall buildings naturally have lower natural frequency (or long natural period) of vibration than shorter buildings. At low frequencies, the amount of turbulent energy in the wind increases creating a larger resonant response in the structure due to buffeting similar to a tuning fork. A further complication related to the height and slenderness of supertall buildings is their susceptibility to resonance from vortices shedding from the building form shown in Figure 4. This vortex shedding creates an alternating force at right angles to the wind direction at a frequency given by the following:

$$f_s=(S_t\ U)/D \qquad (1)$$

where fs is the shedding frequency, St is the Strouhal number, U is the local wind speed and D is the local width. The Strouhal number is a constant for a given cross section and approximately equal to 0.2 for a circle and approximately equal to0.10 to 0.14 for rectangular sections depending on the aspect ratio. From Equation 1, a resonant condition sets up when fs approaches one of the building's natural frequencies.

Equation 1 is relatively straightforward and gives some insight to shaping a building form to mitigate large cross wind loads and motions due to vortex shedding. The cross wind effects are largest when the vortex shedding 'organizes' over the height of a building. Therefore, control of one or both of the local width, D or the Strouhal number, St over the height of the building can act to reduce the vertical alignment or organization of the vortices. Two examples in China where this was done with good success are the Shanghai Center in Shanghai and the Ping An Financial Center (PAFC) in Shenzhen. Photographs of each building in RWDI's wind tunnels are shown in Figure 5a and 5b, respectively.

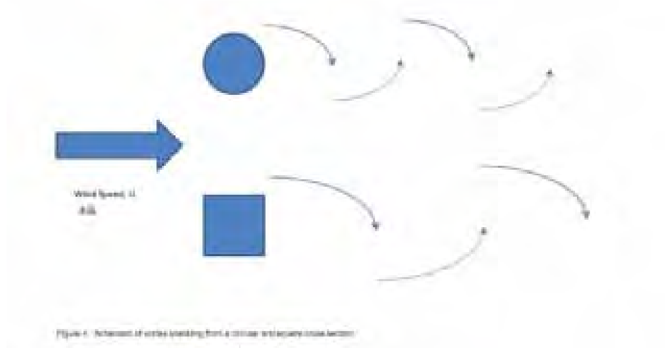

Figure 4. Schematic of vortex shedding from a circular and square section
图4. 一个圆形和方形截面的涡脱落的原理图

此外，高层建筑的结构体系一般比低层建筑有较低的频率（或较长的周期）。在低频率区段，风的湍流能量较高从而会产生与音叉效应类似的结构共振响应。超高层的高度与高细比还可能导致一个更复杂的现象，即由建筑表面漩涡脱落造成的的涡激共振，如图4所示。交替脱落的漩涡会产生一个与风向垂直角的振荡外力，其振荡频率为：

$$f_s=(S_t\ U)/D \qquad (1)$$

其中fs是涡脱频率，St是斯托罗哈数，U是风速，D是特征宽度。斯托罗哈数对一个给定的截面基本上是常数，圆形约为0.2，矩形根据其长宽比为0.10到0.14之间。当式（1）中fs接近建筑物某一固有频率时便出现涡激共振情况。

式1相对直观地给出了优化建筑外形以降低漩涡脱落导致剧烈横风向荷载的依据。当沿整个建筑高度上漩涡脱落保持一致时横风向效应最为强烈。因此，在整个建筑高度上控制局部宽度D或斯托罗哈数St 这两个参数中的一个或全部都可以降低漩涡脱落的竖向一致性。上海中心大厦和深圳平安国际金融中心是两个成功的中国工程实例。图5a和图5b分别为这两栋超高层在 RWDI风洞中的模型照片。

上海中心的截面形式上下基本一致。然而，其截面宽度从下到上略微收缩，截面朝向随高度逐渐转动，如图6所示，由此造成的斯托罗哈数St 和特征宽度 D的逐渐变化干扰了沿楼高方向漩涡脱落的一致性。建筑上部的开孔（包括风力发电机部分）进一步干扰了漩涡脱落。所有这些建筑外形特点对降低大楼的风致响应起了重大作用。从远距离看深圳平安国际金融中心的形状像顶部收缩的立柱，但其实塔楼角部的几何形状是沿高度变化的，如图7所示。这些不起眼的变化也能够破坏漩涡脱落的一致性。与上下一致的传统立柱外形相比，上海中心大厦和平安国际金融中心的外形使其风荷载得到极大的降低。

