

Aerodynamic optimization in super-tall building designs

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ABSTRACT: To ensure the structure safety in strong winds and control the wind-induced motion of super-tall buildings, aerodynamic optimization is considered to be the most efficient way, because the aerodynamic optimization is aimed at the source of problems. However, aerodynamic optimization can be at the cost of other design aspects, such as increased construction cost, reduced usable space and/or increased construction difficulties. Therefore, the aerodynamic optimization can only be reached by interdisciplinary collaboration between wind engineers and architects. This paper summarizes the aerodynamic approaches that have been used in building design, and discusses the principles and effectiveness of these approaches. To provide a guideline for building aerodynamic optimizations, this paper proposes an approach of assessing the effects of tapering, twisting and set-back, three common schemes in super-tall building design for wind response reductions with limited wind tunnel tests.

KEYWORDS: building aerodynamics, across-wind response, vortex shedding, wind tunnel tests, wind spectrum, super-tall buildings.

1 INTRODUCTION

Wind effects are the challenges that designers have to deal with in super-tall building design. In association with high slenderness, low natural frequencies, low inherent damping level and high wind speed at upper lever, super-tall buildings are more susceptible to winds, particularly to vortex shedding excitations. Not only wind loads, the wind-induced building motions are also within the scope of design to ensure the building's safety as well as performance, such as comfort level for building occupancy. It is well known that the behavior of wind response is largely determined by building shapes. Considerations on aerodynamic optimization in early architectural design stage is proved to be the most efficient way in wind-resistant design.

Wind-resistant design and aerodynamic optimization are the modern topics in building design community. However, its practice and success projects can be traced back a long time ago.

In ancient China, tall buildings appear to be traditional pagodas. Some of them even meet the modern definition of super-tall shape.

Figure 1 shows one of the tallest ancient pagodas in China. These three pagodas located in Chong-Sheng Temple (崇圣寺), Dali, Yunnan Province, China, were built 1180 years ago (824-859AD). The tallest one is 69.13m in height with the base width of 9.9m (square), the slenderness (height/width ratio) being 7. The two identical shorter pagodas also have a height of 42.19m. Over the long period of extreme climates and natural disasters, the original temple buildings which were built after the pagodas were destroyed but the original pagodas have survived with wonder. In addition of extremely strong earthquakes (in 1514 and 1925), the pagodas also experienced strong winds in history. Dali



Figure 1. Three pagodas, Dali, Yunnan Province, China

is located in the western part of the Yunnan-Guizhou Plateau where the East-Asian monsoon and southwest monsoon alternately affect the region. Due to its special topography, Dali is well-known as “windy city” with occurrence of strong winds being more than 35 days per year. Statistics show that the return period winds are even higher than those in Shanghai, a typhoon prone coastal city of China. Figure 2 shows the comparison of return period basic wind speeds between Dali and Shanghai. These survived ancient structures at least revive two important concepts for modern design practice.



Figure 2. Comparison of wind speed between Dali Shanghai

(1) Being masonry structures, the ancient pagodas cannot compete in strength to modern structures that are built with steel and pre-stressed concrete. However, the shortcoming in strength seems to be largely compensated by increased inherent damping, which is more effective for dynamic loading.

(2) All these pagodas have their width tapered along the height and also have sizeable overhanging eaves. These features significantly reduce the potential across-wind oscillations that are commonly seen in super-tall buildings. Without these important features, these pagodas might have been damaged several times by severe vortex-induced oscillations at critical vortex shedding speed.

One of the major achievements in modern building design practice is to understand the underlying principles that may have been contained in historical wonders by coincidence and explore more creative ways to apply these principles in design.

Many investigations have been conducted on building aerodynamic optimizations. A pioneer work on building aerodynamics was done by Davenport (1971) who investigated the shape effects by using aerodynamic model tests. With super-tall's booming in 1990's, many more investigations have been done, which include building corner modifications and their impact on aerodynamic forces (Kwok 1988, Dutton and Isyumov 1990, Tamura 1998 and Miyagi 1999), effects of openings and slots (Isyumov 1992, Miyashita et al. 1993), and effects of twisting (Xie et al. 2009). The potential impacts of these aerodynamic modifications on economical aspects (cost and usable space) are also investigated (Tse et al. 2009).

