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Toward a Standard on the Wind Tunnel Method

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Cover Photo: Boundary Layer Wind Tunnel Laboratory, The University of Florence, Prato, Italy.

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Abstract

This document is intended to provide practicing engineers and building code officials with a technical resource that (i) describes current practices for the testing of buildings and other structures in flows simulating natural winds, (ii) provides a basis for discussion on needed improvements to those practices. Improvements are required because, as was demonstrated by recent studies, (i) wind tunnel tests can yield widely different results depending upon the wind tunnel laboratory in which they are conducted, and (ii) standard provisions for wind loads based on insufficiently documented or inadequate wind tunnel tests can be seriously in error.

The report presents an overview of the main elements of the wind effects estimation process inherent in the ASCE 7 Standard's conventional (i.e., analytical and simplified) methods. The overview is so structured that the relevance to engineering design of those elements and of the disciplines with which they are associated (micrometeorology, aerodynamics, statistics, wind climatology, structural reliability) is clearly established. The structure developed for that overview is then used for a discussion of the elements of the wind tunnel method estimation process, which parallel, while being typically more elaborate than, their counterparts in ASCE 7's conventional methods. The report provides suggested guidance on the future development and standardization of the wind tunnel method. Improvements to wind effects modeling and calculation procedures that can be incorporated in standard provisions can contribute significantly to the reduction of losses in strong winds, and of materials and embodied energy consumption.

Keywords: Aerodynamics; building codes; micrometeorology; statistics; structural dynamics; structural reliability; wind climatology; wind tunnels; wind engineering.

Disclaimers:

(1) The policy of the NIST is to use the International System of Units in its technical communications. In this document however, works of authors outside NIST are cited which describe measurements in certain non-SI units. Thus, it is more practical to include the non-SI unit measurements from these references.

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Acronyms:

ASD: Allowable Stress Design

MRI: Mean Recurrence Interval

SD: Strength Design.

CHAPTER 1

1. INTRODUCTION

The ASCE 7-05 Standard (or hereinafter ASCE 7, for short) (ASCE Standard, 2006) specifies three methods for calculating wind effects: two *conventional methods*, referred to as (1) the *analytical method* and (2) the *simplified method*, and (3) the *wind tunnel method*. For all three methods the aerodynamic data are based on wind tunnel tests, the only means currently available for obtaining such data for structural design and codification purposes.[1]

The aerodynamic data used in the conventional methods are drastically simplified and reductive summaries of measurements obtained in wind tunnel facilities under various, largely undocumented or inadequately documented test conditions. Such data can result in severely distorted representations of actual wind effects. The wind tunnel method is used if (i) for reasons of safety or economy, more reliable and detailed data are needed than those available in standards or in the literature, and/or (ii) available tables and plots do not adequately cover the types of structure of interest. The wind tunnel method uses results of generic or ad-hoc aerodynamic tests conducted in wind tunnels that satisfy minimum requirements specified in ASCE 7.

The ASCE 7 requirements on the wind tunnel method are *not* sufficient for producing estimates of wind effects required for structural design. Those requirements need to be complemented so that wind effect estimates can be performed reliably, which is currently not always the case, especially for low-rise buildings. Wind tunnel testing is not performed for its own sake, but rather to serve the purposes of the structural engineer. Inadequate wind effects estimates contribute not only to the occurrence of losses experienced in strong winds. They also contribute to less visible but significant waste inherent in designs that consume unnecessarily large amounts of material and embodied energy. The need for an adequate standard on the wind tunnel method was demonstrated by recent studies which showed that wind tunnel tests – and the wind tunnel method -- can yield widely different results depending upon the wind tunnel laboratory

[1] Computational Fluid Dynamics (CFD), or its application to wind engineering sometimes referred to as Computational Wind Engineering (CWE), is in principle an alternative means. However, although it can be useful for qualitative purposes, at present the information it provides on fluctuating pressures on bluff bodies is not sufficiently reliable to be accepted for structural design. As computational power increases, it is expected that CFD/CWE will become more useful for practical structural engineering applications, but when this will be the case is difficult to ascertain. Full-scale measurements in natural winds are another means of obtaining aerodynamic data; their usefulness is limited to calibration and validation applications. Finally, promising large-scale facilities of the type known as “Wall of Wind” are currently being developed, which allow in principle testing at considerably geometric and velocity scales than those typical of commercial wind tunnel tests (Huang et al., 2009).

performing the tests and on the methodology being used for using the test results for structural engineering purposes. For example:

- Roof corner pressure coefficients and peak wind-induced bending moments in structural frames obtained for the type of low-rise building model from aerodynamic measurements in six reputable wind tunnels were found to differ from each other by amounts exceeding in many cases 50 % (Fritz et al., 2008; see also Bienkewicz et al., 2009).

- For the wind-induced response of the World Trade Center (WTC) towers, two laboratories provided estimates of the response that differed from each other by over 40 % (for details see WTC (2005) and Appendix I). [2]

- According to studies by Ho et al. (2005), St. Pierre et al. (2005), and Coffman et al. (2009), tests recently conducted at one wind tunnel laboratory resulted in aerodynamic pressure coefficients for low-rise buildings that could differ by more than 50 % from their counterparts specified in ASCE 7 on the basis of tests conducted at the same laboratory about two decades earlier.

The process of estimating wind effects for structural design purposes integrates interacting elements that draw on the following disciplines: (1) micrometeorology, (2) aerodynamics, (3) wind climatology, (4) statistics, and (5) structural reliability. (In addition, structural dynamics can be involved in the analytical method, and structural dynamics and/or aeroelasticity can be involved in the wind tunnel method.) It is shown in Chapter 2 that conventional methods use drastically simplified versions of those elements, which distort significantly the representation of wind effects. The simplifications were in part intended to allow quick manual design calculations. However, they were due in some cases to the lack of adequate models or data, or from an inadequate understanding or interpretation of the phenomena involved in the estimation.

A Draft Standard for the Wind Tunnel Testing for Buildings and Other Structures (hereinafter referred to as the Draft Standard) is currently under development, and was recently opened for public comment. The Draft Standard was in principle developed to cover both low-rise and tall buildings. However, the document *ASCE/SEI Wind Tunnel Testing: 2^nd^ Public Comment Period, Voters' Comments and Resolution Report* dated 9 March 2008, states: "Very little testing of low-rise building goes on outside of a few research projects at universities. The bulk of testing is done on large structures and the standard should not become side-tracked by a lot of low-rise issues." This statement is, in our view, unwarranted. Low-rise buildings constitute a large proportion of the constructed environment in the U.S. For this reason the adequacy and effectiveness of low-rise building tests for wind must be assured. A standard on the wind tunnel method is needed, among other reasons, because it is a prerequisite for the development in the future of more adequate conventional method provisions on aerodynamic pressures and forces.

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[2] According to Griffis (2006), "there have been a large number of projects tested by more than one wind tunnel laboratory where results were very close, typically within about 10 %." However, to our knowledge the comparisons to which this statement refers are not available in the public domain or otherwise open to public, independent scrutiny. In addition, they do not consider the well documented WTC case.

For both low-rise and tall buildings it is required that standard provisions on the wind tunnel method: (1) lead to repeatable wind tunnel testing, (2) result in accurate estimates of wind effects, (3) allow the assessment of errors and uncertainties inherent in those estimates, and (4) enable structural engineers to clearly and fully understand every step of the wind effects estimation process, a goal that is far from having been achieved so far (see Appendix I).

The objective of this report is to provide a basis for the development of a standard on the wind tunnel method that meets the requirements stated above, thereby providing the structural engineering profession with the most transparent and best possible tools for estimating wind effects on both low-rise and tall structures. The standard would help to eliminate significant differences that can exist at present between estimates provided by various laboratories. It would also end the perceived need for the policy of commissioning independent wind engineering reports for the same building instituted by some consultants to reduce the risk of basing structural designs on unconservative or over-conservative estimates of wind effects.

Chapter 2 considers the wind effects estimation process inherent in the ASCE 7 conventional methods and presents an overview of the main elements explicitly or implicitly involved in that process. As was stated earlier, these elements draw on the following disciplines: micrometeorology, aerodynamics, wind climatology, statistics, and structural reliability; for flexible buildings, structural dynamics is involved as well. Chapter 2 is so structured that the relevance to design practice of each of those elements, and of the disciplines with which they are associated, is clearly established through reference to ASCE 7, a document familiar to most structural designers. The structure developed in Chapter 2 is used in Chapter 3 for a discussion of the elements of the wind tunnel method estimation process, with a view to providing a comprehensive and coherent basis for its standardization. Chapter 4 discusses minimum requirements for the development of an effective standard on wind tunnel testing. Chapter 5 presents the conclusions of this work. Appendix I includes documentation on current wind engineering laboratory practices for tall buildings.

CHAPTER 2

ELEMENTS OF THE WIND EFFECTS ESTIMATION PROCESS: ASCE 7 CONVENTIONAL METHODS

This chapter presents an overview of the main elements of the wind effects estimation process inherent in the ASCE 7 conventional methods. Those elements are discussed in Sections 2.1 though 2.5, which pertain, respectively, to micrometeorology, aerodynamics, wind climatology, statistics, and structural reliability. Section 2.6 briefly describes the estimation of wind effects by the conventional methods through integration of those elements.

2.1 Micrometeorology

Micrometeorology provides models of the atmospheric flow, which is governed by surface roughness and is characterized by the variation of wind velocities with height and the features of the flow turbulence. In this section we briefly review relevant ASCE 7 models, and discuss the effect of discrepancies between flow simulations on which ASCE 7 specifications are based and actual atmospheric flows. ASCE 7 atmospheric models are based on models applicable to large-scale extratropical storms (i.e., synoptic winds), but it is tacitly assumed that they are also in practice applicable to other types of storms, including hurricanes and thunderstorms.

Wind Speed Profiles. The ASCE 7 conventional methods are based on a simplified model of the atmospheric boundary layer flow in which wind speeds are constant up to an elevation approximately equal to the typical elevation of a one-story residential building, from which they vary with height above the surface in accordance with a power law whose exponent depends on surface exposure.

Relation between Wind Speeds in Different Roughness Regimes. Given the wind speed at 10 m above ground in open exposure, the corresponding wind speed at any elevation over a surface with different exposure is modeled in ASCE 7 by accounting for the respective power law exponents and gradient heights (see, e.g., Simiu and Scanlan, 1996, p. 46).

Relation between Peak Wind Speeds Averaged over Various Time Intervals. For wind speeds at about 10 m above ground over terrain with open exposure, this relation is provided in the Commentary to ASCE 7.

Flow Turbulence. The turbulence of the flow is implicit in the ASCE 7 requirements on (i) the variation of 3-s peak gusts with height above ground, which is less steep (i.e., is characterized by smaller power law exponents) than the variation of mean speeds with height, (ii) the relation between wind speeds averaged over various time intervals, (iii) the longitudinal turbulence intensity (i.e., the height-dependent ratio between the root mean square of the longitudinal velocity fluctuations and the mean wind speed), (iv) the spectral and cross-spectral density of the longitudinal velocity fluctuations, used to estimate along-wind flexible building response for wind normal to a building face, and (v) the integral turbulence scales which, like the cross-spectral density of velocity fluctuations, govern the spatial coherence of the fluctuating wind speeds, meaning that the smaller the integral turbulence scales, the weaker is the degree to which wind speeds at two distinct points within the flow fluctuate in phase.

Simulated vs. Actual Atmospheric Flows. As was noted in Chapter 1, aerodynamic pressures specified in ASCE 7 were obtained at various times in various types of wind tunnel flow, documented incompletely or not at all. According to findings reported by Ho et al. (2005), St. Pierre et al. (2005), and Coffman et al. (2008), ASCE 7 aerodynamic data based on 1970s and 1980s tests on low-rise building models can be strongly *unconservative*. Since those data represent *envelopes* of pressures obtained in the wind tunnel (i.e., typically consist of *larger* pressures than those yielded directly by measurements), the fact that ASCE 7 aerodynamic data can be unconservative implies measurement errors and/or inadequate flow simulations. As the measurement techniques appear to have been carefully calibrated in most cases, the remaining explanation would be the inadequacy of flow simulations. Results by Fritz et al. (2008) (see also Bienkiewicz et al., 2009) strikingly showed, in addition, that, owing to the absence of clear and sufficiently detailed standard provisions with which compliance can be readily verified, achieving reasonably correct wind tunnel simulations of the atmospheric boundary layer flow cannot be taken for granted. The serious difficulties encountered in attempts to simulate wind-induced pressures in small-scale (e.g., 1:100) wind tunnel fluctuating flows had been noted, among others, by Surry, Ho and Kopp (2003), who stated: “Recent experiences with measuring pressures on low buildings…illustrate how difficult it is to obtain … results that are repeatable within the same test facility, let alone in different test facilities.”

