Wind Tunnel Methods

by D. Boggs and A. Lepage

Synopsis: Wind-tunnel testing is introduced as a means of providing accurate design loads for the structural frames of buildings in a timely and economic manner, overcoming the inherent limitations of code and analytical procedures. Various types of model tests and their relative advantages are described. The nature of the information that the building's structural engineer must supply to the wind consultant, and the loading information that can be expected in return, are investigated through examples and explanation.

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Daryl Boggs is Principal and Vice President of Cermak Peterka Petersen, Inc., Fort Collins, Colorado. He specializes in wind-tunnel testing and consulting on wind-sensitive and dynamically active structures. He is a member of ACI 375 – Performance Based Design for Wind Loads, and a corresponding member of the ASCE 7 – Task Committee on Wind Loads.

Andres Lepage is an Assistant Professor in the Department of Architectural Engineering at Pennsylvania State University, University Park. He received his Ph.D. degree from the University of Illinois at Urbana-Champaign. His research interests include the analysis and design of concrete, steel, and hybrid structural systems subjected to extreme events. He is a member of ACI Committees 318-H, 335, 374 and 375.

LIMITATIONS OF CODE AND ANALYTICAL PROCEDURES

Wind loads on building frames are commonly obtained using the simple rules prescribed by building codes or adapted from analytical procedures contained in standards such as ASCE 7. This method—referred to simply as "building code methods" in this paper—is rooted in a few generally applicable concepts, including defining the oncoming wind speed as a function of height for a specified generic exposure condition (the "ground roughness"), and on pressure coefficients or shape factors for a primitive building shape, which were probably obtained by reference to historical wind-tunnel tests. The "generic" exposure condition is characterized by uniform ground roughness selected from one of several predetermined categories, and the "primitive" building shapes are nearly always simple rectangular prisms. For real buildings in real settings both of these simplifications limit the ability to obtain accurate loads using analytical procedures. It is well known, for example, that a building placed within a dense field of nearby buildings of similar or greater height will be shielded from the approaching wind, and will likely experience loads that are significantly lower than those predicted by code. On the other hand, particular arrangements of nearby buildings have been known to increase loads by "channeling" the approaching wind, with an accelerated speed, into a narrow gap. In addition, a single isolated nearby building has been shown to increase loads on a downwind structure by a factor of two or more, for certain relative directions of the oncoming wind, due to mean and turbulent flow characteristics in the wake of the upwind buildings. Real conditions experienced by real buildings are likely to be some combination of all of these phenomena at various directions.

Pressure and shape coefficients for building cross sections other than rectangular are not sufficiently documented to be of use in building codes, and the variational possibilities are far too great to be characterized in any meaningful manner. Even for the primitive shapes of round vs. square, the drag coefficient may range from say 0.8 to 2.5, a variation of more than a factor of 3. Most buildings will be somewhere between these extremes, but building codes must assume a pessimistic value in order to yield, usually, a conservative load. This geometric issue may be true even for square or rectangular shapes when it is considered that the critical wind direction may be other than the square-on case because of possible directional influence by exposure conditions or the wind climate itself. Moreover, the wind flow around buildings is a three-dimensional phenomenon rather than two-dimensional, and the flow field is a turbulent boundary layer rather than smooth and uniform. The variety in these conditions only adds to the impracticality of cataloging accurate pressure and shape coefficients for a wide range of building shapes.

Even those analysis procedures that are well developed, and most of the shape coefficients that are well catalogued, are done so only for the *alongwind* loading condition—i.e., they address only the component of the wind load that is parallel to the direction of the approaching mean wind. Wind also produces torsional loads and *crosswind* loads—perpendicular to the approaching mean wind—that act simultaneously with the alongwind load to produce a complex *load combination*, and they can often be significant even in their own right. In tall buildings of prismatic cross section in a relatively open exposure, for example, it is well known that intense harmonic crosswind excitations can occur due to the phenomenon of vortex shedding. Under certain conditions the frequency of shedding can be close to the natural frequency of vibration of the structure, and excessive dynamic response due to resonance can occur. The resulting crosswind loads are very often as great as the alongwind load, and in some cases can be much greater.

All of the above effects are well known to most building code writers. The national load standard ASCE 7 therefore states that its *analytical procedure* applies only to a "regular shaped building or structure" which has "no unusual geometrical irregularity in spatial form," and which "does not have response characteristics making it subject to across-wind loading, vortex shedding, instability due to galloping or flutter[†]; or does not have a site location for which channeling effects or buffeting in the wake of upwind obstructions warrant special consideration." Buildings not meeting these conditions "shall be designed using recognized literature documenting such wind load effects or shall use the *wind tunnel procedure*." Nearly all modern building codes have similar limiting statements, or in fact reference ASCE 7 directly.