Although aerodynamic shape plays important role for super-tall building design, aerodynamic optimization cannot be reached without considering other design aspects. The major challenge in building aerodynamic optimization is not only to find out the best shape for wind response, but also to find out the best balance between all the design aspects, including architectural concept, economical outcomes, etc. Aerodynamic optimization may therefore be classified into two categories:

Aerodynamic modification: an approach that is applicable to buildings which require mitigations for wind response but cannot have significant geometry changes on overall building concepts. Corner treatments, such as chamfering, slotting and roundness are common approaches in this category. The challenge with this category is that given the available/feasible aerodynamic modifications, the level of improvement may not be enough to meet the design objective. Structural measures or supplemental damping devices are still need in many cases.

Aerodynamic design: an approach that is integrated with architectural design in early stage. All the aerodynamic measures are available in this stage and the outcomes can be most efficient. However, the challenge with is category is to have reasonable estimates on the effects of various aerodynamic schemes on wind response reductions, so that an optimized balance between many

design aspects can be achieved. A series of wind tunnel tests are generally required to serve this purpose.

This paper is to summarize various schemes of aerodynamic approaches in super-tall building design and to discuss the principles of these schemes. To serve the needs of aerodynamic design, a method is proposed in this paper. This method is used to assess the effectiveness of aerodynamic optimization schemes, such as tapering, twisting and set-back, the three common schemes in super-tall building design, with limited amount of wind tunnel tests. The proposed method is approximate and comparative. Detailed wind tunnel tests are still needed for super-tall building designs. However, with ability of parametric analysis for aerodynamic effectiveness, the proposed method can provide a reasonable aerodynamic guideline for architectural design.

2 GENERAL APPROCHES OF AERODYNAMIC OPTIMIZATION

2.1 *Along-wind and across-wind responses*

For wind-resistant design of buildings, it's important to identify the type of wind response that governs the design. For most super-tall buildings, it is often found that the across-wind dynamic response dominates the design wind loads and/or cause excessive motions. Figure 3 presents a typical wind loading azimuth plot where the magnitude of the inertial loads caused by building motions in across-wind direction is much higher than the mean wind loads plus dynamic loads along the wind direction.

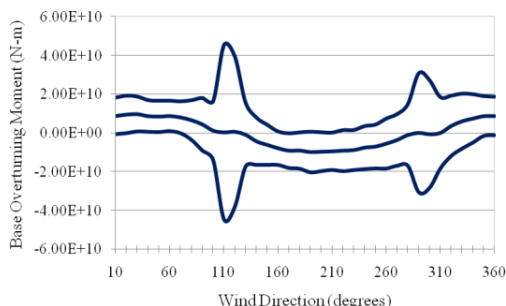


Figure 3. Illustration of across-wind loading at 110°

the building, so called “signature turbulence”. The peak of the across-wind spectrum corresponds to the effective Strouhal number of the building. Compared with along-wind response, across-wind response is more sensitive to wind speed. In lower wind speed, the along-wind loads normally dominant but with increase of wind speed the across-wind loads take over. Due to relatively lower building natural frequency of super-tall buildings (or higher building natural period) plus high wind speed at upper level of the boundary layer, the reduced frequency of a super-tall building at design wind speed can be very close to the peak of the across-wind spectrum. For example of a typical super-tall building, the building width is about 60m and the first sway period is around 8 seconds or higher, the vortex-induced resonance can happen at about 60m/s winds at upper level for a rectangular building or 33m/s at standard 10m height.

Figure 3 presents a typical wind loading azimuth plot where the magnitude of the inertial loads caused by building motions in across-wind direction is much higher than the mean wind loads plus dynamic loads along the wind direction.

The main reason that across-wind can dominate the design for super-tall buildings is explained by Figure 4. Figure 4 shows a typical across-wind spectrum in comparison with an along-wind spectrum. While the along-wind spectrum reflects the approaching wind turbulence properties, the across-wind spectrum is determined by flow separation off

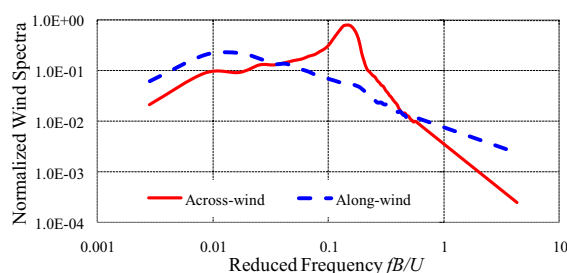


Figure 4. Comparison of along-wind and across-wind spectra

The aerodynamic optimization approaches tend to be different when dealing with along-wind or across-wind response. Although some approaches that can benefit both, many approaches focus on one type or other.

