A discussion of the local wind climate should be included as part of the submission from a wind tunnel laboratory. This discussion should include a description of the prevalent windstorm type(s) that impact the project site, how these storms have been reflected in the subsequent wind tunnel testing, and how they have been treated in the statistical analysis of the wind climate. The treatment of the wind climate may differ for strength and serviceability design requirements. The wind tunnel consultant should clearly document that the local wind climate characteristics and classification have been incorporated into the wind loads and effects predicted for the building.

5.3.2 Data Sources

Data that describe the local wind climate can be either measured or simulated. Measured data are typically obtained from surface weather stations, where the data have often been archived for many decades. The wind velocities measured at surface height, typically 10 m (33 ft) above ground level, are extrapolated to building height or some other clearly defined reference height using models of boundary layer winds. Wind climate analyses conducted for tall buildings typically use measured data as their primary data set, although it may be augmented by other data sources. Surface data are commonly recorded at 1 h intervals, although some stations record data once every 3 h. Many international stations may have sparser records, depending on the location. In addition, many weather stations may have a long history of seemingly consistent data, yet the anemometer may have been relocated or replaced with one of a different type, or vegetation or architectural build-ups may have occurred, resulting in a change in its effective exposure, height above ground, and its gust response characteristics. Such effects must be identified, and the appropriate analysis must be executed to convert all readings to a consistent 3 s gust speed at a height of 10 m (33 ft) in open country. Care and attention must be given to stations that do not have continuous records, and corrections should be applied as appropriate.

Simulated wind data is often used in regions having frequent hurricane or cyclonic wind events to overcome the limitations of measured data. Reliable measurements of hurricane winds are also hampered somewhat by the robustness of instrumentation in extreme events. Monte Carlo methods are used to simulate a large number of time histories of hurricane events (typically between 10,000 and 100,000 events) to increase the population of events used to predict extreme winds, which also enhances the reliability of the statistical analyses for ultimate limit state design.

5.4 INFLUENCE OF TERRAIN

In tall building design practice, the structural engineer works with the client to identify specific performance objectives for serviceability and strength limit states. As noted in Chapter 2, a key design parameter is wind speed—pressure varies as a function of wind speed raised to the power of 2, but building response may vary as a function of speed to higher powers, typically in the range of 2.3 to 4. Site wind speeds for design are affected by both near-field and far-field effects, related to the proximity of surrounding buildings and the aerodynamic roughness of the terrain, respectively.

Near-field effects are understood but difficult to quantify accurately using an analytical approach. It is understood that neighboring buildings having massing similar to the target building can provide shelter if located in close proximity, but interference effects such as turbulent wakes or channeling by multiple buildings can also be more onerous for design. Interference is not typically addressed in codified approaches to calculating wind-induced loads because of the dependency of the wake effect on spacing and upwind building massing and geometry. Because near-field effects are best understood through wind tunnel modeling, they form the focus of Chapter 6.

Far-field effects related to the aerodynamic roughness of the ground influence both the mean and gust wind velocity profiles at a site. In nature, the progression from one terrain type to another is usually gradual, and the range of aerodynamic roughness length covers several orders of magnitude. For tall buildings it is recommended that the influence of terrain on velocity and turbulence be evaluated using rational approaches complementary to code, such as the model of the planetary boundary layer provided by the Engineering Sciences Data Units (ESDU) based on work by Harris and Deaves (1980).

Changes in local topography can affect wind speeds in the near and far field. Slopes with grades greater than about 5 degrees can locally increase wind speeds near the crest of hills and escarpments, particularly close to the earth's surface. Topographic effects are calculable (e.g., the K_{zt} factor in ASCE 7), and analytical methods are provided in all codes of practice. In complex terrain, topographic effects are better quantified through the use of reduced scale wind tunnel models (1:2000 to 1:5000 scale) or computational wind engineering.

The wind consultant's report should include an explanation of the techniques used to assess terrain influence and provide a description of the wind tunnel profiles used in the simulations of wind effects.