Finally, the wind climatology of most sites is such that winds of various speeds are favored by different directions. Typically, the strongest "design" winds are likely to occur only from a limited range of azimuth, while wind with the same probability of occurrence at other directions will be of lower speed. Since the shape factor and/or exposure condition of a building also (generally) varies with direction, it is obvious that the orientation of a specific building at a specific site could be either fortuitously favorable, resulting in reduced loads at a given probability level, or unfortunate, where the higher-speed winds conspire with the least streamlined shape or the most open exposure to cause much higher loads at the same probability level. When using a building code method the designer is generally not able, and is not allowed, to take advantage of any possible load reduction due to these effects, because he does not generally know which wind direction is responsible for the various components of the load. In the case of a high crosswind response to vortex shedding, for example, there are many buildings for which the code yields a reasonably accurate load magnitude, but for entirely the wrong physical reasoning: the load actually occurs for a wind 90 degrees off of that assumed by the

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[†] Galloping and flutter are aerodynamic instabilities that are likely to occur only in very slender lightweight towers, and are not generally of concern in concrete buildings.

analytical procedure. Nevertheless, recent editions of ASCE 7 allow the use of a directionality factor, a load reduction multiplier between 0.85 and 0.95 based on the *statistical* likelihood that the direction of maximum wind speed will not coincide with the most sensitive shape and strength axis. In contrast, when a wind-tunnel study is performed all of the wind-response direction relations will be explicitly determined, and the directional characteristics of the local wind climate can be fully exploited to obtain more accurate directional load factors. These load factors can occasionally be higher than 0.85 (in fact as high as 1.0), but are often significantly less.

MOTIVATION FOR A WIND TUNNEL STUDY

Why would a project developer or design team desire to have a wind-tunnel model study conducted? In view of the above, the most obvious benefit of such a study is that it invariably results in design loads that are *more accurate* than those derived from codes. To the structural engineer this may be justification enough, while the developer may be more concerned with economics than with “academic accuracy.” To this end he may shy from a wind-tunnel study because of the up-front cost and time required, or reduced “short-term” economy. However, wind-tunnel loads are *usually* lower than code, resulting in greater economy in the structural framing. Wind-tunnel results *can* be greater than code loads, resulting in greater safety, reduced risk, and reduced maintenance—all contributing to *long-term* economy.

OVERVIEW OF A WIND-TUNNEL STUDY

A typical wind-tunnel test to evaluate structural loading on a building consists of the following steps:

(1) Simulate the natural wind environment in the tunnel, including profiles of mean speed and turbulence, including both the far field (ambient approach conditions) and near field (the localized effects of nearby buildings or topography).
(2) Construct a model geometrically scaled to the building, place it in the simulated environment, and “observe” what happens using appropriate instrumentation.
(3) Obtain the initial dynamic characteristics of the building from the structural engineer.
(4) Define the site wind climatology and assign design wind speeds.
(5) Analyze and interpret the observed results, in view of design speeds and structural dynamic properties, to obtain static-equivalent loads and accelerations.
(6) Interact with the structural engineer to refine or optimize the structure.

Most often, the building structural loads are but one aspect of useful information that can be obtained from the same, or slightly expanded, test program. Additional “by-products” can include overall structural dynamic response in the form of accelerations to evaluate occupant comfort, cladding pressures for façade design, snow loads, the pedestrian wind environment, and various air-quality issues. Any one of these could in fact be the primary motivation for a wind-tunnel study, with all other results obtained economically.

SIMULATION OF NATURAL WINDS

Modeling the aerodynamic loading on a structure requires special consideration of flow conditions to obtain similitude between the model and the full-scale “prototype.” In general, the requirements are that the model and prototype be geometrically similar, that the approach mean velocity at the model building site have a vertical profile in terms of mean speed and turbulence similar to the full-scale flow, and that the Reynolds number (Re) for the model and prototype be equal.

These criteria are satisfied by constructing a scale model of the structure and its surroundings, and performing the tests in a wind tunnel specifically designed to model atmospheric boundary-layer flows. Reynolds number similarity requires that the product of wind speed and building size be similar for model and prototype. If this is accomplished, fundamental fluid mechanics laws guarantee that flow patterns and pressure distributions will be similar between model and prototype. For most wind tunnels capable of performing building studies of this nature, typical model scales are 1/200 to 1/500 and the model wind speeds are perhaps 1/3 to 1/2 of the full-scale design values. Thus, the model Re is commonly three orders of magnitude less than the prototype value. However, for sufficiently high Re and for blunt shapes in which the points of flow separation are fixed by geometry rather than by aerodynamic considerations, it has been well demonstrated that acceptable flow similarity is achieved without Re equality. These conditions apply to nearly all buildings tested in nearly all wind-tunnel laboratories that routinely conduct such tests. Only in cases of broadly curved building surfaces, with very smooth surface skins, and very smooth wind conditions with unusually low turbulence, does the Re scaling requirement need to be carefully examined. The general use of boundary-layer wind tunnels and similitude requirements in civil engineering applications is discussed by Cermak (1971, 1977) and Davenport and Isyumov (1967).

