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Wind engineering challenges of the new generation of super-tall buildings

Peter A. Irwin

RWDI, 650 Woodlawn Road West, Guelph, Ontario, Canada

A R T I C L E I N F O

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A B S T R A C T

The new generation of tall buildings is going much higher than before. This poses new challenges for wind engineering. The boundary layer models in many building codes and standards have served well for buildings less than about 300 m but more realistic models need to be used above 300 m. The statistics of upper level winds need also to be known with better certainty. New tools such as the archived global re-analysis data coming from weather forecast models can help shed more light on the upper level wind statistics. There are also questions to be answered about the effects on all tall buildings of non-synoptic wind profiles such as occur in thunderstorm downbursts and the Shamal winds of the Middle East. For the super-tall buildings wind tunnel testing is often commenced much earlier in the design than for lesser buildings. This permits the results to be used in a pro-active way to shape both the architectural design and structural design. The wind tunnel methods used include the force balance technique, aeroelastic modeling, high frequency pressure integration tests, as well as the traditional pressure model and pedestrian wind studies. A super-tall building pushes the limits of the force balance method due to difficulties in maintaining sufficient model stiffness and in accounting for the influence of higher modes of vibration. Since the impact of wind on people using terraces and balconies increases with building height, it is an issue needing particular attention for super-tall buildings.

1. Introduction

In the present day we are experiencing an unprecedented level of activity in the design and construction of super-tall buildings. It used to be that a 300 m high building was a threshold that only a few buildings exceeded. The Sears Building, located in Chicago, Illinois, at 440 m, held the record for many years. Now, numerous buildings have either been constructed, are under construction, or, to use an old fashioned expression, are “on the drawing boards” in the height range 400 m and up. The current world’s tallest is Taipei 101 at 509 m. Several are under design with heights well over that of Taipei 101. There are a number of designs being contemplated in the 500–1500 m range. Burj Dubai, Fig. 1, which is scheduled for completion by 2009, will be well over 700 m tall.

This new generation of towers poses new challenges for wind engineering. These are discussed in this paper. It is primarily based on the experience of the author and his colleagues and it is not intended to be a comprehensive review of the literature on the topic. Nonetheless, it is important to acknowledge that many other researchers have made major contributions, too numerous to cite comprehensively in a paper of this length. Some of these appear in the reference lists of the references cited in this paper.

Most building codes still use “traditional” models of the planetary boundary layer, developed in the 1960s, that assume the boundary layer tops out between about 250 and 500 m, depending on exposure. The validity of these models is questionable when dealing with building heights above about 300 in.

The statistics of wind speed and direction used in wind engineering have traditionally been almost entirely based on records from ground based meteorological stations, taken at about 10 m height. It is a long extrapolation to develop roof height wind statistics for super-tall buildings from the ground-based data alone, especially when their response is so sensitive to wind speed, and sometimes, direction. More reliable information on upper level wind statistics is needed.

The aerodynamics of tall buildings can have a huge impact on their cost. The main structural system is a large part of the cost and for super-tall buildings wind is the governing lateral load. Wind affects not only the structural integrity of the tower but also its serviceability. Keeping the motions of the tower within comfortable limits is often a bigger challenge than meeting structural strength requirements. Therefore, the aerodynamics of the tower’s shape needs to be considered as a critical design parameter from the very outset.

The response of the tower to wind depends not only on its shape but also its stiffness distribution, mass distribution and damping. For optimal design the interplay between these variables needs to be carefully examined. Increasingly the structural designers of very

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E-mail address: Peter.Irwin@rwdi.com

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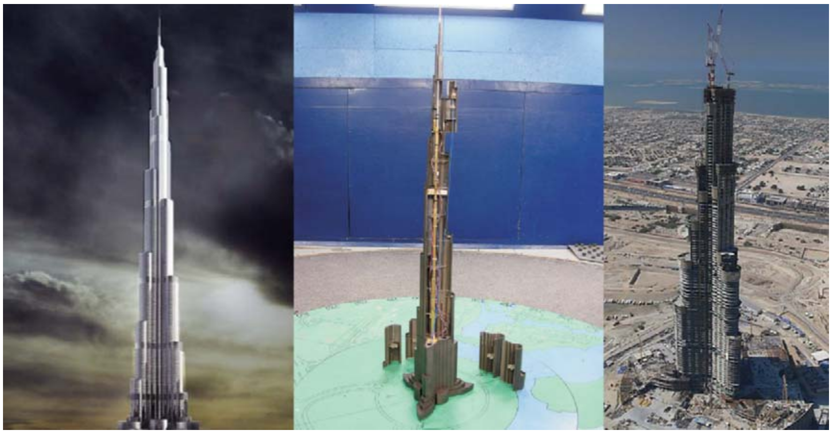