5.5 EXTREME VALUE ANALYSIS

The determination of an applicable design wind speed or pressure is conventionally based on extreme value analysis techniques. This analysis involves fitting a statistical distribution to independent maxima. Most maxima extraction techniques fall into the following categories:

- Annual maxima: The highest magnitude wind speed in a calendar year (nominally January 1 to December 31) is extracted for each year in the available period of record. This limits the number of maxima for fitting to the number of years in the period of record.
- Monthly maxima: The highest magnitude wind speed in each month of each year is extracted. For example, if there are 30 years of data in the historical record, then $12 \times 30 = 360$ maxima are available for fitting.
- Method of independent storms: In this method, independent maxima are extracted using a two-pass algorithm that first identifies independent events and then identifies the maxima within the events. This significantly increases the number of independent maxima to upward of 80 or 90 per year.

The method of independent storms is considered more robust than the annual or monthly maxima methods because statistical independence is implicit in this approach. The wind consultant's report should include a description of the extreme value analysis techniques used as well as a discussion regarding the maxima extraction techniques.

Before fitting, extracted maxima should be classified according to storm type (e.g., synoptic, thunderstorm, and so forth). It is well established that in mixed climates, where multiple storm types contribute to the extreme wind climate, individual extreme value fits should be conducted for each storm type. For example, a site may be subject to thunderstorm, synoptic, and tropical cyclone winds. Extreme value fits should be conducted on the extracted maxima individually and then recombined to determine the overall risk.

For serviceability limit states, it is common practice that the wind demand determined for any given MRI will be based on the wind consultant's statistical evaluation of the extreme wind climate, which is typically at or below the code-prescribed wind speeds or pressures. This analysis also allows for directional wind effects to be included. For strength design, wind loads are typically provided at the MRI of interest based on the code-prescribed wind speed or pressure. In areas where no code-prescribed wind speed or pressure is available, or where the wind consultant and design team feel that the code is inappropriate for the site or building under study, a detailed wind climate report can be prepared by the wind consultant and presented to the local building code official for approval. Sections 26.5.3 and C26.5.3 of ASCE 7-16 (2017) describe the procedures that should be followed for estimating basic wind speeds from regional climatic data. A peer review of the analysis may be recommended.

5.6 DESIGN CRITERIA: MEAN RECURRENCE INTERVALS

Probabilistic modeling of the wind hazard is critical for determining the demand on a tall building structure. In most designs, the occupancy category of a tall building is determined, which sets expectation on performance levels for service and strength design.

Various performance objectives for stability, occupant comfort, drift limits, and strength design are outlined in Chapter 3. Each performance objective is associated with an MRI appropriate for design considerations.

CHAPTER 6
WIND TUNNEL TESTING

6.1 OVERVIEW

This chapter outlines the role that wind tunnel testing plays in determining wind loads on a tall building and accounting for the uncertainties that are contained in code-based wind analysis. The following sections discuss triggers for testing in the wind tunnel, the types and benefits of each test, how to identify the strengths and weaknesses of physical and computational testing, and test inputs and outputs. The benefits of wind tunnel testing for the design of a tall building are highlighted.

6.2 TRIGGERS FOR TESTING

Satisfying the ultimate strength demand for a tall building is not a guarantee that serviceability limit states (commonly, building motion and drift) will be met. For example, even in high seismic zones where strength design is governed by seismic requirements, this is no guarantee that occupant comfort under wind excitation will be achieved. This results from the random nature of the applied wind force having energy spread across a broad range of natural frequencies and the sensitivity of a building's response at varying frequencies. The sensitivity of a building's response is a function of its dynamic structural properties, its geometric form, the velocity and turbulence of the approaching wind (which includes the effects of local topography), and interference effects from nearby structures.

Any combination of the aforementioned variables may serve as the triggers for wind tunnel testing. However, if more than one of the following conditions are fulfilled, the design team should seek specialist advice from a wind consultant and consider the use of a wind tunnel from the early stages of design. Items that might affect the wind effects on a tall building include the following:

1. Height and slenderness ratio: Crosswind response, which is not covered by many codes, will often govern the wind response of buildings with height greater than 120 m (400 ft) and/or a height-to-width aspect ratio greater than 4:1.
2. Irregular plan forms not covered by code provisions: Examples include buildings with unusual architectural features, such as tapered, twisted, or offset stories; rooftop crown features; and building appurtenances.
3. Buildings with plan forms known to be susceptible to crosswind loading or vortex shedding should be evaluated using the wind tunnel approach.
4. The site location: When a tall building is located on a site where buffeting in the wake of upwind obstructions or channeling effects caused by proximity to neighboring buildings is anticipated, special consideration is warranted.
5. Linked tower structures: Where multiple towers have linking structures, such as skybridges, it is important to understand the relative movements between the towers and/or the load transfer through the linking elements.
6. Unusual structural dynamic properties or asymmetric structural systems that may not be well covered by code provisions.

