

Database-Assisted Design for Wind Effects on High-Rise Structures and Its Potential for Assessment of CFD Simulation

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ABSTRACT: Efforts are being made to perform CFD (Computational Fluid Dynamics)-based estimates of wind effects on tall buildings that are sufficiently reliable to allow their use in lieu of estimates based on wind tunnel measurements. For practical purposes the assessment of the quality of the CFD simulation should be based on the adequacy of the simulation of the wind effects induced in the structure by the CFD aerodynamic data, rather than on the precision with which the various parameters that define the oncoming atmospheric boundary layer wind flow are reproduced. This approach requires a capability for estimating dynamic structural response induced by simulated CFD pressures that is effective and transparent. The paper briefly describes such a capability, referred to as database-assisted design, and its potential application in the context of CFD-based pressure time histories simulation. An illustration of the use of pressure time histories to estimate structural wind effects on tall buildings is presented with reference to a 60-story reinforced concrete structure.

1 INTRODUCTION

The quality of the CFD simulation of pressure time histories depends upon the extent to which the various flow parameters that define the atmospheric flow are adequately reproduced. However, it should be kept in mind that the objective of the simulation is to determine structural response to wind. The significance of deviations of the flow parameters from “true” flow parameters needs to be judged in terms of this objective. Therefore, to establish metrics on the degree to which various deviations are acceptable it is necessary to estimate the sensitivity to such deviations of the structural wind effects of interest. This requires in turn the effective, realistic, and transparent estimation of those effects. In this paper we present a procedure, referred to as database-assisted design (DAD), for achieving such estimation. Given the synchronous time histories of simulated pressures at a large number of points on the exterior surface of a given structure, the procedure automatically determines the values of the demand-to-capacity indexes, the inter-story drift, and the top floor accelerations corresponding to mean recurrence intervals (MRIs) specified in standards and codes. In view of interactions among the atmospheric flow parameters sensitivity studies to be conducted in the future should in our opinion be based on experiment design techniques (see, e.g., Filliben and Simiu (2010)), rather than on the considerably less reliable one-factor-at-a time methods.

The paper is organized as follows. In the next section we describe the DAD procedure used to determine the building dynamic response under given synchronous pressure time histories obtained at a large number of points on the external surface of the building envelope. Using wind tunnel data, we then demonstrate the application of the procedure to the CAARC (Commonwealth Aeronautical Advisory Research Council) standard tall building, a structure commonly

utilized in the literature for comparative studies of wind engineering experiments. Our objective in this paper is restricted to drawing the attention of CFD practitioners to the potential offered by database-assisted design to help develop assessment methods for CFD-based computations that, unavoidably, use practical but imperfect models of atmospheric turbulence.

2 DATABASE-ASSISTED DESIGN (DAD)

2.1 Basic Description of the DAD methodology

The DAD methodology for calculating the dynamic response of a high-rise building is represented in Figure 1. An intermediate output of the methodology is a response database of demand-to-capacity indexes, inter-story drift, and top floor accelerations induced by various wind speeds (e.g., 20 m/s to 80 m/s in increments of 10 m/s) for various directions (in increments of, e.g., 10°). Structural dynamic analyses are performed for each wind speed and direction, using time-series of aerodynamic forces acting at the mass center of each floor based on measured pressures. For each wind speed and direction, the responses are obtained from the corresponding directional aerodynamic and inertial floor loads multiplied by the appropriate influence coefficients calculated by conventional structural analysis programs. Two cases pertaining to combinations of gravity and wind loads applied for strength design are:

$$\begin{aligned} 1.2D+1.0L+1.0W & \quad (\text{LC1}) \\ 0.9D+1.0W & \quad (\text{LC2}) \end{aligned} \tag{1}$$

