Probabilistic Performance Criteria for Tall Buildings Subjected to Wind Loads

by

Sofia M.C. Diniz[1], Mihai Iancovici[2], William Fritz[3], Michael A. Riley[3] and Emil Simiu[3]

ABSTRACT

Database-assisted design (DAD) uses time histories of pressures simultaneously measured in the wind tunnel at a large number of pressure taps to calculate structural response to wind. DAD, in combination with reliability-based procedures, allows the estimation of load factors in a more site- and structure-specific manner. In this paper we outline the reliability-based, database-assisted design procedure for tall, flexible buildings. The approach used for developing appropriate load factors is an extension of the approach used for low-rise buildings. In addition to the uncertainties relevant to low-rise buildings, the extended approach must take into account the uncertainties in the estimation of the natural frequencies of vibration, the modal shapes, and the damping coefficients. This extension is currently under development at NIST. The probabilistic performance criteria proposed herein account for those uncertainties and integrate information on the directional wind climate and the building's directional aerodynamics.

KEYWORDS: Database-assisted design, building response, reliability, tall buildings, wind

1.0 INTRODUCTION

Database-assisted design (DAD) for wind loads consists of (1) using simultaneous measurements of wind-induced pressure time histories at a large number of taps on a model structure's envelope, and (2) using those time histories to estimate the structural response in each member, both for rigid (Whalen *et al.*, 2002) and flexible buildings (Iancovici *et al.*, 2003). DAD allows the development of reliability procedures to estimate probabilities that the structure will satisfy specified performance criteria under extreme winds (Diniz and Simiu, 2003). In this paper we review relevant material from Iancovici *et al.* (2003) and outline such a procedure for tall, flexible buildings. The internal forces and their combinations, as they appear in design interaction formulas, are affected by climatological, micrometeorological, aerodynamic, and mechanical parameter uncertainties. The reliability procedure we propose accounts for those uncertainties and integrates information on the directional wind climate and the building's directional aerodynamics.

2.0 DAD AND DYNAMIC TALL BUILDING RESPONSE

Dynamic wind effects on high-rise buildings with no significant aeroelastic effects are currently determined from wind tunnel measurements by the high-frequency force-balance technique (HFFB). HFFB is relatively inexpensive, but (1) it is inapplicable to buildings with non-linear fundamental modes of vibration and

[1] Federal University of Minas Gerais, Brazil
[2] Technical University of Civil Engineering, Romania
[3] National Institute of Standards and Technology

significant higher vibration modes; (2) the base torque measured in a model is the sum of the floor torques, instead of the sum of the floor torques times the respective modal shape coordinates; (3) it provides no information on the mean and fluctuating wind loads distribution over the building height, needed to estimate wind effects at individual floors. DAD has none of these limitations. In addition, the DAD technique allows total peak responses to be calculated without resorting to the unnecessary approximation employed in the HFFB technique.

2.1 Mathematical Modeling of the Dynamic response

For any specified wind speed $V_{hq}(H)$ from direction q, using the appropriate tributary areas, the wind forces in the x-direction (x and y axes in the horizontal plan) at each floor level $F_{xq}(t)$ can be calculated from the wind pressures

$$p_{lx_q}(t) = \frac{1}{2}\rho C_{Plx_q}(t) V_{h\,q}^2(H). \qquad (1)$$

A similar equation holds for wind forces in the y-direction, $F_{yq}(t)$.

The system is assumed to be linear, with equations of motion in the x-direction:

$$[M_x]\{\ddot{x}_q(t)\} + [C_x]\{\dot{x}_q(t)\} + [K_x]\{x_q(t)\} = \{F_{xq}(t)\}, \quad (2)$$

where $[M_x]$, $[C_x]$, and $[K_x]$ are the mass, damping and stiffness matrix, $\{\ddot{x}_q(t)\}\{\dot{x}_q(t)\}$ and $\{x_q(t)\}$ are the floor accelerations, velocities and displacements, and $\{F_{x\,q}(t)\}$ are the forces in the x direction at each floor due to the wind speed $V_{hq}(H)$. Similar equations apply for the y direction and torsion due to the distance between the elastic and aerodynamic centers. The modal equation of x-motion is ($\xi_q(t)$ is the generalized coordinate)

