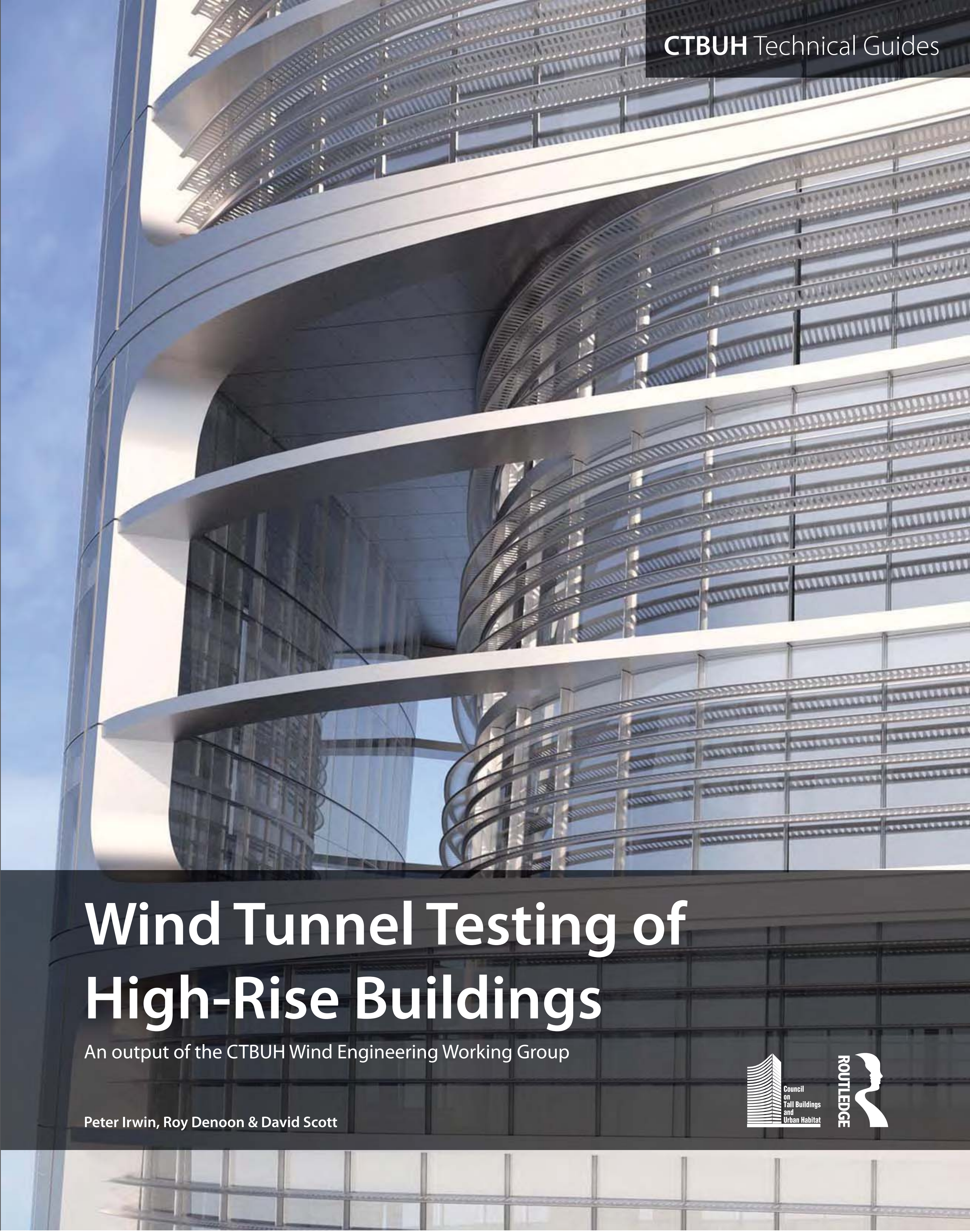

CTBUH Technical Guides

Wind Tunnel Testing of High-Rise Buildings

An output of the CTBUH Wind Engineering Working Group

Peter Irwin, Roy Denoon & David Scott

Council on Tall Buildings and Urban Habitat
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Front Cover: Greenland Center, Wuhan China. Under construction (2017 – expected completion).
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Contents

Preface

Since the 1960s, wind tunnel testing has become a commonly used tool in the design of tall buildings. It was pioneered, in large part, during the design of the World Trade Center Towers in New York. Since those early days of wind engineering, wind tunnel testing techniques have developed in sophistication, but these techniques are not widely understood by the designers using the results. The CTBUH recognized the need to improve understanding of wind tunnel testing in the design community. The CTBUH Wind Engineering Working Group was formed to develop a concise guide for the non-specialist.

