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Aerodynamic optimization of super-tall buildings and its effectiveness assessment

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ABSTRACT

To improve safety and serviceability of super-tall buildings in strong winds, aerodynamic optimization of building shapes is considered to be the most efficient approach. Aerodynamic optimization is aimed at solving the problem from the source in contrast to structural optimization which is aimed at increasing the structural resistance against winds. However, there are two challenges that usually limit the applicability of aerodynamic optimization in design practice. One is a potential conflict between optimization schemes and other design aspects, and another is a potential conflict between cost and effectiveness. To minimize these conflicts, it is important to conduct aerodynamic studies in early design stage to gain reasonable assessment on various optimization options. This paper summarizes the aerodynamic approaches that have been used with success in building designs, and discusses the principles and effectiveness of these approaches. To provide a guideline for preliminary design, this paper proposes a practical approach to assess the effectiveness of tapering, twisting and stepping, the three common schemes of aerodynamic optimization in super-tall building design.

1. Introduction

For super-tall building designs, engineers have to respond to challenges of wind issues. Due to high slenderness, low natural frequencies, low inherent damping levels and high wind speeds at upper level, super-tall buildings are susceptible to wind excitations, particularly to vortex-induced oscillations. From design point of view, not only the wind loads, the wind-induced building motions are also within the scope of design to ensure building's serviceability. It is well known that the behavior of wind response is largely determined by building shapes. Considerations regarding aerodynamic optimization of building shapes in early architectural design stage is proved to be the most efficient way to achieve in wind-resistant design.

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

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

Fig. 1 shows the renowned ancient pagodas in China. These three pagodas located in Chong-Sheng Temple, Dali, Yunnan Province, were built 1180 years ago (824–859AD). The tallest one is 69.13 m in height with a square base of 9.9 m in width, the slenderness (height/width ratio) being 7. The two identical shorter pagodas have a height of 42.19 m. After the completion of these pagodas, a monastery was built. Over the long period of extreme climates and natural disasters, the original monastery was completely destroyed by natural forces but the pagodas have miraculously survived. In addition to extremely strong earthquakes in 1514 and 1925 the pagodas also experienced strong winds in history. Dali 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 distinctive topography, Dali is well-known as "windy city" with occurrence of strong winds being more than 35 days per year. Statistics show that the 50-year return period mean-hourly wind speed is about 30.4 m/s at 10 m height. These surviving ancient structures at least reveal two important facts which are helpful even for modern design practice.

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 inadequacy of strength seems to have been largely compensated by increased inherent damping and weight. A very high mass-damping parameter in fact makes the structures dynamically insensitive to wind effects, although their natural frequencies do not place them in a rigid category. The fundamental frequency of the 69.13 m pagoda is estimated to be between 0.45 and 0.55 Hz by using empirical formulas obtained from field measurements of various ancient pagodas (Li and He, 1990; Guo et al., 2005).
2) All these pagodas have their width tapered along the height and also have sizeable overhanging eaves. These features effectively reduce the synchronized across-wind loads that are commonly seen in tall and slender buildings.

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

One of the major achievements in modern building design practice is the understanding of the underlying principles that may have been contained in historical wonders by coincidence. With this understanding, engineers can explore more creative approaches and design more innovative structures.

Many investigations have been conducted on building aerodynamic optimizations. A pioneering 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 conducted, which include building corner modifications with potential reductions of aerodynamic forces (Kowk, 1988; Dutton and Isyumov, 1990; Kareem and Tamura, 1999; Tamura and Miyagi, 1999), effects of tapering and stepping (Cooper et al., 1997; Kim et al., 2002; Kim and Kanda, 2010a, 2010b), effects of openings and slots (Isyumov et al., 1989; 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). Tamura's group has conducted comprehensive wind tunnel experiments for various building configurations, including basic models (square, circular, rectangular and elliptic plan), corner modified models, tilted models, tapered models, helical (twisted) models, opening models, and composite models (Tanaka et al., 2012; Tamura et al., 2013). The data are not only helpful for preliminary design but also provide valuable references for further research works on building aerodynamics.