For optimization of along-wind response, a basic approach is to reduce the drag coefficient by modifying building corners, such as round or chamfer. Opening is also an option. Adjustment of building orientation to an optimized position where the direction of highest drag coefficient is far away from the local prevailing wind directions is also an effective approach.

For across-wind response, the aerodynamic optimization can be classified into two basic approaches: (1) to reduce the magnitude of wake excitation by modifying the building's cross-section such as corner recession or opening; and (2) to reduce the synchronization and correlation of fluctuating excitation by varying building's shape along the height such as tapering or twisting.

Since across-wind dynamic response is normally the main source that causes excessive wind loading and discomfort for occupants. The following discussion will focus on the aerodynamic optimizations for across-wind dynamic response.

2.2 Modification of cross-sections

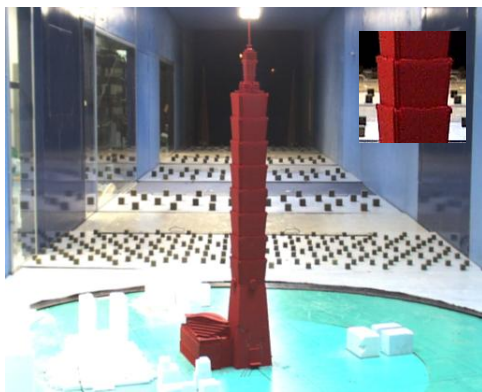


Figure 5. Corner recession

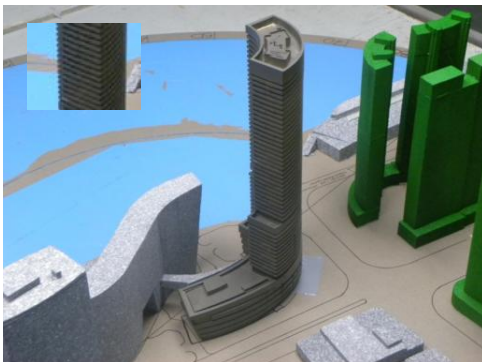


Figure 7. Corner balconies

A few examples of aerodynamic modifications for building cross-sections are shown in Figures 5 through 7. These modifications are proved to be effective for reducing across-wind response. The corner of Taipei 101 Tower, shown in Figure 5, was designed during wind tunnel testing, which effectively reduces the overall design wind loads by about 25% compared with the original design of square section.

During the wind tunnel tests of Taipei 101, other type of corner modifications are also investigated, shown in Figure 6. With the dimension of modifications being about 0.1B (10% of building width), the ef-



Figure 6. Corner modifications considered in Taipei 101 design

fects of these modifications are similar. The final selection of the corner modification was basically the choice of architects.

Helical strike is a traditional device to suppress vortex excitation to chimney stacks. However, few of these devices are used for buildings due to aesthetical concern. However, it has been found that commonly designed corner balconies can perform similar roles in suppressing vortex shedding (Brown et al. 2005). The concept was used again in a recent tall building in a very strong typhoon area, shown in Figure 7, and proved to be able to reduce design

wind loads by about 20%. The overhang eaves shown in ancient pagodas, Figure 1, are also the examples

Opening is not commonly used in design practice due to potential impact on useable spaces. However in some cases the corner slot can not only significantly reduce the across-wind excitation, but also make internal space design more logical, shown in Figure 8.

2.3 Modification of building elevations

The basic concept of this approach is to increase the variation of building shape along the height, either in section geometry, or in section dimension, or in section orientation. There are four basic forms of elevation modification:

- 1) tapering, as shown in Figure 9
- 2) twisting, as shown in Figure 10
- 3) Setting back, as shown in Figure 11
- 4) Sculpture top, as shown in Figure 12

A combination of all these basic forms is shown in Figure 13.

These forms share a common mechanism in reducing wind response. Due to various building geometry along the height, the properties of vortex shedding are also varies with height, leading to much less correlated excitations for across-wind response. The study conducted for twisting effects, shown in Figure 10, indicates that effectiveness increases with the increase of twisting angles within the range of 100° to 180° . However, to balance between the aerodynamic benefits and potential complication on cladding system, the 120° twist from base to top is selected as final version that represents about 15% reduction on wind loading.



