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The New Super Skinny Skyscraper Trend: Some Wind Engineering Considerations

新型超纤细摩天大楼的趋势：风工程学方面的一些考虑

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Abstract | 摘要

A new and almost unprecedented model for skyscrapers is currently being explored within the Manhattan real estate market: these are the so-called super slender ultra-luxury residential tall buildings, towers with relatively compact floor plates and very high slenderness ratios. The commercial and financial success of these structures would have not been possible without the support of sophisticated engineering, including highly specialized wind engineering studies. This technical paper will highlight some of the wind engineering challenges associated with both the design of the lateral stability system and the meeting of serviceability criteria for top-floor motions on the lower return periods for these super slender tall buildings. Also introduced will be the challenges faced with the wind engineering of these types of structures and where the future of wind engineering will need to be if these design trends continue.

Keywords: Wind, and Wind Loads

曼哈顿房地产市场目前正在探索一种几乎前所未有的新型摩天大楼：这些所谓的超纤细超豪华住宅大厦，即楼层截面相对较小而长细比很大的塔楼。若没有先进的工程学支持，其中包括高度专业化的风工程研究的支持，此类建筑结构难以取得商业和经济上的成功。这篇技术论文旨在重点阐述风工程学在横向稳定性设计、以及满足此类超纤细高层建筑顶层运动方面较低重现期适用性标准所面临的种种挑战。本文还介绍了此类建筑结构所存在的风工程学难题，以及在这种设计趋势持续下去的情况下，风工程学还需要得到怎样的发展。

关键词：风、风荷载

Introduction

A new and almost unprecedented model for tall buildings is currently being explored in New York City: these are the so-called super slender ultra-luxury residential tall buildings, towers with floor plates typically in the region of 400 m^2 and slenderness ratios well in excess of 1:10. Some examples of these structures include 432 Park Avenue – topped out in Manhattan in October 2014 (slenderness ratio of 1:15) and 111 West 57th Street – currently under construction in Manhattan (slenderness ratio of 1:23), which will surpass the record currently held by the Highcliff tower in Hong Kong (slenderness ratio of 1:20). With almost 180,000 people added to the urban population each day; approximately 64% of the Asian population foreseen to be urban by 2050; and megacities spreading worldwide, this model is not expected to remain confined to North America.

Monolithic supertall buildings, with height between 300 m and 600 m and slenderness ratios of approximately 1:10, would typically exhibit a first order mode frequency in the region of 0.1 Hz; for these structures, the first order modes would approach the Strouhal

引言

纽约市目前正在探索一种几乎前所未有的新型高层建筑模式：这些所谓的超纤细超豪华住宅大厦，即楼层面积一般在400 m^2左右，而长细比超过1:10的塔楼。此类建筑的范例包括2014年10月封顶的曼哈顿公园大道432号(http://skyscrapercenter.com/building/432-park-avenue/13227)（长细比1:15），及目前在建的曼哈顿西57大街111号（http://skyscrapercenter.com/building/111-west-57th-street/14320）（长细比1:23），此楼将打破香港“晓庐”大厦(http://skyscrapercenter.com/building/highcliff/830)所保持的纪录 （长细比1:20）。随着城市人口每天增加约180,000人，而且据预测，到2050年亚洲约64%的人口为城市人口，特大城市在世界各地不断涌现，这一建筑模式预计不会仅局限于北美地区。

高度300 – 600 米，长细比约为1:10的单体超高层建筑的第一阶模态频率一般在0.1 Hz左右：对于这些建筑结构，第一阶模态在50年或100年重现期相关风速条件下将接近斯托罗哈（Strouhal）条件。

condition at wind speeds associated with 50- or 100-yr return period.

The response characteristics for super slender tall buildings are rather different and aeroelastic phenomena can become crucial in design. With slenderness ratios in the region of 1:20 and first order modes sitting at approximately 0.08 Hz, the critical wind speed for vortex shedding does in fact tend to be much closer to far more frequent wind events (sometimes as low as monthly if not weekly events), posing some interesting challenges in relation to wind-induced motion and associated occupant comfort (e.g., if one assumes a 400 m tall building with 20 m as the smallest size of its cross-section, a period of the first order mode of vibration of 12 s and a Strouhal number of approximately 0.15 – representing an average between faceted and organic architectural forms – then the critical wind speed for vortex shedding – at approximately two-third of the height of the building – would be in the range of 10 m/s). At such frequent speeds the influence of thermal stratification of the free atmosphere of the boundary layer has the potential to become more important, and the associated low levels of turbulence intensities could promote far more well-correlated and narrow-band vortex shedding (it is in fact well known that convective currents are eliminated by the mechanical stirring of the atmosphere only for hourly-mean wind speed at 10 m height greater than 10 m/s, see ESDU Item 82026). Moreover, with "3" being the typical frequency ratio between the second and first order modes of vibration, it is not atypical for the second order modes to dynamically interact with the vortex shedding at wind speeds with return periods pertaining to the Ultimate Limit State design of the building (e.g., 700- or 1,700-yr). Because of this, the peak dynamic bending moment at the inflection point of the second order mode could become of particular interest for the structural designer, as the floor-by-floor wind loading distribution typically aimed at maximizing load effects at foundation level may not be conservative for the wind-induced structural stresses taking place at, say, approximately half of the height of the building (0.5•H). It is also worth noting that accelerations due to higher modes of vibration can become more perceptible than the fundamental ones and at lower levels in the building.

This technical paper will present the outcome of an aeroelastic wind tunnel testing campaign conducted on an idealized super slender tall building with the specific intent to investigate the aerodynamic performance of these novel structures.

超纤细高层建筑的响应特性相当不同，气动弹性现象在设计中可能会变得十分重要。如果长细比在1:20左右，第一阶模态频率约为0.08 Hz，涡旋脱落的临界风速的确往往会更接近频繁发生的风事件（有时低至每月甚至每周风事件），从而造成一些与风致运动及相关住户舒适度方面的独特挑战（例如，如果假设一幢400米高、横截面最小尺寸为20米的建筑，第一阶振型持续时间12秒，斯托罗哈数约0.15 – 代表多面与有机建筑形态之间的平均值，那么涡旋脱落的临界风速 – 在大楼约三分之二的高度 – 即会在10米/秒的范围）。在如此常见的风速下，边界层自由大气的热分层影响就可能会变得更为重要，而相关的低水平湍流强度则可能促成更具关联性的和窄频带的涡旋脱落（实际上众所周知，只有在10米高度小时平均风速大于10米/秒时形成的大气机械扰动才能消除对流气流，详见ESDU（工程科学数据库）第82026号）。另外，由于第二阶和第一阶振型之间典型的频率比为"3"，第二阶模态与建筑最终极限状态设计的相关重现期（如700或1700年）风速条件下的涡旋脱落形成动态交互作用并不罕见。由于这一原因，第二阶模态反曲点的峰值动态弯矩就会受到结构设计师的特别关注，因为常常用于实现基底层荷载效应最大化的逐层风荷载分布对于发生在建筑约一半高度（0.5 H）的风致结构应力可能并不见得保守。同样值得一提的是，更高振型所引起的加速度在建筑的较低楼层可能比基本振型更容易感觉到。