Figure 5. (a) Shanghai Center wind tunnel model, (b) Ping An Finance Center wind tunnel model
图5. (b)上海中心大厦风洞模型，(b)平安财富中心风洞模型

The cross section of the Shanghai Center is the same basic form up the tower. However, there is a slight taper from bottom to top and the orientation of the cross section to the wind changes over the height of the building as shown in Figure 6. Each of these has the effect of a gradual change to both St and D thus disrupting the organization of the vortices. The openings, including wind turbines, at the upper portion of the tower further disrupt the regular shedding of vortices. These features make significant contributions to reduce overall wind-induced response. From a distance, the PAFC appears prismatic in form with the exception of the taper at the top of the building. However, the corner geometry of the tower changes over the height of the tower as shown in Figure 7. The effect of these subtle changes is to again disrupt the vertical alignment of the vortices. For each of the Shanghai Center and PAFC, the form achieved significant reductions in wind loading compared to prismatic form.

Control of Structural Parameters

There are three major structural parameters that a tall building design team has some control: stiffness, mass or mass density, and damping. The first two of these parameters are largely defined by choice of structural system to achieve a safe and economical solution. The third parameter, damping is significantly more variable and is generally within a range of assumed values that have developed over decades of practice with little verification. Good performance of tall buildings, however, indicates that design assumptions used to date have been satisfactory.

Structural damping is the key parameter in assessing the magnitude of motion within a building and its effect on occupant comfort. For tall buildings on the order of 40 to 60 stories in height, structural damping values range from 1% of critical for modest wind events to 2% of critical for significant wind events expected to occur once every several decades or more. Recent research (Wilford and Smith, 2008) indicates that supertall buildings might well have lower levels of damping. Other reports (Kijewski et. al., 2006; Irwin et al, 2011) indicate that structural damping is in line with design assumptions. In either case, the uncertainty of damping reduces reliability when it comes to serviceability responses including drift and occupant comfort which are critical design elements for super tall buildings.

An option to address the uncertainty is to set a target for damping and design to that target through the addition of supplemental damping as either a distributed system or a discrete Tuned Mass Damper (TMD) using a large mass block or Tuned Liquid Damper (TLD) as shown in Figure 8. Addition of supplementary damping reduces the occurrence rates of motion perception and also benefits the building's longer term performance as reduced deflections improve the durability of building components such as the cladding system. Damping systems are gaining more acceptance due in part to a good track record of performance. Passive TMD and TLCD systems designed by RWDI have been in use for more than 10 years. Periodic inspection has revealed no defect and there have been no reported complaints of uncomfortable motions from building managers where these systems are operational.

Natural Ventilation of Super Tall Buildings

Natural ventilation is one of the most accessible and viable means of reducing a building's energy demand. A recent review of Net Zero Buildings (NZB) and Net Zero Capable (NZC) [NBI, 2012] has shown that at least 50% of these buildings use natural ventilation as one strategy to achieve net-zero energy demand. However, as Wood & Salib (2012)

结构参数控制

高层建筑设计中能控制的结构参数主要有三个：刚度、质量（或密度）和阻尼。前两项参数主要取决于满足安全指标和经济指标的结构体系选择。第三项参数-阻尼则存在很大的不确定性，一般是根据以往数十年工程实践中逐步形成的共识假定某个取值范