$$\ddot{\xi}_q(t) + 2\varsigma_x \omega_x \dot{\xi}_q(t) + \omega_x^2 \xi_q(t) = M_x^{-1} Q_{xq}(t), \quad (3)$$

and

$$M_x = \sum_{k=1}^{n_f} m_k x^2(z_k),$$

$$Q_{xq}(t) = \sum_{k=1}^{n_f} x(z_k) F_{xq}(t, z_k) \qquad (4a,b)$$

are the fundamental modal mass and generalized force, respectively, k is the floor number, n_f is the total number of floors, $F_{xq}(t,z_k)$ is the wind force at floor k at time t, and ω_x and ζ_x are the circular frequency and damping ratio in the fundamental mode for direction x. Similar equations hold for the y direction and for torsion.

2.2 Wind and Gravity Effects on Structural Members

Consider a cross-section j of a member i (e.g., a column) at floor k of a tall building with n_f floors. The building has principal axes x and y. Using standard software the following influence coefficients can be calculated: m_{ijxWl} and m_{ijyWl}, the moments induced at the cross-section about the x and y axis by a unit load perpendicular to the building face at tap l; p_{ijWl}, the axial force induced by a unit load perpendicular to the building face at tap l; m_{ijxVxk} and m_{ijyVxk}, the moments induced about x and y by a unit horizontal force acting through the center of mass in the x direction at floor k; m_{ijxVyk} and m_{ijyVyk}, similar moments induced by a unit horizontal force acting through the center of mass in direction y at floor k; p_{ijVxk} and p_{ijVyk}, the axial forces induced by a unit horizontal force acting through the center of mass in the x and y directions at floor k; m_{ijxTk} and m_{ijyTk}, the moments induced about x and y by a unit torque about the center of mass in the z direction at floor k; p_{ijGlk}, the axial force induced at the cross-section by a unit gravity load acting at point l on floor k. These sets of influence coefficients can be combined with the recorded wind pressures and the inertial forces to calculate the internal forces. Given the pressure $p_{lq}(t)$ at tap l and its tributary area A_l, the wind force is $F_{lxq}(t) = p_{lxq}(t)A_l$. The moment at time t about axis x at cross-section j of member i, induced by the speed $V_{h\,q}(H)$ from direction q is

$$M_{ijxq}(t) = \sum_{l=1}^{n_t} m_{ijxWl} F_{lq}(t) + \sum_{k=1}^{n_f} [m_{ijxVxk} m_k \ddot{x}_{xkq}(t) + m_{ijxVyk} m_k \ddot{x}_{ykq}(t) + m_{ijxTk} I_{zk} \ddot{\theta}_{zkq}(t)] \quad (5)$$

where n_t is the total number of taps, m_k is the mass, $\ddot{x}_{xkq}(t)$ and $\ddot{x}_{ykq}(t)$ are the accelerations, and I_{zk} and $\ddot{\theta}_{zkq}(t)$ are the mass moment of inertia and the rotational acceleration about the z axis, with these quantities referred to floor k. The accelerations are yielded by equations such as Eq. 3. Expressions similar to (5) hold for the total moment about y and the total axial load.

2.3 Numerical example

We consider a 198 m tall building in an urban environment, with a 37 m x 37 m square plan (Iancovici *et al.*, 2003). The modal damping ratio is assumed to be 1 %. The gravity load is assumed to be 7 kN/m^2 (mass per floor: 960 x 10^3 kg). The fundamental modal mass and mass moment of inertia are then 21 x 10^6 kg in the x and y directions, and 4.79 x 10^9 kg, respectively. The elastic and mass centers are assumed to coincide. We consider here only the fundamental modes in the x, y directions and in torsion, but our approach allows the inclusion, if necessary, of any number of modes with any modal shapes. We assume that the natural periods of vibration are $T_x = T_y = 6.6$ s, and $T_\theta = 2.2$ s, and that the fundamental modal shapes are linear, e.g., $x(z) = z/H$; then $x_q(t)=x(z)\,\xi_q(t)$. We calculate the shear forces in the x and y directions at selected elevations of the structure for wind blowing from the 80-degree direction. (In the next section we describe an approach that accounts for wind speeds blowing from *all* 8 (or 16) directions q.) We obtain time histories of the total x and y base shears as shown in Fig. 1. We refer to this approach as the exact approach. For simplicity, in this example we do not calculate torsional moments acting at each elevation, whose influence on the results is small.

