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Challenging Paradigms in the Wind Engineering Design of Tall Buildings

高层建筑风工程设计中具有挑战性的范例

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Abstract

Over recent years a fairly standard approach has developed in optimizing forms of tall, and particularly supertall and megatall, buildings during design to minimize wind effects. This paper examines the current typical recommendations for the wind engineering of tall buildings to minimize loads and responses, with examples of their application. These will then be examined within the context of overall design goals, other design criteria, and advances in structural technologies. Issues covered include the consideration of whether loads, deflections, or accelerations are the controlling criteria and different approaches to achieving these in different global locations. It is concluded that long-standing wind engineering assumptions about building shaping are not always correct, especially when modern technologies and development models are taken into account.

Keywords: Wind Engineering, Tall Buildings, Aerodynamic Shaping

摘要

近年来，相当标准化的方法已经制订出来用来优化设计阶段的高层，超高层和摩天大楼的外形以降低风效应。本文检验了当前常用的高层建筑风工程中用于降低风荷载和响应的建议，并给出了应用的范例。这些建议将在整体设计目标，其他设计标准，以及结构科技的发展等领域进行检验。讨论的问题包括荷载、位移或者加速度是否是关键性标准以及在全球不同地点所采用的不同方法。结论是长期以来风工程关于建筑外形的假设并不总是正确的，特别是当考虑到最新科技和发展模式时。

关键词：风工程，高层建筑，气动外形

Introduction

Over recent years a fairly standard approach has developed in optimizing forms of tall, and particularly supertall and megatall, buildings to minimize wind effects in their design.

For tall buildings the main aim is to reduce the cross-wind resonant response due to vortex shedding. For tall slender buildings, the cross-wind excitation typically produces larger wind-induced loads and/or responses than along-wind loading, which is the classic effect covered by most wind loading codes. The most common approach to this is to reduce the strength of vortex shedding by modifying the cross-sectional form of the building to one that is less prone to vortex shedding by modifying dimensions and shapes to disrupt the correlation of vortex shedding over the upper.

This, however, is only one part of the process and is often not considered in the full context of design goals. The first aspect to consider in approaching optimization for wind effects is to determine the design criteria goals. These criteria can be very site and building specific.

简介

近年来，相当标准化的方法已经制订出来用来优化设计阶段的高层，特别是超高层和摩天大楼的外形以降低风效应。

对于高层建筑，主要目标是降低漩涡脱落引起的横风向响应。对于高耸建筑，横风向激励通常产生比顺风向大的风荷载和响应，这个典型效应已经包括在大多数风荷载规范中。最常用的方法是通过改变建筑截面的形状以降低漩涡脱落的强度。通过改变横截面的尺寸和形状可以破坏沿着建筑上部的漩涡脱落的规律性，使得该截面对于漩涡脱落不敏感。

然而，这只是整个设计过程的一部分，并且通常没有在整体设计目标中考虑到。达到风效应优化的第一个方面是确定设计标准。这些设计标准可能与地点和建筑密切相关。

本文检验了常用的假设和建议的背景并挑战了这些假设和建议在实际工程设计和建设环境中是否永远是合适的。

高层建筑风致荷载和响应的基础

高层建筑的风荷载和响应来源于三种激励：顺风向、横风向和扭转。顺风向激励

This paper examines the background to the standard assumptions and recommendations, and challenges whether they are always the appropriate approach in a practical design and construction environment.

Basics of Wind-induced Loads and Responses of Tall Buildings

Wind loads and responses of tall buildings result from three types of excitation: along-wind, cross-wind, and torsion.

Along-wind excitation occurs in the direction of the wind. The net effect of this excitation consists of mean loading, which causes the building to have a mean displacement, and dynamic background and resonant responses. The mean and background responses tend to dominate and can be related to the cross-sectional shape of the building and its drag. Thus, by making the form of the building more aerodynamic, i.e., lowering the drag factor, the loads on the building can be reduced.

Cross-wind excitation occurs on buildings as a result of vortex-shedding, and causes a response in a direction normal to the incident wind direction. The natural frequency of the vortex shedding is a function of the shape of the building, the building width, and the wind speed. When the vortex shedding frequency starts to approach a natural frequency of vibration of the building, large responses can occur. A major difference between along-wind and cross-wind responses is that pure cross-wind response is primarily resonant without any mean component. Cross-wind responses are best understood by an examination of the generalized cross-wind force spectrum coefficient (Cfs) plotted against reduced velocity, which is the mean approach velocity divided by the product of the natural frequency of vibration and a representative building width. The loads and accelerations are proportional to the square root of Cfs.