本技术论文阐述了针对一个理想化的超纤细高层建筑所做的气弹风洞测试活动的结果，此项测试活动专门是为了调查此类新型建筑结构的空气动力特性。

文献综述

除了2015年在第14届国际风工程会议上提交的一篇主题论文外（Galsworthy等人，2015），有关超纤细建筑这一专题的文献资料几乎没有。有鉴于此，在涉及到文献综述时，我们除了回归到一些基础文献外别无选择。由于此类建筑结构具有"似线状"特性，因此欲了解超纤细建筑的相关响应特点及气动弹性现象，上世纪60年代、70年代、80年代针对烟囱风激振动所做的一些先驱性研究工作可为我们提供了一个相当不错的切入点。这就不免要追溯到1960年代Kit Scruton 在Teddington英国国家物理实验室空气动力学分部针对烟囱、塔楼及天线塔所做的一系列研究工作（Scruton 1963），以及再次参阅 Hans Ruschewyh在1970年代为研究烟囱及塔形建筑结构的动态响应而广泛进行的实测研究活动（Ruschewyh & Hirsh 1975），还有，我们当然还需要充分考虑Barry Vickery针对圆截面结构横风向风振所做的出色研究（例如，他在1980年代开发出的数学模型，Vickery & Basu 1983）。

"纤细型"机制

正如在"引言"部分提到的一样，长细比达1:8或1:10高层建筑出现的涡旋脱落现象会与50 – 100年重现期极端风事件的典型风速下建筑结构的基本振型发生交互作用关系。

例如，图1所示为图2"建筑A"（纽约曼哈顿的一个真实商业项目）全方向50年重现期风速条件下风致基底倾覆力矩的各个"次分量"：菱形标记的线代表"平均"荷载分量；十字标记的线代表最大/最小"峰值静态"荷载（即"平均值"加上/减去风荷载的"准静态"分量）；方框标记的线代表1%结构阻尼的最大/最小"峰值动态"荷载（即"平均值"加上/减去风荷载的"准静态"和"共振"分量）。明显值得注意的是，西北偏北风区周围的峰值动态荷载 – 主要受涡致激励影响（平均分量的数字为零）– 比出现于东北偏北风区周围受曳力带动、较为温和的风响应在量值上高出约30%。

"超纤细型"机制

正如在"引言"部分提到的一样，超纤细塔楼的空气动力学机制在一定程度上与传统的高层建筑不同。我们来试着分析一下其中的原因。图3 所示为三个大型特大城市 – 深圳（深受台风事件影响、具有极端风气候的特大城市）、纽约（略受飓风影响）和伦敦（主要受大规模温带低压影响）– 的密集建成环境中不同重现期的约400米高度的小时平均风速（空气动力学粗糙度长度z0 = 0.7 m）。 此外，图中的水平曲线为棱柱/多面形态及有机建筑形态的涡旋脱落临界风速（第一阶及第二阶结构模态）。这两种建筑形态基本结构振型的共振特性均被清楚地表现了出来 – 均大大低于1年重现期风速，而对于风气候主要受天气事件影响的城市 – 尤其是深受台风影响或较接近最终极限状态风速的区域 – 棱柱形第二阶模态的共振特性接近于50年重现期的风事件。图3没有明确展现出来的是，对于有机建筑形态，第三阶振型有可能会与受台风强烈影响区域最终极限状态风速条件下的涡旋脱落形成动态相互作用关系。

为了深入了解超纤细单体建筑的空气动力特性，本文作者设想了一座高宽比为1:20的虚拟建筑（图2的"建筑B"）并在BMT Fluid Mechanics公司的大型边界层风洞设施中进行了全面研究（http://www.bmtfm.com)。