Figure 1 shows an example of a wind tunnel suitable for conducting building model studies. The model is positioned at the center of a turntable that can be rotated to simulate wind approaching from any azimuth—typically 36 directions at 10-degree increments. In contrast to aeronautical wind tunnels that are commonly used to test airplanes and automobiles, it features a long “fetch” upwind of the model, where roughness elements are placed on the floor. As the wind flows over this fetch, a boundary layer is developed by natural means, just as the atmospheric boundary layer is developed due to flow over the real-world roughness of terrain, forests, and buildings. The flow characteristics measured immediately upwind of the turntable are shown in Figure 2. The mean wind speed increase with height and turbulence intensity decrease with height are characteristics of the boundary-layer profile that have been intentionally matched to the approximate values known to exist in the real world for a certain exposure condition. In this case, the wind-tunnel profile is representative of wind approaching over a moderately built-up or “suburban” exposure, such as that designated Category B in ASCE 7. Various exposure categories can be simulated in the wind tunnel by varying the fetch exposure elements (and possibly the trip and spires) as required. In cases of unusual or complex topography upwind of the building, a second “topographical model” study may be first conducted at a scale of say 1/3000 to 1/5000 to ascertain the wind profile characteristics that need to be reproduced as the approach conditions in the primary model setup. In cases where the upwind exposure conditions are essentially uniform but do not extend far enough upwind, before transitioning to a different category of exposure, to fully develop its normal profile, analytical boundary-layer flow models can sometimes be used to determine the "effective" profile which approaches the building site. In any case, the geometry of the wind-tunnel fetch area must be adjusted to obtain the required flow parameters. Continuous adjustments of the fetch area may be required as the turntable is rotated to study the different wind directions.

The flow conditions described thus far are significant only for the "far-field flow," or the wind *approaching* the building under study. As wind nears the subject building the particular effects of individual nearby buildings become significant, and the generic approach conditions are no longer relied upon for an accurate simulation. Instead, the "near-field flow" is simulated by including all significant nearby objects as part of the proximity model on the turntable. The proximity model is a detailed representation of objects within a radius of say 300 to 1000 m, depending on the size of the wind tunnel, the model scale, and the distance to which significant specific buildings may exist.

TYPES OF BUILDING MODELS

There are basically two types of modeling principles that are used to determine wind loads on building frames, depending on how the right-hand side of the equation of motion is treated (see companion paper "The Nature of Wind Loads and Dynamic Response"). In terms of a simple single-degree-of-freedom wind-tunnel model, the equation of motion is

$$m\ddot{x} + c\dot{x} + kx = P(t, x, \dot{x}) \tag{1}$$

where the right-hand side represents all of the excitation forces. If the motion-dependent excitation terms are considered to be important then the nonlinear terms (any involving displacement x or velocity $\dot{x}$) must be retained, and a so-called *aeroelastic model* is used. The dynamic properties of such a model, including mass, stiffness, and damping, must be "tuned" to match the scaled values of the real building. The model's response in the wind tunnel, including base reactions, displacements, and acceleration, are also to scale, and can simply be measured on the model.

If the motion-dependent excitation terms are not important, then

$$m\ddot{x} + c\dot{x} + kx = P(t) \tag{2}$$

and a so-called *aerodynamic model* is used. In this case the incident aerodynamic excitation, $P(t)$, is measured on a nominally rigid model, which for practical purposes does not move and therefore does not alter the wind flow. It is essential that the model not vibrate, otherwise its mass and acceleration will result in inertial forces that are impossible to distinguish from the aerodynamic forces. In spectral terms, the model and measurement system must have a high bandwidth—meaning that the total mechanical system has a relatively high natural frequency to capture the significant part of the aerodynamic load spectrum. It is then possible to solve the above equation analytically for the response x, or the static-equivalent load $P = k\,x$. This analysis is most often performed in the frequency domain using the theory of random vibration, although a numerical solution using transient time-step integration is also useful.

Various techniques can be used to measure the aerodynamic loading. As originally developed, a building model is mounted on a base balance that measures the overturning moments (and sometimes shear forces) and torque at the base of the model. This technique works because the base moment is usually a good approximation to the generalized aerodynamic load. The high bandwidth is attained with an unusually stiff balance and a building model very stiff and lightweight, so that the total mechanical system has a relatively high natural frequency. For typical model sizes and test conditions, the natural frequency should be greater than about 100 Hz. Such systems are difficult to achieve and represent a major instrumentation endeavor by the wind-tunnel laboratory. This method, commonly referred to as the *high-frequency base balance* (HFBB) or *high-frequency force balance* (HFFB) technique, was developed in the early 1980's and is still the most popular form of aerodynamic model. The building model, usually made of balsa wood, can be built quite quickly and inexpensively, and results in the form of static-equivalent base moments that can be delivered to the structural engineer early in the test program. Unfortunately it provides no information regarding the distribution of mean or background forces over the height of the building—unless the base shear is measured along with the base moment in which case a simple first-order approximation can be made. In general, some assumption must be made regarding the load distribution in order to provide useful design loads to the engineer. More accurate information is usually obtained, albeit later in the test program, by integrating the mean pressures measured at a large number of tap locations in a second, *pressure-tapped* model.