An example of this for a square plan tall building with height of six times the building width is shown in Figure 1. In this case, the graph was produced from a wind tunnel test of an isolated tall building of 300 meters in height at a scale of around 1:400 in a simulated atmospheric boundary layer typical of low-rise suburban surroundings. This graph is typical of the type included in the few design codes (such as AS/NZS 1170.2) that provide an estimate of cross-wind response. The reduced velocity at which the response reaches a peak is known as the critical reduced velocity.

One very important difference to note about along-wind and cross-wind responses is that while the along-wind response will increase with the square of the wind speed (being primarily a pressure-driven response), the cross-wind response can increase much more rapidly with wind speed, even up to a power of four close to the critical reduced velocity.

Torsional excitation can be caused by a number of sources including architectural asymmetries or asymmetries in the approaching flow as a result of surroundings or vortex shedding. Torsional responses can result from this excitation, as well as from structural asymmetries.

These are the basic mechanisms that cause the key wind loading and responses on tall buildings and the basis for early design decisions about shaping tall buildings to minimize wind effects.

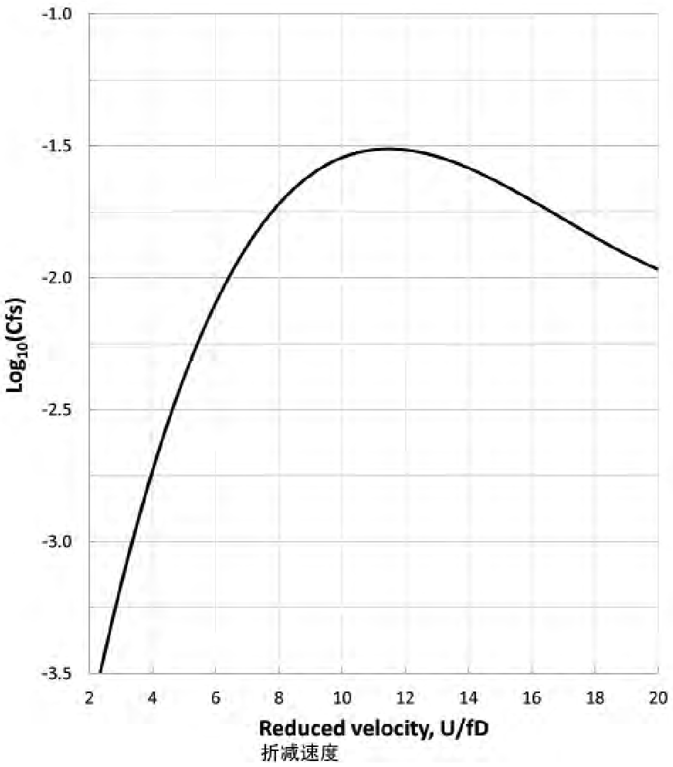

Figure 1. Cross-wind response curve of a square building with 6:1:1 aspect ratio
图1. 比例为6:1:1的正方形截面建筑的横风向响应曲线

沿着风向作用。这个激励的效应包括造成建筑平均位移的平均荷载和动态背景和共振响应。平均和背景响应容易起主导作用并与建筑的截面形状及其阻力有关。因此，通过改变建筑外形以降低阻力系数可以降低建筑上的荷载。

作用于建筑的横风向激励源于漩涡脱落并会产生垂直于来流风向的响应。漩涡脱落的频率是建筑外形，建筑宽度和风速的函数。当漩涡脱落的频率接近于建筑的固有频率时会产生较大的响应。顺风向和横风向响应的最大区别是横风向响应主要是共振，并没有任何平均部分。横风向响应可以通过查看广义横风向力谱系数(Cfs) 和约化速度的关系来理解。这个约化速度是来流平均速度除以振动的固有频率和特征建筑宽度的乘积。荷载和加速度正比于Cfs的平方根。

图1所示的例子是一个正方形截面，高宽比为6的建筑。这个例子中的图来自于一个300米高的高层建筑的单体风洞试验，模型比例大约为1：400，大气边界层为典型的拥有低矮建筑的郊区环境。这个图是典型的一些风荷载规范中所采用的类型（比如AS/NZS 1170.2）用来评估横风向响应。响应最大时的约化风速称为临界约化速度。

关于顺风向和横风向响应的一个重要区别是顺风向响应与风速的平方成正比（主要是风压引起的响应），而横风向响应能够随着风速更加快速地增加，最高可以在接近临界速度时达到4次方。