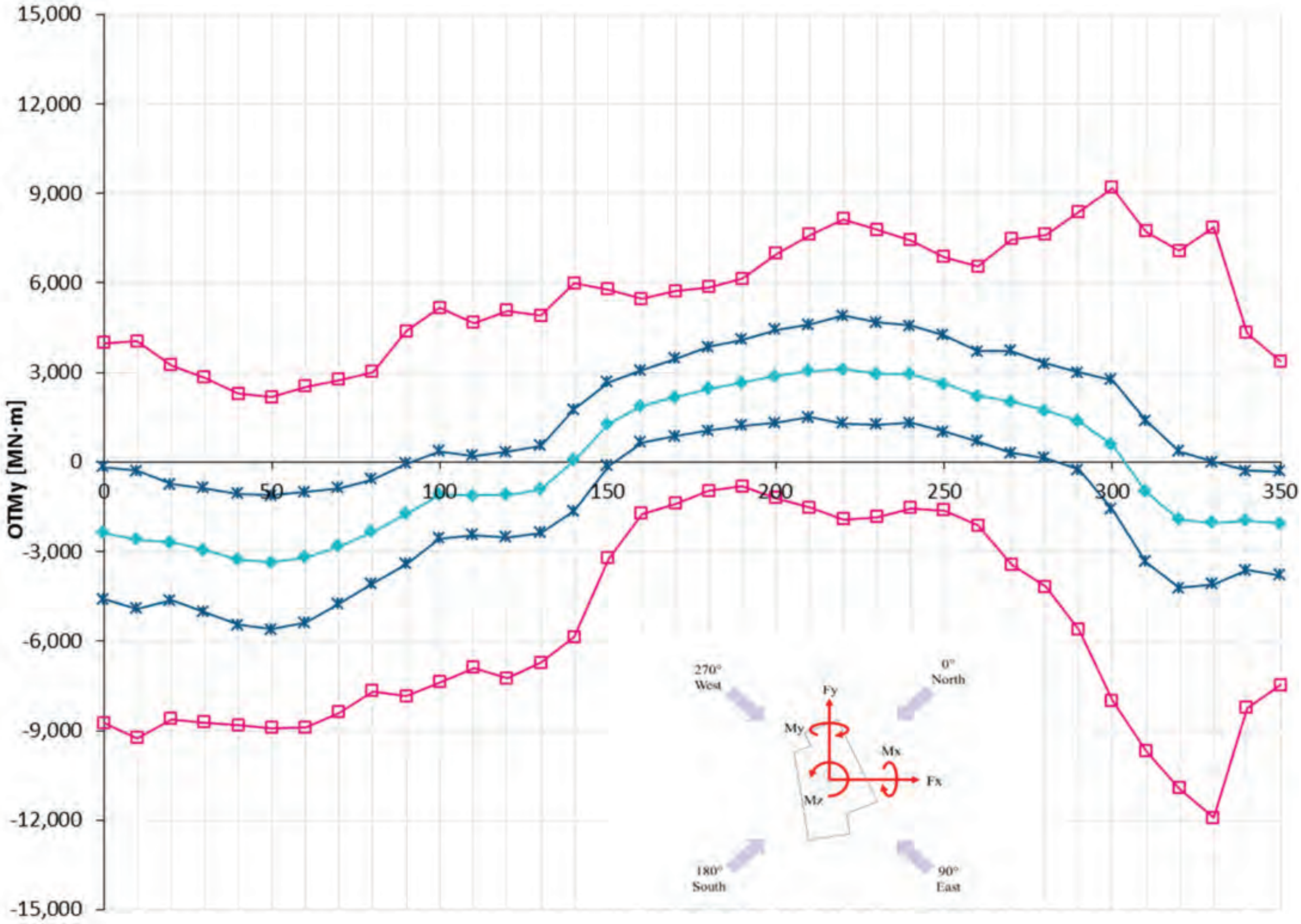

Figure 1. Wind-induced base overturning moment for "Building A" (Source: BMT Fluid Mechanics Ltd.)
图1. "建筑A"风致基底倾覆力矩（来源：BMT Fluid Mechanics 有限公司）

Literature Review

With the exception of one of the keynote papers presented in 2015 at the 14th International Conference on Wind Engineering (Galsworthy et al. 2015), the literature on the specific subject of super slender buildings is nearly non-existent. With this in mind, when it comes to literature review, one is therefore left with no option but to go back to the basics. The line-like nature of these structures makes the pioneering work on wind-excited oscillations of chimneys of the 60s, 70s and 80s an attractive starting point when one is trying to understand the response characteristics and the aeroelastic phenomena pertaining to super slender buildings. This inevitably means going back to the work on stacks, towers and masts of Kit Scruton at the Aerodynamic Division of the National Physical Laboratory in Teddington in the 1960s (Scruton 1963); revisiting the extensive full-scale measurement campaigns focused on the investigation of the dynamic response of chimneys and tower-shaped structures conducted by Hans Ruschewyh in the 1970s (Ruschewyh & Hirsh 1975); and taking of course into consideration the excellent work on across-wind vibrations of structures of circular cross-section conducted by Barry Vickery (e.g., the mathematical model he co-developed in the 1980s; Vickery & Basu 1983).

"Slender" Regime

As mentioned in the "Introduction" section, tall buildings with slenderness ratios of say up to 1:8 or 1:10 would feature an interaction between the vortex shedding phenomenon and the fundamental mode of vibration of the structure at speeds typically associated with extreme wind events of 50- to 100-year return periods.

As an example, Figure 1 shows the different "sub-components" of the wind-induced base overturning moment for "Building A" of Figure 2 (a real commercial project in midtown Manhattan, New York City) generated by an omnidirectional 50-yr return period wind speed. The line marked by full diamonds represents the "mean" loading component; the ones marked by crosses the maximum/minimum "peak static" load (that is "mean" plus/minus the "quasi-static" component of the wind load); and the ones marked by

风洞测试

进行风洞测试活动是为了调查一幢宽高比为1:20的超纤细高层建筑的风致响应（图2"建筑B"）。选取的这幢理想化的建筑高度为400米，横截面为20 米×20米带圆角的正方形（曲率半径为2米），建筑密度约为250 kg/m3。

风流调节

风洞测试在平滑流（Iu < 0.5%）以及边界层湍流（z0 = 0.7 m，即Iu ~ 15%，在大楼上部三分之一）两种条件下进行，后者为工程学数据库（ESDU）第01008号所建议的分析模型。

气弹风洞技术

由于超纤细建筑结构在空气动力学方面的非线性度，本技术论文的作者认为，针对此项调查工作所选择及采用的最合适的风洞测试技术应为气动弹性法：采用气弹模型方法可在风洞中准确模拟实际的风-结构的相互作用情况。

气弹风洞模型必须在设计及建造上确保其在风洞中的特性与实际建筑结构相仿 – 对阵风荷载激励及涡致力的响应和振动。

此类模型的建造需与实际建筑在结构特性（即：质量与刚度分布）上准确匹配，而

Figure 2. Characteristics of "Building A" and "Building B" (Source: BMT Fluid Mechanics Ltd.)
图2. "建筑A"与"建筑B"的特点（来源：BMT Fluid Mechanics 有限公司）

empty squares the maximum/minimum "peak dynamic" load for 1% structural damping (that is "mean" plus/minus the "quasi-static" and the "resonant" component of the wind load). It is clearly noticeable how the peak dynamic load around the north-northwest wind sector – heavily driven by vortex-induced excitation (mean component numerically zero) – is approximately 30% greater in magnitude than the more benign drag-driven along-wind response taking place around the north-northeast wind sector.

"Super Slender" Regime

As noted in the "Introduction" section, the aerodynamic regime of super slender towers somewhat differs from the one of more conventional tall buildings. Let's try to understand why. Figure 3 shows the variation with return period of the mean-hourly wind speed at a height of approximately 400 m within a densely built-up environment (with an aerodynamic roughness length of z0 = 0.7 m)

且在整体测量仪器配备上需确保此高层建筑对风荷载的结构响应可在试验期间进行实时测量。

完整的气弹风洞模型的另一大优势就是能够对更高振型对风荷载的加成作用进行量化，这一点对于超纤细建筑结构尤其重要。

气弹风洞模型

用于进行风洞测试的风洞气弹模型是按1:400的几何比例进行设计和建造的。风洞气弹模型的刚度通过内部起支撑作用的锥形格栅式铜支架提供，并需要能够再现高层建筑挠曲形变与剪切形变之间的平衡。模型的外部包覆层采用端点连接至内部支架的10节壳体段（采用选择性激光烧结（SLS）技术制作而成，从而可以达到±0.1 mm的模型比例容差）进行模拟（图4）。模型的底座连接至一个高频测力天平，而模型本身则装配了一系列低量程高分辨率加速度仪。试验所使用的6分量高频测力天平为定制的压电式天平系统，固有刚度超过2 kHz。

在风洞测试之前的模型校准过程中对风洞模型的模态特性（模态频率、模态阻尼及模态质量–基于振型针对近楼顶位置（即0.95·H）归一化）进行了测定，测量结果在图5中与全尺寸当量一起进行概括。此外，图6所示为经测得的风洞气弹模型的振型。