Objectives of this Guide

The primary goal of this guide is to provide an overview of the wind tunnel testing process for design professionals. This knowledge should allow readers to ask the correct questions of their wind engineering consultants throughout the design process. The guide is not intended to be an in-depth guide to the technical intricacies of wind tunnel testing, as these are covered in several other publications. The guide does, however, introduce one topic that has not been addressed previously, but which the design community needs: a methodology for the presentation of wind tunnel results to allow straightforward comparison of results from different wind tunnel laboratories. The wind loads provided by wind engineering specialists have a major effect on the construction costs of many tall buildings. Parallel wind tunnel tests by different laboratories are becoming more frequent, either as part of a peer review process, or as a more direct attempt to reduce design loads. The loads provided by different wind engineering consultants are never identical, and can sometimes be markedly different. The framework presented here is specifically designed to facilitate comparisons of results and to allow the identification of the sources of any differences.

Content Overview

Wind tunnel testing is used in the design of most major tall buildings to identify the wind-induced structural loads and responses for which the superstructure must be designed. The processes by which wind engineers predict these loads and responses can appear arcane to many of the designers who have to use the results. This can, in some cases, lead to a reluctance to rely on wind tunnel predictions. This guide is intended to shed light on the science of wind engineering and the derivation of the conclusions provided in wind tunnel test reports.

The first wind engineering task for many designers is to determine whether to design using a local wind loading code or standard, or whether to employ wind tunnel testing. This guide begins with basic advice on when a tall building is likely to be sufficiently sensitive to wind effects to benefit from a wind tunnel test and provides background for assessing whether design codes and standards are applicable.

Once a decision to proceed with wind tunnel testing has been reached, it is important to ensure that the appropriate tests are being specified and conducted. In addition to providing details of the types of tests that are commonly conducted, descriptions of the fundamentals of wind climate and the interaction of wind and tall buildings is provided in order for the reader to be able to put the use of wind tunnel tests into context. While the majority of this guide concentrates on the testing that is conducted to determine the overall structural loads and responses, brief descriptions of other studies that may be conducted during design are also provided to alert the reader to aspects of wind engineering that may be relevant to particular design features.

Different laboratories use different techniques to combine the basic loads measured in the wind tunnel with the statistical descriptions of wind climate that are necessary to provide loads and responses with a known probability of exceedance, or which are consistent with a specified return period. This can be one of the largest causes of differences in results from different laboratories. In this guide, these different approaches are explained clearly, and the advantages and disadvantages of each summarized. Understanding that results from different laboratories may be different, it is important for a design team to identify the sources of such differences. This guide provides a standardized results presentation format to facilitate comparison. This provides a straightforward method for a design team to assess whether differences are due to factors such as fundamentally different aerodynamic characteristics being measured in the wind tunnel, or different conclusions having been reached in the wind climate analysis, or different methods having been used to combine the wind climate and aerodynamic coefficients. This knowledge then affords educated design decisions regarding wind loads.

The Wind Engineering Working Group hopes this guide is useful to the design professionals for whom it is intended and welcomes any feedback that can be used to improve future editions.

1.0 Introduction

The main structure of a tall building and its façade must be designed to safely withstand the extreme winds to which the building will be subjected during its expected life. Determining what the wind loads will be for specific mean recurrence intervals, and what the uncertainties are in these loads is critical. The wind loads, and appropriate load factors that allow for uncertainty in ordinary buildings, are often prescribed by the analytical methods given in building codes. But for tall buildings, in view of the importance of wind loads to their cost and safety, these analytical methods often lack the precision needed. Also, they do not account well for important wind phenomena, such as crosswind excitation, aerodynamic interactions between adjacent buildings, and aerodynamic instability, all of which affect not only loads but may also cause building motions that occupants find excessive. For these reasons, the wind loads and motions of tall buildings are typically determined by wind tunnel tests on scale models of the building and its surroundings, through which much more precise, project-specific information is obtained. Computational Fluid Dynamics (CFD) is increasingly used for qualitative evaluation of wind effects, particularly ground-level wind speeds, but is not yet capable of providing quantitative results of sufficient accuracy for the determination of design wind loads.