where D is the total dead load, L is the live load, and W is the wind load with the specified MRI (see, e.g., ASCE 7-10 Draft Standard (2010)). Peak responses with specified MRIs of wind effects are obtained by producing a one-dimensional vector of responses from the directional responses, that is, the responses induced by the directional wind speeds in each of a large number of storm events. This is done by selecting the maximum of the directional responses for each storm event (Simiu et al., 2008). For hurricanes such wind speeds are listed, e.g., in www.nist.gov/wind. For non-hurricane regions the wind speeds are generated by numerical simulation from measured data (Grigoriu, 2009). The response with any MRI is obtained from the one-dimensional vector using non-parametric statistics (see Sect. 2.4.3.2.2 in Simiu and Miyata (2006)). Note that wind speeds in the climatological database must be transformed to hourly speeds at the top of the building by accounting for the terrain exposure of the building. The design is satisfactory if the peak responses for specific mean recurrence intervals, such as demand-to-capacity index, inter-story drift, and accelerations, satisfy safety and serviceability requirements. Otherwise, an iteration of the procedure just described is required until the design is satisfactory.

The DAD approach entails a clear division of tasks between the wind engineer and the structural engineer, and has the advantages of transparency and accountability. Wind climatology and aerodynamics are the province of the wind engineering consultant and are automatically transformed by DAD into loadings. DAD makes use of the loadings for structural dynamics, analysis, and design purposes. This joint potential of wind and structural engineering is made possible by the vast computational resources now routinely available. DAD can also make use of pressures measured on aeroelastic models (see Diana et al. (2009)).