扭转激励有很多来源包括建筑的不对称，因为周边环境或者漩涡脱落引起的来流的不对称等。扭转响应可以来自这个激励和结构的不对称。

这些是导致高层建筑风荷载和响应的主要机理和初期高层建筑外形设计以降低风效应的基础。

The Use of Building Shaping to Reduce Wind Effects

It is becoming increasingly common in the design of tall buildings to develop an architecture that minimizes the wind effects on the

降低风效应的建筑外形的应用

在高层建筑的设计中采用能够降低风效应的建筑形状越来越普遍。高层建筑上的风冲击会产生荷载，建筑位移，和建筑水平加

building. Wind impinging on a tall building results in loading, building deflections, and building lateral accelerations all of which need to be accounted for in design. Building shaping can be effective in reducing each of these, but most commonly, the intent is to reduce the cross-wind response. There have been many research studies conducted on the effects of altering building shape on tall building response with one of the most comprehensive being the recent study by Tamura et al. (2011). These studies examine the effects of modifying the plan shape on vortex shedding, with tapering, stepping, and/or twisting the building with height used to disrupt the correlation of the vortex shedding over the tower. Typically, however, this type of study is largely carried out in "aerodynamic isolation" with little consideration to the practicalities of how the proposed shaping modifications relate to the function of the building, the range of potential dynamic characteristics of the building, the climate that the building might experience, site limitations, or local design factors. Each of these can have a significant influence on the viability and value of shaping.

Wind Climate

The wind climate at a given site will have a large influence on the value of aerodynamic shaping and how it is best conducted. The wind directionality is a key factor in this. Where there are strong prevailing wind directions (on either a serviceability or extreme basis), then there is the potential to reduce responses by shaping the building relative to these key directions.

One factor that plays into the goals of building shaping is the local regulatory environment. In most locations, it is necessary to base loads on a mandated basic design wind speed specified in local building codes and/or standards. In some cases, these mandated design wind speeds can be significantly higher than the best-estimate wind speeds for the same return period. For the prediction of accelerations, it is much more common to use the best-estimate wind speeds, as this is a serviceability issue. The prediction of deflections is most commonly based on the wind speed model used for load predictions but, as a serviceability issue, could also be based on a best-estimate wind speed model.

The relationship of the day-to-day (generally synoptic) winds to the extreme winds needs to be examined both in terms of the directionality and in terms of the storm type generating these winds. In some parts of the world, the extreme winds are driven by the same large-scale synoptic weather patterns; while in other parts of the world, the extreme winds can be dominated by more rarely occurring discrete events, such as thunderstorms or tropical cyclones. This means that the wind speed models used for acceleration predictions can be very different from those used for loading. This is of particular significance, as discussed in a following section, on determination of appropriate acceleration criteria.

The structure of thunderstorms is significantly different from synoptic winds. It is generally accepted that the peak wind speeds in severe downburst-type thunderstorms occur at heights below 200 meters. This means that for supertall buildings the use of boundary layer profiles in combination with thunderstorm gust wind speeds measured at 10 meters above ground level are likely to result in conservative predictions of wind-induced loads and accelerations. For megatall buildings this effect can be magnified due to the temporal characteristics of thunderstorms, where the peak wind speeds can be of a sufficiently short duration to preclude a full resonant response from developing. With megatall buildings the wind direction over the upper section of the building, even during synoptic winds, is also

速度等，这些都需要在设计中加以考虑。建筑外形可以有效地降低这其中的任何一种，但更普遍的是，降低横风向响应。已经有很多研究进行了改变建筑外形对高层建筑响应的影响，其中一个最全面的是最近 Tamura 等进行的研究 (2011)。这些研究检查了改变截面形状对漩涡脱落的影响，通过对建筑沿着高度锥形化，阶梯缩进和截面沿高度旋转等方法来破坏漩涡脱落沿着塔楼的相关性。但是通常这种类型的研究主要是在气动隔离的情况下进行的，很少考虑到外形的改变和建筑功能、建筑潜在动态特性的范围、建筑可能经受的气候、场地限制或者当地设计系数等的关系。这些中的每一项都可能对改变外形的可行性和实用性产生重要的影响。

风气候

每个地点的风气候会对气动外形改变的作用和如何实施产生很大的影响。风的方向性是一个关键因素。当存在很强的主导风向时，不管是使用状态还是极限状态，就有潜在的可能通过改变相对于这些关键风向的建筑外形来降低响应。