More recently, pressure-tapped models have also been used to determine the aerodynamic loading, by measuring the pressure at a large number of tap locations (typically 500 to 1000) simultaneously. By assigning a tributary area to each pressure tap, the pressure signals can be spatially integrated over the building surface, and modal weighting can also be included to obtain time signals of the fluctuating generalized load. This method has the advantage of being able to incorporate the required modal weighting more accurately than is possible in a base balance, but it is often limited by the number of pressure taps that can be measured simultaneously by the space available for tubing (especially in a very tall slender model). The basic types of wind-tunnel models and the above characteristics are summarized in Table 1.

The type of model to use is typically recommended by the wind-tunnel consultant, but must be agreed to by the structural engineer. Of particular significance is the decision to ignore motion-dependent excitation forces or not. For most buildings this can be done, allowing an aerodynamic model test, which can proceed as soon as the outside shape of the building has been decided and a set of architectural plans and elevations is supplied. The model can then be constructed and tested to determine the aerodynamic forces. The actual design loads, which account for the dynamic response of the building structure, are then computed once the engineer provides the required dynamic structural characteristics. See further discussion later in *Structural Optimization*. Design loads can be supplied quite quickly, sometimes less than a week after the building shape and structure properties are set. In contrast, results from an aeroelastic test would typically take a month or more. The choice of a multi-pressure or HFBB type of aerodynamic model should be immaterial to the engineer, and is normally decided by the wind-tunnel consultant based on capabilities, size issues described above, and economics related to anticipated minor architectural modification and the timing for which cladding pressure information is needed. In contrast, certain tall, slender, lightweight towers, and especially those having a very open exposure, may be prone to crosswind excitation by vortex shedding, and the load results provided by an aerodynamic model could be unconservative. In such cases the wind-tunnel consultant should strongly recommend that an aeroelastic test be conducted, either initially or as a provisional supplement to the results that can be economically and quickly obtained from an initial aerodynamic model.

The development of HFBB aerodynamic models, and their validity relative to aeroelastic models under the effects of vortex shedding, is discussed by Davenport and Tschanz (1981), Tschanz (1982), Boggs and Peterka (1989), and Boggs (1992).

STRUCTURAL PROPERTIES

The structural information required by the wind tunnel laboratory include the structure's modal properties, mass distribution, damping, and performance levels (limit states) to be analyzed.

Modal properties are routinely computed by structural engineers using commercial structural analysis programs. Usually the first six modes of vibration, at minimum, should be provided (to ensure that the three fundamental modes are included, as opposed to higher-order modes that will not be used). Natural frequencies are of primary importance, followed by the mass distribution and mode shapes, which should be tabulated by floor level.

The wind-tunnel analysis incorporates the natural frequencies to determine the resonant portion of the generalized response, indicated in Figure 5 of the companion paper "The Nature of Wind Loads and Dynamic Response". This generalized response is approximately equivalent to the overturning base moment, and the mode shapes are used to obtain the small adjustment factor needed to report base moments directly. The mode shapes and mass distribution are used to determine the distribution of the resonant forces over the height of the building, as static-equivalent forces acting at each floor.

Static-equivalent loads can only be generated at those elevations where mass and mode shape are supplied to the wind-tunnel laboratory. Often secondary elevations such as mezzanines, roof decks, and penthouses are omitted from the structural engineer's analysis, thus limiting the accuracy of information that can be returned from the wind-tunnel laboratory. Whenever a large portion of the loading at each floor is due to dynamic resonance, for example, that load is generated according to the engineer's assumptions when performing the dynamic analysis as reflected by the lumped mass data provided to the wind-tunnel laboratory. Because of this, apparent anomalies may occur in the form of locally high loads if the structural analyst has taken certain liberties, such as lumping the mass of penthouse roofs or equipment at the floor below.

Because the dynamic wind loads are fundamentally dependent on the natural frequency of the structure, which in turn depends on the stiffness and mass, these properties must be carefully considered. The member effective stiffnesses used in the analysis should correspond to the secant value associated with the maximum expected force when subjected to the design event. RC members are commonly modeled using a fraction of their gross section properties. The mass data used in the analysis should include all mass sources that could be expected to exist at the time of maximum winds. This includes, for example, self-weight, design dead load, and the "sustained" live load which may be 25 to 50 percent of the full design live load.

The wind-tunnel analysis generally has no way of computing deflections which require detailed knowledge of the stiffness distributed throughout the structure. However, the stiffness associated with resonant dynamic response can be computed from the combination of generalized mass (i.e., from the mode shape and mass distribution) and natural frequency. The wind-tunnel laboratory will utilize this feature to compute the building acceleration, for comparison to human comfort serviceability criteria. For this reason, the frequency data and the mass data should *not* be supplied independently, and there are significant implications regarding the nature of the mass data supplied—namely, that the mass data must be consistent with that used to compute the frequencies, and not independently adjusted.

A structural parameter equally important as the natural frequency is the damping ratio. No analysis is available to predict this, ant it will generally be assigned by wind-tunnel lab in consultation with the structural engineer depending on materials and structural system. See discussion in companion paper "The Nature of Wind Loads and Dynamic Response".