Errors in the simulation of the atmospheric boundary layer flow are due to four factors. First, flow simulations in the wind tunnel are affected by the violation of the Reynolds number. In particular, high frequency fluctuations in atmospheric flows, which can affect significantly bluff body aerodynamics and dynamics (see Simiu and Miyata, 2006, Sect. 2.5.6.2), have wind tunnel counterparts that tend to be suppressed by internal friction. This can cause distortions in the simulation of negative pressures in separation zones. Second, atmospheric boundary layer flows are developed by friction at the Earth’s surface over long distances, whereas in the wind tunnel they are developed in large part by means of such devices as spires, in addition to boundary layer development distances of sometimes modest dimensions [for examples of wind tunnels with relatively large and small development lengths, see Simiu and Scanlan (1996, pp. 283-294), and Simiu and Miyata (2006, p. 171)]. Such flow generation methods may not be able to reproduce faithfully features of actual atmospheric flows, and in particular integral turbulence scales, which in the wind tunnel tend to be smaller in relation to characteristic building dimensions than is the case for the prototype, resulting in unconservative estimates of wind effects[3]. Third, veering of the flow, which can be aerodynamically significant for tall buildings, is due in atmospheric flows to the effect of the Coriolis acceleration, which is not reproduced in the wind tunnel. Fourth, target flows correspond at best to average conditions. In reality every storm event differs from conventional storm models. This results in additional uncertainties in the aerodynamic effects. Research has yet to be performed into the corresponding errors in the estimation of wind effects.

2.2 Aerodynamics

Aerodynamic pressure and force coefficients specified in ASCE 7 conventional methods are affected principally by four types of error: (1) errors due to summarizing large numbers of measured aerodynamic data into reductive tables and plots; (2) errors due to inadequate simulations of the wind tunnel flows in which those data were measured; (3) errors inherent in the fact that wind speeds considered in the calculation of pressures do not take into account dependence upon direction; and (4) measurement errors.

Summary Aerodynamic Data. Aerodynamic pressure and force coefficients specified in ASCE 7 are drastically simplified summaries of data obtained in wind tunnel tests. For this reason they entail significant errors in the representation of actual aerodynamic effects, resulting in possibly significant overestimation of wind effects for some portions of the structure, and/or underestimation for other portions.

Aerodynamic Effects of Imperfect Atmospheric Boundary Layer Simulations. The deviations from actual wind effects inherent in the imperfect simulation of the atmospheric boundary layer flow (see end of Sect. 2.1) are added in ASCE 7 to those due to the summarized aerodynamic data discussed in the preceding paragraph. These deviations notwithstanding, ASCE 7 provisions are consistent with: (a) the assumed variation of wind speeds with height above ground; (b) the fact that flow turbulence affects the pressure distribution around the body (see, e.g., Simiu and Scanlan, 1996, pp. 166-168, and Simiu and Miyata, 2006, Sect. 2.5.6.2); and (c) an imperfect spatial coherence of the velocity fluctuations. Note that the decrease of the equivalent pressures specified in ASCE 7 as the area over which they act increases is explained only in part, if at all, by that imperfect coherence; most of this decrease is due to effects of flow features induced by the aerodynamic interaction between the body and the oncoming flow, that is, to effects of body-induced flow fluctuations sometimes called “signature turbulence.”

Aerodynamics and Wind Directionality. Aerodynamic pressures specified in ASCE 7 do not account for wind directionality in a physically explicit manner, owing in part to the specification of largest wind speeds without regard for their direction. This limitation is discussed in Sect. 2.3.

Pressure measurement issues are discussed in Sect. 3.2.3.

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[3] Smaller integral scales imply weaker spatial pressure correlations, meaning that pressures acting at points separated by a given distance tend to act less in an additive manner and more at cross-purposes than when the scales are large.

2.3 Wind Climatology

In this section we explain by means of an example the difference between (a) specifying wind speeds by accounting explicitly for wind directionality and (b) considering wind speeds without regard for their direction, as is the case for ASCE 7's conventional methods. Wind climatology entails *statistical estimation* issues pertaining to extreme wind speeds governing design for strength and serviceability (Sect. 2.4). *Structural reliability* considerations are involved in the specification of mean recurrence intervals (MRIs) of design wind speeds or wind-induced effects (Sect. 2.5).

Wind Directionality. Wind speeds specified in ASCE 7 were estimated by applying probabilistic extreme value estimation methods to sets of wind speeds regardless of their direction. To clarify the role of wind directionality we consider, as a simple example, directional wind speeds in three successive wind storms for which we assume, for simplicity, that winds blow from just two directions.

Let the wind speed time series v_{ij} (in m/s) consist of three storm events (i=1, 2, 3) with two wind directions (j=1, 2):

Event 1: 54 (dir. 1), 47 (dir. 2),

Event 2: 41 (dir. 1), 46 (dir. 2),

Event 3: 47 (dir. 1), 39 (dir. 2).

This set of data describes the wind speeds themselves as well as their dependence on direction. The description of the wind speeds in the three storm events that considers only the maximum wind speed in each event is the following:

Event 1: 54

Event 2: 46

Event 3: 47.

Clearly, this description is one that contains less information. This loss of information comes at a price. To see why, consider the case where the aerodynamic coefficients $C_{p,j}$ for the two directions are

0.8 (dir. 1), 1.0 (dir. 2)

The corresponding nominal wind effects are assumed to be, to within a constant dimensional factor, equal to the quantities $C_{p,j}v_{ij}^2$. For the three events, the quantities $C_{p,j}v_{ij}^2$ are equal to the squares of the quantities $[C_{p,j}v_{ij}^2]^{1/2}$. The latter are

Event 1: 48 (dir. 1), 47 (dir. 2),

Event 2: 37 (dir. 1), 46 (dir. 2),

Event 3: 42 (dir. 1), 39 (dir. 2),

(e.g., for event 1, dir. 1, $[0.8 \text{ x } 54^2]^{1/2}$=48).

Since for each storm event it is the *largest* nominal wind effect that matters, for design purposes we extract from those quantities the following time series (in m/s):

Event 1: 48

Event 2: 46

Event 3: 42

Assuming further that the rate of occurrence of the storm events is 1/yr, it follows from the above calculations that the largest and second largest of these quantities are, respectively, 48 and 46 m/s. The wind effects are proportional to the squares of these quantities, that is, with 2304 and 2116 $(m/s)^2$. respectively.

If the calculations were performed without accounting for the directionality of the wind speeds and the largest pressure coefficient (in this example C_p=1) were used for all directions, then the largest and the second largest of the quantities $[\max_j(C_{p,j})\max_j(v_{ij})^2]$ are 54^2=2916 and 47^2=2209 $(m/s)^2$.

On the basis of incomplete studies a 0.85 directionality reduction factor is used in ASCE 7 to account summarily for directionality effects on rigid buildings. However, estimates of extreme wind effects that use this blanket factor, rather than accounting explicitly for wind directionality, can be in error either on the conservative or unconservative side. Multiplication of the 2916 $(m/s)^2$ and 2209 $(m/s)^2$ wind effects by this factor would yield largest and second largest wind effects of 2480 and 1878 $(m/s)^2$, rather than 2304 and 2116 $(m/s)^2$, as obtained by using a physically realistic model.

Note that the largest of the wind effects estimated by disregarding wind directionality and using the blanket directionality reduction factor (2480 $(m/s)^2$) is greater than the largest physics-based estimate of the wind effect (2304 $(m/s)^2$). However, if the second largest wind effect were of interest, the difference between the result based on the use of the directionality factor (1878 $(m/s)^2$) and the physics-based result (2116 $(m/s)^2$) would be -11 % (i.e., in this case, the directionality factor approach would yield an unconservative estimate). It also follows from the numerical illustration presented in this section that the MRI of the wind speeds, regardless of their direction, is not equal to the MRI of the wind effects induced by the directional wind speeds. For example, in our illustration it would be assumed that the ranking of the wind effect induced by the 47 m/s non-directional speed associated with storm event 3 is *two*. In fact, if directional effects are taken into account, the ranking of the wind effect induced by storm 3 is *three*.

The approach just described is applicable to any wind effects, including pressures, dynamic response, and sums of demand-to-capacity ratios used in axial force-bending moments interaction equations. The approach amounts to converting a multi-dimensional time series consisting of the effects of *m* storms in *p* directions into a one-dimensional time series consisting of the largest effects induced by the *m* storms, regardless of their direction. To use terminology introduced by structural reliability research, we do not operate the space of wind speed variables, but rather in the space of wind effect variables.

2.4 Statistics

Statistics plays an important part in the specification of wind effects, and is used for: (1) the estimation of extreme wind *speeds* with specified MRIs; (2) the estimation of extreme wind *effects* with specified MRIs; (3) the estimation of peaks of time series of wind effects; and (4) assessing uncertainties in the estimation of wind speeds and effects.

Estimation of Extreme Wind Speeds. Wind speeds are random variables, and their estimation requires the application of methods for the estimation of extreme values. An important ingredient in these methods is the selection of the data set. The methods and data sets used in the development of the ASCE 7 wind map depended on whether or not the area being considered experiences hurricane winds. In both cases extreme wind speeds were estimated without regard for directionality. The specification of the MRIs of the wind speeds used in design is based on reliability considerations discussed in Sect. 2.5.

For *hurricane-prone regions* the wind speed data sets were obtained from Monte Carlo simulations applied to physical and probabilistic models of tropical cyclones and hurricanes (e.g., Batts et al., 1979, see www.nist.gov for publicly available directional wind speed data sets for the Gulf and Atlantic coasts); Vickery and Twisdale, 1995; Simiu and Scanlan, 1996; Heckert et al., 1998; Vickery et al., 2009). The estimation of wind speeds with various MRIs was performed non-parametrically, using order statistics and estimated storm arrival rates (for details see, e.g., Simiu and Miyata, 2006, pp. 33-35).

For *non-hurricane regions* a Type I Extreme Value distribution was applied to recorded wind speed data, without distinguishing between types of storm (e.g., whether the winds were associated with thunderstorms or large-scale extratropical storms). The data sets used in the ASCE 7 statistical wind speed estimates at any given location were taken from several individual meteorological stations and consolidated into a “superstation,” without regard for fundamental climatological and/or micrometeorological differences among the stations. For example, data observed in Massachusetts were consolidated into the same “superstation” with data observed in Central Park, New York, NY (Simiu et al., 2001). In addition, data from the same station were used in more than one “superstation.” For these reasons the ASCE 7 wind map presents an unrealistically uniform picture of the wind speeds over large areas of the U.S. Implicit in this picture are significant underestimations or overestimations of extreme wind speeds at numerous sites (Simiu et al., 2001; Simiu et al., 2003).

Estimation of Extreme Wind Effects. Because the ASCE 7 conventional methods do not account explicitly for wind directionality, the nominal MRIs of the wind effects of interest are by definition the same as the nominal MRIs of the wind speeds that induce them. For example, a bending moment induced in accordance with ASCE 7 by a wind speed with a nominal 720-yr MRI is defined as having a nominal 720-yr MRI. In fact, this definition is, in general, incorrect from a physical point of view, meaning that the MRI of a wind effect induced by directional wind speeds corresponding to a 720-yr MRI of the associated non-directional wind speed is in general different from 720 years.

Estimation of Peak Wind Effects. Wind effects are time-varying random processes, that is, they take on random values during, e.g., the duration of a storm. For design purposes it is necessary to estimate their *peaks*, which are themselves random variables and are therefore characterized by probability distributions. The distributions of the peak of any given record can be estimated by using methods derived from the theory of random stationary processes, see Sadek and Simiu (2002) and www.nist.gov/wind, item III B. The ASCE 7 uses a peak factor typically incorporated in the specified aerodynamic pressure or force coefficients, or multiplying the root mean square value of the random process of interest. Except for pressures at some "hot spots," the peak factor specified or implicit in ASCE 7 typically has the same value as the gust response factor specified in ASCE 7 for the quasi-static along-wind response induced on a building by wind normal to a building face. This approach is computationally convenient but when applied by ASCE 7 to, e.g., effects on roofs, side walls, or leeward walls, it bears little or no relation to the respective actual peak wind effects.

Estimation of Uncertainties. Uncertainties in the estimation of wind effects are calculated by accounting for uncertainties in the atmospheric boundary layer flow characterization, the wind tunnel flow simulation, aerodynamic pressure coefficient or force coefficient estimates, extreme wind speed estimates, and peak wind effects estimates. ASCE 7 includes no explicit estimates of such uncertainties. However, these uncertainties are implicitly accounted for via wind load factors specified in ASCE 7, Chapter 2. A discussion of those wind load factors is presented in Sect. 2.5.