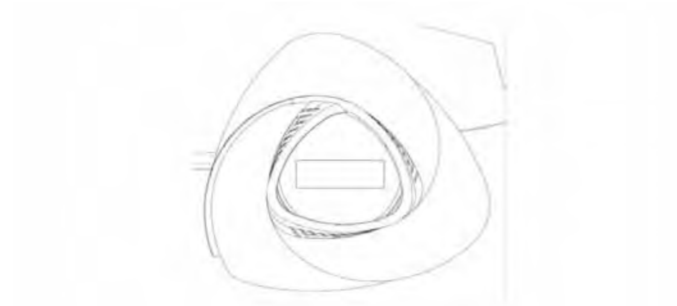

Figure 6. 'Rotating' cross sections of the Shanghai Center
图6. 上海中心大厦 “旋转”横切面

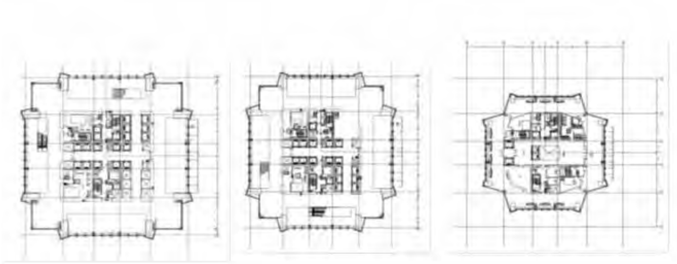

Figure 7. Changing cross sections of the Ping An Financial Center
图7. 平安财富中心变化的横切面

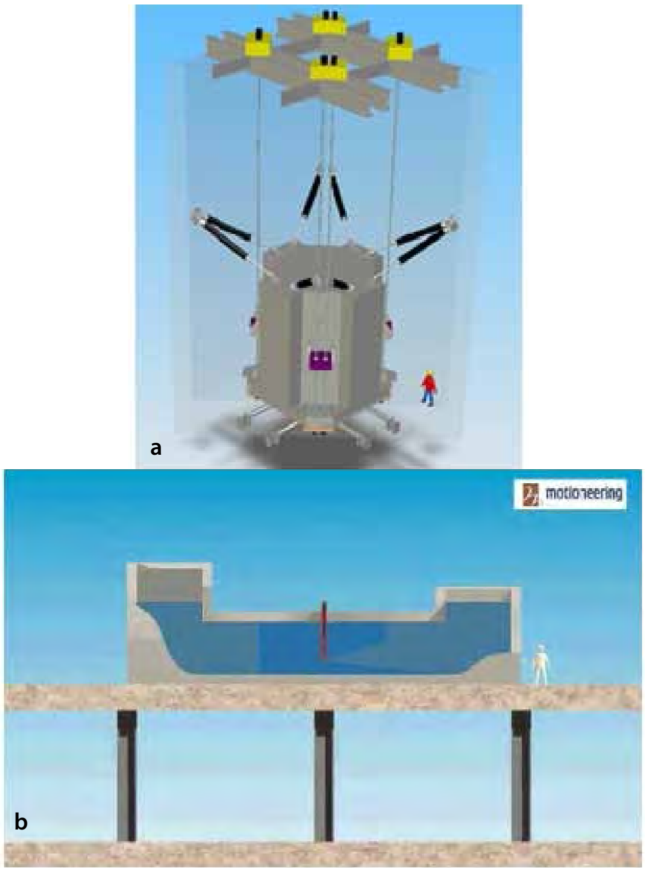

Figure 8. (a) Schematic of a simple pendulum Tuned Mass Damper (TMD), Schematic of a Tuned Liquid Column Damper (TLCD)
图8. (a)单摆调谐质量阻尼器(TMD)示意图，(b)调谐液体阻尼器（TLCD）示意图

point out, natural ventilation of super tall buildings has eluded the design community. There are many reasons for this, including higher wind speeds at upper elevations, complications in managing stack effect, and poor meteorological data for design of natural ventilation in tall buildings.

Temperature and Relative Humidity Distributions

Two crucial parameters involved in the viability of natural ventilation strategies are temperature and relative humidity. These parameters are used to define a climate type as hot & dry, temperate, tropical, etc. Wood & Salib (2012) provide descriptions of four different climate zones and the impact this has on the design of natural ventilation. For example, in tropical climates, air movement is crucial to achieving comfortable natural ventilation, while in hot dry climates natural ventilation during the day is difficult, however storing coolth at night within thermal mass has benefits.