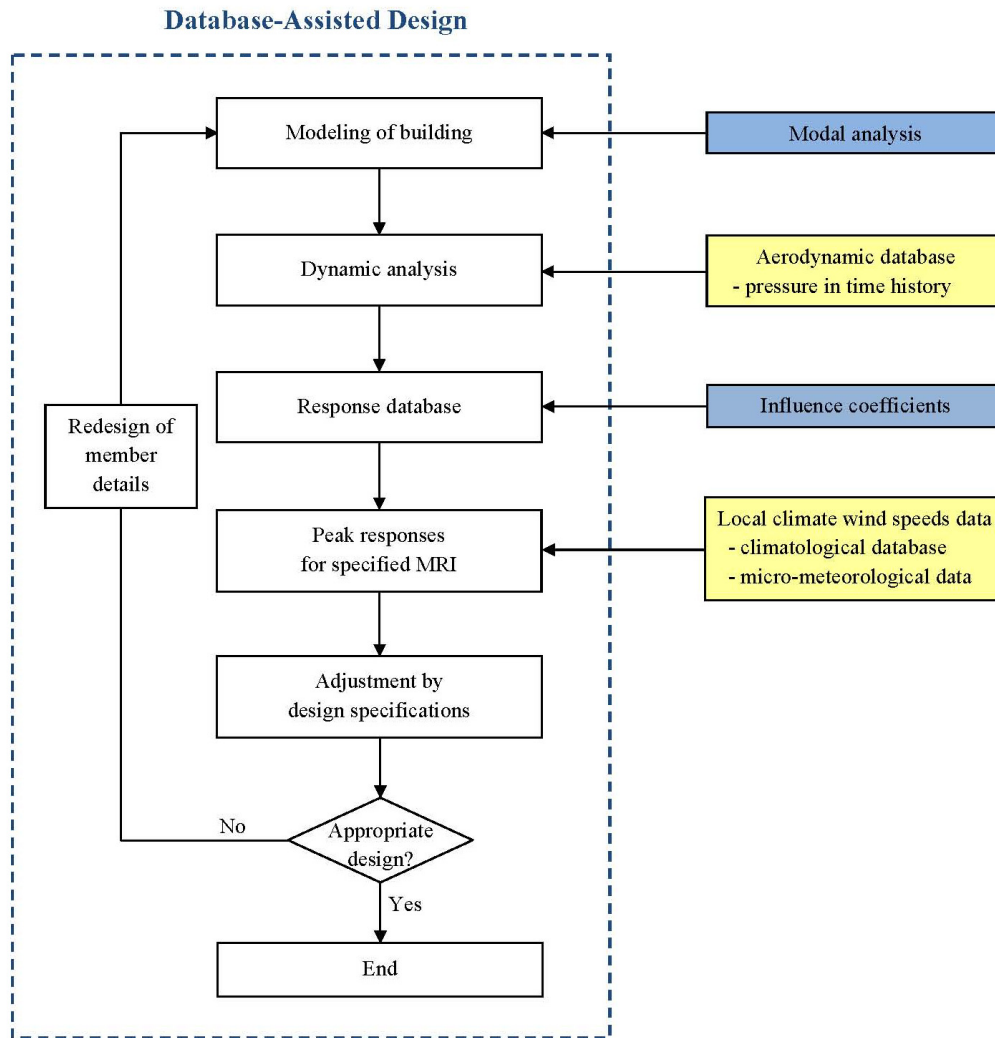


Figure 1. DAD procedure

2.2 Structural responses due to wind

The DAD methodology contains a module for checking whether the design satisfies design specifications for safety and serviceability. For steel structures see Spence (2009). For reinforced concrete structures the specifications used are those in Building Code Requirements for Structural Concrete 318-08 (ACI, 2008) and ASCE 7-05 Standard (ASCE, 2005). The responses considered are the demand-to-capacity index, the inter-story drift, and accelerations at the top floor.

2.2.1 Demand-to-capacity index

The demand-to-capacity index (DCI) measures the adequacy of the strength of a structural member and is defined as a function of the ratios of the internal forces at a cross section to the cross section's strength. An index higher than unity indicates that the strength is inadequate. For reinforced concrete two demand-to-capacity indexes are of interest: B_{ij}^{PM} for axial and/or flexural

loads, and B_{ij}^{VT} for shear and torsion. The index B_{ij}^{PM} pertains to the interaction of axial and/or flexural loads for columns and beams:

$$\begin{aligned} B_{ij}^{PM} &= \frac{M_u}{\phi_m M_n} && \text{(for tension-controlled sections)} \\ &= \frac{P_u}{\phi_p P_n} && \text{(for compression-controlled sections)} \end{aligned} \quad (2)$$

where M_u and P_u are the bending moment and axial force, M_n and P_n are the nominal moment and axial strengths, and ϕ_m and ϕ_p are reduction factors for flexural and axial strengths, respectively. Expressions for columns under bi-axial bending moments and axial force are given in ACI 318-08 for compression-controlled sections and PCA (2008) for tension-controlled sections.

The index B_{ij}^{VT} pertains to the interaction of shear and torsion for columns and beams:

$$B_{ij}^{VT} = \frac{\sqrt{V_u^2 + \left(\frac{T_u p_h b_w d}{1.7 A_{oh}^2} \right)^2}}{\phi_v (V_c + V_s)} \quad (3)$$

where V_c and V_s are the nominal shear strengths of the concrete and reinforcement, respectively, V_u is the shear force, T_u is the torsional moment, ϕ_v is the reduction factor for shear strength, p_h is the perimeter enclosed by the centerline of the outermost closed stirrups, A_{oh} is the area enclosed by the centerline of the outermost closed stirrups, b_w is the width of the member, and d is the distance from extreme compression fiber to the centroid of the longitudinal tension reinforcement.

2.2.2 Inter-story drift

Time-series of inter-story drifts at the i^{th} floor in the x direction, $d_{i,x}(t)$, is:

$$d_{i,x}(t) = \frac{[x_{i+1}(t) - D_{i+1,y} \theta_{i+1}(t)] - [x_i(t) - D_{i,y} \theta_i(t)]}{h_i} \quad (4)$$

where $x_i(t)$ and $\theta_i(t)$ are the displacements and rotation of the mass center at the i^{th} floor, $D_{i,y}$ is y -axis distance from the mass center to the point of interest on the i^{th} floor, and h_i is the i^{th} story height. A similar expression holds for the y -direction.

The limit of inter-story drift used in this study is 1/400 for MRI = 20 years specified by the ASCE 7-05 commentary (see Section CC.1.2 in ASCE 7-05).