2.5 Structural Reliability

Structures are designed for wind effects that are sufficiently large to ensure that, under reasonable assumptions regarding structural capacity, their probability of performing inadequately under wind and other loads is acceptably small. Design criteria aimed at assuring adequate structural reliability are specified in Chapter 2 of ASCE 7 in terms of wind loads that induce effects associated with either allowable stress design (ASD) or Strength Design (SD). For flexible buildings additional criteria pertain to inter-story drift and top floor accelerations (see, e.g., Simiu and Miyata, 2006).

The purpose of the design criteria specified in ASCE 7, Chapter 2 is to assure that demand-to-capacity indexes (i.e., sums of demand-to-capacity ratios used in interaction equations) are adequate, see Simiu and Miyata (2006, p. 160-164). However, meeting the requirements implicit in those design criteria is a mere indication, not a guarantee, that a structure's behavior under very strong winds will be adequate. In some engineers' opinion the experience of the last decades, during which no spectacular wind-induced structural collapses of engineering structures were recorded, and engineering judgment based on that experience, support the belief that current design criteria are safe. However, it should be kept in mind that before the devastation wrought by Hurricane Katrina it was assumed by some engineers that the design criteria used for the New Orleans levees were also supported by experience. Given the approximations, simplifications, and uncertainties inherent in current design criteria for wind, the most careful modeling possible of the relevant phenomena is warranted. Nonlinear analyses accounting for post-elastic strength reserves under wind loads would be useful in this regard, but in the present state of the art they can seldom be performed in practice, especially for structures with significant dynamic or potential aeroelastic effects. From this point of view structural design is far less advanced for wind than for earthquakes. Nevertheless, exploratory work was performed in recent years based on finite element estimates of nonlinear structural behavior of rigid structures under wind loads estimated from data measured simultaneously at large numbers of taps (Jang et al., 2002; Duthinh et al. 2008). That work is a first step toward a structural reliability approach that accounts for the behavior of the entire structure up to incipient collapse, rather than just for the behavior of individual members, as in ASCE 7 (see Sect. 3.5).

ASCE 7 is based on the assumption that a wind load factor of 1.6 assures an adequate nominal reliability with respect to wind loads for both hurricane and non-hurricane regions. The ASCE 7 Commentary defines the wind load factor as the square of the ratio between the wind speed with an approximately 720-yr MRI and the basic wind speed specified in the ASCE 7 wind map. In fact, the wind load factor was originally defined as a function of uncertainties in the estimation of wind effects; in accordance with this definition, the 1.6 value is typically appropriate for *rigid* buildings in *non-hurricane regions* (Ellingwood et al., 1980). Uncertainties inherent in wind effects on buildings with significant dynamic effects can be larger than for rigid buildings, owing to (a) the presence of uncertainties in the damping and natural frequencies, which are not relevant for rigid structures, and (b) the stronger effect of uncertainties in the wind speeds, since wind effects on flexible buildings are proportional to wind speeds raised to powers larger than two, rather than just two, as in the case of rigid buildings. For this reason wind load factors applied to flexible buildings should typically be *larger* than 1.6 (i.e., larger than the square of the typical ratio between the nominal 720-yr winds and the basic wind speeds), see Gabbai et al. (2008) and Simiu et al. (2008); the indiscriminate use of the 1.6 wind load factor can therefore lead to situations where the nominal safety level inherent in the LRFD approach would be *lower* for, say, a 500 m tall building than for a one-story building.

For non-hurricane regions the basic wind speed specified in ASCE 7 is an estimate of the 50-yr speed (Peterka and Shahid, 1998). For hurricane-prone regions the basic wind speed specified in ASCE 7 has a longer but unspecified MRI; its value was determined as the ratio between the estimated wind speed with an approximately 720-yr MRI and the square root of 1.6. The adoption of a basic speed with an MRI larger than 50 years allows the use of the same load factor for both non-hurricane and hurricane regions, even though the probability distributions of extreme wind speeds have longer tails for hurricane-prone than for non-hurricane regions and are therefore characterized by larger ratios of 720-yr to 50-yr wind speeds.

2.6 Wind Effects Estimation

Wind effects are estimated through the integration in ASCE 7 of the elements discussed in Sects. 2.1-2.5. As noted earlier, the output of the estimation consists of: for ASD, the wind effects corresponding nominally (though not physically) to the MRIs of the basic wind speeds used in the calculations; for SD, the wind effects corresponding nominally to a 720-yr MRI. The aerodynamic data in ASCE 7 are adversely affected by the specification of drastically reductive aerodynamic data sets, as well as by the quality of atmospheric boundary layer simulations achieved in insufficiently documented or undocumented wind tunnel tests. Directionality effects are accounted for, nominally rather than on physical grounds, by using a blanket wind directionality reduction factor. The ASCE 7 analytical method contains a procedure for estimating the along-wind dynamic response of tall buildings, which depends on the wind loads and on the mechanical properties of the structure (fundamental modal shape and frequency, and damping ratio in the fundamental mode). The ASCE 7 conventional methods specifically exclude aeroelastically active structures or wind effects due to vortex shedding.

CHAPTER 3

ELEMENTS OF THE WIND EFFECTS ESTIMATION PROCESS: WIND TUNNEL METHOD

A standard on the wind tunnel method must enable structural engineers to develop transparent, clearly documented estimates of the response to wind, including statements of uncertainty. Standard provisions must result in estimates of the response that are approximately the same regardless of who performs them. This requires that the standard cover adequately each of the inter-related elements involved in the estimation process.

Those elements, which pertain to disciplines with which designers typically have limited familiarity, were introduced in Chapter 2 with reference to their use in ASCE 7, a document well known to the structural engineering profession. Simplifications and limitations of ASCE 7 models associated with those elements were also noted in Chapter 2.

In this chapter we revisit the elements of the wind effects estimation process from the points of view of (i) their relevance to estimates performed within the framework of the wind tunnel method, and (ii) the extent to which their use in the wind tunnel method allows the elimination of simplifications and inadequacies discussed in Chapter 2. Using an organization of the material paralleling that of Chapter 2, we examine elements of the wind effects estimation process related to: micrometeorology (Sect. 3.1), aerodynamics (Sect. 3.2), wind climatology (Sect. 3.3), statistics (Sect. 3.4), and structural reliability (Sect. 3.5). Section 3.6 briefly describes the estimation of wind effects on rigid and flexible structures. For structures prone to aeroelastic response we refer the reader to Zhou and Kareem (2003). Section 3.7 provides a summary of salient points discussed in Chapter 3.

3.1 Micrometeorology

Estimates of aerodynamic pressures and forces depend upon the features of the atmospheric flow being adequately simulated in the wind tunnel. Models for at least some features of the flows being simulated are expected to be more elaborate than those used in ASCE7's conventional methods. Those features are listed below.

1. The *mean wind profile*. Alternative descriptions of the mean wind profile in horizontally homogeneous terrain are the power law, characterized by its exponent (Hellman, 1916; Davenport, 1966), and the logarithmic law, characterized by the surface roughness length. For strong winds the applicability of the logarithmic law up to elevations of about 400 m has been established theoretically by Csanady (1967) (for additional references and details see also Simiu, 1973; Simiu and Scanlan, 1996) and by measurements in the atmosphere by Powell et al. (2003). These results supersede the earlier belief (Davenport, 1966) that the logarithmic law is valid for

any wind speed up to about 50 m elevation.

Reference is made in the literature to a similarity criterion requiring that the ratio between a characteristic dimension of the structure and the roughness length be the same in the wind tunnel and in the laboratory. In practice such a similarity criterion is not applicable because the roughness length is not a directly measurable quantity either in the field or in the wind tunnel. Rather, using various empirical simulation devices, a mean wind profile is created in the laboratory which is intended to be reasonably similar throughout its height to the target full-scale profile. *Veering* of the mean wind speed increases with height above the surface (Simiu and Miyata, 2006, p. 15).

2. The *turbulence intensity*. The turbulence intensity at elevation z corresponding to the longitudinal flow fluctuations (i.e., the fluctuations in the mean speed direction) is defined as the ratio at elevation z between the fluctuations' r.m.s. and the mean wind speed:

$$I(z) = \frac{\sqrt{\overline{u^2(z)}}}{U(z)}$$

Similar definitions hold for flow fluctuations in the lateral and vertical directions.

3. The *integral turbulence length* of the longitudinal flow velocity fluctuations at a point are measures of the average spatial dimensions of those fluctuations. Similar definitions hold for the lateral and vertical flow fluctuations (see, e.g., Simiu and Scanlan (1996) for details.) The larger the turbulence scale, the larger is the building dimension affected by the corresponding turbulent fluctuations. For example, a sufficiently large longitudinal integral turbulence scale of the longitudinal turbulent fluctuations means that, if the flow is normal to the windward face of a structure, those fluctuations can affect both its windward and the leeward face. A large lateral scale of the longitudinal turbulent fluctuations means that those fluctuations impinge almost simultaneously over a relatively large area normal to the mean wind speed, resulting in correspondingly large longitudinal fluctuating wind loads.

4. The *relation between wind speeds averaged over different time intervals* (e.g., the ratio between wind speeds averaged over 3 s and wind speeds averaged over 10 min)

5. The *spectral density* (or spectrum) of the longitudinal velocity fluctuations is a plot representing the contributions of components with various frequencies to the variance of the fluctuations. Similar definitions hold for lateral and vertical fluctuations. Note that the turbulence intensity and the integral turbulence length depend upon the spectral density (Simiu and Scanlan, 1996). In practice the spectra of the turbulent fluctuations cannot be reproduced in civil engineering wind tunnels owing partly to the violation of the Reynolds number by factors of the order of 10^3, which inhibits the simulation of high-frequency velocity fluctuations, and partly to the difficulty of achieving large integral turbulence scales in the laboratory.

6. The *cross-spectral density* of longitudinal velocity fluctuations at two points is an approximate measure of the degree of coherence between the respective fluctuations. Similar definitions apply

to lateral and vertical fluctuations. *For small structures,* (e.g., typical homes) for which the turbulence length scales of interest are sufficiently large in relation to the structure's dimensions, the bulk of the fluctuating longitudinal wind speed components may be assumed to be almost perfectly coherent over lengths comparable to the dimensions of the structures' exterior faces.

The properties just listed depend to a significant extent upon whether the storm to which the structure is subjected is of the large-scale extratropical (synoptic) type, or a hurricane, a thunderstorm, a chinook wind, and so forth. In current commercial practice the type of flow being simulated is the atmospheric boundary layer typical of synoptic storms (straight line winds), and it is assumed that simulations in this type of flow are adequate even if the structure is subjected to other types of storm.

In wind engineering practice it is important to remember that the parameters of any given model of the wind flow are characterized by uncertainties in the sense that they can vary from storm to storm. Such variability should be accounted for in any uncertainty analysis of the wind effect estimates.

3.2 Aerodynamics

As was first shown by Flachsbart (1932)[4] (see also Simiu and Scanlan, 1996, p. 173), aerodynamic pressures and forces on a model differ in uniform, smooth flow from their counterparts in shear, turbulent flows. With some exceptions that will be discussed later in this section, since the 1960s measurements of aerodynamic effects on models of structures have no longer been made in uniform flow, but rather in flows with features replicating more or less correctly their counterparts in atmospheric boundary layer flows. In this section we discuss the effects of the wind tunnel flow features on the aerodynamic effects of interest, and the measurement, specification, and practical use of aerodynamic pressures/forces. We also discuss the possibility of a novel laboratory wind flow simulation method that is simple, lends itself to effective standardization, can therefore produce aerodynamic information reproducible with no significant variability by various laboratories and, when used in large facilities, can result in flows that do not violate significantly Reynolds number similarity[5].

3.2.1 Atmospheric boundary layer flow features and aerodynamic pressure/force simulations.

To simulate atmospheric flows various laboratories resort to various experimental set-ups. These can result in fairly widely varying properties of the respective flows.

1. *Mean wind velocity profile.* Laboratories that participated in an international comparison of wind tunnel estimates of wind effects on low-rise buildings (Fritz et al., 2008)

[4] Flachsbart's work, performed under Prandtl's guidance, was unknown to wind engineers. Following his refusal to divorce his Jewish wife, as demanded by the Nazi authorities, he was prohibited from publishing (O. Mahrenholz, private communication, 1998). His pre-1935 work was rediscovered more than fifty years later in an internal Goettingen Aerodynamics Establishment report available in the National Institute of Standards and Technology library (Simiu and Scanlan, 1986 and 1996).