Although aerodynamic shape plays an important role in super-tall building design, its optimization cannot be reached without compromising all other design aspects, which usually limit the number of available options. As such, one of the major challenges in aerodynamic optimization is not to look for the best aerodynamic shape, but to achieve the best balance between aerodynamic efficiency and other design aspects, such as the architectural concept and economical outcomes. In practice, aerodynamic optimization may therefore be classified into two categories:

Aerodynamic modification: an approach that is normally taken in a situation when building's aerodynamic mitigations are found to be necessary but only limited shape changes are permitted in order to keep the building's overall concepts unaffected. Corner modifications, such as chamfering, slotting and roundness are common approaches in this category. However, given the confinement in this category and applicable/feasible aerodynamic modifications, the level of improvement may not be sufficient to meet all design objectives in some cases. Structural measures or supplemental damping devices may have to be introduced for further improvement.

Aerodynamic design: an approach that integrates architectural design with aerodynamic considerations in early design stage. Much more aerodynamic options are available in this category and the outcomes can be most efficient. However, the challenge with this category is to quantitatively assess the level of effectiveness of various aerodynamic options, so that an optimized balance can be reached between the costs and benefits. Traditionally this requires comprehensive wind tunnel tests on various configurations. Significant time consumptions and considerable wind tunnel costs are the main concern with this approach.

The present paper summarizes the aerodynamic approaches that have been used with success in previous building designs, and discusses the principles of these approaches. To respond to the needs of aerodynamic assessment in early design stage, a method is proposed in this paper to comparatively assess the aerodynamic effectiveness of tapering, twisting and stepping, the three common configurations in super-tall building design. The given method requires minimum amount of wind tunnel tests and is able to provide a practical guideline for architectural design.

2. General approaches of aerodynamic optimization

2.1. Along-wind and across-wind responses

For wind-resistant design of buildings, it is important to identify the type of wind response that governs the design. For most super-tall buildings, it is often found that across-wind dynamic response dominates the design wind loads and sometimes causes excessive motions in terms of building's serviceability criterion. Fig. 2 presents a typical azimuth plot of overall wind-induced shear force in *y*-direction for a building. The plot indicates that for along-winds (i.e., 25° and 205°), the mean loads are -3.5×10^7 N and $+3.3 \times 10^7$ N, and the peak absolute loads are 6.7×10^7 N and 6.6×10^7 N, respectively. For across-wind directions (i.e., 115° and 295°), the mean loads are almost zero but the peak absolute loads reach to 1.4×10^8 N and 1.0×10^8 N.

The main reason that the across-wind loads can dominate the design of super-tall buildings is explained in Fig. 3. Fig. 3 shows a typical across-wind force spectrum in comparison with an along-wind force spectrum. While the along-wind force spectrum mainly reflects the approaching wind turbulence properties, the across-wind force spectrum is largely determined by flow separation and vortex formation, so called "signature turbulence". The peak of the across-wind force spectrum corresponds to the effective Strouhal number of the building. Compared with along-wind response, across-wind response is more sensitive to wind speed. At lower wind speeds, the along-wind loads normally dominate but with increase of wind speed the across-wind loads take over. Due to relatively lower natural frequencies of super-tall buildings (or longer natural periods),

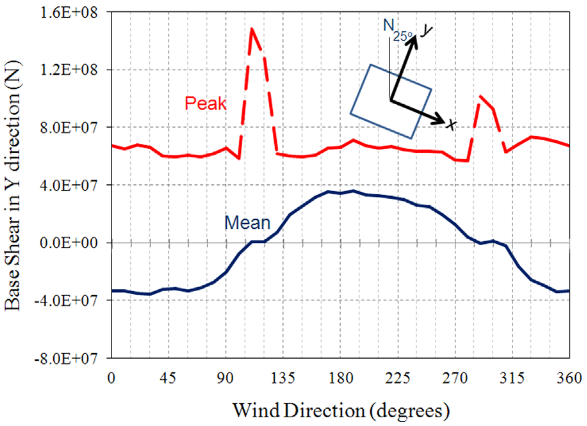

Fig. 2. Azimuth plots of wind loading in the *y*-direction.