6.3 TYPES OF WIND TUNNEL TESTS

For the design of tall buildings, stakeholders typically seek distributed wind loads for the design of the main wind force resisting systems (MWFRS) and foundations, and predictions of building drifts and motions for serviceability and occupant comfort. To evaluate the wind-induced responses of a tall building in the wind tunnel, there are two basic types of wind tunnel tests: (1) static (rigid) model tests, and (2) elastic model tests. In general, static model tests are undertaken using one of two methods: the high-frequency balance (HFB) approach, in which wind forces (moments and shears) are measured directly at the model's base, or by using integration of simultaneously measured surface pressures known as high-frequency pressure integration (HFPI). The model is rigid for both approaches. The elastic model technique, known as the aeroelastic model method, incorporates a scaled elastic model of the tall building. Brief explanations of the wind tunnel test types are provided subsequently.

6.3.1 High-Frequency Balance

The HFB is a device capable of measuring up to six components of force and/or moment. The balance is typically integrated with a lightweight wind tunnel model to develop high stiffness, yielding natural frequencies of vibration of the combined model/balance system that are beyond the range of interest for post-test analyses, hence the term, high-frequency balance (Figure 6-1). Mean and fluctuating loads integrated over the rigid model's surface are measured directly by the balance. The measured, applied base moments are combined with the estimated structural modal properties to determine design wind loads. Care must be taken by the wind consultant to ensure that corrections are applied to the measured data where the building mode shapes deviate from a linear variation with height. This is an aerodynamic type model test, in which the effects of the dynamic properties are incorporated analytically.

The high-frequency balance approach is well suited to wind tunnel investigations early in the design process because the models are relatively simple to build and instrument. This method is the most suitable for form-finding workshops in which geometric form is being evaluated and early design feedback is required for evaluating different structural systems.

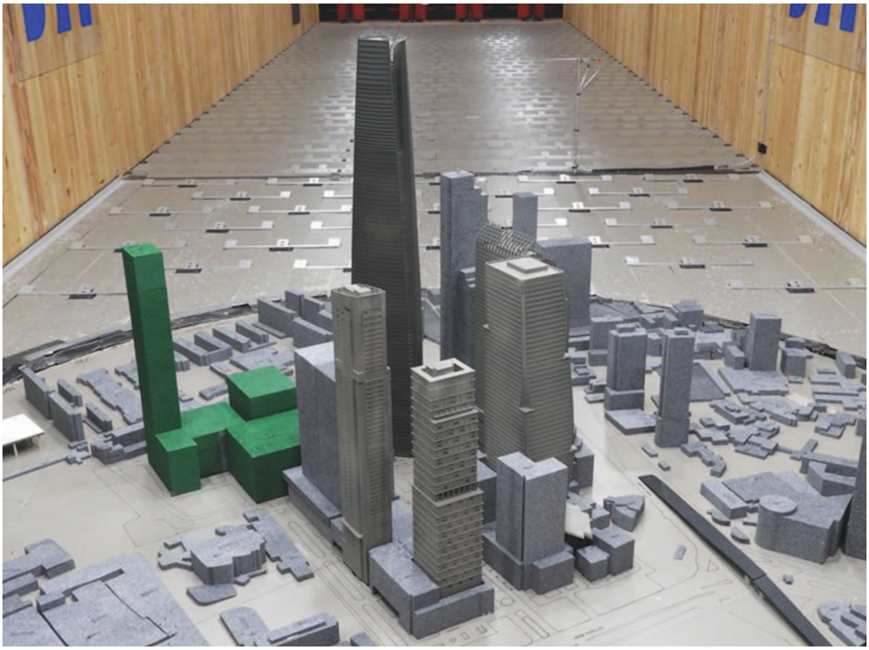

Figure 6-1. HFB model: One Bangkok Tower.
Source: Courtesy of RWDI.