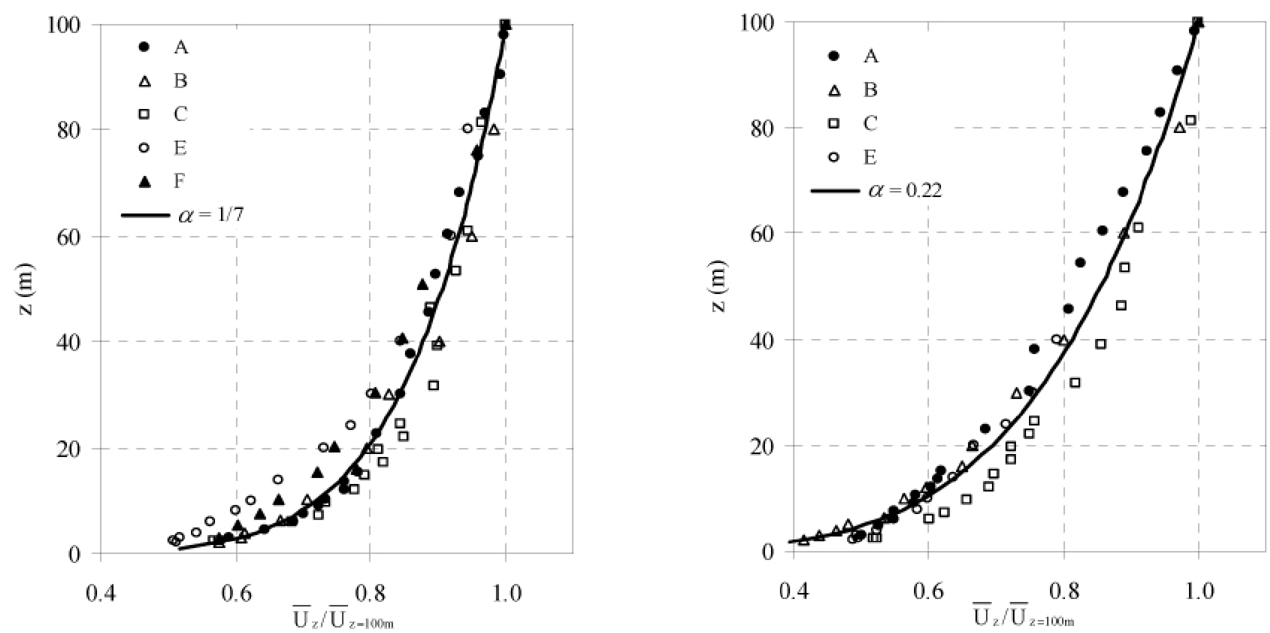
[5] Such facilities are commonly referred to as "Walls of Wind," see Huang et al., 2009.

achieved mean wind profiles with power law exponents that varied between 0.139 and 0.191 (typical target value 1/7=0.143) and between 0.165 and 0.234 (target value 0.22) for open and suburban exposure, respectively (Bienkiewicz et al., 2009), see Fig. 3.1. These differences contributed to the discrepancies among the respective test results.

It was noted earlier that veering is a factor that must be taken into account in design. A standard needs to provide guidance on how veering is accounted for.

2. *Turbulence intensity.* Longitudinal turbulence intensities achieved in flows simulated by six laboratories (Fritz et al., 2008) exhibited strong variations, especially for suburban exposure (Fig. 3.2).

3. *Integral turbulence scales.* As was noted in Sect. 3.1, the aerodynamic significance of the integral turbulence scales is that they provide a measure of the extent to which turbulence envelops or acts in phase on a structure or part thereof.



(a) Open exposure

(b) Suburban exposure

Figure 3.1. Wind speed profiles in simulations by wind tunnels participating in the Fritz et al. (2008) comparison (Bienkiewicz et al., 2009).

4. *Spectral and cross-spectral densities.* The spectral density of the longitudinal velocity fluctuations provides a measure of the strength of the fluctuations' frequency components. Flexible structures experience a resonant response induced by the turbulence in the oncoming flow roughly proportional to the square root of the spectral ordinate at the structure's fundamental frequency of vibration. The fluctuating velocities

5. impinge on the structure and thus increase the pressures induced by the mean speed. This effect is due almost entirely to the *low-frequency turbulent fluctuations*, which are the only significant contributors to the turbulence intensity, the integral turbulence scale, and the flow gustiness.

Nevertheless, the *high-frequency turbulent fluctuations* have an important aerodynamic effect insofar as they transport across separation layers particles with high momentum from zones outside the separation bubbles, thereby promoting flow reattachment and affecting suctions in separation zones (Simiu and Miyata, 2006, p. 41). In commercial wind tunnels, the Reynolds number (a measure of the ratio between inertial and viscous forces within the flow) are orders of magnitude smaller than at full scale, meaning that the viscous stresses within the small (high-frequency) eddies of the laboratory flow are higher. The wind-tunnel counterparts of full-scale high-frequency fluctuations are therefore partly suppressed by those stresses. This can affect significantly the extent to which laboratory and full-scale suctions are similar, especially in flow separation regions where the suctions are strong. Indeed, measurements have shown that, in zones of strong suctions, absolute values of pressure coefficients are far lower in the wind tunnel than at full scale (Fig. 3.3).

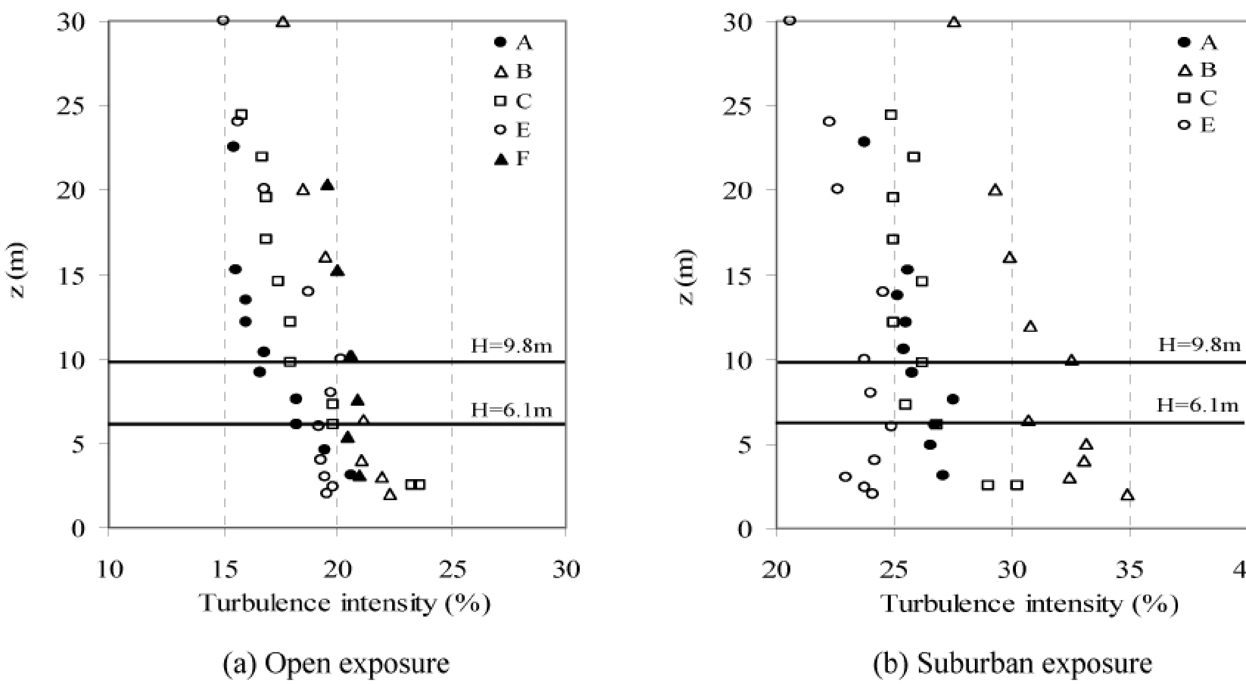


Figure 3.2. Turbulence intensities in simulations by wind tunnels participating in the Fritz et al. (2008) comparison (Bienkiewicz et al., 2009).

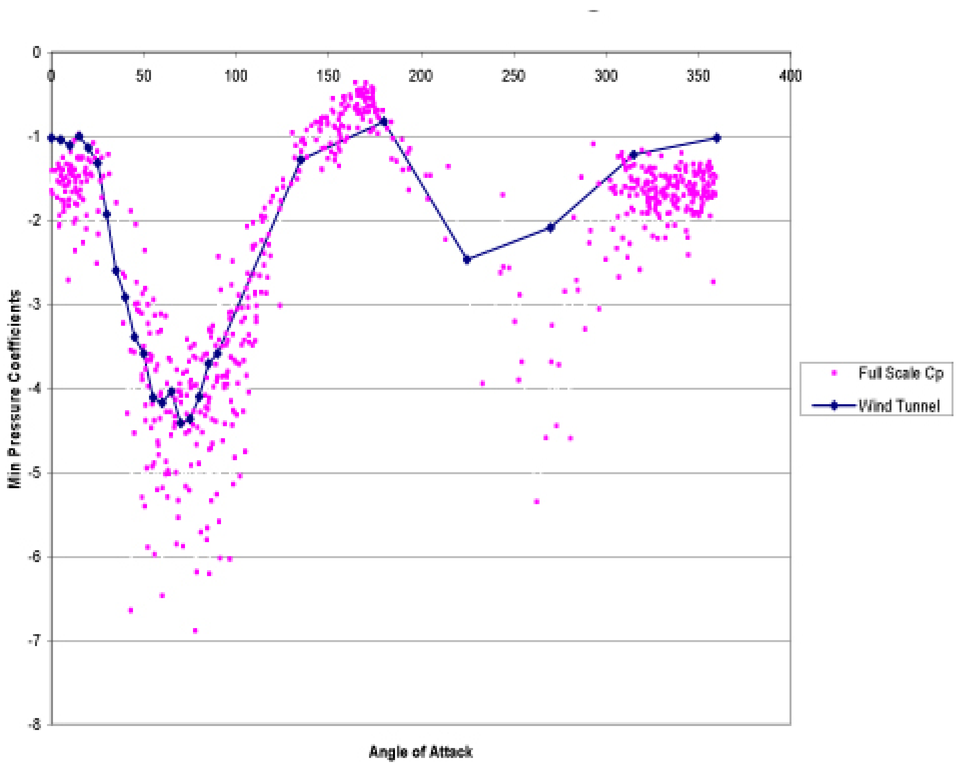


Fig. 3.3. Pressure coefficients measured at building corner, eave level, Texas Tech University experimental building (Long et al., 2006).

The increase of the wind-induced pressures due to the superposition of low-frequency wind speed fluctuations onto the mean wind speed depends on the ratio between the integral turbulence scales and the dimensions of the structure. For large structures (e.g., tall buildings) the imperfect spatial coherence of the turbulent fluctuations diminishes the magnitude of the fluctuating wind effects with respect to what it would be if the spatial coherence was perfect. However, for small structures it may be assumed approximately that the low-frequency fluctuations are perfectly coherent over areas comparable to the areas of the facades.

3.2.2 Simulation of wind effects on low-rise buildings with small dimensions

The latter observation has important implications from the point of view of *aerodynamic testing of low-rise buildings*. If the low-frequency fluctuations can be assumed to be approximately coherent over dimensions comparable to the building dimensions, the aerodynamic behavior they induce is in practice indistinguishable from the aerodynamic behavior induced by the mean velocity. Flow velocities may be viewed as sums of (i) mean velocities, (ii) large velocity fluctuations associated with significant low-frequency fluctuations, and (iii) small velocity fluctuations associated with high-frequency velocity fluctuations. In estimating aerodynamic effects on small buildings, the low-frequency velocity fluctuations can, without significant loss of accuracy, be replaced in the laboratory by a velocity constant in time added onto the mean wind velocity, that is, by a larger mean velocity -- provided that the ratio that prevails in atmospheric flows between peak wind speeds and mean wind speeds is duly accounted for. While the assumption that the low-frequency fluctuations are coherent over areas with dimensions comparable to the characteristic building dimensions is reasonable for small structures, testing is needed to establish the extent to which this simplification of the flow simulation is acceptable. In particular, such testing can be conducted in facilities in which the variation of mean speeds with height is correctly reproduced, and in which low- and high-frequency turbulence fluctuations can be generated *independently* of each other. Such a facility has recently been developed at Florida International University (FIU) (Huang et al., 2009).