气弹风洞测试：结果及讨论

风洞测试在BMT Fluid Mechanics公司位于（英国）Teddington的大型边界层风洞

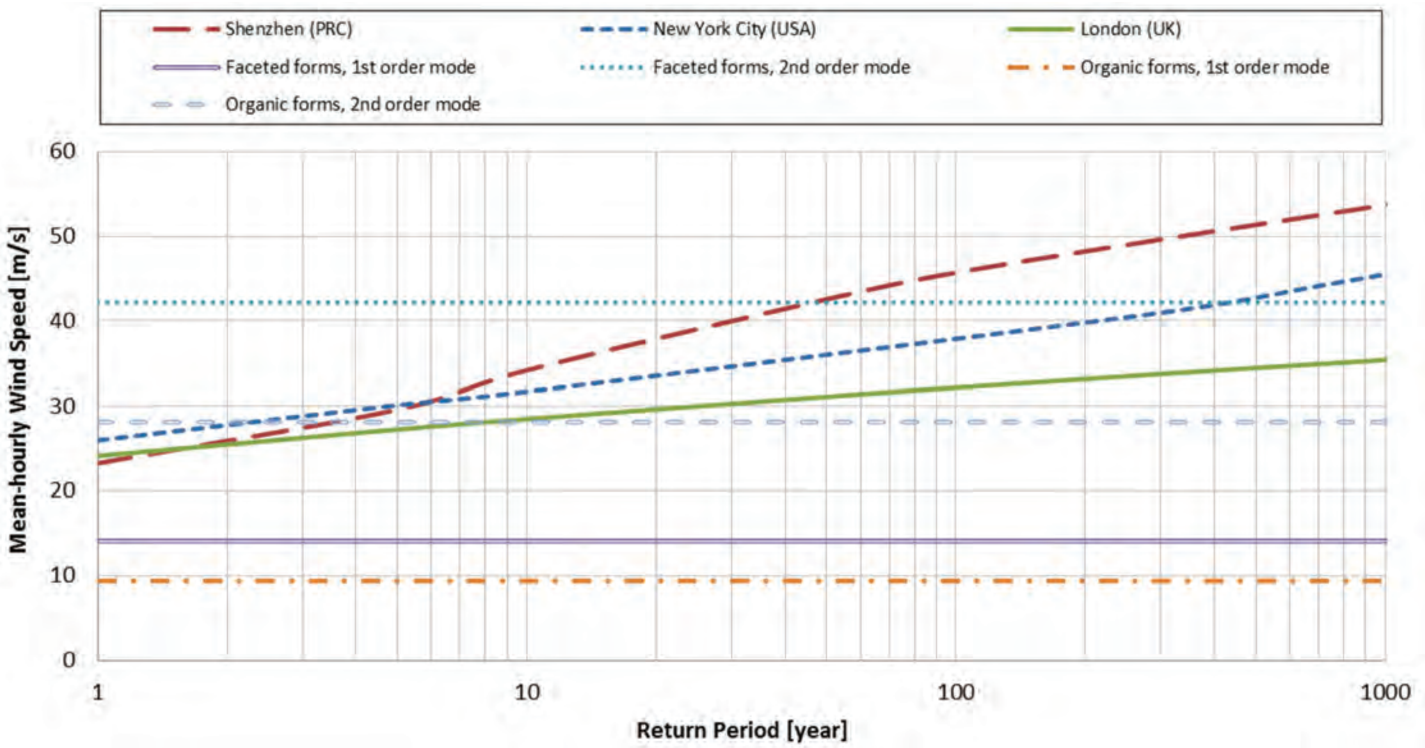

Figure 3. Mean-hourly wind speed at 400 m vs. return period with highlighted critical wind speeds for vortex shedding. (Source: BMT Fluid Mechanics Ltd.)
图3. 400m高度的小时平均风速与重现期，重点显示涡旋脱落的临界风速（来源：BMT Fluid Mechanics 有限公司）

for three large mega-cities: Shenzhen (a mega-city with an extreme wind climate heavily affected by typhoon events), New York City (mildly influenced by hurricanes) and London (primarily affected by large extra-tropical depressions). Also shown, as horizontal lines, are the critical wind speeds for vortex shedding (first as well as second order structural modes) for both prismatic/faceted and more organic architectural forms. The resonant behavior in the fundamental structural mode of vibration clearly manifests itself – for both types of architectural shapes – well below the 1-yr return period wind speeds, whilst the resonant behavior in the second order mode for the more prismatic shapes can occur close to the 50-yr return period winds – for regions strongly influenced by typhoons or closer to the Ultimate Limit State speeds – for those with a wind climate mainly influenced by synoptic events. Although not explicitly shown in Figure 3, for the more organic forms there is the potential for the third order modes of vibration to dynamically interact with vortex shedding at the Ultimate Limit State speeds in regions strongly influenced by typhoons.

In order to deepen the understanding of the aerodynamic behavior of super slender monolithic buildings, a fictitious building (see "Building B" in Figure 2) with an aspect ratio of 1:20 was therefore conceived by the authors of this technical paper and thoroughly studied in BMT Fluid Mechanics' large boundary layer facility (http://www.bmtfm.com).

Wind Tunnel Testing

A wind tunnel testing campaign was conducted with the aim of investigating the wind-induced response of a super slender tall building with an aspect ratio of 1:20 (see "Building B" in Figure 2). The idealized building was chosen to be 400 m tall with a 20 m × 20 m square cross-section with rounded corners (radius of curvature of 2 m) and a building density of approximately 250 kg/m3.

Flow conditioning Wind tunnel tests were conducted both in smooth flow (Iu < 0.5%) and – following the analytical model proposed in the Engineering Sciences Data Unit (ESDU) Item 01008 – in turbulent boundary layer flow (z0 = 0.7 m, i.e., Iu ~ 15% over the top third of the tower).

Aeroelastic Wind Tunnel Technology

Because of the non-linearity associated with the aerodynamics of super slender structures, the authors of this technical paper felt that the most appropriate wind tunnel testing technique to be chosen and adopted for this investigative work was the aeroelastic technique: the aeroelastic modeling technique allows the wind-structure interaction to be accurately simulated in the wind tunnel.

Aeroelastic wind tunnel models must be designed and constructed to behave in the wind tunnel like the real structure, vibrating and responding to gust wind loading excitation as well as to vortex-induced forcing.

These types of models need to be constructed to accurately match the structural properties of the real building (that is: mass and stiffness distribution), and are generally instrumented so that the structural response of the tall building to wind loading can be measured in real time during the experiment.