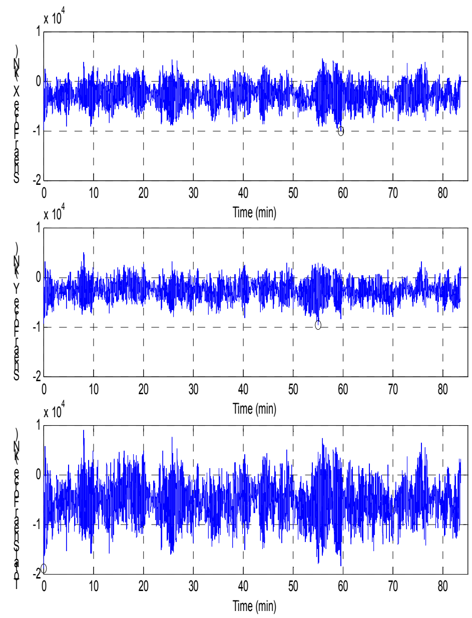

Figure 1. Base shear forces in the x direction (top), in the y direction (middle) and the total shear (algebraic sum).

Table 1 compares the results from the exact, point-in-time, and combination reduction factors approaches at selected elevations of the building. In this example the peak plus point-in-time approach underestimates the peak shear forces on the structure. The combination reduction factors approach is highly dependent on the factor α and yields in most cases estimates lower than the exact ones. The differences are greater at the lower portions of the building where base shear values are of greater importance.

Floor	Exact	Point-in-time	Comb. Red. Factors	
			$\alpha = 0.5$	$\alpha = 0.8$
1	19050	18455 (-3)	14992 (-21)	17880 (-6)
10	17946	17345 (-3)	14324 (-20)	17083 (-5)
20	16263	15429 (-5)	13112 (-19)	15485 (-5)
29	13563	13180 (-3)	11230 (-17)	13197 (-3)
38	11261	10943 (-3)	9323 (-17)	11028 (-2)
50	7449	6709 (-10)	6104 (-18)	7218 (-3)
56	4256	3896 (-8)	3666 (-14)	4292 (+1)
61	2564	2428 (-5)	2105 (-18)	2506 (-2)
64	1202	1051 (-13)	1007 (-16)	1184 (-1)
66	299	283 (-5)	273 (-9)	313 (+5)

Note. Numbers in parentheses are percentage differences with respect to the exact approach.

Table 1. Shear forces (in kN) at selected floors according to different approaches.

3.0 WIND DIRECTIONALITY, AND MEAN RETURN PERIODS OF WIND EFFECTS

For wind speeds blowing from direction q, the calculated moments and axial loads are then used in appropriate design equations; e.g., for a steel column with relatively large axial force in Load and Resistance Factor Design,

$$b_{ijq}(t) = \frac{P_{ij,q,tot}(t)}{\phi P_{ni}} + \frac{8}{9}\left(\frac{M_{ijx,q,tot}(t)}{\phi_b M_{nix}} + \frac{M_{ijy,q,tot}(t)}{\phi_b M_{niy}}\right) \tag{6}$$

where P_{ni}, M_{nix}, and M_{niy} are the nominal axial and flexural strengths of member i, ϕ and ϕ_b are the axial and flexural resistance factors (AISC, 2001 Sect. H), and the quantities in the numerators are the total (hence the subscript *tot*) axial load and moments due to the combination of wind effects from direction q and gravity effects, each affected by the appropriate load factor(s).

Assume that in year p (or storm p) the mean hourly wind speeds in directions q =1,2,..,8 (or q=1,2,..,16) at the top of the building are $V_{pq}(H)$. By using Eqs. 3 to 6 (and similar equations) it is possible to calculate the corresponding wind effects b_{ijqp} for each q, where the subscript p denotes the year (or the storm) being considered. We are interested in each year (storm) p in the largest of the q maximum wind effects $\max_t\{b_{ijqp}(t)\}$, denoted by b_{ijp}. We thus obtain a sample of size p of the wind effects b_{ijp}. Let us consider the case of p hurricanes and assume p=1,000, and a rate of arrival of hurricanes at the site being considered ν=0.5/year. We rank order the time series b_{ijp}. The largest, the second largest, and the 40th largest of the p values of the rank-ordered series is an estimator of the wind effect b_{ij} (also referred to as a "response index") with a mean recurrence interval of 1,000/0.5=2,000 years, 1,000 years, and 50 years, respectively. If the size of the directional wind speeds data sample is small (e.g., 20-yr), it can be augmented by numerical simulation. The computations just described can be rendered more efficient by constructing time series that do not include the effects associated with gravity loads in Eq. 6 or similar equations. The terms associated with gravity loads would be added at the end of the computational process to yield the response indices needed to verify the adequacy of the design.