Wind-tunnel results can be determined for various limit states as well as different methods of analysis. At present, it is most common to report accelerations for the serviceability state (5 to 10 years recurrence), and loads for a "pseudo-ultimate" state corresponding to the traditional 50- or 100-year (nominal) recurrence interval from which the designer simulates "ultimate" loads (500 to 1000-year recurrence) by using factored loads. In contrast, "true ultimate" loads can also be determined by the wind-tunnel analysis by using actual wind speeds associated with a maximum considered wind event. Different structural properties should be considered for each method. Table 2 illustrates a typical set of parameters utilized in the wind-tunnel study of a 40-story concrete building. More information is available in the companion paper "The Nature of Wind Loads and Dynamic Response".

DESIGN WIND SPEEDS

The immediate results of the model wind-tunnel study are load coefficients that can be scaled to any desired prototype wind speed. To provide results for any of the limit states/analysis methods discussed above, appropriate wind speeds must be determined for each wind direction studied. Generally this analysis is performed by the wind-tunnel laboratory, and the structural engineer need not be concerned with the details. Only an overview is given here.

At the most basic level, wind speeds for the nominal 50-year recurrence interval in the U.S. can be obtained from the wind-speed map in ASCE 7. Speeds for other recurrence intervals can be obtained from tabulated conversion factors. However, speeds determined this way represent only the "all-direction" case and do not consider the reduced wind speeds that could be appropriate for certain azimuths, as discussed earlier in *Limitations of Code and Analytical Procedures*. In addition, the ASCE 7 data do not quantify certain "special wind regions." Therefore, the wind-tunnel laboratory will probably conduct (or have access to from previous studies) a statistical analysis based on regional climatic data and/or simulation of hurricanes (for coastal areas). The laboratory must incorporate the appropriate transformations to convert the climate data to the reference velocity used in the model study, accounting for the type of gust measurement, height of the measurement, and exposure conditions.

Certain types of buildings are usually required to be designed for an elevated level of reliability, characterized by a nominal recurrence interval of 100 years instead of 50 years. In ASCE 7, such buildings are selected depending on the nature of their occupancy, and the 100-year recurrence is accomplished (implicitly) by multiplying wind pressures by an "importance factor," $I = 1.15$. If the building is very flexible such that dynamic response is significant, a slightly more accurate procedure results if the wind-tunnel laboratory reduces their data for the actual corresponding wind speed (approximately equal to the nominal 50-year speed multiplied by the square root of 1.15), rather than simply multiply the resulting loads by 1.15. It is essential that the building developer and the wind-tunnel laboratory agree on the appropriate importance factor.

APPLICATION OF RESULTS

Summary data

The wind-tunnel report should include structural load data summarized in a form that provides, in an easily digestible form, an overview of the building's behavior at different wind directions, how load cases might be identified, and how the loads vary with the dynamic characteristics of the structure. An example of this is shown in Figure 3. Mean and peak base moments are shown as a function of wind direction, for three different values of natural frequency. The first set of values, plotted using a box symbol, corresponds to the "base" values that were supplied to the wind-tunnel laboratory by the structural engineer. The two other values, plotted using circle and triangle symbols, correspond to ±25 percent variations in natural frequency. These three curves provide an immediate indication of the sensitivity of the design loads to changes in natural frequency, and serve as a guide to whether “tweaking” the structure properties could be an effective means of improving performance or economy, or to the significance of various uncertainties in calculating the natural frequencies—such as member section properties, joint rigidity, foundation and/or diaphragm flexibility, etc.

The grouping of three plots, for the three moment components, also serves as a guide to load combinations—i.e., consideration of loads that act simultaneously in different directions. One such combination is depicted in the graph using bold “X” symbols, wherein the “principal” M_y component experiences its maximum value of any wind direction, while the M_x and M_z values are “companion” loads that were determined to act concurrently with the principal value. The companion loads are somewhere between their respective mean and peak values at that same wind direction, depending on the degree of correlation in the fluctuating parts of the companion and principal components. Typically (but not always) the correlation is found to be low, meaning that the peak value of the companion loads is unlikely to occur at the same time instant as the peak of the principal load, and therefore need not be designed for—except in other load cases where those components are treated as principal components. In the case of M_x in load case 1 as shown, the selected design value is actually numerically smaller than even the mean value, because the wind-tunnel data showed that M_x and M_y were *positively* correlated: both tend to fluctuate from their mean values with the same sign, so that when M_y experiences its full peak positive value, M_x is likely to be somewhat more positive than its mean value. Usually 10 to 20 or so load cases are defined by the wind-tunnel laboratory, designed to maximize the positive and negative value of each component, and additional cases where each component may be somewhat less than its maximum value but the vector resultant could be critical.

Floor Loads

However the load cases are defined, the end result of the wind-tunnel report is usually a simple table that specifies concentrated forces and torques to be applied at each floor level. The loads corresponding to Load Case 1 in Figure 3 are shown in Table 3. In general, the various load cases occur at different wind directions (or at least are statistically dominated by different directions) and are therefore characterized by different distributions over the height of the structure, necessitating that different tables be given for different load cases. Occasionally these different distributions are ignored, however, and different load cases are approximated simply by applying various scale factors to the three different components.