Another great advantage of full aeroelastic wind tunnel models, particularly important in the realm of super slender structures, is that it enables the contribution to wind loading coming from higher modes of vibration to be quantified.

Aeroelastic Wind Tunnel Model

The wind tunnel aeroelastic model designed and constructed for the wind tunnel testing was at a geometrical scale of 1:400. The stiffness of the wind tunnel aeroelastic model was provided by an internal supporting tapered lattice brass spine which needed to replicate the balance between flexural and shear deformation of the tall building. The outer cladding of the model was modeled by making use of 10 shell sections (manufactured using the Selective Laser Sintering (SLS) technology, which allowed a model scale tolerance of ±0.1 mm to be achieved) point-connected to the inner spine (Figure 4). The base of the model was connected to a High Frequency Force Balance and the model itself equipped with a number of low-range high-resolution accelerometers. The 6-component High Frequency Force Balance utilized during the experiments was a custom-made piezoelectric base balance system with an inherent stiffness in excess of 2 kHz.

The modal properties of the wind tunnel model (modal frequencies, modal damping and modal masses – based on mode shapes normalized to unity near the top of the building, i.e., 0.95·H) were measured during the model calibration process that took place ahead of the wind tunnel testing and are summarized in Figure 5 along-side the full-scale equivalent. Also, illustrated in Figure 6 are the measured mode shapes of the wind tunnel aeroelastic model.

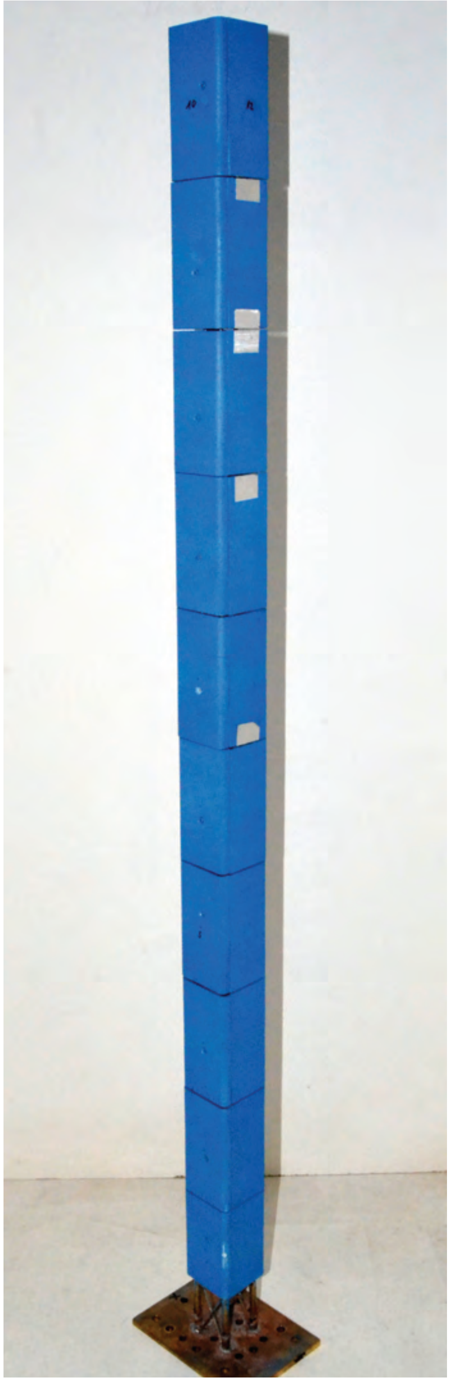

Figure 4. Wind tunnel aeroelastic model. (Source: BMT Fluid Mechanics Ltd.)
图4. 风洞气弹模型（来源：BMT Fluid Mechanics 有限公司）

设施内进行。此设施是一个4.8米（宽）× 2.4米（高）× 15米（长）的闭式回路风洞，工作风速范围为0.2米/秒 – 45米/秒(http://www.bmtfm.com/about-us/wind-tunnel-facilities)。测试重点采用单一风向进行（即与建筑四个面其中的一个面正交）。

风洞气弹模型在安装上确保其横风向与"模态1"和"模态3"完全一致（分别为第一阶和第二阶模态）。因此，本技术论文中展示的结果仅集中于该大楼在平滑流及边界层湍流工况下的横向风响应，并考

Aeroelastic Wind Tunnel Test: Results and Discussion

The wind tunnel tests have been conducted in BMT Fluid Mechanics' large boundary layer wind tunnel facility in Teddington (UK). This facility is a 4.8 m wide × 2.4 m high × 15 m long closed circuit wind tunnel with an operating wind speed range of 0.2 m/s to 45 m/s. The tests have been focused on a single wind direction (normal to one of the four faces of the building).

The wind tunnel aeroelastic model was installed such that its across-wind direction was perfectly aligned with "Mode 1" and "Mode 3" (respectively first and second order modes). The results presented within this technical paper will therefore only be focused on the across-wind response of the tower, in smooth as well as boundary layer turbulent flow, taking into account both fundamental and second order modes.

Figure 7 and Figure 8 present the normalized standard deviation modal acceleration (mode shapes normalized to unity near the top of the building, at 0.95·H) respectively for first and second order modes' smooth and turbulent shear flow. It should be noted that, whilst both graphs are presented versus the same normalized top of the building mean wind speed U/Ucr,1, the normalizing parameters used in the y-axis are approximately out of an order of magnitude from each other ((44/13)2): this makes the response in turbulent flow around the region of lock-in with the second order mode (U/Ucr,1 ~ 3) approximately 40% higher than the one driven by the fundamental mode at the same speed. Should, as illustrated in Figure 1, U/Ucr,1 ~1 occur far more frequent then say once a year, U/Ucr,1 ~3 could – depending on the type of wind climate – be potentially of great importance for the Ultimate Limit State design of the building. More specifically, the peak overturning moment near the inflection point of the second order mode of vibration (approximately 0.5•H) could be particularly critical and would require a closer look through the use of non-conventional influence lines. The criticality of this portion of the structure could be influenced by the surrounding buildings, especially if these would have a height of approximately half of the one of the super slender tower. It should also be noted that, at high slenderness ratios, the shape similarity between the second order across-wind pressure modes and the second order structural modes of the building could influence the structural behavior of the tower, far more than in conventional buildings (Cammelli et al., 2016).