Fig. 1. Burj Dubai—future view, aeroelastic model and recent construction photo.

tall towers are prepared to extend their thinking beyond the traditional structural variables of stiffness and mass, and to treat the damping as a third controllable structural parameter. Supplementary damping systems allow them to do this and open up a whole new range of possibilities for optimizing the design. To date their use has been targeted primarily towards satisfying serviceability criteria. However, they also have the potential to mitigate ultimate design wind loads, in a similar manner to their use in earthquake design.

The wind tunnel techniques used for super-tall buildings are largely the same as for lesser towers but their extreme height can pose challenges. Typically smaller model scales become necessary, and, because of the importance of aerodynamics, more iterations of shape may well be needed during the design optimization process. Because of the time required to build super-tall towers the design of the upper portions is often still underway during construction. However, wind tunnel tests to establish base loads may well have to be done while there is still uncertainty as to what the top part of the tower will finally look like. Therefore, initial testing to supply foundation loads must allow for the possible range of shapes that the final design might take.

Another issue that arises for super-tall towers is that wind speeds on terraces high up on the tower can be expected to be much higher than on normal buildings. Yet there is often a desire to have these terraces as usable space.

2. Wind statistics and wind profiles

In North America the ASCE 7-05 standard sets the standard for wind design in the USA and in Canada the National Building Code serves this purpose. The boundary layer models in these documents are very similar to each other and were developed empirically in the 1960s. They will be referred to here as "traditional models". They have boundary layer depths ranging from about 210 m in very flat open terrain to 460 m in dense urban terrain. These models appear to have served well for the vast majority of buildings. However, they are purely empirical and not based on much consideration of atmospheric physics. The vast majority of buildings on which our experience is based come nowhere near high enough to test the assumptions concerning boundary layer depth in these traditional models. However, the new generation of super-tall towers certainly does.

The Harris and Deaves (1981) model, which was adopted in the 1980s by ESDU (1993), is based on more fundamental physical considerations than the traditional model and at high wind speeds indicates considerably deeper boundary layers in synoptic type winds, more in the 2000–3000 m range. Not only does the wind speed in this model continue to increase with height all the way to the tops of super-tall buildings (and beyond) but, just as important, the flow is turbulent up there. The traditional model would have the tops of these buildings in smooth uniform flow. Turbulence can have important influences on vibration phenomena and aerodynamic instabilities such as vortex shedding and galloping. The continuation of the boundary layer to much greater heights than predicted by the traditional models is also supported by balloon measurements and weather forecasting computer models.

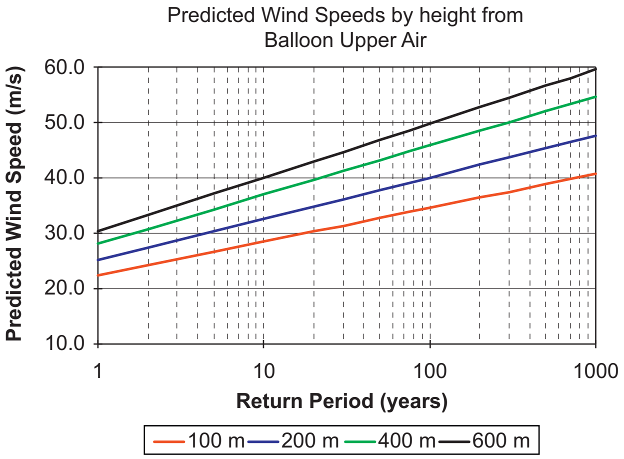

Fig. 2. Estimated extreme wind speeds for Las Vegas at various heights from balloon data.

Figs. 2 and 3 show estimated extreme mean hourly wind speeds at various heights for the Las Vegas area based, respectively, on 12 years of twice daily upper air balloon soundings and 20 years of global re-analysis data. The results were obtained using extreme value analysis methods on the monthly extremes. The 20 years (1987–2006) of re-analysis data were obtained from the National Center for Atmospheric Research/National Centers for Environmental Prediction (NCAR/NCEP). The NCAR/NCEP datasets are based on a worldwide meteorological observation network, including surface and upper air balloon measurements, satellite and radar measurements, etc. The data were available at 3 h intervals on a three-dimensional grid and were derived by meteorological modeling software similar to that used for weather forecasting.