With meteorological data measurements available at ground level, a number of strategies exist to extrapolate these to upper levels of the atmosphere. The standard lapse rate for temperature is approximately 1°C / 150m: this is set by international agreements (White, 1986). This would mean that at the top of a 600m building, the temperature would be approximately 4°C cooler. This value includes the influence of humidity in the air. Air at 100% relative humidity would result in a temperature difference over a 600m tall building of approximately 3°C. These are different from the dry lapse rate of 1°C/100 m typically quoted and often used in calculations: this is the value for dry air. It is also true that the absolute humidity usually drops as one climbs in elevation. This means that the two factors that reduce comfort in naturally ventilated buildings, e.g. elevated temperature and relative humidity, are lower at increased elevations. Hence it would make sense that natural ventilation would be easier at higher elevations in a building.

However, there is a lack of measured data that permits one to link the upper level temperatures with humidity, solar radiation and wind speeds. Without this data it is not possible to draw conclusions as to whether natural ventilation of tall buildings is as easy as thought or if there are other factors that influence the viability of natural ventilation at upper elevations.

One mechanism to generate interpolated weather data at upper levels is to use the same meteorological modelling process as is used for wind engineering. Specifically, WRF simulations can be used and meteorological data for temperature, RH, solar radiation and other parameters extracted. Used in this manner, WRF uses existing weather measurement databases as seed locations to simulate weather conditions within the domain of interest. Climate information in a 3D field is generated which permits one to compare conditions at the ground, and upper elevations, on an hour-by-hour basis.

Energy Modeling of a Tall Naturally Ventilated Building

To test the hypothesis that natural ventilation has greater energy saving benefits in a tall building, an energy model was constructed of a "typical" office floor for a tall building in a hot humid climate (Figure 9). The floor plate was approximately 1500 m^2. The model was created such that it could represent conditions at both grade and at upper elevations. The model included internal heat loads (e.g. occupants, lighting), infiltration, natural ventilation (for temperatures below a specific threshold), the energy associated with cooling and heating the space. The difference between the simulations was associated with shading of the lower levels of the building by adjacent buildings and the meteorology around them. The surrounding buildings were assumed to be the same height as the floor analysed: hence early

围，该取值范围虽然很少得到实际验证，但高层建筑的良好品质可以作为该假定满足至今为止设计要求的佐证。

结构阻尼比是确定建筑物振动幅度及其使用舒适度的关键参数。对40至60层高度的高层建筑来说，结构阻尼比的范围从弱风时的1%到几十年以上一遇强风时的2%左右。近期研究结果（Wilford和Smith，2008）表明超高层建筑可能有着较低水平的阻尼。其它报告（Kijewski等，2006；Irwin等，2011）则表明结构阻尼比与设计中的假定基本一致。因此，在验算位移和居住舒适性等运营品质的关键指标时，阻尼比的不确定性降低了结果的可靠度。

解决该不确定性的方法之一是首先设定要求达到的目标阻尼值，然后通过设置外部阻尼系统达到这一目标值。外部阻尼系统可以由分布式阻尼单元组成，也可以是调谐质量阻尼器（TMD）或调谐液体阻尼器（TLD）等离散阻尼系统，如图8所示。增加的额外阻尼降低了住户感觉振动的发生频率并提高了建筑物的长期品质，减少大楼的变形位移可以改善幕墙系统等建筑构件的耐久性。由于其良好的性能记录，阻尼系统目前已得到了更多的认可。RWDI设计的被动式调谐质量阻尼器和调谐液体阻尼器已经投入使用超过10年。对这些阻尼系统的周期性检查表明这些系统运行良好，安装阻尼系统的物业管理部门从未收到过关于住户对大楼振动的抱怨。

超高层建筑的自然通风

自然通风是降低建筑物能耗最容易和最可行的方法之一。近期对零能耗建筑（NZB）和准零能耗建筑（NZC）（NBI，2012）的考察结果表明这些建筑物中至少有50%使用自然通风作为达到零能耗的策略之一。但正如Wood和Salib（2012）所指出的，超高层建筑设计领域却一直避免采用自然通风，其原因是多方面的，包括高层的风速过大、控制烟囱效应的复杂性、以及缺少高层建筑自然通风设计中所需要的可靠的气象数据。