The objective of this document is to lay out general guidelines for wind tunnel tests, as applied to tall buildings, in a format that is useful to building professionals and regulatory authorities involved in tall buildings, as well as wind specialists. It is not intended to be a detailed manual of practice, such as is provided in: ASCE, 1999; AWES, 2001; BCJ, 1993 & 2008; KCTBUH, 2009; and ASCE 49–12, 2012. However, it is intended to describe best practice and make it easier to compare results from different wind consultants.

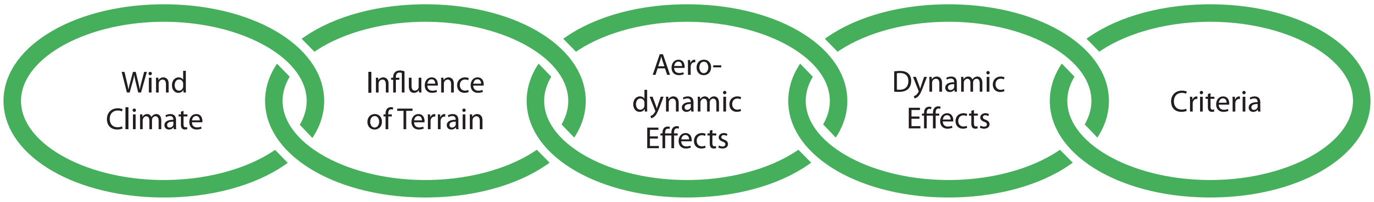
1.1 Basis of Design

Wind tunnel testing involves highly developed and specialized methodologies and terminology. Designers, developers, and building officials cannot be expected to have the in-depth knowledge of such a specialized field but it will help them to obtain most value from wind tunnel tests of their projects if they have a basic understanding of the principles involved. Also, as with any branch of knowledge, it is important to be aware of the sources of uncertainty in wind studies so that proper judgement can be exercised when applying the results or comparing results from different wind tunnel test laboratories.

The wind load formulae of building codes have been developed primarily for low-rise buildings and typically address, with a few exceptions, only wind loads in the along-wind direction. They are specified as the product of various factors, such as a reference pressure q, an exposure factor k, a drag coefficient

The wind load formulae of building codes have been developed primarily for low-rise buildings and typically address only wind loads in the along-wind direction.

▲ Figure 1.1: Tall buildings designed for dense urban settings such as Chicago (above) benefit from the precise, project-specific information obtained from wind tunnel testing.



▲ Figure 1.2: The Alan G. Davenport Chain of Wind Loading.

Cd, and a gust factor *Cg*. This has sometimes led to the expectation that the purpose of the wind tunnel test is simply to determine the drag coefficient and possibly the gust factor, the values of which are then to be inserted into the formula. This expectation misses the important point that, for buildings dominated by crosswind loading, the format of the typical code formula does not capture the essential physics of the problem. The objective of the wind tunnel tests is to fully replicate the real physics of wind loading at model scale. This includes along-wind loading, crosswind loading, torsional loading, load combinations, building motions, local wind pressures for cladding design, and the influences of terrain roughness, topography, directionality, and other nearby structures (see Figure 1.1).

When does a building's height make it sufficiently sensitive to dynamic effects and crosswind loading to require a wind tunnel test? The answer depends on many factors, including its shape, exposure, slenderness, structural system, and the wind regime of the site location. A wind tunnel test may be advisable if any one of the following applies:

(i) The height of the building is over 120 meters.
(ii) The height of the building is greater than four times its average b_{av} (width normal to the wind direction over the top half of the building).
(iii) The lowest natural frequency of the building is less than 0.25 Hz.
(iv) The reduced velocity $U / (f_1 b_{av})$ at ultimate conditions is greater than five, where U is the mean hourly wind velocity evaluated at the top of the building, f_1 is the lowest natural frequency of the building and b_{av} is the average width defined in (ii).

It should be noted that these are approximate guidelines only, and can depend on other factors, such as exposure of the building being considered, local topography, and the presence of other major buildings in the proximity.

There are five key steps involved in determining wind loadings derived from wind tunnel tests. This has been described as a "chain" (Davenport 1982), which is appropriate, since the outcome is only as strong as the weakest link. The Alan G. Davenport Chain is illustrated in Figure 1.2.