实现改变建筑外形的目标的一个因素是当地的监管环境。在很多地方，需要根据当地的建筑规范和标准规定的基本设计风速来确定荷载。在一些情况下，这个强制性设计风速可能显著的高于同一回归期下的最佳估计风速。对于评估加速度，通常采用最佳估计风速，因为这是使用品质的问题。位移的评估通常采用荷载评估的风速模型，但是作为使用品质的问题，也可以采用最佳估计风速模型。

日常风（通常为天气尺度风）与极端风的关系需要从风向和产生这些风的风暴类型来调查。在世界的一些地方，极端风由同样的大尺寸天气模式决定，而在其他一些地方，极端风可能会由很少发生的间断气候如雷暴或者热带气旋。这意味着用来加速度评估的风速模型与荷载的风速模型可能有很大不同。这个对于确定适当的加速度标准特别重要，参见下文的讨论。

雷暴的结构与天气风有显著的不同。通常认为在严重的下击暴流类型的雷暴下峰值风速发生在200米以下。这意味着对于超高层，使用边界层剖面和离地面10米的雷暴的阵风风速会导致保守的估计风荷载和加速度。对于摩天大厦这个效应会因为雷暴的时间特性而加剧，峰值风速会足够的短以导致共振响应无法形成。对于摩天大厦，建筑上部区域的风向，即使是天气风，也会与地面的风向不同。这些作用在目前的风洞试验技术中并没有得到完全的调查，因此需要进一步的研究以确保这些作用可靠的考虑到。

高层建筑的设计者需要考虑风荷载和地震荷载的关系。在世界上地震活跃的区域，地震荷载可能会超过风荷载。但这并不意味着风效应可以忽略，因为仍然需要达到关于舒适性的可接受的加速度。

结构动态特性

高层建筑风致共振荷载是固有频率的函数，而加速度是固有频率和模态质量的函数。增加模态质量可以降低加速度，但是因此降低的固有频率会增加荷载。这两个是通常采用的改变建筑风致响应的动态特性。另一个影响共振响应的参数是结构阻尼。众所周知，内有的结构阻尼取决于振幅，在使用阶段加速度的振幅下，这个阻尼可能会很低。然而，附加阻尼系统可以显著地增加阻尼。传统上，附加阻尼只用于控制加速度。最近，采用分布式阻尼的附加阻尼系统可以有效地控制极端风情况下的建筑运动，从而显著的降低设计荷载（Smith & Wilford 2007）。当横风向共振响应降低到低于顺风向响应时就意味着改变建筑外形的目标就从传统上的降低横风向响应转变为降低关键风向下的顺风向阻力。

likely to be different from the wind direction at ground level. These are effects that cannot be fully investigated using current wind tunnel testing technology. Further research is required for these effects to be reliably quantified.

Tall building designers need to consider the relationship between wind loading and seismic loading. In seismically active regions of the world, the seismic loads may exceed the wind loads. This does not mean that wind effects should be ignored, however, as acceptable serviceability accelerations for occupant comfort still need to be achieved.

Structural Dynamic Characteristics

Wind-induced resonant loads of tall buildings are a function of the natural frequency, while accelerations are a function of both the natural frequency and the modal mass. Increasing the modal mass will act to reduce accelerations, although any consequent decrease in natural frequency will increase the loads. These are two of the structural dynamic characteristics that have traditionally been used to alter the wind-induced response of buildings.

The other parameter that affects the resonant response is structural damping. Inherent structural damping is known to be amplitude dependent and can be very low at serviceability acceleration amplitudes. However, supplementary damping systems can increase this significantly. Traditionally, supplementary dampers have been used only in the control of accelerations. Recently, supplementary damping system designs using distributed dampers allow for reliable control of building motions during extreme wind events and hence allow significant reductions in design loads (Smith & Wilford 2007). When the resonant cross-wind responses are reduced to below the along-wind responses this means that the goal of building shaping shifts from the traditional approach of mitigating cross-wind response to minimizing along-wind drag for critical directions.

Acceptability of Perceptible Building Motion

Building motion can become perceptible from a number of sources. It has been well documented in numerous publications that kinesthetic motion perception is frequency-dependent. In North America, there is still a tendency to use acceleration guidelines that do not take this into account.