	Model Scale		Full Scale	
	Mode 1	Mode 3	Mode 1	Mode 3
Frequency [Hz]	13	44	0.08	0.25
Damping [%]	0.5	0.6	0.5	0.5
Modal Mass [kg]	0.165	0.274	10560000	17536000
Mode Desciption	1st order	2nd order	1st order	2nd order

Figure 5. Modal properties of the wind tunnel aeroelastic model. (Source: BMT Fluid Mechanics Ltd.)
图5. Modal properties of the wind tunnel aeroelastic model.（来源： BMT Fluid Mechanics 有限公司）

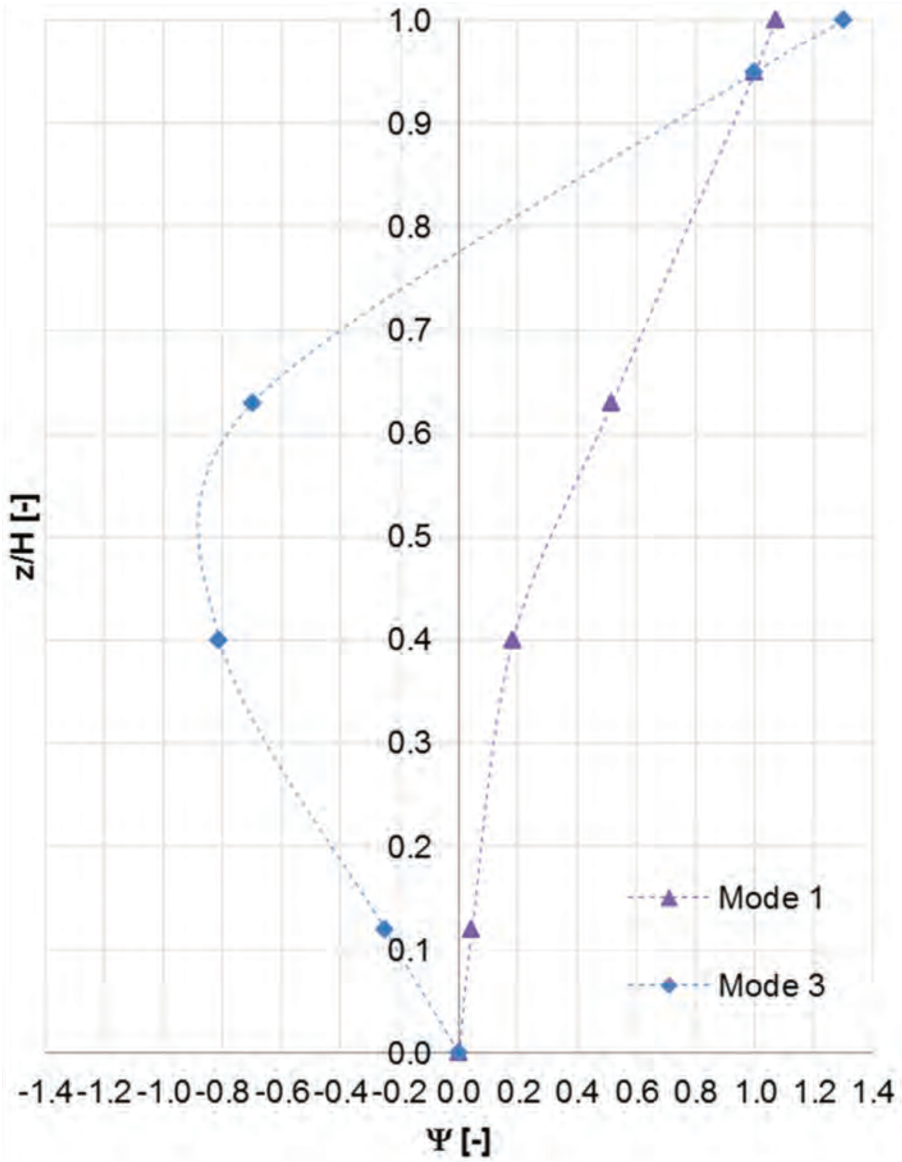

Figure 6. Measured structural modes of vibration of the wind tunnel aeroelastic model. (Source: BMT Fluid Mechanics Ltd.)
图6. 风洞气弹模型的测定结构振型（来源： BMT Fluid Mechanics 有限公司）

虑了基本及第二阶模态。

图7和图8所示分别为第一阶和第二阶模态平滑流及紊剪流条件下经归一化的标准差模态加速度（振型针对近楼顶位置（即0.95·H ）归一化）。应指出的是，尽管两图所示的X轴是同一个经归一化的楼顶平均风速U/Ucr,1， Y轴所用的归一化参数之间相差大约是一个量级（(44/13)2）：这就使得湍流条件下第二阶模态（U/Ucr,1 ~ 3）锁定区域附近的响应比同样风速下基本模态产生的响应高出约40%。 如果 – 如图1所示 – U/Ucr,1 ~ 1 出现的频率远远多于一年一次，U/Ucr,1 ~ 3 可能（取决于风气候类型）对于建筑的最终极限状态设计就具有十分重要的意义。更确切地说，靠近第二阶振型反曲点（约0.5•H）的峰值倾覆力矩可能就尤为关键，而且需要通过非常规影响线进行更深入的研究。该建筑结构此部分的关键性可能会收到周边建筑物的影响，尤其是当这些建筑物的高度约为其中一个超纤细塔楼一半高度的时候。同时还应指出的是，在长细比较大的情况下，第二阶横向风压模

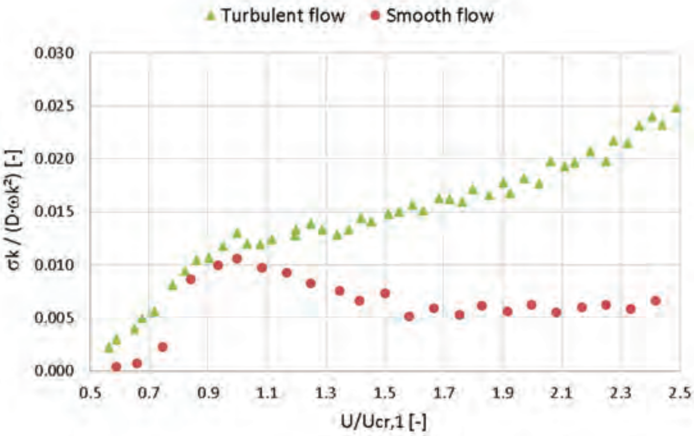

Figure 7. Normalized standard deviation modal acceleration (first order mode) for both smooth and turbulent flow. (Source: BMT Fluid Mechanics Ltd.)
图7. 归一化标准差模态加速度（第一阶模态） – 平滑流与湍流（来源：BMT Fluid Mechanics 有限公司）