6.3.2 High-Frequency Pressure Integration

The HFPI technique is another aerodynamic model test that uses a rigid pressure-tapped model, typically the same model used for the determination of local cladding pressures (Figure 6-2). For this reason this approach is best suited for a building whose geometry and external features that may impact building aerodynamics are relatively finalized. Rather than measure forces directly, the simultaneous pressure integration approach instantaneously combines pressures over the envelope to derive mean and fluctuating components of the applied wind pressures. The model must contain a density of pressure taps on the surface of the model sufficient to capture key aerodynamic flow characteristics.

The resonant component of the wind-induced response is calculated by directly integrating local surface pressures with the dynamic modal properties. This also permits higher modes of vibration to be included in the dynamic analysis, something that is not possible with a typical HFB test. This may be important for tall buildings with extremely long fundamental periods of vibration (i.e., greater than 10–12 s), in which secondary sway modes may be sensitive to wind-induced excitation.

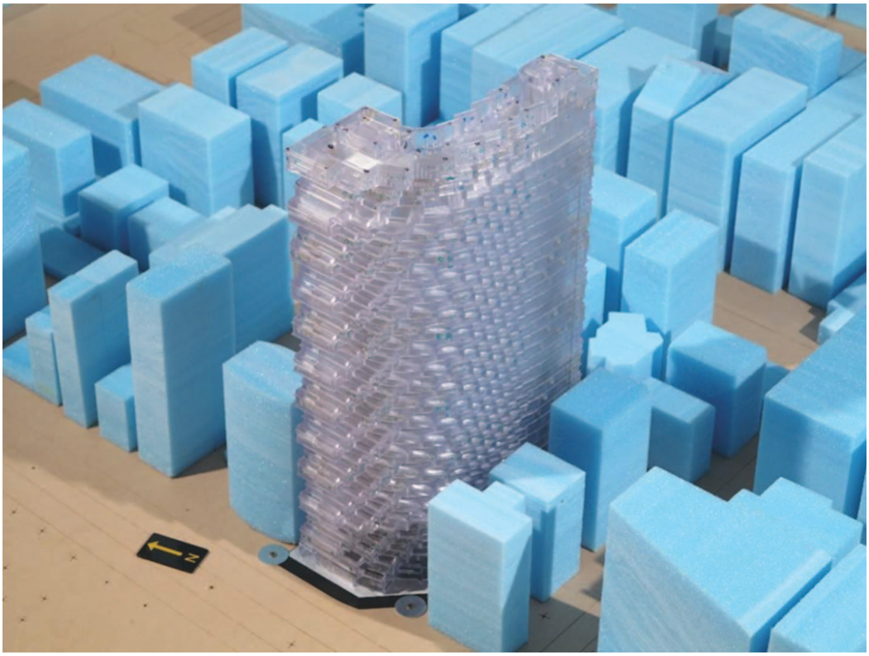

Figure 6-2. High-frequency pressure integration model: Torre Shyris 18, Quito, Ecuador.
Source: Courtesy of CPP.

The pressure integration technique allows the wind force distribution with height to be resolved with improved precision compared to the high-frequency balance approach. This is beneficial in predicting the distribution of quasi-static (background) loads among floors and resonant response when torsion is important. The pressure integration technique is also useful for tall buildings with different structural systems over its height, for example, a concrete tower with a lightweight steel rooftop crown feature. The integration of pressures can be undertaken to inform the design of smaller architectural/structural features such as rooftop crowns and winter gardens, among others, and does not require a separate test. Where higher modes of vibration may be excited by the wind, it is recommended to verify wind-induced response predictions from early HFB studies using the simultaneous pressure integration approach where possible.

For particularly tall and slender buildings, or those with aerodynamically significant architectural elements that cannot be pressure tapped, the high-frequency pressure integration approach may not be possible because of the large number of pressure taps required and the inability to extract the tubes associated with these within the small plan form of the building. Similarly, for buildings with very complex architecture, it may not be possible to include a sufficient number of pressure taps to adequately define the instantaneous pressure fields over the building envelope.