It has been shown (Denoon 2011) that, in the field, complaints about building motion come from two principal sources: fear and alarm as a result of unexpected motion, and annoyance resulting from frequently perceptible motion. One key finding is that expectation of building motion significantly reduces the fear and alarm aspect. In some situations this can be addressed by education of building occupants. In some locations, this can happen almost organically, as long-term occupants of "lively" buildings assuage concerns of new tenants.

In locations such as Hong Kong, where there is a generally mild wind climate, perceptible motion generally only occurs during typhoon events. This means that perceptible motions do not occur on a regular basis, and as such the only concerns need be fear and alarm and discomfort over the duration of the typhoon. In Hong Kong, it is well known that tall buildings sway during typhoon events and hence perceptible motions during these events do not cause as much concern as would be the case in other locations. A more relaxed acceleration criterion could be applied to office buildings where it is known that they will be evacuated during typhoon events.

可察觉的建筑运动的接受标准

建筑运动有好几个来源可以被察觉到。很多文献表明动态运动感知与频率相关。在北美依然倾向于采用不考虑频率的加速度标准。

实测表明（Denoon 2011），对于建筑运动的抱怨主要来源于两个方面：对于出乎意料的运动的恐惧和频繁感受到的运动的反感。一个主要发现是预料之中的建筑运动可以显著的降低恐惧。在一些情况下，这个问题可以通过对建筑的住户进行培训解决。在一些地方，这个问题可以有组织的进行，建筑的长期住户可以缓解新住户的忧虑。

在一些地方比如香港，风气候通常比较缓和，可察觉的建筑运动通常发生在台风期间。这表明可察觉的运动并不是日常发生的，恐惧和不舒适的问题只发生在台风期间。在香港，众所周知高层建筑在台风情况下会发生摇摆，因此对于可察觉的运动的忧虑并不会象其他地方一样严重。对于办公楼，可以采用更宽松的加速度标准，因为办公楼在台风期间会清空。

与上面情况相反的是雷暴引起的中等高度的建筑的运动。有芝加哥的报道（Kijewski-Correa et al. 2012）指出，在一些建筑中有越来越多的投诉因为雷暴引起的运动。这些是因为出乎意料的突然运动引起的恐惧。

还需要指出的是，在一些情况下，运动感知可能来自其他运动的提示，比如视听的提示。视觉的提示更为常见，通常来自于建筑内部比如灯的晃动和门的晃动等。这些作用可能并不常见。最常见的听觉提示是第一个住户察觉到运动并让其他人知道。很显然，这是一个取决于建筑住户的因素，更可能发生在住宅环境中，而不是很宽敞的办公室环境中。

影响建筑外形实施的常见设计限制

在开始建筑设计时，开发商通常规定建筑所需要的建筑面积。一些规划规范也可能限定允许的最高建筑高度。在充分开发的都市区域，场地也可能只有有限的覆盖区域。

降低风效应的改变建筑外形的最通常方法是采用锥形化的建筑，引进阶梯缩进和角部处理等。当对一个场地受限的工程采用上面的建筑形状时，要保持同样的建筑面积就需要增加建筑高度。这个高度的增加有可能稍微增加风荷载。Tse等人（2006）先前的研究指出，即使因为角部处理而需要增加建筑高度，总的效果依然是会降低建筑的费用。锥形化会产生不同的情况。风速会随着高度的增加而增加，如果建筑宽度也减小，这样会使得建筑上部在低回归期时对漩涡脱落更为敏感。如果高度和覆盖面积保持不变，可以预料固有频率会增加从而降低响应。楼板的减少需要与通过锥形化来破坏漩涡脱落的规律性得到的益处相平衡。

建筑外形改变效果的范例

如前文所述，关于建筑外形的研究大多数从气动方面来进行，并没有考虑到在实践中一些其他因素。本文进行了如图1所示的模型的试验。对其他具有同样体积，锥度比在-4° （宽度随高度而增加）到 +4° 的模型也进行了试验。建筑具有同样的密度，频率随着质量分布而变化，没有锥度化的建筑的基本频率是0.153 Hz 。该建筑的内部结构阻尼比对荷载假设为2%，对加速度假设为1%。所有结果是在风向垂直于建筑表面的情况下。

图2给出了具有同样高度和体积，不同覆盖面积和锥度化的建筑的基底力矩随着建筑顶部的平均风速的变化。建筑的密度保持不变而每个建筑的频率会变化。正如所预料的，建筑的锥度化的增加会降低在所有风速下的顺风向和横风向荷载。图3给出了具有同样建筑体量的加速度的变化。该图给出了不同的趋势，顺风向加速度随着锥度化的增加而减少，而横风向加速度随着锥度化的