温度和相对湿度分布

自然通风方案的可行性中有两项关键参数：温度和相对湿度。这两项参数用于定义气候类型，如燥热、温和、热带等。Wood和Salib（2012）提供了有关对四种不同气候区域的描述及其对自然通风设计的影响。例如在热带气候下为达到舒适的自然通风，空气流动是关键；而在燥热气候下，日间的自然通风会较困难，但将夜间较凉爽空气通过热质量储存是有益的。

根据地面层测量的气象数据推算出高层数据的方法有多个。由国际协定规定的温度随高度的标准递减率大约为每150米降低1°C（White，1986）。这意味着达到600米高的建筑物顶端，温度大约降低4摄氏度，其中包括空气中湿度的影响。100%的空气相对湿度会在600米高的大楼上产生3摄氏度的温度差。这与干燥空气的递减率不同，用于计算的干燥空气递减率通常取每100米降低1°C。一般情况下绝对湿度随着高度上升而下降。这意味着在自然通风的建筑物中对舒适性不利的两个因素-温度和相对湿度会随著标高的增加而降低。由此可以认为自然通风在建筑高层区域应该较容易实现。

但是，由于缺乏实测数据，无法将高层的温度与湿度、太阳辐射、风速等联系起来。因此也无法给出高层建筑自然通风是否有如想象那样容易实现，或是否还有影响高层建筑上部自然通风可行性的其它因素等结论性的意见。

采用与风工程同样的气象模型分析是生成高层气象数据的一种方法，即采用WRF模型进行模拟计算得到包括温度、相对湿度、太阳辐射及其它参数的气象数据。WRF模型中以气象观测数据库为控制点，对所需要的区域的气象状态进行模拟计算。根据所得到的三维气候资料，可以对地面层和高层的气候情况进行逐时比较。

morning and late afternoon solar loads were rejected. Solar loads in the middle of the day were consistent between the two levels.

The weather data at grade and 600m above grade were extracted from a WRF database. The data were converted into a standard energy modelling data format (e.g. EPW) and energy simulations conducted for the two different elevations. EPW is the EnergyPlus weather file format. EnergyPlus is an industry standard energy modelling tool used to predict energy demand of buildings. The sources of data that are used to generate EPW file formats come from measured data, which are then screened to generate representative years of "typical" data that reflects average conditions over an extended period of time (e.g. 30 years) with priority on capturing solar intensity information to select "typical" conditions. The data used for this analysis used a TMY2 data set which used the World Meteorological Organization (WMO) data as the source.

Energy Modelling Results

Table 1 below presents the results of the energy modelling. Five scenarios were evaluated. These are:

- A reference scenario using the standard energy modelling file (TMY2) for the location at grade.
- A simulation of the building at grade using WRF data.
- A simulation of the building at grade using WRF without natural ventilation or infiltration.
- A simulation of the building at 600m using WRF data.
- A simulation of the building at 600m using WRF data without natural ventilation or infiltration.

The internal loads associated with lighting, electrical devices (plug loads) and occupants remained the same. The differences between the simulations were the heating and cooling loads and the associated pump and fan energy to deliver the heating and cooling.

The total energy demands of the five scenarios are presented in the column to the far right of Table 1. Scenarios 1 and 2 can be used to compare the appropriateness of using the WRF data (Scenario 2) for energy modeling as it is compared to the standard data set (Scenario 1). The difference of 7 kWh/yr represents a 3% variation. Comparing Scenarios 2 and 4 permits one to assess the difference in energy demand of the building at two levels. Clearly the difference is very small (<3 kWhr/yr). This is counter-intuitive as one would expect that the energy demand at upper levels would be lower since it there are lower temperatures at that level. Given the reduced temperatures, one would expect to be able to use natural ventilation for a greater period of the year. One would also expect the cooling load to be lower because the ambient temperature is lower.