2.2.3 Top floor acceleration

The time series of resultant acceleration at the roof, $a_r(t)$ is:

$$a_r(t) = \sqrt{[\ddot{x}_{top}(t) - D_{top,y} \ddot{\theta}_{top}(t)]^2 + [\ddot{y}_{top}(t) + D_{top,x} \ddot{\theta}_{top}(t)]^2} \quad (5)$$

where $\ddot{x}_{top}(t)$, $\ddot{y}_{top}(t)$, and $\ddot{\theta}_{top}(t)$ are the accelerations of the top floor mass center for the x , y , and θ axes, and $D_{top,x}$ and $D_{top,y}$ are distances from the mass center to the corners of the top floor.

The limit of peak acceleration used in this study is 25 mg for a 10-year MRI for office buildings (Isyumov et al., 1992).

2.3 Design requirements of wind-induced forces from experiments

The forces and pressures estimated through wind tunnel testing shall be limited to not less than 80% of their ASCE 7-based counterpart (ASCE 7-05 Section C6.6). This lower limit is also ap-

plicable to CFD-based designs. If DAD-based overturning moments do not satisfy this requirement the demand-to-capacity index is adjusted as:

$$B_{ij}^* = \gamma B_{ij}$$

$$\gamma = \frac{0.8}{M_o^{DAD} / M_o^{ASCE7}} \quad (6)$$

where M_o^{DAD} and M_o^{ASCE7} are the overturning moments obtained from DAD and ASCE 7-05.

3 DESCRIPTION OF THE CAARC BUILDING

The 60-story reinforced concrete building used in this study has $45.72 \text{ m} \times 30.48 \text{ m}$ horizontal dimensions, is 182.88 m high, and is known as the CAARC building. The building has a moment-resistant frame structural system (Figure 2) similar to the structural system studied by Teshigawara (2001), and consists of 2880 columns, 4920 beams, and diaphragm slabs assumed to be rigid. The building was assumed to have suburban exposure near Miami, Florida. Directional wind climatological data are listed in www.nist.gov/wind. The long side of the building was assumed to be normal to the South-North direction. The damping ratio was assumed to be 2 % in all three modes. Structural properties were determined iteratively, first by using the ASCE 7 Standard procedure for calculating dynamic along-wind response, and then by using the HR_DAD_RC (High-Rise Database-Assisted Design for Reinforced Concrete structures) software developed by NIST for reinforced concrete structures. Details of the HR_DAD_RC software are given in www.nist.gov/wind.