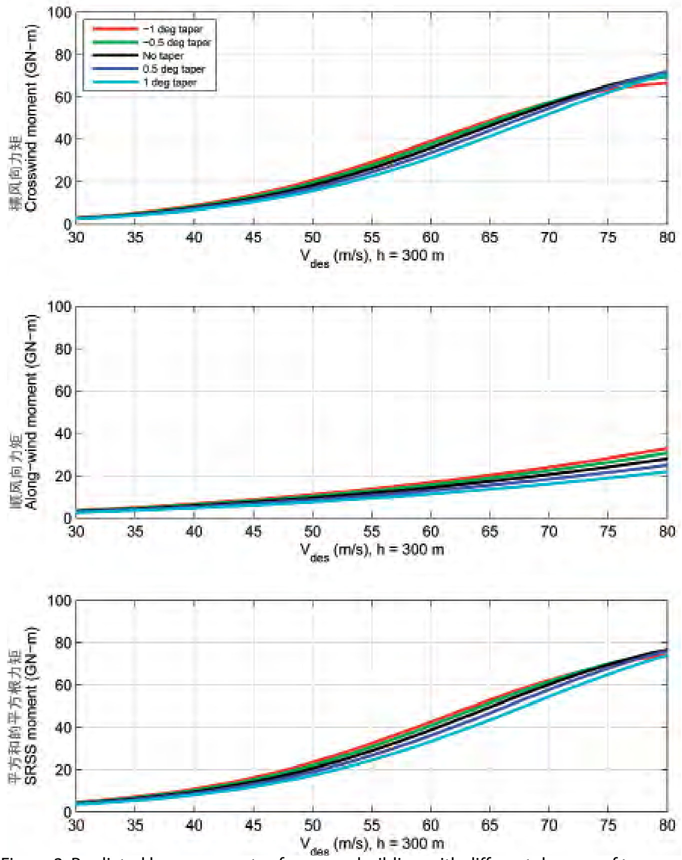

Figure 2. Predicted base moments of a square building with different degrees of taper, constant volume, and constant height

图2. 不同锥度化，相同体积和高度的正方形截面建筑的预测基底力矩

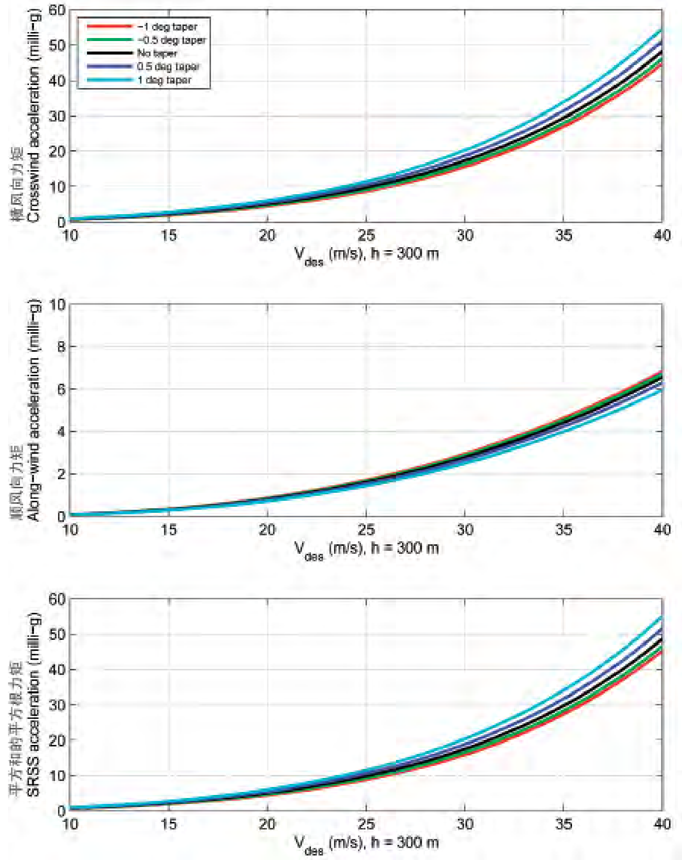

Figure 3. Predicted accelerations of a square building with different degrees of taper, constant volume, varying footprint, and constant height

图3. 不同锥度化，不同覆盖面积，相同体积和高度的正方形截面建筑的预测加速度

The opposite of this case is with moderate height buildings that can be excited by thunderstorms. It has been reported from Chicago (Kijewski-Correa et al. 2012) that increased complaint rates in some buildings have resulted from thunderstorm events. This has been due to fear and alarm from the sudden and unexpected onset of perceptible motion.