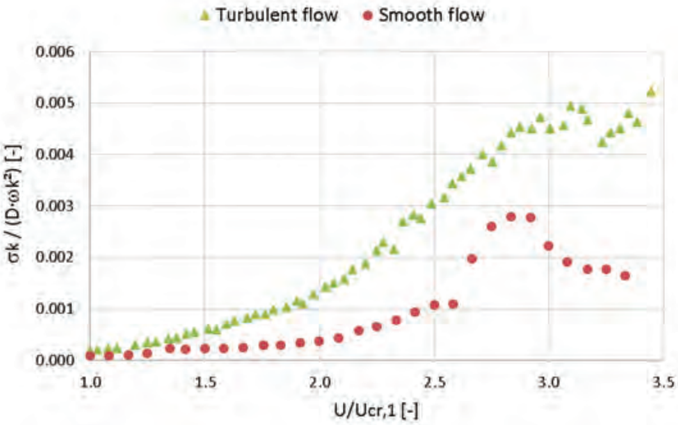

Figure 8. Normalized standard deviation modal acceleration (second order mode) for both smooth and turbulent flow. (Source: BMT Fluid Mechanics Ltd.)
图8. 归一化标准差模态加速度（第二阶模态） – 平滑流与湍流（来源：BMT Fluid Mechanics 有限公司）

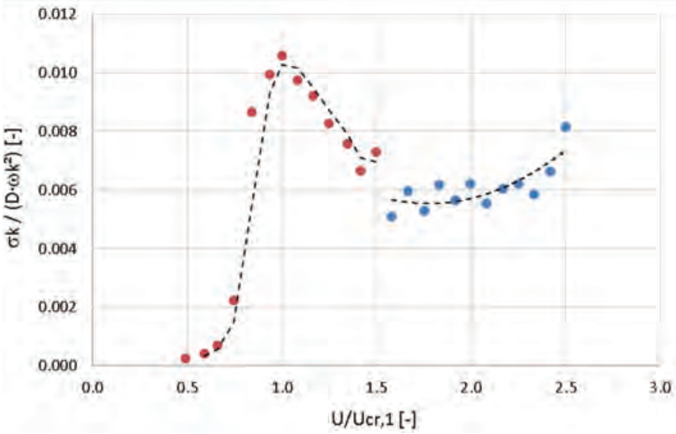

Figure 9. Normalized standard deviation modal acceleration (first order mode) around the lock-in region (smooth flow). (Source: BMT Fluid Mechanics Ltd.)
图9. 锁定区域附近的归一化标准差模态加速度（第一阶模态） – 平滑流（来源：BMT Fluid Mechanics 有限公司）

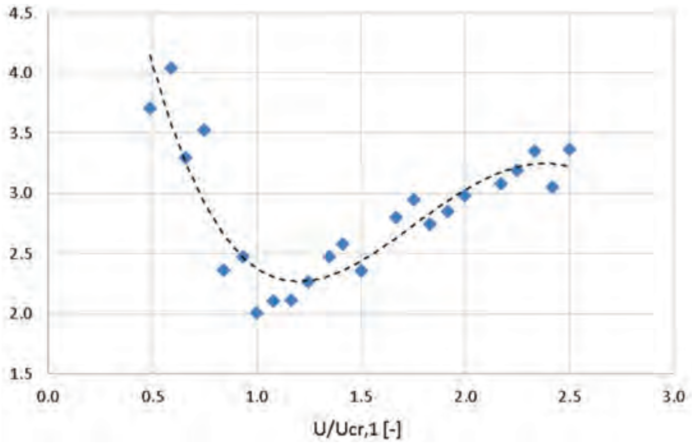

Figure 10. First order mode acceleration peak factor (smooth flow) versus normalized top of the building wind speed. (Source: BMT Fluid Mechanics Ltd.)
图10. 第一阶模态加速度峰值系数与归一化楼顶风速（平滑流）（来源：BMT Fluid Mechanics 有限公司

Another aspect of particular interest highlighted by both Figure 7 and Figure 8 is the far less well-defined low and high speeds lock-in regions exhibited by the turbulent flow case compared to the smooth flow scenario. Also, Figure 9, which zooms into Figure 7 (smooth flow case only), clearly shows the reconstitution of the gust-excited behavior (U/Ucr,1 > 1.5) immediately after the lock-in region associated with the vortex shedding phenomenon (U/Ucr,1 ~ 1). Figure 9 is of particular interest as, at the low speeds at which the lock-in takes place, the neutral condition of the atmosphere is unlikely to be met and therefore the results of a laminar flow experiment have the potential to be of particular value.

The wind-induced acceleration time-histories measured on the wind tunnel aeroelastic model were also analyzed making use of the so-called Random Decrement technique (Tamura et al. 2000) and the Random Decrement signatures subsequently treated using modal identification techniques (Tamura 2005) in order to identify the total damping of the system undergoing different wind speeds. The results of this piece of work are summarized in Figure 10 and Figure 11: the

态与建筑第二阶结构模态之间的振型相似性对塔楼结构特性的影响会大大超过常规建筑（Cammelli等人2016）。

图7和图8所展示的另外一个有着特殊意义的方面就是与平滑流工况相比，湍流工况所表现出的低风速及高风速锁定区域并不那么明确。此外，图9（图7的放大 – 仅平滑流工况）清楚显示出紧随着涡旋脱落现象（U/Ucr,1 ~ 1）的相关锁定区域后的阵风激励特性的体现情况（U/Ucr，1 > 1.5）。图9的特殊意义在于，在发生锁定情况的低风速条件下，可能达不到大气中性条件，因此层流试验的结果即可能具有特殊价值。

我们还采用所谓的随机减量法（Tamura等人 2000）对通过风洞气弹模型测得的风致加速度时程进行了分析，并随后采用模态识别法（Tamura 2005） 对随机减量标志进行了处理，以确定不同风速条件下系统的总阻尼。此项工作的结果在图10和图11中加以概括：前者所示为第一阶模态加速度峰值系数，而后者所示为第一阶模态总阻尼，两图均对照经归一化的楼顶平均风速（U/Ucr,1）进行标绘。这其中特别值得注意的是两条曲线在U/Ucr,1 ~ 1附近的弯曲度：此风速区域内建筑物非线性气弹特性的非高斯性可体现为将峰值系数从~ 4（典型的高斯过程）降至~ 2以及负气动阻尼在量值上几乎与固有结构阻尼一样大。以前的文献中曾报告过与此类似的特性（Vickery & Steckley 1993）。图12所示为紊剪流对峰值系数的影响：由于较高水平的湍流有助于降低涡旋脱落与大楼高度的关联度，在接近U/Ucr,1 ~ 1时峰值系数的降低未如平滑流情况下那样明确。