The first link in the chain is the wind climate, i.e., the statistics of the wind speed and direction for the region where the building is located. The next link is the influence of the surrounding terrain, including the surface roughness and topography (see Figure 1.3). This is followed by a link representing the local aerodynamics of the building and interference effects from other nearby structures. The next link, dynamic effects, represents the building's wind-induced response, including any aeroelastic effects. The final link represents the criteria used to assess the building and its response to wind. The objective of present-day wind tunnel studies is to evaluate each link in detail using rational methods and with maximum accuracy. Then, when all links are assembled, the final answer is the best available using rational scientific knowledge. If one or more of the links is not treated with due diligence, the value of the whole study can be seriously degraded. For this reason, it is usually not a good idea to break off one part of the chain of the wind tunnel study and substitute part of the code analytical procedure, which is inherently more approximate, in its place. The analytical procedure of the code and the wind tunnel procedure are best treated as two totally separate processes, each targeted at the same level of structural reliability, and only their end results compared.

1.2 Wind Climate

Wind climate involves the statistics of wind speed and direction. Building codes generally specify the recurrence interval and the corresponding wind speed at a selected reference height, typically at 10 meters in open terrain. Some codes go so far as to specify different wind speeds for different wind directions. Depending on the country involved and the location within that country, more or less effort will have gone into the determination of the appropriate design wind speed. Where the design wind speed is based on well documented research by established experts, it would be normal for the wind

3.0 Wind Tunnel Testing Methods

3.1 Simulation of the Natural Wind at Small Scale

In view of the way the mean velocity profile and turbulence characteristics of the wind affect wind loads, it is important that flow in the wind tunnel replicates these factors at model scale. The methods for doing this are well established and typically involve a combination of special flow devices, such as spires at the start of the working section, followed by a length of roughness on the wind tunnel floor, representing the terrain roughness over which the wind flows at full scale. These methods are described in the detailed standards and manuals of practice on wind tunnel testing referenced in the Introduction. Figures 3.1–3.3 show examples of typical test set-ups and Figures 3.4 & 3.5 show typical mean velocity and turbulence intensity profiles generated in the wind tunnel for open terrain compared with target profiles derived from full-scale data. The mean velocity profile shown is the ratio of mean velocity U to the mean velocity at a reference height, in this case 400 meters. In addition to mean velocity and turbulence intensity profiles, the power spectrum of turbulence is also simulated, which effectively ensures that the sizes of the turbulent eddies impacting the model have been scaled down to the appropriate scale. The simulation of the wind profiles can be adjusted to various types of terrain roughness, and for most sites it is necessary to change the wind simulation several times during the tests to reflect the variation of upwind conditions with wind direction. It should be noted that most wind tunnel laboratories have a set of several standard wind profiles and pick the closest to that needed for each wind direction. Analytical methods can then be used to correct for minor residual differences between actual and target profiles (see for example Irwin et al. 2005).

The wind forces on a building model can be affected by the size of the model relative to the cross-sectional area of the working section of the wind tunnel, this being called the blockage effect.

The wind forces on a building model can be affected by the size of the model relative to the cross-sectional area of the working section of the wind tunnel. This is called the blockage effect. The airflow is constrained to flow through effectively a smaller cross-sectional area as it flows around the model, and so accelerates, causing the wind forces to be higher than would otherwise be the case.

There are other secondary effects on the wind profiles approaching the model, since they are now subject to pressure gradients. Much of the blockage effect can be eliminated if the reference velocity is measured in the accelerated flow, i.e., directly above the model, but there are also other methods for making blockage corrections to results. In general it is advisable to keep the blockage area to less than 10% of the working cross-sectional area. Open jet wind tunnels can be subject to negative blockage, i.e., the flow effectively decelerates at the model station, and some wind tunnels are made blockage-tolerant by building working section surfaces that are not completely solid.