One example of the practical application of the ideas just discussed is the testing of rigid trussed frameworks. In this case the effect of high-frequency turbulence components may be assumed to be insignificant, since no flow reattachment can be expected to occur on typical truss members, even in the presence of high-frequency turbulence fluctuations. Low-frequency turbulence components may be assumed approximately to be perfectly coherent over the width of vertical frameworks or the depth of horizontal frameworks. The tacit acceptance of these assumptions explains why, even after the advent of boundary layer-wind tunnels, aerodynamic testing of trussed frameworks has been performed in smooth flow (Whitbread, 1979), i.e., flow with constant velocity and no significant turbulence fluctuations.

For bluff bodies with small dimensions (e.g., residential homes, or tributary areas of a individual portal frames in industrial buildings) this extreme simplification of the testing is not appropriate because high-frequency flow fluctuations can strongly influence test results. However, as suggested earlier, aerodynamic testing can be conducted in facilities that produce flows with specified mean velocity profiles *and* high-frequency fluctuations, while low-frequency fluctuations are weak or absent. This implies the possibility that, for small bodies, it is appropriate to perform aerodynamic testing in which the simulation of atmospheric boundary layer turbulence intensities, integral turbulence scales, and spectral density functions is unnecessary. Given the practical difficulties encountered in performing simulations of atmospheric boundary layer flows, such testing would lend itself to effective standardization and eliminate a major source of discrepancies among tests conducted in various laboratories. Comparisons between test results obtained in the presence and in the absence of low-frequency fluctuations similar to those occurring in natural flows are currently being conducted at Florida International University's Wall of Wind (WoW) facility. The results of the comparisons will determine the extent to which such facilities are effective in producing controlled, repeatable tests of low-rise buildings that are realistic and can be standardized effectively.

To assure the repeatable laboratory simulation of flows intended to simulate atmospheric boundary flows, including low-frequency turbulence fluctuations, it is necessary to develop (i) performance criteria assuring that spires, fences, roughness elements, and wind-tunnel boundary-layer development lengths are adequate, and (ii) transparent methods for enforcing those criteria via measurements. In addition, standardized protocols need to be developed for correcting wind tunnel results where well-documented benchmark full-scale measurements show that those results are inadequate owing to Reynolds number similarity violation.

3.2.3 Measurement of Aerodynamic Pressures/Forces

Wind pressures are measured by using pressure sensors (taps). From the 1990s on increased use has been made of newly developed pressure sensors, which provide simultaneous records of pressures at as many as 1,000 taps. To illustrate the use of such records: the force at any time *t* on a panel with, say, four synchronous pressure taps is approximately equal to the sum of the pressures at the four taps at time *t* times the respective tap tributary areas; the bending moment at time *t* in the bend of a portal frame is approximately equal to the pressures at tile *t* at the taps located in areas tributary to the frame, times the respective tap tributary areas, times the respective influence coefficients representing the moment induced in the bend by a unit force at each tap location.

Topics that need to be covered in a standard on the wind tunnel method include tubing diameter and length, transducer type, tubing frequency response, reference static pressure instrument and location, dynamic pressure instrument and location, sampling frequency, sampling duration, filtering, number of channels, simultaneous sampling, and blockage.[6]

Aerodynamic forces and moments are measured principally by devices that measure strains. For tall buildings, base shear and bending moments can be obtained by using a high frequency force balance (HFFB). Estimates of internal forces based on HFFB measurements depend upon modal shapes and wind force distribution along the building height. If the distribution is not known -- as is the case when aerodynamic interference due to neighboring buildings is present – those estimates can entail large errors. Topics that need to be covered in a standard include details on HFFB construction and use, and errors entailed in the use of HFFB devices.

3.2.4 Specification and Use of Aerodynamic Pressures

Aerodynamic pressures can be specified via:

(1) Generic databases of aerodynamic pressures for various types of building with various dimensions, roof types and slopes, and terrain exposure

(2) Ad-hoc databases of aerodynamic pressures for specific buildings and terrain exposures.

The use of generic databases is permitted by ASCE 7, as is the use of ad-hoc databases, provided that for both cases the flow features conform to ASCE 7 requirements. Aerodynamic pressure coefficients available in generic databases obtained in wind tunnels with state-of-the-art flow simulations are needed for the development of realistic pressure tables to supersede the inadequate tables included in ASCE 7.

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[6] Thanks are due to Professor Chris Letchford, who developed within the framework of the NIST-TTU Cooperative Agreement *Windstorm Mitigation Initiative* a list from which these items are taken.

3.3 Wind Climatology

The wind tunnel method typically uses directional wind speed data whenever such data are available (see Sect. 2.3). In some cases, directional wind speed observations are available for each of a number of equally spaced directions, but for some of the directions the number of observations is too small to allow meaningful estimates of the respective extremes. In those cases a conservative assumption is required to construct appropriate sets of data for the directions with insufficient observations by using data available for other directions. For an example of such as assumption, see Grigoriu (2009).

If wind speeds regardless of their direction are used in design, it is assumed in ASCE 7 that the nominal MRI of the response induced by a wind speed with an *N*-yr MRI is also *N* years. As was indicated in Chapter 2, this assumption is physically incorrect. This point will be further discussed in Sects. 3.4 and 3.5.

3.4 Statistics

Statistics concerns the estimation of:

(1) Peak effects of a one-dimensional stochastic process *induced by a given wind speed*. Such peak effects may pertain to accelerations at the top of the structure, inter-story drifts, internal forces, and sums of demand-to-capacity ratios used in interaction equations (e.g., the sum of (a) the ratio of the axial force divided by axial force capacity and (b) the ratio of the bending moment divided by the moment capacity). The estimation can take advantage of the fact that most wind effects of interest are sums of many comparable randomly distributed contributions, rendering those effects Gaussian. For this case simple, well-known techniques are available for estimating the mean values of the peaks. If the wind effects of interest are not Gaussian (this may be the case, e.g., for wind effects in low-rise buildings), techniques for estimating statistics of their peaks are also available, see, e.g., Sadek and Simiu (2002) or www.nist.gov/wind, item III.

    Two cases are of interest. The first case involves stochastic processes specified by their time histories (i.e., in the *time domain*). For example, such a stochastic process may consist of the internal force induced in a member by the sway response in direction *x and* the sway response in direction *y.* The peak internal force of interest is then simply the peak of the sum of the internal forces associated with the two sway responses. A similar simple summation yields the requisite peaks of processes consisting of sums of any number of stochastic processes.

The second case involves stochastic processes specified by their spectral densities (i.e., in the *frequency domain*). Such specification was -- and still is -- routinely used in wind engineering dynamic analyses on account of the difficulty, up to the 1980s, of dealing computationally with the solution of dynamic problems in the time domain. Obtaining the peak of a sum of several stochastic processes is no longer possible by summing up those processes, because in the frequency domain the phase information inherent in the respective time histories is lost. Therefore the estimation of peaks requires the use of sums of weighted component processes (e.g., axial forces and bending moments), with weights specified by engineering judgment. As many as dozens of such weighted combinations are prescribed to structural designers by wind engineering laboratories, in an attempt to make sure that relevant peaks are not missed. This is time-consuming from the point of view of the designer, as well as less accurate than the much simpler, more transparent, and more effective time-domain approach. Additional drawbacks are the difficulty of accounting for wind directionality effects in a transparent and physically meaningful way (see Simiu and Miyata, 2006), and the difficulty or impossibility even seasoned professionals experience in following and understanding wind engineering reports, see Appendix I.

(2) Peak effects (e.g., accelerations, inter-story drifts, sums of demand-to-capacity ratios in interaction equations) *with specified MRIs.* As was mentioned earlier (Section 3.3), if wind directionality is not taken into account explicitly (i.e., other than through the use of a blanket reduction factor, as is done in ASCE 7), then the MRI of a peak wind effect is simply assumed to be the MRI of the wind speed inducing it. Estimation methods for extreme wind speeds with specified MRIs, regardless of their direction, are discussed, e.g., in Simiu and Miyata (2006).

If directionality is explicitly accounted for in the calculations, the peak wind effects with specified MRI are obtained as follows. Assume the directional wind speed data consist of m sets (e.g., m storm events) of n directional wind speeds each (corresponding to, e.g., n=16, or n=36 directions). For each of the m sets, calculate the peak response induced by each of the n directional wind speeds, and retain only the largest of these n responses. This yields a set of m largest peak responses. The m peak responses are then rank-ordered. If the rate of arrival of the events associated with the m sets is r/year, then the estimated MRI of the largest of the m peak responses is $(m+1)/r$ years; the p largest is $(m+1)/(pr)$ years. This estimate is non-parametric.

In hurricane-prone regions, directional wind speeds in any specified number of storms are typically obtained by Monte Carlo simulation using physical and probabilistic storm models (e.g., Batts, 1980; Vickery and Twisdale, 1995; Vickery et al., 2009). If the size of an existing database of hurricane wind speeds needs to be augmented (as may be necessary for the only public hurricane wind speeds database that covers the entire Gulf and Atlantic coasts, and contains 999 simulated storms for each station, listed on www.nist.gov/wind), this augmentation can be achieved by using software developed by Grigoriu (2009). For straight line (synoptic) and thunderstorm wind speed data, large sets of simulated data and associated errors in their estimation can also be obtained using the methods developed by Grigoriu (2009).

3.5 Structural Reliability

The purpose of structural reliability is to develop design criteria assuring that the probability of inadequate strength and serviceability performance is acceptably small.

In its simplest form allowable stress design (ASD) achieves this purpose by requiring, for each member, that the stress induced by the sum of the basic design loads not exceed the allowable stress, typically defined as the nominal yield stress divided by a safety factor. The basic design loads and the safety factor are based on experience gained in past practice. For example, the basic design wind load is typically specified as the wind load with a nominal 50-yr MRI. If for A36 steel [nominal yield stress 36 ksi (249.2 MPa)], the allowable stress for non-compact sections is 22 ksi (151.7 MPa), then the safety factor is 36/22=1.64. ASD's probabilistic content consists of the specification of the MRI of the basic design wind load and of the definition of the nominal yield stress as a specified percentage point of its probability distribution.

Strength design (SD) requires in its simplest form that, for each member, the stress induced by the sum of the basic design loads, each multiplied by a load factor that depends upon type of load, not exceed the yield stress multiplied by a resistance factor smaller than unity. Consider, for example, the case where wind is the only significant load acting on an A36 steel member with non-compact cross section. The wind load factor specified by ASCE 7 is 1.6, and if the resistance factor is 0.9, SD design requires that the basic wind load induce in the member a stress of at most 36 x 0.9/1.6 = 20.25 ksi (139.6 MPa), rather than 22 ksi (151.7 MPa) as required by ASD. In this example SD design is more conservative than ASD. This is in part due to the specification by ASCE 7 of a wind load factor equal to 1.6, even though the original intent of the standard was to specify a wind load factor equal to 1.5 (see ASCE 7 Commentary Sect. C6.5.4). Had the latter value of the wind load factor been specified, the SD would have been required that a stress of 36 x 0.9/1.5 = 21.6 ksi (148.9 MPa) not be exceeded under the basic wind load, i.e. a stress substantially equal to the 22 ksi (151.7 MPa) stress required in ASD.

To see why the difference between ASD and SD can be significant, consider the case of a member subjected to dead load and wind load. The uncertainties inherent in the wind load being larger than those inherent in the dead load, it is appropriate that the safety margin with respect to the loading (i.e., the load factor) be larger for the wind than for the dead load. This is reflected in ASCE 7, Section 2.3, which specifies for the dead load factor a value smaller than 1.5 or 1.6. In contrast, for ASD the dead loads and the wind loads are both affected by a factor equal to unity.

The probabilistic content is richer for SD than for ASD inasmuch as the various load factors account for estimated probability distributions of the total uncertainties, which include uncertainties in the wind speed and in the wind effect.

Uncertainties in the wind speed. The design value may well be smaller than the actual value affecting the structure during its life, since the wind speed is a random variable characterized by a probability distribution. In addition, that distribution may be affected by modeling errors (e.g., it could be a Type I Extreme Value distribution, a Type III Extreme Value distribution, a penultimate distribution, a mixed distribution of synoptic and thunderstorm wind speeds, and so forth). Finally, the assumed distribution and/or its estimated parameters are affected by sampling errors due the relatively small size of the observed data sample, by observation errors, and, in the case of hurricanes, by physical modeling errors of climatological parameters used in Monte Carlo simulations of the wind speeds, e.g., the radius of maximum wind speeds, the pressure defect at the center of the eye, and so forth.