超纤细塔楼的舒适度极限状态设计与最终极限状态设计一样具有挑战性。十分频繁的、结构频率远低于0.1 Hz的低振幅风致运动对使用者的影响目前仍是风工程学界一个十分活跃的研究领域。在超纤细建筑领域，设计稳固而有效的振动控制装置的最大挑战是：空间要求（不仅在靠近建筑楼顶的位置，而且可能在靠近建筑中间高度的位置均需要有用于安装阻尼装置的空间）；空间限制因素（由于楼层面积过于紧凑，这些限制因素通常比非细型建筑结构更突出）；有效性（可能需要超纤细建筑结构中的阻尼器系统可有效适用于多种结构频率）。当无法进行气动外形优化时，分布式粘滞阻尼器或主动式装置可确保在非常有效地应对上述挑战的同时也达到特定的舒适度标准。

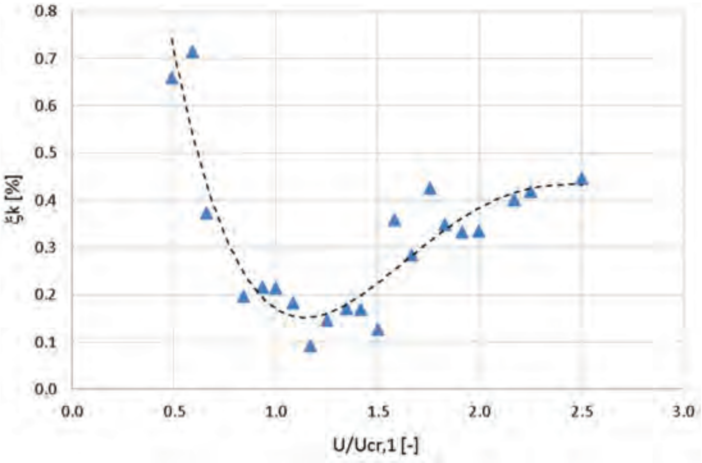

Figure 11. Total first order mode damping (smooth flow) versus normalized top of the building wind speed. (Source: BMT Fluid Mechanics Ltd.)
图11. 第一阶模态总阻尼与归一化楼顶风速（平滑流）（来源：BMT Fluid Mechanics 有限公司）

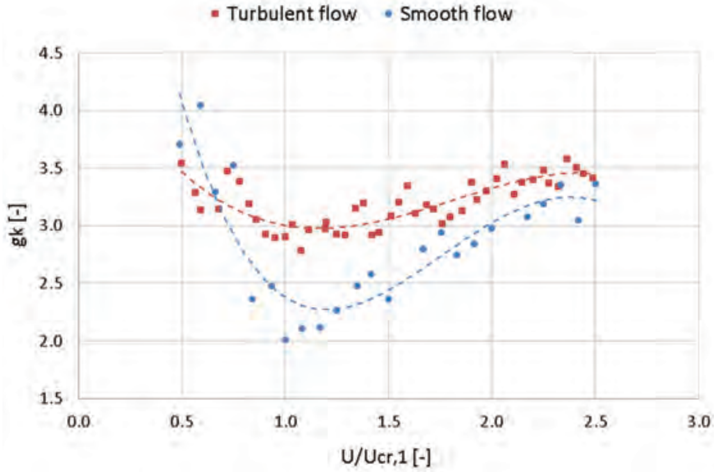

Figure 12. First order mode acceleration peak factor (smooth and turbulent flow) versus normalized top of the building wind speed. (Source: BMT Fluid Mechanics Ltd.)
图12. 第一阶模态加速度峰值系数与归一化楼顶风速（平滑流与湍流）（来源：BMT Fluid Mechanics 有限公司）

former shows the first order mode acceleration peak factor whilst the latter the total first order mode damping, both plotted versus normalized top of the building mean wind speed (U/Ucr,1). Of particular interest is the flexing of both curves around U/Ucr,1 ~1: the non-Gaussian nature of the non-linear aeroelastic behavior of the building in this wind speed region is very well described by the reduction of the peak factor from ~ 4 (typical of a Gaussian process) down to ~ 2, and by a negative aerodynamic damping becoming, in magnitude, almost as large as the inherent structural damping. A similar type of behavior was also previously reported in the literature (Vickery & Steckley 1993). Figure 12 illustrates the effect of a turbulent shear flow on the peak factor: because the relatively high level of turbulence helps minimize the level of correlation of the vortex shedding along the height of the tower, the reduction of the peak factor when approaching U/Ucr,1 ~ 1 is not as well-defined as in the smooth flow case.

The Serviceability Limit State design of super slender towers is no less challenging than the Ultimate Limit State design. The impact on humans of very frequent low amplitude wind-induced motion at structural frequencies well below 0.1 Hz is still a very active area of research within the wind engineering community. In the realm of super slender buildings, the biggest challenges associated with the design development of robust and effective vibration control devices are: space requirements (space for the installation of damping devices might be required not only near the top of the building but potentially also close to mid-height); space constraints (due to the incredibly compact floor plates, these constrains are normally a lot tighter than in less slender structures); and effectiveness (dampers in super slender structures might be required to be effective over a wide range of structural frequencies). When aerodynamic shape optimizations cannot be adopted, distributed viscous dampers or active devices can ensure that specific comfort criteria are met whilst very effectively dealing with the above challenges.

Concluding Remarks

This technical paper has presented some of the wind engineering challenges associated with the design of tall buildings with slenderness ratios in the region of 1:20, a new and almost unprecedented model for skyscrapers currently being explored in New York City.

The importance of both fundamental and second order mode lock-in was discussed; considerations on the nature of the atmosphere during lock-in taking place on a monthly if not weekly basis were made; the role of the second order modes of vibration in relation to the Ultimate Limit State design of the super-structure was discussed; and considerations in connection with Serviceability Limit State design of the building were made.

Whilst there is no doubt that the commercial and financial success of super slender buildings cannot be achieved without the support of wind engineering, it is the authors' opinion that – should the trend of designing super slender towers continue – in order to technically and financially de-risk such projects, boundary layer aeroelastic wind tunnel studies might need to be brought forward from the Design Development phase into Schematic Design.

结论

本技术论文提出了长细比在1:20左右的高层建筑在设计方面的一些风工程学难题，此类建筑是纽约市目前正在探索采用的一种前所未有的新型摩天大楼模式。

文章对基本及第二阶模态锁定的重要性进行了探讨；并考虑了每月（甚至每周）锁定情况发生期间的大气特性；对与超高建筑最终极限状态设计相关的第二阶振型的作用进行了探讨；并考虑了该建筑的舒适度极限状态设计问题。

虽然毫无疑问，若没有风工程学支持，超纤细建筑难以取得商业和经济上的成功，本文作者认为 – 如果设计超纤细塔楼的趋势继续下去，为了消除此类项目在技术和财政层面的风险，从设计开发环节到方案设计均可能需要展开边界层气弹风洞研究。

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