In principle this approach would require the solution of a fairly large number of ordinary differential equations similar to Eq. 3. However, in practice it is sufficient to solve such equations for, say, the 50th, 40th, 30th, 20th, 10th, and first highest speeds $V_{pq}(H)$ for each q. This would allow interpolations of responses b_{ijqp} for intermediate speeds. Note also that the linearity of equations similar to Eq. 5 ensures that once a set of three differential equations (two for translational motions and one for torsional motion) for a specified wind speed $V_{pq}(H)$ have been solved, all the corresponding quantities b_{ijpq} are obtained by linear algebraic operations.

4.0 LOAD FACTORS AND PROBABILISTIC PERFORMANCE CRITERIA

For load and resistance factor design, the design of the cross-section *j* of a member *i* is adequate if its response index (e.g., for the type of response associated with Eq. 6, the quantity b_{ij}) should, according to the ASCE 7 Standard (ASCE, 2002), corresponds to a mean recurrence interval of 500 years. This statement constitutes a performance criterion that, in conjunction with the use of the load factors and load combinations specified in the ASCE 7 Standard, would in our opinion be compatible with the ASCE 7 Standard requirements. However, for special projects, it may be appropriate to adopt a mean recurrence interval longer than 500 years. In our opinion the adoption of the performance criterion just stated, based as it is on the methodology described in this paper and the load combinations and load factors specified in the ASCE Standard, would be a useful advance in the state of the art.

Additional progress can be made by replacing the wind load factors specified in the ASCE 7 Standard by load factors accounting in a more site- and structure-specific manner for the uncertainties inherent in the estimation of the wind effects. Research into the development of such factors would eventually result in even more reliable designs of tall buildings. The approach used for developing appropriate load factors is an extension of the approach used for low-rise buildings in Diniz and Simiu (2003) and Minciarelli *et al.* (2001). In addition to the uncertainties relevant to the low-rise building case, the extended approach must take into account the uncertainties in the estimation of the natural frequencies of vibration, the modal shapes, and the damping coefficients. This extension is currently under development at NIST.

5.0 CONCLUSIONS

Database-assisted design (DAD) uses time histories of pressures simultaneously measured in the wind tunnel at a large number of pressure taps to calculate structural response to wind. DAD allows the development of reliability procedures to estimate probabilities that the structure will satisfy specified performance criteria under extreme winds. In this paper we outline such a procedure for tall, flexible buildings. The internal forces and their combinations are affected by climatological, micrometeorological, aerodynamic, and mechanical parameter uncertainties. The reliability procedure we propose accounts for those uncertainties and integrates information on the directional wind climate and the building's directional aerodynamics.

6.0 REFERENCES

American Institute of Steel Construction (2001), *Manual of steel construction: load and resistance factor design*, 3rd Edition.

American Society of Civil Engineers (2002), *ASCE Standard ASCE 7-02, Minimum design loads for buildings and other structures*, American Society of Civil Engineers.

Diniz, S.M.C. and Simiu, E. (2003), "Probabilistic description of wind effects and wind load factors for database-assisted design", In: *Proc. 11th Int. Conf. on Wind Engineering, Lubbock, TX, 2003*, 739-746.

Iancovici, M., Riley, M.A., Sadek, F., and Simiu, E. (2003), “Wind effects on high-rise buildings: database-assisted design versus the high-frequency force-balance technique”, In: *Proc. 11th Int. Conf. on Wind Engineering, Lubbock, TX, 2003*.

Minciarelli, F., Gioffrè, M., Grigoriu, M., and Simiu, E. (2001), “Estimates of extreme wind effects and wind load factors: influence of knowledge uncertainties”, *Probabilistic Eng. Mechanics*, **16**, 331-340.

Whalen, T., Sadek, F., and Simiu, E. (2002), “Database-assisted design for wind: basic concepts and software development”, *Journal of Wind Engineering and Industrial Aerodynamics*, **90**, 1349-1368.