The difference in energy demand can be explained by comparing the base building that is naturally ventilated (Scenarios 2 & 4) to one that is "sealed" (Scenarios 3 & 5) and has no infiltration/exfiltration to the building. For the sealed buildings (Scenarios 3 & 5), the energy demand for heating / cooling of the upper level (Scenario 5) is higher than that for the lower levels (Scenario 3). In fact, closer and detailed inspection of the resultant data for the natural ventilation scenarios showed that the reason the energy demand at upper levels (Scenario 4) is essentially equivalent to that at the lower level (Scenario 2) is because of infiltration through the natural ventilation components. While natural ventilation in the shoulder season has a greater benefit for the upper level, during the summer the increased infiltration

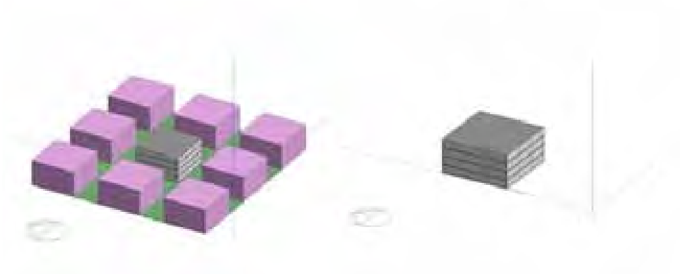

Figure 9. Energy Model of a Building at Grade (left) and 600m (right)
图9. 一座建筑在水平面上（左）和600米处（右）的能量模型

高层建筑自然通风的能量建模

为验证高层建筑自然通风节省能耗的假设，我们建立了湿热气候下一栋高层建筑标准办公楼层的能量模型（图9）。楼层面积为1500平方米。该模型可以显示地面楼层和高区楼层的情况。模型中包括内部热负荷（如住户、光等）、渗透、自然通风（针对温度低于某一给定的界限）、与空调制冷和制热有关的能耗。不同楼层模拟之间的区别在于低区楼层受周边建筑物的遮挡作用以及各楼层周围的气侯状态。这里假定周围建筑物的高度与分析楼层相同，因此清晨与傍晚的太阳能负荷是被遮挡的，而正午的太阳能负荷对上下两个楼层则是相同的。

从WRF分析数据库中得到地面与600米高度的气象数据，然后将数据转换成标准能量模型数据格式（如EPW）并对两个不同楼层进行能量模拟分析。EPW是EnergyPlus气象文件格式的缩写，而EnergyPlus则是符合工业标准的建筑能耗分析软件，用于估计建筑物的能耗需求。建立EPW文件格式的原始数据来自于过滤后的实测数据，用以代表较长时期内（30年）典型的平均状态，其中着重于太阳辐射强度的典型性。分析数据取自TMY2数据集，而TMY2数据集则源自世界气象组织WMO的数据。

能量模拟结果

表1显示了能耗模拟分析的结果，其中包括五种测试工况：

- 使用标准能耗模型文件（EPW）的参考工况。
- 使用WRF数据对建筑地面层的模拟。
- 使用WRF数据对建筑地面层的模拟（无自然通风或渗漏的情况）。
- 使用WRF数据对建筑600米高度的模拟。
- 使用WRF数据对建筑600米高度的模拟（无自然通风或渗漏的情况）。

光、电器设备和住户产生的内部负荷保持不变。各模拟间的不同之处在于制热和制冷负荷的不同，以及相应的传递热空气与冷空气的泵或风扇的负荷。

表1的右列给出五种工况各自的总能耗。使用WRF数据（工况2）进行的能耗模拟与采用标准数据集（工况1）的分析对比可以说明WRF数据的适用性。每年7千瓦时的差别等于3%的变化。对比工况2和工况4可以确定建筑物中两个不同楼层的能耗差别，显然差别非常小（小于每年3千瓦时）。这与直观判断相悖，通常人们会认为由于高区楼层温度较低所以对其供能的需求也较少，可以更长时间地使用自然通风，周围较低的温度会使制冷负荷也较低。

能耗的不同可以通过比较没有内外渗透的密闭建筑（工况3或5）和自然通风的建筑（工况2或4）得到解释。对密闭建筑（工况3或5），高区楼层（工况5）制热或制冷的能耗高于低区楼层（工况3）。对自然通风建筑，结果的详细分析表明由于自然通风单元的渗漏，高区楼层（工况4）的能耗与低区楼层（工况2）基本