Uncertainties in the wind effect. Uncertainties in aerodynamic pressure or force coefficients are due to measurement errors and/or to errors in the simulation of the flows that induce those pressures. For rigid structures the responses induced by aerodynamic pressures are proportional to the square of the wind speeds. For flexible structures the responses are proportional to the wind speeds raised to powers larger than two. The contribution to errors in the estimation of the wind response of estimation errors in the wind speeds is therefore greater for flexible than for rigid structures. Another contribution is due to the effect of errors in the estimation of natural frequencies of vibration, modal shapes, and damping ratios.

The wind load factor specified in ASCE 7 was estimated by accounting in an approximate manner for the uncertainties in the wind speeds and wind effects affecting *rigid* structures in *non-hurricane* wind climates. The resulting estimate was approximately 1.6 (or 1.5, depending upon the version of ASCE 7 being considered). To simplify codification the ASCE 7 conventional methods assume, for non-hurricane regions, that the MRI of the wind effect that induces yield stresses is the MRI of the wind speed defined by the basic wind speed times the square root of the wind load factor. Calculations based on simplifying assumptions described in the ASCE Commentary show that this MRI is nominally about 500 years for a wind load factor of 1.5 and about 720 years for a wind load factor of 1.6. SD calculations can then be based on wind effects on rigid structures induced by 500-yr (or 720-yr) wind speeds. Note that in ASCE 7 the effective value of the wind load factor for hurricane-prone regions is larger than 1.6. This is achieved by maintaining the nominal 1.6 value of the load factor, while increasing the MRI of the basic speeds (see ASCE 7 Commentary C6.5.4).

It is assumed in current wind engineering practice that this approximate approach is applicable not only to rigid structures, but to flexible structures as well. To see why this assumption can be unwarranted, we consider the following first-order second-moment calculation (Ellingwood et al., 1980) for typical rigid structures.

The approximate value of wind effect of interest may be written in the form

$$W_r = c \; C_p \; G \; E_z \, v^2$$

where c, C_p, G, E_z, and v denote a proportionality factor, pressure coefficient, peak (gust response) factor, terrain exposure factor, and wind speed, respectively, and the subscript r denotes "rigid.". The approximate value of the coefficient of variation of W_r is then

$$V_{Wr} = [V_{Cp}^2 + V_G^2 + V_{Ez}^2 + 2\, V_v^2]^{1/2}$$

where V followed by a subscript denotes coefficient of variation. For tall, flexible buildings the wind effect is proportional to the velocity raised to a power closer larger than 2; assuming for simplicity

$$W_f = c \; C_p \; G \; E_z \, v^3,$$

where the index f denotes "flexible," the approximate value of the coefficient of variation of W_f is

$V_{Wf} = [V_{Cp}^2 + V_G^2 + V_{Ez}^2 + 3\ V_v^2]^{1/2}$

Assume $V_{Cp} = 0.10$ for both rigid and tall buildings; $V_G = 0.10$ for rigid buildings and $V_G = 0.14$ for tall buildings (since the uncertainty in the dynamic parameters adds to the uncertainty in the ratio between peak and mean response); $V_{Ez} = 0.12$ for rigid buildings and $V_{Ez} = 0.10$ for tall buildings, since the uncertainties in the features of the wind flow are likely to be smaller if ad-hoc testing is performed; and $V_v = 0.18$, including aleatory variability, observation errors, and sampling errors.

Given these assumptions we have: $V_{Wr} = 0.315$; and $V_{Wf} = 0.37$. The difference between the respective estimates is about 17.4 %. Since the wind load factor is, very approximately, an increasing linear function of the coefficient of variation of the wind effect, it follows that the load factor should indeed be larger for tall buildings than for rigid buildings. Estimates based on coefficients of variation are crude, and far more accurate estimates can be obtained by numerical simulations based on a detailed model of the dynamic response that accounts for the effect of wind directionality[7] (Gabbai and Simiu, 2008; Simiu et al, 2008). Note that the value of the load factor depends upon the characteristics of the building and upon the structural member being considered. Current calculations assume that one wind load factor is appropriate for all buildings and all their structural members. A far more differentiated approach is needed, however. The development of highly efficient software now allows the use of such an approach.

As was noted earlier, the ASD and SD approaches are applied to individual members and do not consider the reliability of the building as a whole. A step forward was achieved by applying methods that allow the estimation of the MRI of incipient structural collapse, a limit state beyond which it may be assumed that the structure’s strength reserves have largely been exhausted for practical purposes. Modern finite element methods and sets of directional wind tunnel pressure data obtained simultaneously at large numbers of taps have been applied recently to obtain such estimates for rigid buildings (Jang at al., 2002; Duthinh et al., 2008).

3.6 Wind Effects Estimation

It was mentioned earlier that the state of the art in estimating seismic load effects on structures is far more advanced than its wind engineering counterpart. This is largely due to the vast amount of research performed on nonlinear response to earthquakes, and the much more modest amount of work performed on nonlinear response under wind loads.

There is another sense in which seismic engineering is more advanced than wind engineering from a structural design viewpoint. In determining seismic effects on structures a clear division of labor is in effect between seismic engineering professionals and structural engineers, except for soil-structure interaction effects. The seismic engineers provide basic information on seismic excitation, which is used by the structural engineers to estimate structural response. In contrast, wind engineering professionals develop information on wind excitation *and* provide on its basis

[7] Estimates of wind load factors based on the along-wind and across-wind response due to wind normal to a building face do not reflect correctly the margins of safety applicable to a building subjected, as it is in reality, to winds blowing from any direction. Note also that the notion of along-wind and across-wind response, assumed in the past to apply only to the case of wind normal to a building face, in fact also applies to the case of winds skewed with respect to a building face.

estimates of structural response. There are historical reasons for this state of affairs, which in our opinion is no longer justified and is undesirable.

To assure transparency and accountability in the wind effects estimation process, *wind engineering laboratories should provide*:

1. Records of the requisite wind climatological data. These consist of relevant measured and/or synthetic directional wind speeds obtained from legitimate sources, e.g., meteorological stations or reliable hurricane wind speed databases, augmented if necessary by methods such as those developed by Grigoriu (2009).
2. Information, typically based on wind tunnel tests, on the ratio between directional wind speeds at the reference site (e.g., 3 s peak gusts or 1-min speeds at 10 m above ground over terrain with open exposure) and the corresponding nominal mean hourly wind speeds and the top of the building being considered. This information is required because wind tunnel data are referenced with respect to those mean speeds. In addition, the wind tunnel laboratory needs to provide estimates of veering angles.
3. Wind tunnel measurement records of primary wind effects on structures.
    - For *rigid structures* the measurement records of interest typically consist of time histories of simultaneously measured pressures at large numbers of taps on the structure's exterior surface.
    - For *dynamically active structure*s with no significant aeroelastic effects under winds that may be expected to occur during their lifetime, the measurement records consist, for each of the wind directions for which wind speed data are considered, either of time histories of simultaneously measured pressures at large numbers of taps on the structure's exterior surface, or of time histories of strains measured on a high-frequency force balance at the base of rigid building models.
    - For *structures that exhibit aeroelastic effects* we refer the reader to Zhou and Kareem (2003) and Diana et al., 2009).

Once this information is available to the structural designer, clear, transparent procedures and the attendant software are available, whose output consists of structural design information. This information is far more comprehensive and differentiated than what wind engineering laboratories currently provide and includes, for any given set of the building's structural member sizes, demand-to-capacity ratios (which typically account for axial force and bending moment in interaction formulas), and inter-story drift, corresponding to the respective specified MRIs. The calculations involve structural analyses to obtain the requisite sets of influence coefficients. In addition, for flexible structures, analyses are needed to estimate natural frequencies of vibration and the corresponding modal shapes. For details, see Main (2006), Simiu and Miyata (2006), Simiu et al. (2008), and Spence (2008). Initial member sizes are based on preliminary calculations. Final member sizes are obtained by repeating the calculations if necessary. Research is ongoing on an iterative optimization process for obtaining member sizes consistent with strength and serviceability constraints (Spence and Gioffre, 2009).

The innovation that makes possible the clear separation between tasks incumbent on the wind engineering laboratory on the one hand and the structural designer on the other is the estimation of wind effects by using time domain instead of frequency domain methods. Frequency domain methods, in which differential equations are converted into algebraic equations at the cost of losing phase information, were introduced by Liepmann (1952) for aeronautical engineering applications and were adapted to structural engineering applications by Davenport (1961). As was noted earlier, their use was justified by the fact that, for computational reasons, modal equations of motion could not in practice be solved in the time domain. This constraint no longer exists. Nevertheless the use of frequency domain methods persists in spite of their significant drawbacks, see Sect. 3.4, item (1).

3.7 Summary

A fundamental difficulty in achieving reproducible wind tunnel measurements of wind effects, especially on low-rise buildings, is the simulation of atmospheric flows. In particular, the correct simulation of suctions in separation bubbles requires the reproduction of high-frequency atmospheric turbulence, which is prevented in large part by the action of viscous dissipation at model scales typically used in commercial wind tunnels. Low-frequency fluctuating components, which are the major contributors to the flow's turbulence intensities and integral turbulence scales, may be expected to affect aerodynamic response insignificantly provided (i) that the characteristic dimensions of the structure of interest are sufficiently small, as is the case for, e.g., residential homes, and (ii) that the mean speeds in the simulated flow are commensurate with the peak speeds in the atmospheric flow. For structures with dimensions for which testing proves that this proposition holds, valid aerodynamic simulations can be obtained in flows that simulate only mean speeds and high-frequency flow fluctuations, provided that the mean velocity profile is correctly modeled (Huang et al., 2009).

Statistics is an essential element in the definition of wind effects for design purposes. *First*, statistics concerns the estimation of: (1) peak effects of a one-dimensional stochastic process *induced by a given wind speed* (e.g., accelerations at the top of the structure, inter-story drifts, internal forces, and sums of demand-to-capacity ratios used in interaction equations). For the case of Gaussian processes simple, well-known techniques are available for estimating the mean values of the peaks. For non-Gaussian processes techniques for estimating statistics of their peaks are also available. For stochastic processes specified in the *time domain*, the peak of the sum of the stochastic processes (e.g., the peak internal force induced in a member by the sway responses in two directions) is simply the peak of the algebraic sum of the two processes. For stochastic processes specified in the *frequency domain* combinations involving the spectral densities of the additive processes require guesswork as to how the processes should be combined. As many as dozens of combinations are prescribed by wind engineering laboratories to structural designers, in an attempt to make sure that relevant peaks are not missed. This is time-consuming from the point of view of the designer, as well as less accurate than the much simpler, more transparent, and more effective time-domain approach. *Second*, statistical methods concern the estimation of peak effects *with specified MRIs.* If directionality is explicitly accounted for in the calculations, peak wind effects with specified MRI can be obtained simply and rigorously. Estimation methods for extreme wind speeds with specified MRIs, regardless of their direction, are discussed, e.g., in Simiu and Miyata (2006). If the size of an existing database of hurricane wind speeds needs to be augmented (as may be necessary for the only public hurricane wind speeds database that covers the entire Gulf and Atlantic coasts, which contains only about 1,000 simulated storms for each station, see www.nist.gov/wind), this augmentation can be achieved by using software developed by Grigoriu (2009). For synoptic and thunderstorm wind speed data, large sets of simulated data, and associated errors, can also be obtained from small sets of measured data using the methods developed by Grigoriu (2009).

The purpose of structural reliability is to develop design criteria assuring that the probability of inadequate strength and serviceability performance is acceptably small. In its simplest form allowable stress design (ASD) achieves this purpose by requiring that the stress induced by the sum of the basic design loads not exceed the allowable stress, typically defined as the nominal yield stress divided by a safety factor. The basic design loads and the safety factor are based on experience gained in past practice, but extrapolation to new types of structure based on past experience with conventional types of structure should be made prudently. ASD's probabilistic content consists of the specification of the MRI of the basic design wind load and of the definition of the nominal yield stress as a specified percentage point of its probability distribution. Strength design (SD) requires in its simplest form that the stress induced by the sum of the basic design loads, each multiplied by a load factor that depends upon type of load, not exceed the yield stress multiplied by a resistance factor smaller than unity. The probabilistic content is richer for SD than for ASD inasmuch as the various load factors are typically based on uncertainty analyses. In particular, the wind load factor accounts in general for uncertainties in the wind speed and the wind effects, including the aerodynamic pressures. For rigid structures the responses induced by aerodynamic pressures are proportional to the square of the wind speeds. For flexible structures the responses are proportional to the wind speeds raised to powers larger than two. Wind response estimation errors induced by errors in the estimation of the wind speeds are therefore greater for flexible structures than for rigid structures. This is also the case because, unlike for rigid structures, the wind response of flexible structures can be affected by errors in the estimation of natural frequencies of vibration, modal shapes, and damping ratios. The wind load factor specified in ASCE 7, and the MRI of the wind effect magnified by that load factor, were originally estimated by accounting in an approximate manner for the uncertainties in the wind speeds and wind effects affecting *rigid* structures. The current assumption in wind engineering practice is that the same wind load factor and MRI are also applicable for tall buildings. This assumption can be unconservative, that is, it can result in inadequate safety levels for tall structures.