Figure 6. Corner slot

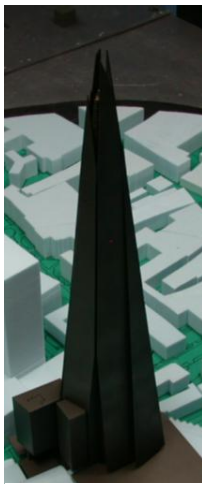


Figure 9. Tapering



Figure 10. Twisting



Figure 11. Set-back



Figure 12. Topping

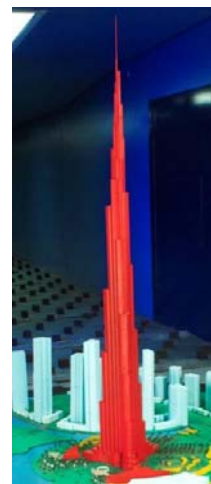


Figure 13. Combination

The effects of tapering in reducing across-wind response can be explained in a similar manner as for the twisting. Since the vortex shedding frequency is inversely proportional to a building width, the tapered width causes the outstanding frequency of wake excitation varies along the building height so that the outstanding frequencies of excitation are spread out to a wide range.

As mentioned before, modifications on building elevations are much more dramatic in visual impacts and can lead to a totally different design. Therefore modifications on building elevation are more suitable during the early stage of architectural design.

While aerodynamic modifications bring in benefits for reduced design wind loads and vibrations, these modifications often create conflicts with other design aspects. A good design is to reach optimized balance among many design aspects. For this reason, it is important to have an approach to estimate the level of effects with different modification schemes, so that the pros and cons of these aerodynamic modifications can be assessed and an overall optimized balance can be reached. A series of wind tunnel tests to examine various modification schemes is technically feasible but financially expensive and time consuming.

The next section is to discuss a method that is based on minor wind tunnel tests and major numerical analysis. This method is especially useful at early stage of architectural design to assess the aerodynamic improvements by tapering, twisting or set-back.

3 DILEMMA AND CHALLENGES IN OPTIMIZATION PRACTICE

3.1 Expression of sectional wind loads at level z

Basic parameters that describe sectional wind loads acting at level z of a building include:

Reference wind pressure:

$$q_z = \frac{1}{2} \rho U_z^2 = q_0 V_q(z) \quad (1)$$

Reference dimension (building width):

$$B_z = B_0 V_B(z) \quad (2)$$

Building twisting:

$$\theta(z) = \theta_0 V_\theta(z) \quad (3)$$

A common case is considered in the paper that the basic shape of building cross section remains the same along the height, but its dimensions and orientations vary. The varied dimension represents tapered width and varied orientation characterizes twisting. Some special set-back scheme can also be addressed with this typical case. The basic aerodynamic properties at Level z are given as follows.

Static drag coefficient:

$$C_D(z) = C_{D0} V_{Cd}(z) = C_{D0} V_{Cd}(\theta(z))$$

Static Lift coefficient:

$$C_L(z) = C_{L0} V_{Cl}(z) = C_{L0} V_{Cl}(\theta(z))$$

Dynamic Lift coefficient:

$$\tilde{C}_L(z) = \tilde{C}_{L0} V_{\tilde{C}_L}(z) = \tilde{C}_{L0} V_{\tilde{C}_L}(\theta(z))$$

The sectional drag and lift force can be expressed by

$$F_D(z, t) = \frac{1}{2} \rho (U_z + u_z(t))^2 B_z \left(C_D(z) + \frac{dC_D(z)}{d\alpha} \alpha \right) \quad (4)$$

$$F_L(z, t) = \frac{1}{2} \rho (U_z + u_z(t))^2 B_z \left(C_L(z) + \frac{dC_L(z)}{d\alpha} \alpha + \tilde{C}_L(z, t) \right) \quad (5)$$

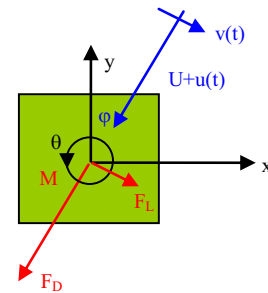


Figure 14. Wind loads on Level z

where

$$\alpha = -\frac{v_z(t)}{U_z} \quad \frac{dC_D(z)}{d\alpha} = C'_{D0}(z) \quad \tilde{C}_L(z, t) = \tilde{C}_L(z)T(t)$$