	Lighting (kWh) 照明(度)	Occupants(kWh) 人员 (度)	Plug Loads (kWh) 设备 (度)	Cooling (kWh) 降温 (度)	Heating (kWh) 取暖(度)	DHW (kWh) 热水 (度)	Fans + Pumps (kWh) 风扇/泵 (度)	Total (kWh) 总量 (度)
Ground - original Weather File (EPW) 地面层-原始天气分析	34.3	6.3	29.4	123.4	0.8	11.2	22.3	227.6
Ground - WRF EPW 地面层- WRF模型分析	34.3	6.2	29.4	130.4	0.7	11.6	23.1	235.7
Ground - WRF EPW no Infiltration or Nat Vent 地面层-WRF模型-无空气渗入或自然通风	34.3	6.3	29.4	145.2	0.0	12.4	24.7	252.2
600m - WRF EPW 600m高-WRF模型分析	34.3	6.4	29.4	129.5	3.8	11.7	23.4	238.4
600m - WRF EPW no Infiltration or Nat Vent 600m高-WRF模型-无空气渗入或自然通风	34.3	6.3	29.4	156.2	0.0	13.0	26.0	265.2

Table 1. Energy modeling results for a number of scenarios (Note: DHW = Domestic Hot Water)
表1. 一些情况下的能量模拟结果(备注：DHW = 生活用热水)

through leaky windows and other components offsets the energy savings and results in a net equivalent. This is shown in Figure 10. The upper plot shows the energy associated with air exchange: below zero shows outdoor air reduces temperatures, above zero shows the infiltration of air increasing internal temperatures. The lower plot presents the outdoor air (natural ventilation + infiltration) flow rate.

This means that natural ventilation saves energy, but the savings are lost because of components that let in warm summer air. The higher wind speeds at upper levels exacerbate this issue.

Ultimately, the purpose of conducting this exercise has been to evaluate the assumption that natural ventilation in tall buildings will help. The quick analysis has shown that it is not necessarily true and that designers need to be aware of the drawbacks of natural ventilation in tall towers before installing components to permit it.

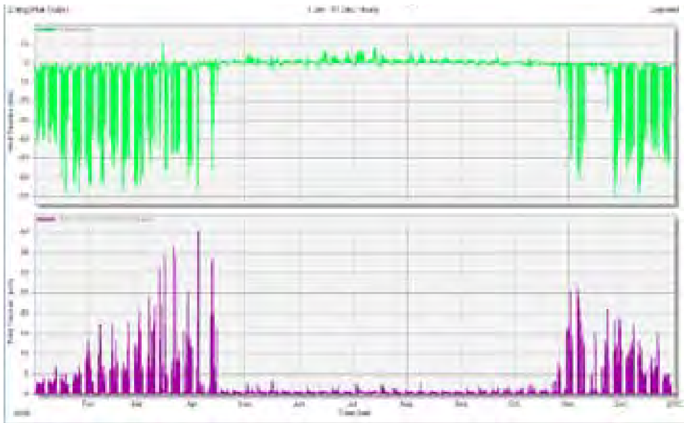

Figure 10. Energy Benefit / Deficit Associated with Outdoor Air Entering the Space
图10. 与室外空气进入相关的能量的受益和缺失

相同。在冷暖适中的季节里自然通风对高区楼层确实有利，但在夏季时通过窗户或其它单元所增加的渗漏抵消了节约的能量而使总利弊几乎相等。 这种情况表示在图10中，其中上图表示与空气交换有关的能量：小于零的数值代表室外冷空气降低室内温度，而大于零的数值则代表室外热空气渗入增加了室内温度。图10中下图则为室外空气流量（自然通风+渗入）。

以上表明自然通风节省了能耗，但夏季热空气的渗入会抵消所节约的能耗。高区楼层较高的风速会加剧室外空气渗入的情况。

以上模拟计算的目的是验证有关高层建筑自然通风是否有利的假定。计算结果表明高层建筑自然通风不一定是有利的，设计人员在高层建筑上安装自然通风单元时应当对可能的不利因素有清晰的理解。

Conclusions

The paper presents a series of design considerations that improve the sustainability of super tall buildings. The use of Weather Research Forecasting tools can greatly improve the understanding of wind speed, wind direction, temperature and relative humidity over the full height of a tall building in its specific climate. This data could lead to efficiencies in both structural and mechanical system design.

