Simplified Wind Flow Model for the Estimation of Aerodynamic Effects on Small Structures

DongHun Yeo, M.ASCE[1]; and Arindam Gan Chowdhury, M.ASCE[2]

Abstract: The reliable measurement of pressures on low-rise buildings in the atmospheric boundary layer (ABL) flow remains a challenge, as has been shown by the large discrepancies among results obtained in different wind tunnel facilities or even in the same wind tunnel. Two major causes of the discrepancies are the difficulty of simulating large-scale, low-frequency turbulent fluctuations uniformly across laboratories and the small scale of models in typical civil engineering wind tunnels. To address these issues, it was proposed that a simplified flow be used in laboratory simulations, rather than a conventional ABL flow. In the simplified flow the reference mean wind speed is larger than the mean wind speed of the ABL flow, and the low-frequency fluctuations present in the ABL flow are suppressed; that is, the peak energy of the missing low-frequency fluctuations is supplied in the simplified flow by the increment in the mean wind speed, which may be regarded as a flow fluctuation with zero frequency. High-frequency turbulent fluctuations, which typically affect flow reattachment, are approximately the same in the ABL and the simplified flow. Because, over small distances, low-frequency fluctuations are highly coherent spatially for small low-rise buildings with dimensions of up to approximately 20 m (e.g., single-family residential homes), the peak aerodynamic effects of the two flows may be hypothesized to be approximately the same. Preliminary experimental results obtained in University of Western Ontario's ABL wind tunnel facility and Florida International University's small-scale Wall of Wind facility are shown to support this hypothesis. The use of the proposed simplified flow is currently being tested by the authors for application to computational wind engineering (CWE) applications. Such use eliminates the need to simulate the lower frequency fluctuations of the boundary layer flow and thus makes it possible to achieve practical CWE calculations, and it is advantageous in experiments from the points of view of measurement accuracy, model scaling, repeatability of the simulations, and computational efficiency. **DOI:** 10.1061/(ASCE)EM.1943-7889.0000508. © *2013 American Society of Civil Engineers.*

CE Database subject headings: Boundary layers; Wind loads; Low-rise buildings; Wind tunnels.

Author keywords: Atmospheric boundary layer; Computational wind engineering; Flow modeling; Low-rise buildings; Wind engineering; Wind tunnel tests.

Introduction

Challenges for Testing Low-Rise Buildings

Performing wind tunnel experiments is more difficult for low-rise buildings than for high-rise buildings, as it entails partial simulation of the entire atmospheric boundary layer (ABL) and accurate modeling of wind turbulence in the lower reaches of the atmospheric surface layer (ASL) (Cermak 1995; Kozmar 2011; Stathopoulos 2003; Uematsu and Isyumov 1999). An international comparison reported by Fritz et al. (2008) showed that, depending upon low-rise building dimensions, terrain exposure, and wind speed direction, the ratio between the largest and the smallest of the internal forces obtained from pressure measurements in six wind tunnels (Clemson University, Colorado State University, Texas Tech University, University of Western Ontario, Nantes Centre Scientifique et Technique du Bâtiment, and Tsukuba Building Research Institute) varied between 1.5 and 3.5. For additional results, see Surry et al. (2003), St. Pierre et al. (2005), and Coffman et al. (2010). Bienkiewicz et al. (2009) showed that discrepancies among results obtained in different wind tunnels, and even in the same wind tunnel, were the result of mutual inconsistencies in the simulation of atmospheric flows.

It is clear from these studies that reliable measurement of pressures on low-rise buildings in the ABL flow remains a challenge. Two major causes of the discrepancies in the results are (1) the difficulty of simulating large-scale, low-frequency turbulent fluctuations uniformly across laboratories and (2) the small scale of models in typical civil engineering wind tunnels. Owing to limitations of the test section sizes, the integral turbulence scales of flows generated in typical civil engineering wind tunnels range in most cases from 1:200 to 1:500. Low-rise building models built at such scales, as specified by ASCE 7-10, Section 31.2 (ASCE 2010), are too small to allow the development in the incident flow of roof-height small-scale turbulence capable of generating peak suctions in the roof comparable to full-scale suctions (Mahmood 2011; Stathopoulos 2003; Tieleman 2003). In addition, the small models are not of sufficient size to accommodate a large number of pressure taps. New simulation techniques must be developed to allow for testing of large-scale models for low-rise structures to better capture the peak aerodynamic effects (Banks and Meroney 2001; Tieleman 2003).

To address these issues, it is proposed that a simplified flow, rather than a conventional ABL flow, be used in laboratory simulations of pressures on small low-rise buildings. It is hypothesized that the low-frequency fluctuations within the turbulent spectrum of the oncoming flow can be replaced by a commensurate increment in

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Note. This manuscript was submitted on October 13, 2011; approved on July 5, 2012; published online on July 30, 2012. Discussion period open until August 1, 2013; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Engineering Mechanics***, Vol. 139, No. 3, March 1, 2013. ©ASCE, ISSN 0733-9399/2013/3-367–375/$25.00.