Displacements and Accelerations

Although the load distributions reported by the wind tunnel can be quite accurate, the laboratory generally cannot determine the displacements and usually does not report them. The displacements depend on detailed information about the distribution of stiffness throughout the structure that the laboratory does not have. This is especially true for the mean and background portions of the load. However, the resonant portion of the load produces deflection corresponding to the mode shape and generalized stiffness, which the wind tunnel does have. Thus the resonant displacement can be reported and, to the extent that the mean and background displacement shape resembles the mode shape, estimates could be given for the total deflection. This is usually not done.

The *acceleration* of the structure is not affected by the mean loading, and the background acceleration is usually small compared to the resonant acceleration. Therefore, it is usually dominated by resonance and the wind tunnel laboratory is well prepared to predict it. In fact, the acceleration can be predicted reasonably well knowing only the externally applied aerodynamic base moment, since this is a reasonable approximation to the generalized modal excitation. Thus, for example, an HFBB test is capable of predicting the building acceleration, while it may not give a good prediction of the *distribution* of loading over the height of the building without being supplemented by the results of a pressure-model test.

The predicted acceleration is needed to judge the acceptability of the building environment to occupants, who may be sensitive to wind-induced motion. Usually only the acceleration at the top occupied floor is reported, since acceptability criteria have generally been based on the motion at the top of the building. Unfortunately there is no criterion that is universally accepted, since human perception and tolerance to motion in real-world socio-psychological environments defies quantification. There is disagreement, for example, on the recurrence interval that should be evaluated, the relative importance of *perception* vs. *tolerance* of the motion, whether or how occupants become more tolerant of motion with experience, whether office occupancy should be treated differently from residential occupancy, whether the frequency of motion is important, and even whether it is some form of averaged acceleration (such as the root-mean-square value) over say a one-hour period, or simply the peak acceleration occurring during that period, that is most significant. Example criteria that might be specified for commercial buildings include “5 milli-g rms acceleration occurring on average every 5 years,” or “21 milli-g peak acceleration occurring on average every 10 years.” Residential buildings often target values that are somewhat lower. Variations occur in the specifications for all of the reasons noted above. The wind consultant can provide more information. The wind-tunnel test report should include, as minimum, the predicted top-floor acceleration (rms and/or peak) for a range of recurrence intervals, and comparison to one or more comfort criteria.

Other factors affecting occupant comfort include visual cues, such as swaying of doors or chandeliers, which heighten awareness of building motion. A visual cue often cited, which applies to occupants having a window view, is the sensation of the world swaying outside as the building twists. The predicted torsional velocity of the building is sometimes reported as an indication of the severity of this motion cue. Unfortunately, there is no basis to quantitatively relate twist velocity to occupant comfort, so the value of such a prediction is limited.

STRUCTURAL OPTIMIZATION

A major advantage of the aerodynamic model method over the aeroelastic model is that it is much better suited to optimizing the structure under wind loading. This is because, first, the results are available much earlier in the design process; second, it is a relatively quick and inexpensive matter for the wind tunnel to reanalyze the aerodynamic load data to obtain static-equivalent design loads if the dynamic properties of the structure change.

Thus the engineer, upon receipt of the data report from the wind tunnel, can easily note the overall design loads (e.g., in the form of overturning base moments) or serviceability (accelerations) in comparison to target values or preliminary design assumptions. A first step in the optimization process may already be available from the wind tunnel if their report of overall loads shows the effect of a range of natural frequency, as in Figure 3. The stiffness of the structure can be modified slightly, followed by a rerun of the eigen analysis. If the revised natural frequency falls within the range provided, and the mode shapes do not change significantly, then all of the loads can be scaled to the new base loads obtained from Figure 3 by interpolation, with reasonable accuracy.

If it is necessary or desirable to modify the structure more extensively, then after rerunning the eigen analysis the new set of dynamic properties must be reported to the wind-tunnel laboratory. The laboratory can typically respond with a revised set of design loads within a few days. The revised design loads will accurately account for changes in natural frequency, mode shapes, and mass distributions. The process can then iterate for as many cycles as the design team feels is beneficial.

Damping is another parameter that the engineer may wish to consider, in view of its uncertainty especially in unusual construction types. The wind-tunnel laboratory can easily provide loads for various assumed values to aid the engineer in dealing with this uncertainty. In extreme cases, the possibility of adding damping—using various devises such as tuned mass dampers, sloshing dampers, visco-elastic dampers, etc.—can be considered as an effective means of reducing the resonant portion of loads or acceleration.

CONCLUSIONS

(1) Building code procedures are based on general assumptions, are usually but not always conservative, and do not provide accurate wind loads because of exposure conditions, directional properties of the wind climate, complex geometrical shapes, torsion, aerodynamic interactions, and load combinations.
(2) Wind-tunnel tests, which are capable of more accurate load definition, have become faster and more economical as a result of improved methodologies.
(3) Structural reliability under wind loading improves significantly with wind-tunnel study and can be addressed in terms of loading and serviceability limit states.

(4) Interactions between the structural engineer and the wind consultant are now commonplace and have facilitated the process of structural optimization for wind response.

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Table 1 — Comparison of types of wind-tunnel models.