The mean loads are given by

$$\bar{F}_D(z) = q_z B_z C_D(z) = (q_0 B_0 V_q(z) V_B(z)) C_D(\theta_z) \quad (6)$$

$$\bar{F}_L(z) = q_z B_z C_L(z) = (q_0 B_0 V_q(z) V_B(z)) C_L(\theta_z) \quad (7)$$

The dynamic portion can be expressed in the form of power spectra, i.e.,

$$S_D(f, z) = (q_0 B_0 V_q(z) V_B(z))^2 \sigma_D^2(\theta_z) S_D^*(f_z^*, \theta_z) \quad (8)$$

$$S_L(f, z) = (q_0 B_0 V_q(z) V_B(z))^2 \sigma_L^2(\theta_z) S_L^*(f_z^*, \theta_z) \quad (9)$$

where $f_z^* = \frac{f B_z}{U_z}$

With simultaneous pressure measurements, the above non-dimensional aerodynamic properties can be easily determined, including C_D , C_L , σ_D^2 , S_D^* , and σ_L^2 , S_L^* .

3.2 Overall wind loads on building structures

The overall mean loads can be determined by simply integration as follows.

$$\text{Mean along-wind loads: } \bar{F}_D = q_0 B_0 \int_h V_q(z) V_B(z) C_D(\theta_z) \cdot dz \quad (10)$$

$$\text{Mean across-wind loads: } \bar{F}_L = q_0 B_0 \int_h V_q(z) V_B(z) C_L(\theta_z) \cdot dz \quad (11)$$

The overall dynamic along-wind and across-wind loads are given by

$$S_D(f) = (q_0 B_0)^2 \iint_H V_q(z_1) V_q(z_2) V_B(z_1) V_B(z_2) \sigma_D(\theta_{z1}) \sigma_D(\theta_{z2}) \sqrt{S_D^*(f_{z1}^*, \theta_{z1}) S_D^*(f_{z2}^*, \theta_{z2})} C_{HD}(f, \Delta z_{12}) \cdot dz_1 dz_2 \quad (12)$$

$$S_L(f) = (q_0 B_0)^2 \iint_H V_q(z_1) V_q(z_2) V_B(z_1) V_B(z_2) \sigma_L(\theta_{z1}) \sigma_L(\theta_{z2}) \sqrt{S_L^*(f_{z1}^*, \theta_{z1}) S_L^*(f_{z2}^*, \theta_{z2})} C_{HL}(f, \Delta z_{12}) \cdot dz_1 dz_2 \quad (13)$$

Although the expressions for the along-wind and across-wind are similar, they can be very different in properties. The spectrum S^* and cross-coherence C_H are governed by approaching wind turbulence for along-wind, but by signature turbulence for across-wind. Most interesting portion for aerodynamic optimization of super-tall buildings is to examine the generalized forces excited by across-wind excitations, which can be expressed by

$$S_j(f) = (q_0 B_0)^2 \iint_H V_q(z_1) V_q(z_2) V_B(z_1) V_B(z_2) \sigma_L(\theta_{z1}) \sigma_L(\theta_{z2}) \sqrt{S_L^*(f_{z1}^*, \theta_{z1}) S_L^*(f_{z2}^*, \theta_{z2})} C_{HL}(f, \Delta z_{12}) \Phi_{j,z1} \Phi_{j,z2} \cdot dz_1 dz_2 \quad (14)$$

where Φ_j is the j -th mode shape.

The effectiveness of shape variations on across-wind response can thus be assessed by comparing the difference of the spectra as follows:

$$R = \sqrt{\frac{S_j(f_j)}{S_{0j}(f_j)}} \quad (15)$$

where $S_{0j}(f_j)$ is the spectrum for a reference building geometry.

4 CONCLUSION REMARKS

Aerodynamic optimization is an important portion of super-tall building design. Two categories of optimization are discussed in the paper: aerodynamic modifications which are mostly considered as remedial measures with a limitation of not making significant changes on building's overall geometry or visual image; and aerodynamic designs which are feasible only with collaboration with architects in early design stage and can be very effective. While aerodynamic modifications mostly involved building corner treatments, aerodynamic designs have much more freedom in building geometry including overall building elevation optimizations, such as tapering, twisting, opening, set-back, top sculpture, etc. But aerodynamic designs are also limited by other design aspects, such as cladding, internal spacing, etc. The method proposed in this paper can be used to assess the effectiveness of various aerodynamic optimization schemes in order to achieve a balance between aerodynamic satisfaction and fulfillment of other design aspects.

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