3.2 Test Methods to Determine Wind Loads on the Structural System

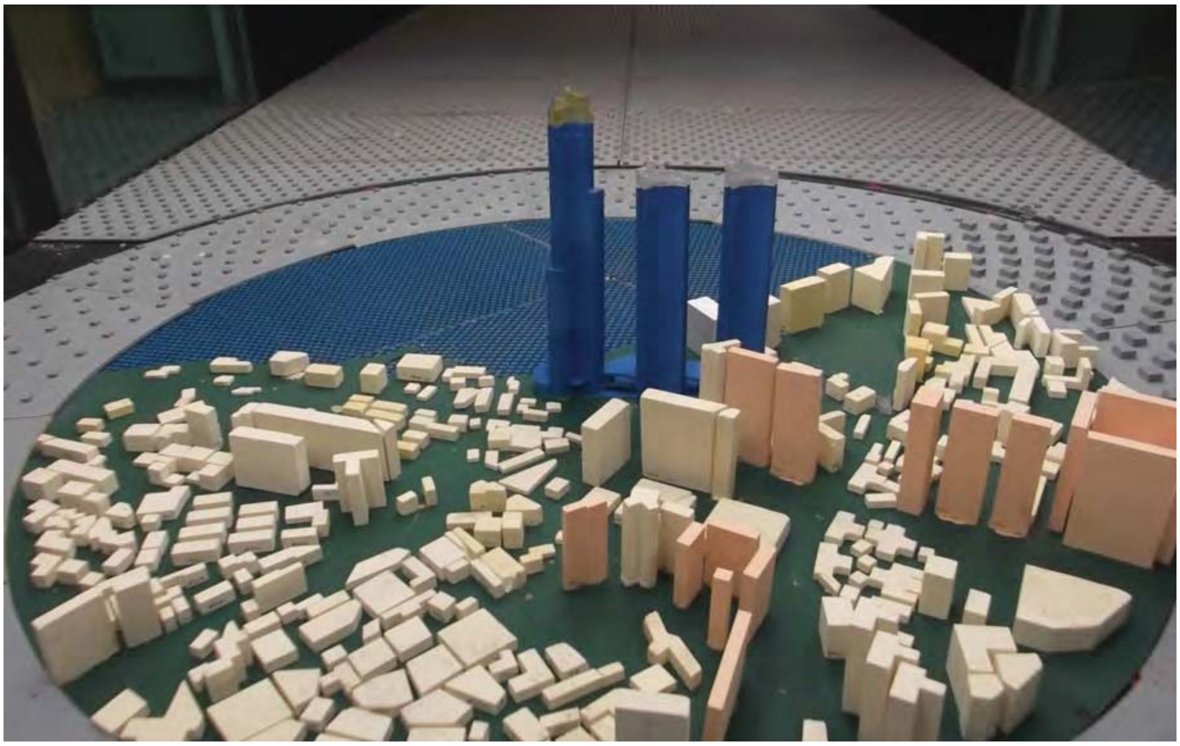
There are several different methods of using the wind tunnel to predict the overall structural loads and responses of tall buildings. The three most common techniques are the high-frequency-balance (HFB) method, the high-frequency-pressure-integration (HFPI) method, and the aeroelastic model method.

The HFB method is also known as the high-frequency force balance method and the high-frequency base balance method. The balance is usually a strain gauge or piezoelectric device, mounted at or near the base of a rigid building model (see Figure 3.6). The balance is capable of measuring instantaneous base moments and, in some balances, base shears. The base moments in particular are closely related to the aerodynamic modal forces acting on the building's lowest modes of vibration. The measurements can be used to determine not only the integrated mean forces on the building, but also the instantaneous fluctuating aerodynamic forces and the modal forces exciting each mode of vibration. These applied aerodynamic forces are combined with the predicted structural dynamic properties of the building to determine the anticipated wind-induced loads and building responses.

The reason the method is called "high-frequency" is because the natural frequency of the model/balance system should be significantly higher than the scaled-prototype natural frequencies of vibration of the building being tested. This ensures that the measured signal is not contaminated by resonant effects from the model/balance system itself.

High-frequency balances come in a number of forms, but all should be able to measure the base bending moments

▲ Figure 3.1: Shanghai Tower, Shanghai, China. Wind tunnel test performed in March 2009. © RWDI



▲ Figure 3.2: Haeundae Beach Towers, Busan, Korea. Wind tunnel testing performed in February 2012. © BMT Fluid Mechanics

4.0 Prediction of Load Effects for Strength Design and Serviceability

4.1 Structural Properties of the Building

For the prediction of a building's dynamic response at various wind speeds and directions, it is necessary to know the natural modes of vibration of the structure, including the natural frequencies and modal deflection shapes. It is also necessary to know the damping in each mode. The natural frequencies and mode shapes may be computed using a number of available commercial finite element software packages. However, the results will be influenced by the assumptions made when developing the finite element model.

For the purpose of determining the dynamic response to wind loading, it is important to be aware that, in general, lower frequencies will lead to increased response, which is the opposite situation to that of seismic response. Also, it has been noted that due to the cracking behavior of concrete structures, particularly in elements like link beams, there is a tendency for the stiffness, and thus the frequency, to decrease as the amplitude of motion increases.