Characteristic	Aeroelastic model	Aerodynamic model (HFBB)	Aerodynamic model (Multi-pressure)
Cost	Expensive	Model is very inexpensive; equipment is costly but capitalized over many projects	Model is expensive but can also be used to obtain cladding pressure information
Speed	Slow	Very fast	Fast
Accuracy in terms of mode shape	Limited to ideal shapes	Limited to ideal shapes	Good
Accuracy in terms of aerodynamic load	Good	Good, although motion-dependent loads are not accounted for	Good provided that sufficient number of tap locations can be utilized
Accuracy in terms of motion-dependent load	Good, but limited by idealized mode shape	Not accounted for	Not accounted for
Optimization capabilities	Changes in structural properties may require retesting	Retesting not required to accommodate structural modifications	Retesting not required to accommodate structural modifications

Table 2 — Structural properties for various limit states and analysis methods.

	General recommendations		
	Serviceability	Traditional factored load design	Maximum considered event
Recurrence interval	10 years	50 years (nominal)	720 years
Application	Acceleration, drift	Structural member actions using 1.6 load factor to obtain "pseudo-ultimate" loads	Structural member actions based on loads induced by maximum wind event
Structure condition	Partially cracked	Fully-cracked sections	Fully-cracked sections
	Example parameters for a specific building		
Natural frequency/period	x: 0.170 Hz / 5.89 sec y: 0.183 Hz / 5.47 sec z: 0.195 Hz / 5.13 sec	x: 0.137 Hz / 7.30 sec y: 0.147 Hz / 6.79 sec z: 0.158 Hz / 6.34 sec	x: 0.137 Hz / 7.30 sec y: 0.147 Hz / 6.79 sec z: 0.158 Hz / 6.34 sec
Damping ratio	0.015	0.020	0.030
Recommended load factor	N/A	1.6	1.0

Table 3 — Sample wind load specification from a wind-tunnel report.

Load case: 1
Wind dir: 100 deg

Floor Label	Elev. (m)	Fx (principal) (kN)	Fy (companion) (kN)	Tz (companion) (kN-m)	Eccentricity (m)* Ex	Eccentricity (m)* Ey
TOP	141.69	132.4	60.5	286	0.816	-1.787
HPH	135.19	186.0	47.1	304	0.389	-1.538
LPH	133.66	173.6	29.0	219	0.205	-1.229
L29	129.24	293.0	27.6	-332	-0.106	1.124
L28	124.83	327.6	31.8	-653	-0.192	1.976
L27	120.41	324.5	36.2	-567	-0.193	1.727
L26	115.99	324.5	37.7	-511	-0.180	1.554
L25	111.57	317.8	41.8	-431	-0.176	1.335
L24	107.15	310.4	46.0	-350	-0.164	1.104
L23	102.73	306.9	49.9	-345	-0.178	1.095
L22	98.32	297.1	56.1	-321	-0.197	1.042
L21	93.90	286.9	62.4	-295	-0.214	0.984
L20	89.48	298.9	59.7	-376	-0.242	1.211
L19	85.06	285.2	66.1	-395	-0.305	1.315
L18	80.64	271.1	72.5	-414	-0.381	1.424
L17	76.22	256.6	78.7	-435	-0.475	1.550
L16	71.81	241.9	82.5	-516	-0.652	1.912
L15	67.39	237.6	97.0	-622	-0.917	2.246
L14	62.21	252.3	36.6	-692	-0.390	2.688
L13	57.03	247.2	-42.7	-466	0.316	1.830
L12	51.85	200.9	-38.4	-292	0.268	1.402
L11	48.60	157.1	-32.9	-174	0.222	1.061
L10	45.35	148.4	-30.9	-128	0.172	0.824
L9	42.10	139.8	-27.7	-128	0.175	0.883
L8	38.85	131.5	-24.6	-130	0.178	0.953
L7	35.60	123.3	-21.6	-132	0.182	1.039
L6	32.35	115.2	-18.7	-135	0.185	1.141
L5	29.10	104.7	-14.2	-145	0.184	1.356
L4	25.85	99.1	-9.6	-187	0.181	1.872
L3	22.59	91.0	-5.2	-214	0.133	2.346
L2	19.34	122.3	-4.0	-456	0.122	3.729
L1	14.16	73.6	-1.3	-307	0.071	4.171
B1	10.91	1.1	-0.3	-4	1.006	3.436
BASE	7.66	0.0	0.0	0	0.000	0.000
Base shear (kN)		Vx 6876.6	Vy 747.1			
Base moment (MN-m)		My 492.13	Mx -76.34	Mz -9.34		

*Apply forces Fx, Fy at eccentricities Ey, Ex as alternative to applying Tz at z axis.