It also needs to be recognized that, in many cases, kinesthetic perception of motion can be triggered by other motion cues, such as visual or aural motion cues. The visual cues are most common and result from internal indicators such as lights swinging, doors swaying, etc. These effects may be less prevalent at very low frequencies. The most common aural cue is the first occupant to perceive the motion making others aware of it. Clearly, this is another factor that depends on the building occupancy and is less likely to occur in a residential environment than in a large open-plan office environment.

Typical Design Constraints Affecting Feasibility of Building Shaping

At the start of the design process, a developer generally stipulates the amount of floor area that the building must contain. Planning rules may also dictate the maximum height of the building. In highly developed urban areas, the site is also likely to have a very limited footprint.

The most typical approaches to building shaping to reduce wind effects are: tapering the building, introducing step-backs, and corner modifications. When any of the shaping options above are introduced on a project with a restricted site, then the height of the building needs to be increased to retain the same floor area. This increase in height has the potential for a slight increase in wind loads. Previous

增加而增加。整体作用有可能增加加速度。这是因为建筑的锥度化减少顶部的模态质量，使得顶部变窄，这意味着在给定速度下，约化速度会增加。表1总结了图2和3中的建筑的固有频率和主要尺寸。

图4给出了具有同样体积和覆盖面积，不同高度和锥度化的建筑的风荷载随着风速的变化。在负锥度化的情况下，楼顶平面保持不变，而底部的减少使得建筑可以在场地允许的限制内。表2总结了图4所给出的建筑的固有频率和主要尺寸。结果显示了比固定高度工况下的更复杂的情况。因为锥度化而增加的高度和降低的固有频率使得顺风向荷载随着锥度化的增加而增加。同样的原因，负锥度化也导致荷载的增加，虽然荷载的增加很大一部分是因为更低的固有频率和更大的顶部面积。横风向响应更加复杂，并且因为大于顺风向响应，这个也是净荷载要考虑的工况。这个也表明了锥度化的效果很大程度上取决于场地的设计风速。锥度化并不总是有益。

结论

用于降低风致荷载和响应的建筑外形的气动措施需要针对设计目标认真地考虑。在考虑到所有的设计因素时，传统的关于截面形状的假设，比如锥度化总是有益，可能是错误的。在新的设计技术比如分布附加阻尼变得更加普遍后，对建筑截面形状的要求会变化到降低顺风向阻力上。风工程设计标准需要反映每一个工程的要求，而不是假设一种方法适用于所有工程。

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work by Tse et al. (2006) has suggested that even with height increases as a result of corner modifications, the net effects will still reduce building construction cost.

The taper situation is potentially different. Wind speeds increase with height. If the building width reduces, this will combine with the increased wind speed to move the upper part of the building into more critical vortex shedding regimes at lower return periods; although, if the height and footprint remain constant it can be expected that the natural frequency will increase and hence reduce the responses. This loss of floor plate has to be balanced against the beneficial effects of tapering in disrupting vortex-shedding correlation.

Example of the Effects of Building Shaping

As discussed earlier, most of the studies that have been conducted on building shaping have approached the problem from an aerodynamic standpoint, without consideration of some of the other factors that come into play in a practical environment. For this paper, generic testing of the model described in Figure 1 was conducted. Alternative models retaining the same volume were also tested with various tapers from -4° (width increasing with height) to +4°. The building was given a uniform density and the frequency was varied based on the mass distribution from a baseline of 0.153 Hz for the untapered building. The building was assumed to have an inherent structural damping ratio of 2% of critical for loading and 1% for accelerations. All of the results presented are for a wind direction normal to the building face.

Figure 2 shows the variation in base moments with mean wind speed at roof height for a building of fixed height and volume, and varying footprint and degrees of taper. The density of the building has been kept constant and hence the frequencies vary for each case. As is normally expected, it can be seen that increasing taper of the building reduces both along-wind and cross-wind loads over a full range of operating wind speeds. Figure 3 shows the variation of accelerations for the same massings. This shows a slightly different trend, with along-wind accelerations reducing with increasing taper, but cross-wind accelerations increasing. This has the effect of increasing the net accelerations. This occurs due to the positively tapered building having a reduced modal mass and narrower upper section, meaning that for a given wind speed the operating reduced velocity is increased. Table 1 summarizes the natural frequencies and key dimensions of the buildings used for Figures 2 and 3.