In steel buildings, a somewhat similar behavior has been observed, which has been attributed to slippage occurring at connections as amplitudes increase. These changes will clearly affect the response to wind. Therefore it is advisable to assess the sensitivity of wind tunnel predictions to the effect of different cracking or stiffness assumptions. Greater reductions in stiffness may be expected at deflections corresponding to ultimate load conditions than those at which accelerations are assessed.

The damping inherent in the structural systems of tall buildings cannot currently be predicted using detailed analytical methods. Common practice over several decades has been to assume damping ratios of approximately 0.010 to 0.015 for slender steel buildings and about 0.010 to 0.020 for slender concrete buildings. The lower ends of these ranges are applied when assessing building motions; upper end is applied when determining wind loading for structural integrity. Higher values have also been adopted in some cases where ultimate limit state wind speeds have been applied directly without load factors. More detailed empirical relationships have been developed in Japan based on extensive monitoring studies on buildings up to 200 meters in height (Tamura 2012). These show an initial increase of damping ratio as deflections increase, but the damping then levels off beyond a "critical" deflection somewhere in the range of:

$$2\times10^{-5} < x_H / H < 1\times10^{-4} \qquad (4)$$

where x_H = deflection at the top of the building
H = height of building

Representative values found for the damping ratio were 0.0115 for office buildings of average height 113 meters and 0.0145 for hotels and apartment buildings of average height 100 meters. Other recent data (Willford et al. 2008) indicate that for tall and slender towers above 250 meters in height, where cantilever action dominates over moment frame action, the damping could be below the ranges described above.

As with assumptions concerning stiffness, it is advisable to undertake sensitivity studies of the building response with different damping assumptions. Where lower bound damping assumptions create or accentuate motion or loading problems, the use of supplementary damping systems can be considered as a means of increasing the damping and reducing uncertainty as to what the total damping will be.

4.2 Load Effects

In structural design the important variables for the designer are typically load effects, such as the base bending moments, base shears, base torsion, and corresponding force and torque distributions with height. These global load effects are selected because they are closely correlated with the load levels reached in individual structural members and components. For the design of cladding, the local, peak positive and negative pressures on small areas, such as the area of a cladding element are needed.

For strength design, the load effects may be needed for return periods on the order of 50 to 100 years at service limit state, or 500 to 2,000 years at ultimate limit state. Other load effects, such as accelerations or rotational velocities, may be needed for shorter return periods in the range from a few months up to 10 years in order to evaluate the comfort of occupants. Wind tunnel tests enable a selected wind load effect E to be determined in detail as a function of wind speed and wind direction, but to convert this information into the load effect E_T for the T-year return period requires that the wind tunnel data be combined with the statistics of wind speed and direction at the site. This latter information is usually obtained by extrapolation from the records available from meteorological stations in the area, often from nearby airports. In areas affected by hurricanes and typhoons, the necessary statistics are generated by Monte Carlo simulation.

There are several methods used to combine the wind tunnel data with the meteorological data, and it is important to be aware of the differences. It is also important to realize that the event that causes the T-year wind speed is not necessarily the same event that causes the T-year load effect. Because the wind loading and response of tall buildings is highly dependent on wind direction as well as speed, there is no simple generally applicable explicit relationship between the overall T-year speed and the T-year load effect. To obtain the T-year load effect, special analysis methods are needed for combining wind tunnel data with meteorological data, as explained in the following sections.

4.3 Non-Directional Method

The Non-Directional method is the simplest of the analysis methods, because it simply assumes that the T-year wind speed occurs from all directions, one of which will be the aerodynamically worst direction for the building. Clearly, there is inherent conservatism in this assumption.

Denoting the T-year return-period speed for the building site, including winds from all directions, as U_T then in the Non-Directional method the T-year return period load effect E_T is evaluated as follows:

From the wind tunnel data, which must cover sufficient wind directions to resolve all peak responses (typically 10-degree intervals are sufficient), the load effect $E(U_T)$ at speed U_T is determined for every tested direction. Figure 4.1 illustrates this for the case where E is the base moment, and shows the mean value and the peak positive and negative values for each wind direction evaluated at speed U_T. Note that the overall T-year return period wind speed U_T is taken as constant, independent of wind direction.