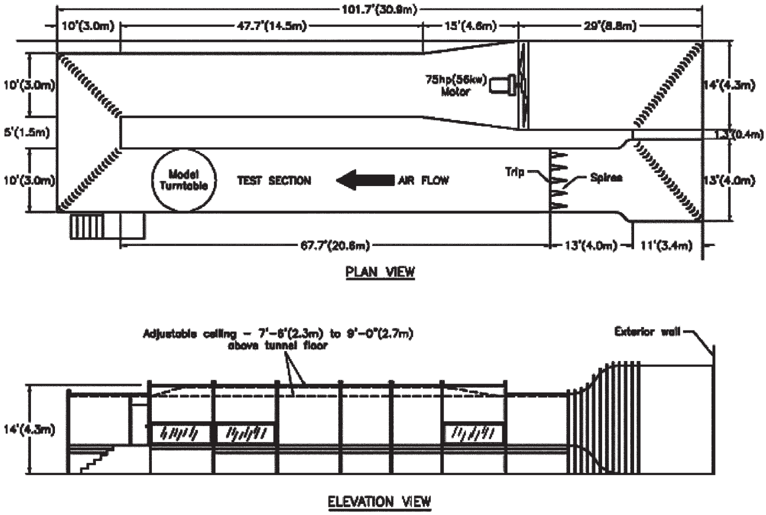

Figure 1 — A boundary-layer wind tunnel designed for model building studies.

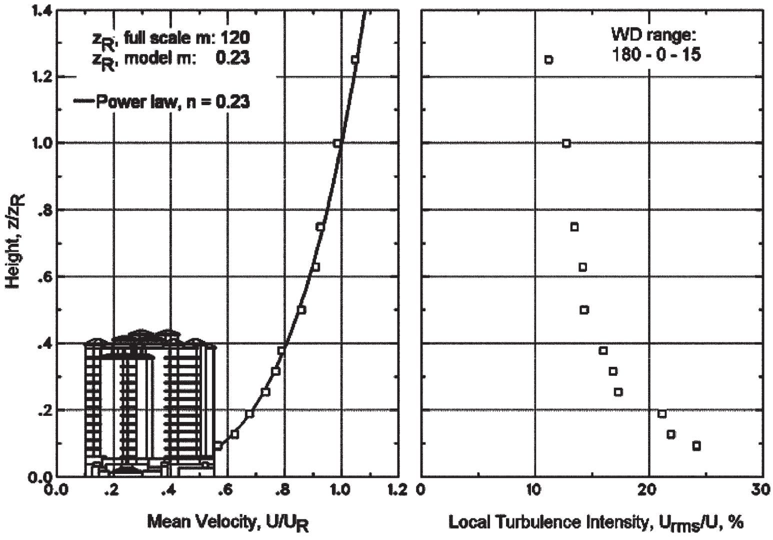

Figure 2 — Profile characteristics of wind approaching the model turntable.

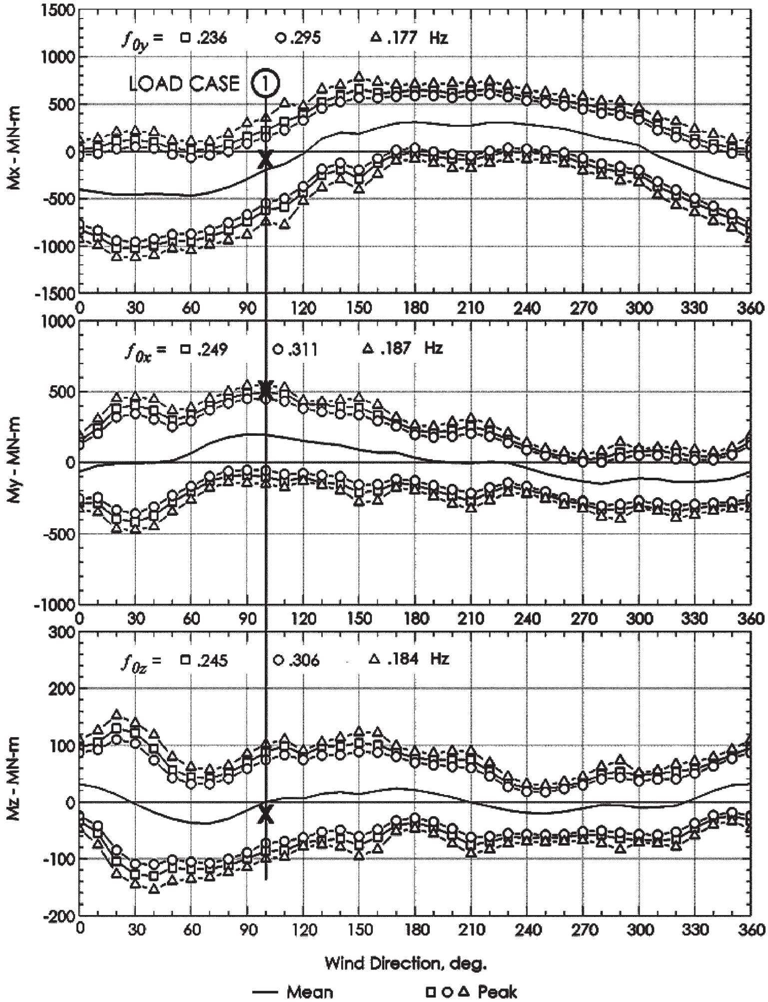

Figure 3 — Sample summary data from a report of an aerodynamic model test.