Like the ASD approach, the SD approach is applied to individual members and does not consider the reliability of the building as a whole. A step forward was achieved by methods that allow the estimation, in some cases, of the MRI of incipient structural collapse, a limit state beyond which it may be assumed that the structure's strength reserves have largely been exhausted for practical purposes. Modern finite element methods and sets of wind tunnel data obtained simultaneously at large numbers of taps have been applied recently to obtain such estimates while accounting rigorously for wind directionality effects.

CHAPTER 4

MINIMUM REQUIREMENTS FOR THE DEVELOPMENT OF AN EFFECTIVE STANDARD ON THE WIND TUNNEL METHOD

4.1 Introduction

The wind tunnel method's objectives are:

1) To validate aerodynamic wind effects against certified wind tunnel measurements or credible full-scale measurements in natural winds.
2) To obtain in wind tunnel tests, and record, measurements of aerodynamic wind effects (e.g., pressure coefficients at individual taps, flow-induced base moments and shears obtained in High Frequency Force Balance (HFFB) measurements) reproducible to within acceptable errors in the same wind tunnel and in different wind tunnels.
3) To use a clear, transparent, and effective methodology to convert the measured aerodynamic wind effects into internal forces, demand-to-capacity ratios, or interaction equations needed by structural engineers for design purposes.

To meet these objectives it is first necessary to achieve adequate wind tunnel simulations of the atmospheric flow. Because prescriptive methods constrain the development of innovative procedures, it is advisable to develop performance-based methods. For these to be effective, performance criteria must be enforceable through measurements.

It has been common practice for such measurements to pertain to selected wind tunnel flow features, including mean wind profiles, turbulence intensities, integral turbulence scales, turbulence spectra, and turbulence cross-spectra. This practice is necessary, but not sufficient. To define the flow in sufficient detail, measurements of the flow features should pertain to the entire flow field affecting the aerodynamics of the body being tested. In practice the measurements required to fully characterize the flow can be prohibitively complex and time-consuming. For this reason wind tunnel measurements typically characterize flow partially and inadequately. For example, they can provide information of an integral turbulence scale measurement at some elevation, but that measurement does not guarantee that the turbulence scale is adequate at other elevations.

In fact rigorous simulation of each individual feature of the flow is not the ultimate goal of the flow simulation; rather, the goal is to simulate correctly the wind effects of interest, even though some flow features might be simulated imperfectly – as they are unavoidably in practice. Those wind effects can consist of pressures at individual taps, and/or of integrated pressure effects, including effects measured on HFFBs, total forces on an element of the structure, internal forces in structural members, and so forth. For example, in addition to pressures at "hot spots," the quantities that were the object of comparisons among results obtained by Fritz et al. (2008) were moments in the bent of portal frames of a low-rise industrial structure.

A certification program for wind tunnels needs in our opinion to be instituted that would verify a facility's capability to reproduce various wind effects credibly. The criteria used in the program, and the enforcement mechanisms, would have to be established by professional consensus. Baseline wind effects could be based on full-scale pressure measurements. A number of useful full-scale measurements have been performed (see, e.g., Richards et al., 2001; Long et al., 2006) that can be used for this purpose. However, to date no user-friendly, well organized compendium has been developed containing carefully scrutinized data that may be used to validate or certify wind tunnel simulations of wind effects. In addition, the data could be used to effect systematic corrections to such simulations. Corrections are needed, for example, for simulations of "hot spot" pressures, which do not match prototype values owing to the Reynolds number violation in the wind tunnel. The development of a compendium along the lines just described, and of the methodology required to use it effectively, is in our opinion an indispensable task.

To obtain wind effects for structural design purposes it is necessary to use measurements obtained in the wind tunnel in conjunction with extreme wind climatological data and statistical and structural reliability criteria and tools (see Section 3.6). As was noted earlier, estimates of wind effects for structural design purposes are currently supplied by wind engineering laboratories that use in-house procedures capable of yielding mutually incompatible results (see Simiu and Miyata, 2006). A consensus is required as to which procedure is the most realistic and should be specified in the standard.

In our opinion the role of wind engineers should be limited to supplying in user-friendly formats the requisite wind engineering data, that is, wind tunnel measurements, wind climatological data, and information relating wind speeds measured in the wind tunnel on the one hand and at meteorological sites on the other. Just as has been done for the design of structures for seismic effects, clear, transparent, and effective procedures need to be adopted for use by structural engineers in conjunction with the wind engineering laboratory input to determine wind effects for both strength and serviceability design.

4.2 Wind Tunnels and Structural Design

The ultimate objective of wind tunnel testing is the development of information on internal forces, displacements, and accelerations that can be used directly for design purposes. Differences between results obtained by various wind tunnel laboratories are due not only to the respective wind tunnel simulations and measurements, but also to the methodologies used by those laboratories to convert the wind tunnel measurement results into design information. We now focus on those methodologies.

4.2. 1 Rigid structures

For rigid structures, including low-rise buildings, so-called "pseudo-pressures" incorporated in ASCE 7 were developed in the late 1970s and early 1980s as follows. Pressures were measured at a number of taps. (That number was lower by at least one order of magnitude than the number made possible by current technologies. In addition, the measurements were conducted for only four or eight directions, as opposed to up to 36, as is currently the case.) The pressures were multiplied on line by the respective tributary areas of the taps, and by the respective influence coefficients for the wind effects of interest (e.g., knee moments in portal frames). The influence coefficients were calculated for a configuration and set of structural properties of the main wind load resisting system assumed to be generic, rather than for the particular system being considered. Pseudo-pressures were then defined as fictitious pressures that would produce some of the wind effects of interest for winds with the most unfavorable wind direction. It is clear that this methodology can – and does – entail serious errors.

Subsequent advances in information technology allowed the recording and storing of many hundreds of simultaneously measured pressure time histories. The availability of those time histories allows designers to calculate internal forces and displacements based on actual structural configurations, rather than by tacitly assuming, as was done for the derivation of the ASCE 7 pressure coefficients, that the distance between portal frames and structural properties of the main wind load resisting system are universal constants. A computational framework of a methodology for using simultaneous pressure time history data measured in the wind tunnel, referred to by some practitioners as database-assisted design, was developed for low-rise buildings by Main (2006), see www.nist.gov/wind.

For the calculation of wind effects (e.g., internal forces in structural members), the wind engineering laboratory must supply the data listed in Section 3.6.

With this input, the structural engineer can calculate the requisite wind effects corresponding to any MRI by using, e.g., the non-parametric procedure described in Simiu and Miyata (2006)[8]. In this procedure the interface between the aerodynamic and wind climatological information is simple, transparent, and rigorously correct from a physics point of view (see Sect. 2.3).

The approach just outlined clearly separates the attributions of the wind engineer and the structural engineer, and has the following advantages: (a) the requisite aerodynamic, wind climatological, and micrometeorological inputs to the wind effects estimation process are provided in their entirety by the wind engineering laboratory in clear and user-friendly formats; (b) once the wind engineering input is available, the integrity of the structural analysis and design process is assured by the use of simple and clear procedures and software, under the full control of the structural engineer; (c) the calculation of the wind effects is thoroughly documented.

Alternative methods for interfacing wind climatological and pressure data have been proposed in the literature, and are being used by various laboratories. A standard on the wind tunnel method should include only methods: (i) that are clearly described in the archived literature and are clearly understandable to structural engineering users, and (ii) whose performance has been thoroughly scrutinized and evaluated. Failure to do so can contribute significantly to errors in the estimation of the wind effects of interest to the designer, as has been the case for the estimates discussed in Appendix I.

[8] The procedure can be summarized as follows: calculate, for each of the *n* storms or yearly maxima being considered, all the directional wind effects of interest; retain only the largest of those wind effects; rank order the *n* largest wind effects so obtained; obtain from the rank-ordered set so obtained the wind effect with the MRI of interest.

4.2.2 Flexible Structures

Wind effects on flexible structures that do not exhibit significant aeroelastic effects can be estimated for any estimated MRI by using an approach similar to the approach described for rigid structures. The input provided by the wind engineering laboratory for the case in which the aerodynamic measurements consist of pressure time histories at multiple taps is the same as that described for rigid structures in Sect. 4.2.1. For tall buildings an alternative set of measurements consists of High Frequency Force Balance (HFFB) measurements of the time histories of flow-induced base moments and shears.

Unlike in the case of rigid structures, the structural engineer must calculate wind effects by accounting for the dynamic response induced by wind. The methodology and tools needed by the structural engineer to perform the estimation of wind effects once the wind engineering input is available have been developed recently for the case of aerodynamic pressures measured simultaneously at large numbers of taps (Simiu et al., 2008; Spence, 2009). In this methodology the calculations are performed in the time domain. Procedures for processing HFFB measurements are routinely performed in the frequency domain. However, some wind tunnel laboratories have recently used procedures based on time domain calculations, which are considerably more accurate, as well as being far more economical from the point of view of the structural engineer insofar as they involve only one instead of multiple combinations (see Sect. 3.4).

The important issue of the value of the wind load factors is discussed in Section 2.5. The 1.6 value of the wind load factor is specified by ASCE 7 for non-hurricane regions on the basis of the incorrect notion that it is universally applicable for all structures. For such regions the ratio of the 720-yr to the 50-yr speed, regardless of direction, is nominally equal to the 1.6. Because of the assumed universality of the 1.6 value of the wind load factor, it is assumed, again incorrectly, that the Strength Design of all structures should be performed for a 720-yr mean recurrence interval of the wind effects. In fact, wind load factors for flexible buildings are typically larger than for rigid buildings, and can be estimated by Monte Carlo simulation, as indicated in Gabbai et al. (2008) and Simiu at al. (2008). The corresponding Strength Design value of the wind effect of interest has an *N*-year MRI, where *N*, typically larger than 720 years, is the MRI of the product of the wind effect with a 50-yr MRI by the calculated wind load factor.

4.3 Structures Susceptible of Experiencing Aeroelastic Effects. For such structures we refer the reader to Zhou and Kareem (2003). An innovative approach to the estimation of aeroelastic approach proposed by mmm is to measure synchronously pressures at multiple taps on an aerolelastic model for a sufficient number of wind speed and directions. Response calculations can then be performed by following steps similar to those described for rigid buildings by Simiu et al. (2008) and Spence (2009).

CHAPTER 5
CONCLUSIONS

The development of a standard on the wind tunnel method must address clearly and effectively the following issues:

- Achieving a simulation of the atmospheric wind flow that is adequate for the estimation of the wind effects of interest. The adequacy of the performance of the simulation needs to be validated against certified test results. A protocol for such validation and a user-friendly compendium of certified results need to be developed. Wind tunnel results that, owing to the violation of the Reynolds number, cannot be reproduced in the wind tunnel, must be corrected by using a specially developed, clear, and user-friendly correction protocol based on the certified full-scale data included in the compendium.
- Clarifying the role of the wind engineering laboratory in producing structural design information. A clear division of attributions between the wind engineer and the structural designer must be established. Unlike in the twentieth century, computational resources now make it possible to develop procedures and software that accept (i) wind engineering input (wind tunnel measurements of tap pressures or integrated weighted pressures, wind speed data, and ratios between wind speed data corresponding to standard meteorological conditions and mean wind speeds at the top of the building of interest) and (ii) mechanical characteristics of the structure (e.g., influence coefficients, modal shapes, natural frequencies of vibration, damping ratios) to calculate the peak wind effects of interest (internal forces or interaction formula sums for any member, stresses, inter-story drift, deflections, accelerations) corresponding to specified mean recurrence intervals. User-friendly procedures and software have already been produced that incorporate advances in computational capabilities and allow time-domain methods to be used in lieu of obsolete frequency-domain methods. These procedures need to be expanded, e.g., for application to reinforced concrete structures, which have so far not been addressed. All procedures need to be the object of informed consensus among wind engineering and structural design professionals.
- Developing a protocol for the estimation of wind load factors that account for the uncertainties in the estimation of the wind effects for the structure of interest, and of mean recurrence intervals of the wind effects for strength and serviceability design that, unlike those of ASCE 7, are consistent in all cases with the estimated wind load factors.

Resolving those issues so that an effective standard on the wind tunnel method can be achieved requires an improvement in the mode of operation of standard development work. Such an improvement would entail more effective reliance on documentation, the development of specialized working groups fully conversant with the technical substance of the issues involved, and an improved mechanism for scrutinizing proposed standard provisions allowing adequate time for the scrutiny.