6.3.3 Aeroelastic Method

An aeroelastic model is designed to have scaled geometry, mass, stiffness, modal displacements, and damping characteristics that represent the full-scale prototype of the building (Figure 6-3). In other words, the model will respond to applied wind forces elastically by vibrating in the same fashion as the actual building. The benefit of the elastic response is that aerodynamic forces that may occur owing to large-amplitude motion of the building will be captured in the measurements of the model's response. Aeroelastic models may be simplified to evaluate only the fundamental sway modes, or they may be more complex to permit measurement of the response of the building in higher modes or in torsion.

An important aeroelastic response occurs when the motion of a structure results in a change in the wind loading. If the resulting change in wind loading acts in phase with the structure's velocity, it may reduce the aerodynamic stability of the structure. It is convenient to include these velocity-induced forces in the response equation of the structure, and the commonly used term for these forces is *aerodynamic damping*. For most tall buildings, aerodynamic damping will be positive. This can be beneficial in cases in which the predicted wind-induced response(s) marginally exceeds the performance criteria established by the design team, and the positive

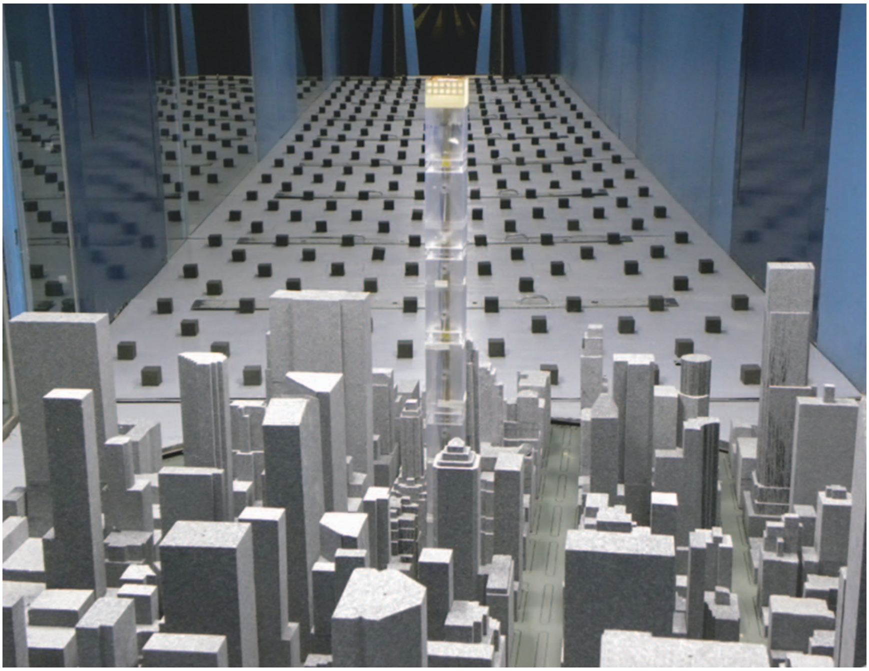

Figure 6-3. Full aeroelastic model: 432 Park Avenue.
Source: Courtesy of RWDI.

aerodynamic damping will lead to small reductions in the response. For particularly slender buildings, aerodynamic damping in the crosswind direction may be negative, particularly around critical wind speeds for vortex shedding. This effectively reduces the total damping of the building. This is not an effect that may be measured using rigid model methods approaches, although the results from HFB and HFPI testing can give an indication that the building is operating in a wind speed range where this is possible. Where negative aerodynamic damping may occur, an aeroelastic model test is recommended. When designing for ultimate limit states, the controlling response may occur at shorter MRI wind speeds. This would be as a result of vortex shedding, and the impact of negative aerodynamic damping needs to be considered.

The aeroelastic study is the most cost- and time-intensive wind tunnel test for a tall building. If deemed necessary, it is often performed in the latter stages of design. The aeroelastic model can provide a final high-fidelity confirmation of the wind-induced response when required, although care needs to be taken with buildings with complex coupled modes to ensure that the necessary parameters are adequately modeled (ASCE 49-12).