Case studies of super tall buildings in China where aerodynamic shaping has been used effectively to reduce wind loads are also presented as has an example energy model of a tall tower that is naturally ventilated. An approach to design for damping to improve the long term performance of building components is presented. Finally, an analysis of the benefits of natural ventilation to sustainable design is presented through a case study of a tall building in a hot humid climate. This analysis has shown that natural ventilation is not necessarily an energy saving feature. Careful design is required to take advantage of lower temperatures at upper elevations.

结论

本文阐述了一系列改善超高层建筑可持续性的设计思路。气象研究预测模型的应用可以极大地增强对高层建筑在特定气候条件下沿高度变化的风速、风向、温度和相对湿度等的了解。而这些资料对提高建筑结构和机电系统设计的效率是有帮助的。

本文还介绍了采用空气动力外形优化有效地减少风荷载的两栋中国超高层建筑，讨论了采用阻尼装置提高建筑物长期的运行品质。另外通过对湿热气候下的一栋高层建筑的能耗模型分析，考察了自然通风的益处。结果表明，高层建筑的自然通风不一定能节省能耗，必须在设计中予以仔细分析考虑才能真正利用高区楼层温度较低的优势。

References（参考书目）:

AIJ-Damping (2000), **Damping in Buildings,** Architectural Institute of Japan, Maruzen, pp.287, 2000

American Society of Civil Engineers, **Minimum Design Loads for Buildings and Other Structures, ASCE Standard, ASCE/SEI 7-10,** 2010.

Australia/New Zealand Standard, **Structural Design Actions, Part 2: Wind Actions, AS/NZS 1170.2:2011.**

ESDU (1982): **Strong Winds in the Atmospheric Boundary Layer. Part 1: Mean Hourly Speeds,** Item 82026, Issued September 1982 with Amendments A and B April 1993. Engineering Sciences Data Unit, ESDU International, 27 Corsham Street, London N16UA.

ESDU (1983): **Strong Winds in the Atmospheric Boundary Layer. Part 2: Discrete Gust Speeds,** Item 83045, Issued November 1983 with Amendments to 1993. Engineering Sciences Data Unit, ESDU International, 27 Corsham Street, London N16UA.

Irwin, P.A., 2006, **Exposure Categories and Transitions for Design Wind Loads,** ASCE J. Structural Engineering, Vol. 132, No. 11, pp. 1755 – 1763.

Irwin, P.A., Kilpatrick, J and Galsworthy, J.K., **The Role of Damping in Controlling the Wind Response of Tall Buildings,** IABSE-IASS Symposium, London, UK, September 20 - 23, 2011.

Kijewski-Correa, T, Kilpatrick, J., Kareem, A, Kwon, D-K., Bashor, R., Kochly, M., Young, B.S., Abdelrazaq, A., Galsworthy, J.K. Isyumov, N.I., Morrish, D.P, Sinn, R.C. & Baker, W.F. , **Validating Wind-Induced Response of Tall Buildings: Synopsis of the Chicago** Full-Scale Monitoring Program, J. Struct. Eng., Volume 132, Number 10, October 2006, 1509-1523.

nbi (2012), **Getting to Zero 2012 Status Update, Research Report,** New Buildings Institute (NBI), Vancouver, WA.

Smith, R and Willford, M., **Damping in Tall Buildings - Uncertainties and Solutions,** 17th Congress of IABSE, Chicago 2008.

Qiu, X., Lepage, M., Sifton, V., Tang, V. & Irwin, P.A., **Extreme Wind Profiles in the Persian Gulf Region,** 6th Asia Pacific Conference on Wind Engineering, Seoul, Korea, 12-14 September, 2005.

White, Frank M. (1986), Fluid Mechanics 2nd Edition, McGraw Hill: Toronto, Canada.