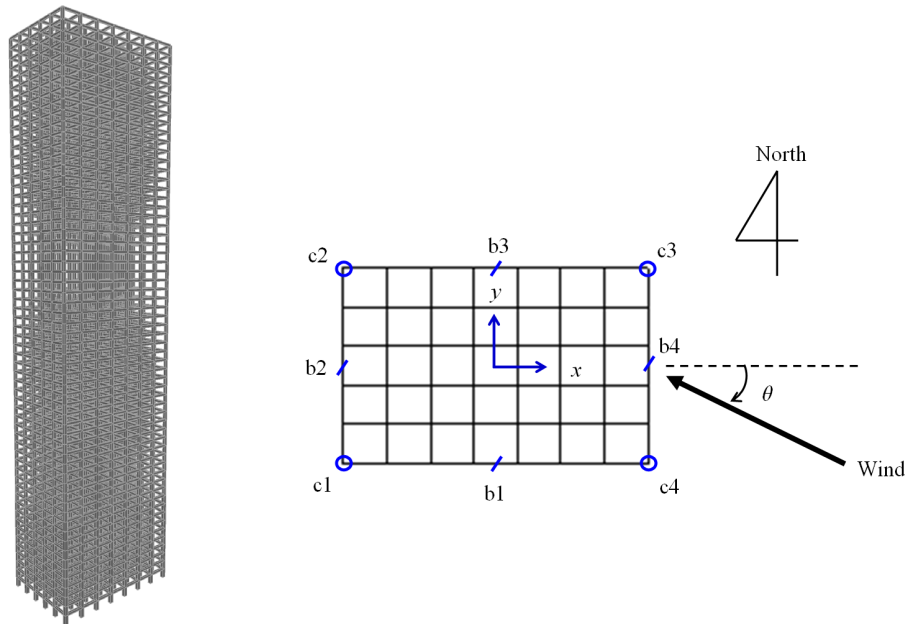


Figure 2. Schematic and plan views of a building

4 ESTIMATES OF STRUCTURAL RESPONSE

To illustrate the estimation of structural wind effects on the CAARC building we used synchronous pressure time histories at a total of 120 pressure taps obtained at the Prato (Italy) Inter-University Research Centre on Building Aerodynamics and Wind Engineering (CRIACIV-DIC) Boundary Layer Wind Tunnel (Figure 3). The model scale was 1:500, and the sampling frequency was 250 Hz. The reference model mean wind speed was 23.2 m/s at the top of the building.

Demand-to-capacity indexes (DCIs) corresponding to 700-year and 1700-year mean recurrence intervals (MRI) were obtained for four corner columns on the 1st floor and four spandrel beams on the 31st floor (Figure 2). Results are also presented 20-year MRI inter-story drift and 10-yr MRI top floor accelerations.

Peak overturning moments. Ratios of peak overturning moments based on DAD and on ASCE 7 are less than 0.8 for MRI = 700 years and MRI = 1700 years and the corresponding index adjustment coefficients γ are 1.16 and 1.19, respectively (Table 1). Peak DCIs for both MRIs in DAD were adjusted by multiplying the adjustment coefficients by the peak DCIs obtained from the peak response database.

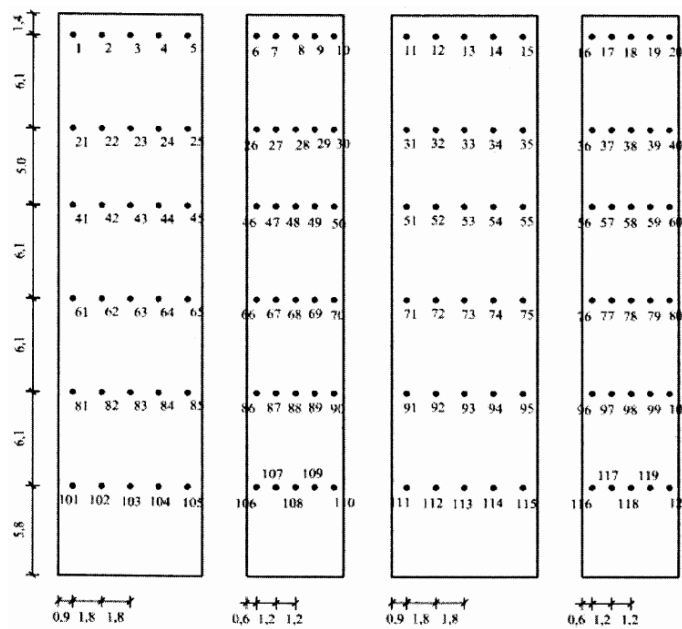


Figure 3. Location of pressure taps, dimensions in meter $\times 10^{-2}$ (Venanzi, 2005)

Table 1. Peak overturning moments

	MRI = 700 years	MRI = 1700 years
$M_{ox}^{DAD} / M_{ox}^{ASCE7}$	0.69	0.67
$M_{ov}^{DAD} / M_{ov}^{ASCE7}$	0.78	0.74
γ	1.16	1.19

Demand-to-capacity indexes (DCIs). For the corner columns, DCIs for axial force and bending moments interaction (B_{ij}^{PM}) were 0.81 to 0.86 for MRI = 700 years and 0.95 to 1.00 for MRI = 1700 years. The DCIs for the shear force and torsional moment interaction (B_{ij}^{VT}) were 0.44 to 0.73 and 0.44 to 0.48 for MRIs of 700 and 1700 years, respectively (Figure 4). For the spandrel beams, values of B_{ij}^{PM} were 0.37 to 0.60 and 0.44 to 0.74 and values of B_{ij}^{VT} were 0.28 to 0.44 and 0.32 to 0.53, corresponding to MRI = 700 and 1700 years (Figure 4). The results show that the structural members on the faces of the East and the West have higher DCIs than those on the South and the North faces. Note that differences between DCIs for the two MRIs are member-dependent.