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APPENDIX

WTC WIND LOAD ESTIMATES, OUTSIDE EXPERTS FOR BASELINE STRUCTURAL PERFORMANCE

Note. The material that follows reproduces NIST document NCSTAR1-2, Appendix D, dated 13 April 2004. Appendix D was submitted by Skidmore, Owings and Merrill LLP, Chicago, Illinois and is in the public domain (wtc.nist.gov). The documents listed in Sections 3.1, 3.2, and 3.3 are not in the public domain, however. The material is included in this report to illustrate difficulties encountered by structural engineers in evaluating wind engineering laboratory reports, and contains useful comments on the state of the art in wind engineering as seen by a team of prominent structural engineers.

1.0 Table of Contents

2.0 Overview

2.1 Project Overview

The objectives for Project 2 of the WTC Investigation include the development of reference structural models and design loads for the WTC Towers. These will be used to establish the baseline performance of each of the towers under design gravity and wind loading conditions. The work includes expert review of databases and baseline structural analysis models developed by others as well as the review and critique of the wind loading criteria developed by NIST.

2.2 Report Overview

This report covers work on the development of wind loadings associated with Project 2. This task involves the review of wind loading recommendations developed by NIST for use in structural analysis computer models. The NIST recommendations are derived from wind tunnel testing/wind engineering reports developed by independent wind engineering consultants in support of insurance litigation concerning the WTC towers. The reports were provided voluntarily to NIST by the parties to the insurance litigation.

As the third party outside experts assigned to this Project, SOM's role during this task was to review and critique the NIST developed wind loading criteria for use in computer analysis models. This critique was based on a review of documents provided by NIST, specifically the wind tunnel/wind engineering reports and associated correspondence from independent wind engineering consultants and the resulting interpretation and recommendations developed by NIST.

3.0 NIST-Supplied Documents

3.1 Rowan Williams Davies Irwin (RWDI) Wind Tunnel Reports

Final Report
Wind-Induced Structural Responses
World Trade Center – Tower 1
New York, New York
Project Number: 02-1310A
October 4, 2002

Final Report
Wind-Induced Structural Responses
World Trade Center – Tower 2
New York, New York
Project Number:02-1310B
October 4, 2002

3.2 Cermak Peterka Petersen, Inc. (CPP) Wind Tunnel Report
Wind-Tunnel Tests – World Trade Center, New York, NY

CPP Project 02-2420
August 2002

3.3 Correspondence

Letter dated October 2, 2002
From: Peter Irwin/RWDI
To: Matthys Levy/Weidlinger Associates
Re: Peer Review of Wind Tunnel Tests
World Trade Center
RWDI Reference #02-1310

Weidlinger Associates Memorandum dated March 19, 2003
From: Andrew Cheung
To: Najib Abboud
Re: ERRATA to WAI Rebuttal Report

Letter dated September 12, 2003
From: Najib N. Abboud/Hart-Weidlinger
To: S. Shyam Sunder and Fahim Sadek (sic)/NIST
Re: Responses to NIST's Questions on:
"*Wind-Induced Structural Responses, World Trade Center,* Project Number 02-1310A and 02-1310B October 2002, By RWDI, Prepared for Hart-Weidlinger"

Letter dated April 6, 2004
From: Najib N. Abboud /Weidlinger Associates
To: Fahim Sadek and Emil Simiu
Re: Response to NIST's question dated March 30, 2004 regarding "Final Report, Wind- Induced Structural Responses, World Trade Center – Tower 2, RWDI, Oct 4, 2002"

3.4 NIST Report

Estimates of Wind Loads on the WTC Towers
Emil Simiu and Fahim Sadek
April 7, 2004

4.0 Discussion and Comments

4.1 General

This report covers a review and critique of the NIST recommended wind loads derived from wind load estimates provided by two independent private sector wind engineering groups, RWDI and CPP. These wind engineering groups performed wind tunnel testing and wind engineering calculations for various private sector parties involved in insurance litigation concerning the destroyed WTC Towers in New York. There are substantial disparities (greater than 40%) in the predictions of base shears and base overturning moments between the RWDI and CPP wind reports. NIST has attempted to reconcile these differences and provide wind loads to be used for the baseline structural analysis.

4.2 Wind Tunnel Reports and Wind Engineering

The CPP estimated wind base moments far exceed the RWDI estimates. These differences far exceed SOM's experience in wind force estimates for a particular building by independent wind tunnel groups.

In an attempt to understand the basis of the discrepancies, NIST performed a critique of the reports. Because the wind tunnel reports only summarize the wind tunnel test data and wind engineering calculations, precise evaluations are not possible with the provided information. For this reason, NIST was only able to approximately evaluate the differences. NIST was able to numerically estimate some corrections to the CPP report but was only able to make some qualitative assessments of the RWDI report. **It is important to note that wind engineering is an emerging technology and there is no consensus on certain aspects of current practice.** Such aspects include the correlation of wind tunnel tests to full-scale (building) behavior, methods and computational details of treating local statistical (historical) wind data in overall predictions of structural response, and types of suitable aeroelastic models for extremely tall and slender structures. It is unlikely that the two wind engineering groups involved with the WTC assessment would agree with NIST in all aspects of its critique. This presumptive disagreement should not be seen as a negative, but reflects the state of wind tunnel practice. It is to be expected that well-qualified experts will respectfully disagree with each other in a field as complex as wind engineering.

SOM's review of the NIST report and the referenced wind tunnel reports and correspondence has only involved discussions with NIST; it did not involve direct communication with either CPP or RWDI. SOM has called upon its experience with wind tunnel testing on numerous tall building projects in developing the following comments.

4.2.1 CPP Wind Tunnel Report

The NIST critique of the CPP report is focused on two issues: a potential overestimation of the wind speed and an underestimation of load resulting from the method used for integrating the wind tunnel data with climatic data. NIST made an independent estimate of the wind speeds for a 720-year return period. These more rare wind events are dominated by hurricanes that are reported by rather broad directional sectors (22.5 °). The critical direction for the towers is from the azimuth direction of 205-210 °. This wind direction is directly against the nominal "south" face of the towers (the plan north of the site is rotated approximately 30 degrees from the true north) and generates dominant cross-wind excitation from vortex shedding. The nearest sector data are centered on azimuth 202.5 (SSW) and 225 (SW). There is a substantial drop (12 %) in the NIST wind velocity from the SSW sector to the SW sector. The change in velocity with direction is less dramatic in the CCP 720-year velocities or in the ARA hurricane wind roses included in the RWDI report. This sensitivity to directionality is a cause for concern in trying to estimate a wind speed for a particular direction. However, it should be noted that the magnitude of the NIST interpolated estimated velocity for the 210 azimuth direction is similar to the ARA wind rose. The reduction of forces has been estimated by NIST based on a square of the velocity, however, a power of 2.3 may be appropriate based on a comparison of the CPP 50-year (nominal) and 720-year base moments and velocities.

The NIST critique of the CPP use of sector by sector approach of integrating wind tunnel and climatic data is fairly compelling. The likelihood of some degree of underestimation is high but SOM is not able to verify the magnitude of error (15%) which is estimated by NIST. This estimate would need to be verified by future research, as noted by NIST.

4.2.2 RWDI Wind Tunnel Report

The NIST critique of RWDI has raised some issues but has not directly estimated the effects. These concerns are related to the wind velocity profiles with height used for hurricanes and the method used for up-crossing.

NIST questioned the profile used for hurricanes and had an exchange of correspondence with RWDI. While RWDI's written response is not sufficiently quantified to permit a precise evaluation of NIST's concerns, significant numerical corroboration on this issue may be found in the April 6 letter (Question 2) from N. Abboud (Weidlinger Associates) to F. Sadek and E. Simiu (NIST).

NIST is also concerned about RWDI's up-crossing method used for integrating wind tunnel test data and climatic data. This method is computationally complex and verification is not possible because sufficient details of the method used to estimate the return period of extreme events are not provided.

4.2.3 Building Period used in Wind Tunnel Reports

SOM noted that both wind tunnel reports use fundamental periods of vibrations that exceed those measured in the actual (north tower) buildings. The calculation of building periods are at best approximate and generally underestimate the stiffness of a building thus overestimating the building period. The wind load estimates for the WTC towers are sensitive to the periods of vibration and often increase with increased period as demonstrated by a comparison of the RWDI base moments with and without P-Delta effects. Although SOM generally recommends tall building design and analysis be based on P-Delta effects, in this case even the first order period analysis (without P-Delta) exceeds the actual measurements. It would have been desirable for both RWDI and CPP to have used the measured building periods.

4.2.4 NYCBC Wind Speed

SOM recommends that the wind velocity based on a climatic study or ASCE 7-02 wind velocity be used in lieu of the New York City Building Code (NYCBC) wind velocity. The NYCBC wind velocity testing approach does not permit hurricanes to be accommodated by wind tunnel testing as intended by earlier ASCE 7 fastest mile versions because it is based on a method that used an importance factor to correct 50-year wind speeds for hurricanes. Because the estimated wind forces are not multiplied by an importance factor, this hurricane correction is incorporated in analytical methods of determining wind forces but is lost in the wind tunnel testing approach of determining wind forces.

4.2.5 Incorporating Wind Tunnel Results in Structural Evaluations

It is expected that ASCE 7 load factors will also be used for member forces for evaluating the WTC towers. Unfortunately, the use of ASCE 7 with wind tunnel-produced loadings is not straight forward. Neither wind tunnel report gives guidance on how to use the provided forces with ASCE 7 load factors.

The ASCE 7 load factors are applied to the nominal wind forces and, according to the ASCE 7 commentary, are intended to scale these lower forces up to wind forces associated with long return period wind speeds. The approach of taking 500-year return period wind speeds and dividing the speeds by the square root of 1.5 to create a nominal design wind speed; determining the building forces from these reduced nominal design wind speeds; and then magnifying these forces by a load factor (often 1.6) is, at best, convoluted. For a building that is as aerodynamically active as the WTC, an approach of directly determining the forces at the higher long return period wind speeds would be preferred. The CPP data did provide the building forces for their estimates of both 720-years (a load factor of 1.6) and the reduced nominal design wind speeds. A comparison of the wind forces demonstrates the potential error in using nominal wind speeds in lieu of directly using the underlying long period wind speeds.

It should also be noted that the analytical method of calculating wind forces in ASCE 7 provides an importance factor of 1.15 for buildings such as the WTC in order to provide more conservative designs for buildings with high occupancies. Unfortunately, no similar clear guidance is provided for high occupancy buildings where the wind loads are determined by wind tunnel testing. Utilizing methods provided in the ASCE 7 Commentary would suggest that a return period of 1800 years with wind tunnel-derived loads would be comparable to the ASCE 7 analytical approach to determining wind loads for a high occupancy building.

It would be appropriate for the wind tunnel private sector laboratories or NIST, as future research beyond the scope of this project, to address how to incorporate wind tunnel loadings into an ASCE 7-based design.

4.2.6 Summary

The NIST review is critical of both the CPP and RWDI wind tunnel reports. It finds substantive errors in the CPP approach and questions some of the methodology used by RWDI. It should be noted that boundary layer wind tunnel testing and wind engineering is still a developing branch of engineering and there is not industry-wide consensus on all aspects of the practice. For this reason, some level of disagreement is to be expected.

Determining the design wind loads is only a portion of the difficulty. As a topic of future research beyond the scope of this project, NIST or wind tunnel private sector laboratories should investigate how to incorporate these wind tunnel-derived results with the ASCE 7 Load Factors.

4.3 NIST Recommended Wind Loads

NIST recommends a wind load that is between the RWDI and CPP estimates. The NIST recommended values are approximately 83 % of the CPP estimates and 115 % of the RWDI estimates. SOM appreciates the need for NIST to reconcile the disparate wind tunnel results. It is often that engineering estimates must be done with less than the desired level of information. In the absence of a wind tunnel testing and wind engineering done to NIST specifications, NIST has taken a reasonable approach to estimate appropriate values to be used in the WTC study. However, SOM is not able to independently confirm the precise values developed by NIST.

The wind loads are to be used in the evaluation of the WTC structure. It is therefore recommended that NIST provide clear guidelines on what standards are used in the evaluations and how they are to incorporate the provided wind loads.

5.0 References

[1] American Society of Civil Engineers, *Minimum Design Loads for Buildings and Other Structures*, ASCE 7-02, 2002.

[2] American Society of Civil Engineers, *Minimum Design Loads for Buildings and Other Structures*, ASCE 7-93, 1993.