Figure 4 shows the variation of wind loads with wind speed for a building with fixed volume and fixed footprint, but varying height and degrees of taper. In this case, where there is a negative taper, the roof plan has remained constant and the base reduced in order to keep the building within site constraints. Table 2 summarizes the natural frequencies and key dimensions of the buildings used for Figure 4. The results demonstrate a more complex scenario than for the fixed height case. Due to the increase in height with taper and the reduced natural frequency, the along-wind loads increase with taper. For similar reasons, the negative tapers also cause loading increases, although these increases are larger due to the even lower natural frequency and the greater exposed area at the top of the building. The cross-wind responses are much more complex, and as these are larger than the along-wind loads this is also the case for the net loads. This shows that the most effective taper is very highly dependent on the design wind speed at the site. It is not the case that tapering is always beneficial.

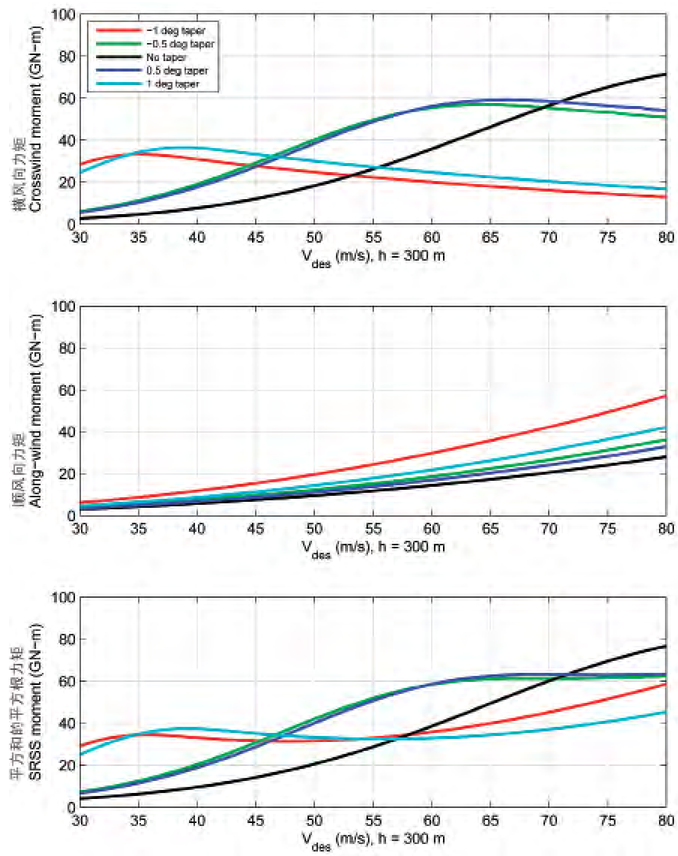

Figure 4. Predicted base moments of a square building with different degrees of taper, constant volume, constant footprint, and varying height
图4. 不同锥度化，不同高度，相同体积和覆盖面积的正方形截面建筑的预测基底力矩

Parameter 参数	Taper Angle 锥度化角度				
	-1.0	-0.5	0	0.5	1.0
Natural frequency (Hz) 固有频率（Hz）	.13	.14	.15	.17	.19
Side length at base (m) 底部边长（米）	30	40	50	59	67
Side length at top (m) 顶部边长（米）	68	59	50	41	31

Table 1. Key parameters used for constant height, variable footprint buildings
表1. 相同高度，不同覆盖面积建筑的主要参数

Parameter 参数	Taper Angle 锥度化角度				
	-1.0	-0.5	0	0.5	1.0
Natural frequency (Hz) 固有频率（Hz）	.08	.12	.15	.14	.11
Height (m) 高度（米）	495	355	300	355	495
Side length at base (m) 底部边长（米）	27	42	50	50	50
Side length at top (m) 顶部边长（米）	50	50	50	42	27

Table 2. Key parameters used for constant footprint, variable height buildings
表2. 相同覆盖面积，不同高度建筑的主要参数

Conclusions

Aerodynamic treatment of architectural form to reduce wind-induced loads and responses needs to be carefully targeted to specific design targets. Classical assumptions about shaping, such as tapering always being beneficial, can be shown to be incorrect when all design parameters are taken into account. As newer design technologies such as distributed supplementary damping become more commonplace in construction, the requirements of building shaping will change with more of a focus on reducing along-wind drag. Wind engineering design criteria need to reflect individual project requirements, rather than assuming that one approach fits all projects.

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