The T-year return-period load effect is then taken to be the maximum value of $E(U_T)$ out of all the directions, as illustrated in Figure 4.1 for both negative and positive moments. Provided the load effect's dependence on speed is monotonic for every direction, i.e., there is no peak response at speeds lower than U_T, the load effect determined by the Non-Directional method will be an upper bound for the T-year return period value E_T. Use of upper bound loads, rather than the true value of E_T would usually result in significant increases in construction cost. For this reason more accurate methods than the simple Non-Directional method are typically used for tall buildings, except where the available meteorological data are insufficient to establish the wind's directional behavior with confidence.

- *Advantages:* Very simple. Easily compatible with code-mandated design wind speeds.
- *Disadvantages:* Can be very conservative.

4.4 Sector Velocity Method

The Sector Velocity method improves on the Non-Directional method by applying a different design velocity to each sector of wind direction, using higher wind velocities for directions of higher probability for strong winds (Holmes 1990). The load effect for each wind direction is calculated using these different sector velocities and the highest load effect out of all the directions is taken to be the T-year return period value E_T.

An advantage of this straightforward approach is that it seems intuitive to use higher design speeds for directions where historical records show greater frequency of strong winds, and lower speeds in other sectors. A disadvantage is that there is a theoretical difficulty in selecting appropriate speeds for the various directional sectors. This is because in the general case the overall probability of a given load effect being exceeded is the sum of the probabilities from all the sectors. One does not know in advance, for any particular project, how many sectors will contribute significantly.

The number of sectors that contribute affects the level of probability at which to select the wind speed for each

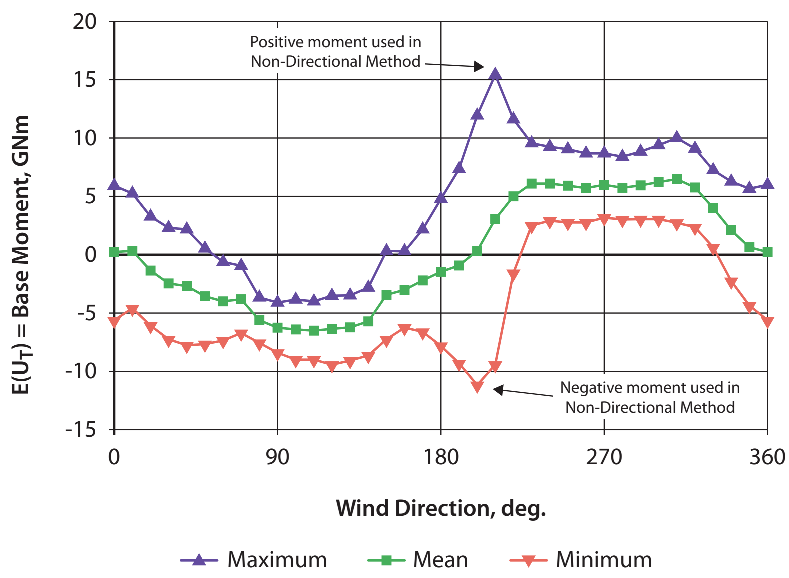


Figure 4.1: Example of Non-Directional method applied to base moment. Note that moments are evaluated at the same wind velocity U_T for all wind directions.

Since the 1960s, wind tunnel testing has become a commonly used tool in the design of tall buildings. It was pioneered, in large part, during the design of the World Trade Center Towers in New York. Since those early days of wind engineering, wind tunnel testing techniques have developed in sophistication, but these techniques are not widely understood by the designers using the results. As a direct result, the CTBUH Wind Engineering Working Group was formed to develop a concise guide for the non-specialist.

The primary goal of this guide is to provide an overview of the wind tunnel testing process for design professionals. This knowledge allows readers to ask the correct questions of their wind engineering consultants throughout the design process. This is not an in-depth guide to the technical intricacies of wind tunnel testing, it focusses instead on the information the design community needs, including:

- a unique methodology for the presentation of wind tunnel results to allow straightforward comparison of results from different wind tunnel laboratories
- advice on when a tall building is likely to be sufficiently sensitive to wind effects to benefit from a wind tunnel test
- background for assessing whether design codes and standards are applicable
- details of the types of tests that are commonly conducted
- descriptions of the fundamentals of wind climate and the interaction of wind and tall buildings.

This unique book is an essential guide for all designers of tall buildings, and anyone else interested in the process of wind tunnel testing for tall buildings.

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