Interstory drift and top floor acceleration. The largest inter-story drift (i.e., y -direction drift in this study) was $d_{i,y} = 0.0029$ at the four corners at the 44th floor, rather than $1/400 = 0.0025$. The peak resultant accelerations were about the same at the building corners, with the largest values being 27.9 mg, rather than 25 mg. The design is seen to be governed by serviceability constraints.

DAD's efficiency in determining building response corresponding to various set of simulated pressure time histories makes it possible to assess the significance of the various parameters that determine the response and of uncertainties in those parameters.

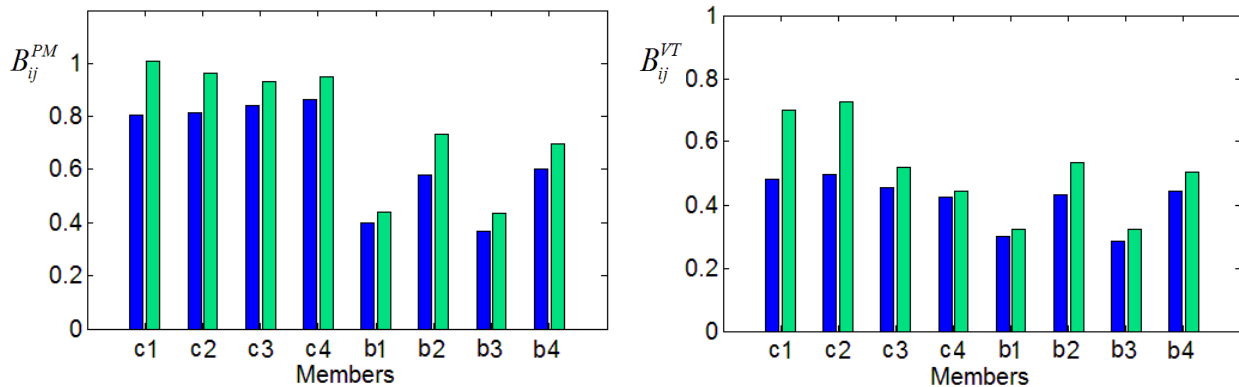


Figure 4. Demand-to-capacity indexes for selected members
 (left bar for MRI = 700 years, right bar for MRI = 1700 years)

5 CONCLUDING REMARKS

The quality of the CFD simulation of pressure time histories depends upon the extent to which the various flow parameters that define the atmospheric flow are adequately reproduced. However, the significance of deviations of the flow parameters from “true” flow parameters needs to be judged in structural engineering, rather than in strictly fluid dynamics terms. To establish metrics on acceptable deviations from conventional models of atmospheric boundary layer flows it is therefore necessary to perform sensitivity studies on the structural responses of interest as functions of such deviations. This requires in turn the effective, realistic, and transparent estimation of the structural response induced by various simulated flows. In this paper we present a database-assisted design procedure, applicable to tall, dynamically sensitive buildings, for determin-

ing the calculated structural response corresponding to any given CFD simulation of aerodynamic time histories. Given the synchronous time histories of simulated pressures at a large number of points on the exterior surface of a given structure, the procedure automatically determines the values of the demand-to-capacity indexes, the inter-story drift, and the top floor accelerations corresponding to mean recurrence intervals (MRIs) specified in standards and codes. The DAD procedure in this study helps CFD practitioners develop assessment methods for CFD-based computations that, unavoidably, use practical but imperfect models of atmospheric turbulence.

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