Probabilistic Performance Criteria for Tall Buildings Subjected to Wind Loads

by

Sofia M.C. Diniz¹, Mihai Iancovici², William Fritz³, Michael A. Riley³ and Emil Simiu³

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

\[
p_{xq}(t) = \frac{1}{2} \rho C_{plq}(t) V_{hq}^2 (H). \tag{1}
\]

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:

\[
[M_x] \{\ddot{v}_q(t)\} + [C_x] \{\dot{v}_q(t)\} + [K_x] \{v_q(t)\} = \{F_x(t)\}, \tag{2}
\]

where \([M_x]\), \([C_x]\), and \([K_x]\) are the mass, damping and stiffness matrix, \(\{v_q(t)\}\) and \(\{\dot{v}_q(t)\}\) are the floor accelerations, velocities and displacements, and \(\{F_x(t)\}\) 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)

\[
\dddot{\xi}_q(t) + 2\zeta_x \omega_n \ddot{\xi}_q(t) + \omega_n^2 \dot{\xi}_q(t) = M_x^{-1} Q_{xq}(t), \tag{3}
\]

and

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

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

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 \( \omega_n \) and \( \zeta_x \) 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 \( k \); \( p_{ijVxk} \) and \( p_{ijVyk} \), the axial forces induced by a unit horizontal force acting through the center of mass in \( x \) and \( y \); \( m_{ijxTz} \) and \( m_{ijyTz} \), similar moments induced by a unit horizontal force acting through the center of mass in \( x \) and \( y \) directions at floor \( k \); \( p_{ijTz} \) and \( p_{ijTy} \), the axial forces induced by a unit horizontal force acting through the center of mass in the \( x \) and \( y \) directions 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 \( F_{lq}(t) = p_{lq}(t)A_l \). The moment at time \( t \) about axis \( x \) at cross-section \( j \) of member \( i \), induced by the speed \( V_{lq}(t) \), is

\[
M_{ijq}(t) = \sum_{l=1}^{n_t} m_{ijlq} F_{q}(t) + \sum_{k=1}^{n_t} m_{ijrk} \ddot{x}_{skq}(t) + m_{ijxq} I_{zkq} \ddot{\theta}_{aq}(t)
\]

where \( n_t \) is the total number of taps, \( m_k \) is the mass, \( \ddot{x}_{skq}(t) \) and \( \ddot{\theta}_{aq}(t) \) are the accelerations, and \( I_{zk} \) and \( \ddot{\theta}_{aq}(t) \) 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: \( 960 \times 10^3 \) kg). The fundamental modal mass and mass moment of inertia are then \( 21 \times 10^6 \) kg in the \( x \) and \( y \) directions, and \( 4.79 \times 10^9 \) 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 \( x_i(t) = x(z) \xi_{q}(t) \).

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.

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

<table>
<thead>
<tr>
<th>Floor</th>
<th>Exact</th>
<th>Point-in-time</th>
<th>Comb. Red. Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\alpha = 0.5$</td>
</tr>
<tr>
<td>1</td>
<td>19050</td>
<td>18455 (-3)</td>
<td>14992 (-21)</td>
</tr>
<tr>
<td>10</td>
<td>17946</td>
<td>17345 (-3)</td>
<td>14324 (-20)</td>
</tr>
<tr>
<td>20</td>
<td>16263</td>
<td>15429 (-5)</td>
<td>13112 (-19)</td>
</tr>
<tr>
<td>29</td>
<td>13563</td>
<td>13180 (-3)</td>
<td>11230 (-17)</td>
</tr>
<tr>
<td>38</td>
<td>11261</td>
<td>10943 (-3)</td>
<td>9323 (-17)</td>
</tr>
<tr>
<td>50</td>
<td>7449</td>
<td>6709 (-10)</td>
<td>6104 (-18)</td>
</tr>
<tr>
<td>56</td>
<td>4256</td>
<td>3896 (-8)</td>
<td>3666 (-14)</td>
</tr>
<tr>
<td>61</td>
<td>2564</td>
<td>2428 (-5)</td>
<td>2105 (-18)</td>
</tr>
<tr>
<td>64</td>
<td>1202</td>
<td>1051 (-13)</td>
<td>1007 (-16)</td>
</tr>
<tr>
<td>66</td>
<td>299</td>
<td>283 (-5)</td>
<td>273 (-9)</td>
</tr>
</tbody>
</table>

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

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,

$$b_{ij}(t) = \frac{P_{ij,q,tot}(t)}{\phi_{Pi}} + \frac{8}{9}\left(\frac{M_{ij,x,q,tot}(t)}{\phi_{Pi}M_{nix}} + \frac{M_{ij,y,q,tot}(t)}{\phi_{Pi}M_{nij}}\right)$$

(6)

where $P_{ni}$, $M_{nix}$, and $M_{nij}$ are the nominal axial and flexural strengths of member $i$. $\phi$ and $\phi_b$ 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 $b_{ijp}$ 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 $\max\{b_{ijp}(t)\}$, denoted by $b_{ij}$.

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 $\nu=0.5$/year. We rank order the time series $b_{ijp}$. The largest, the second largest, and the $40^{th}$ 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 $50^{th}$, $40^{th}$, $30^{th}$, $20^{th}$, $10^{th}$, and first highest speeds $V_{pq}(H)$ for each $q$. This would allow interpolations of
responses $b_{ijpq}$ 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


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