mean speed. Indeed, over dimensions comparable to small building dimensions, the ABL flow fluctuations are reasonably close to being perfectly coherent spatially. Therefore, over the time interval during which the low-frequency components of the simulated ABL flow fluctuations attain their peak, the flow-structure interaction can be expected not to differ substantially from its counterpart in a simplified flow with (1) no low-frequency components and (2) mean speeds greater than the mean speeds of the simulated ABL flow by a factor of $c > 1$, described later in this paper, that compensates for the missing contribution of those components to the peak aerodynamic effect. This simplified flow model enables the improvement of the reliability and repeatability of pressure simulations for such buildings in ABL wind flow. For low-rise buildings tested in commercial wind tunnels, the ratio of the integral turbulence length to the characteristic dimension of the model is typically smaller than its corresponding ratio for the prototype [ASCE 7-93 (ASCE 1994, p. 11)]. This means that replacing the lower-frequency fluctuations with a theoretically based increment in the mean wind speed (see section Requisite Increase of the Mean Wind Speed in Simplified Flows: Rectangular Buildings, Mean Wind Normal to a Building Face) results in a more realistic simulation of wind effects than is the case for wind tunnel simulations.

Organization of the Paper

This paper presents analytical and experimental investigations of the role of spatial coherence on the total force exerted on a face of a rectangular building by an ABL flow normal to that face. The results of the investigation are shown to lend support to the hypothesis that the simplified flow model is useful and to estimate the increase in the mean speed of the simplified flow required to compensate for the elimination of the low-frequency fluctuations present in the ABL. The paper discusses, for peak pressures acting throughout the external building surface and for two representative angles of attack: (1) the extent to which the simplified flow induces peak pressures similar to those induced by the ABL flow and (2) the repeatability of the tests. We comment on the relevance of those results for CWE simulations of pressures on buildings with relatively small dimensions, and we present the conclusions of this work.

Spatial Coherence of Peak Along-Wind Fluctuating Load

To assess the hypothesis that the reduction of wind effects as the result of imperfect spatial coherence is small for relatively small buildings, we consider peak along-wind loads on the windward face of a building in a flow with mean speed described by a power law. A 1:100 model of a 1:12 gable-roofed building was selected for this purpose. The prototype dimensions of the building are 7.32 m in eave height, 19.05 m in width, and 12.19 m in length. Pressure time series were measured in the wind tunnel of the University of Western Ontario and are available in the NIST aerodynamic database (NIST 2008). The simulated flow in the wind tunnel test included a significant low-frequency component. Pressure taps of interest on the 19.05×7.32-m wall were located on four rows; the first row at 0.91 m, the second at 2.74 m, the third at 5.18 m, and the fourth at 6.71 m above ground (Fig. 1). We considered the following sets of taps: (1) the set of taps located on line 4 of Fig. 1 (i.e., at the center line of the wall); (2) the two sets of taps located on lines 4 and 5; (3) the three sets of taps located on lines 3, 4, and 5; (4) the four sets of taps located on lines 3, 4, 5, and 6; (5) the five sets of taps located on lines 2, 3, 4, 5, and 6; (6) the six sets of taps located on lines 2, 3, 4, 5, 6, and 7; and (7) the seven sets of taps located on lines 1, 2, 3, 4, 5, 6, and 7. The horizontal widths of the areas tributary to the sets of Taps 1–7 vary from 1.905 to 13.335 m in increments of 1.905 m. Owing to the imperfect correlation between taps separated by a horizontal distance, the peak total force $F_{\text{peak}}{}^{(i)}$, resulting from the taps of set (i), is smaller than i times the peak total force $F_{\text{peak}}{}^{(1)}$ resulting from Set 1 ($i = 2, 3, \ldots, 7$). For the set of taps (i), we denote the tributary area of set (i) by $A^{(i)}$. Finally, we denote the ratio $[F_{\text{peak}}{}^{(i)}/A^{(i)}]/[F_{\text{peak}}{}^{(1)}/A^{(1)}]$ by $R_p(i)$. Fig. 2 shows a plot of $R_p(i)$ as a function of i or of the width of the tributary area $A^{(i)}$ (in meters).

For purposes of comparison, Fig. 2 also shows the ratios of $R_p(i)$ calculated analytically, as explained in the following section. The results show that the spatial coherence that determines the peak along-wind force acting on the relatively small building being considered is indeed high. In other words, for small buildings, the effects of the imperfect spatial cross-correlation of the longitudinal velocity fluctuations are reasonably small, and the peak aerodynamic effects in the presence of low-frequency turbulence differ by acceptably small amounts from those induced by time-invariant speeds. This result supports the hypothesis that wind effects on small buildings (i.e., buildings with dimensions of the order of approximately 20 m) may be measured to within acceptable approximations in flows without low-frequency fluctuations and augmented mean wind speeds.

Requisite Increase of the Mean Wind Speed in Simplified Flows: Rectangular Buildings, Mean Wind Normal to a Building Face

For the simple case of flow normal to the windward face of a rectangular building, it is possible to calculate analytically the peak force induced by a conventional ABL flow and by a simplified flow. As shown in Fig. 3, the longitudinal wind speed $U(y, z, t)$ is assumed to vary with time t, width (across-flow dimension) y, and height above ground z, and consists of the mean wind speed $U(z)$ and the wind speed longitudinal fluctuations about the mean, $u(y, z, t)$. $U(z)$ is assumed to be normal to the wider face of the building. The objective is to create a simplified flow that induces on the windward face of the building a peak total aerodynamic force F_{peak} that is approximately equal to its counterpart induced by the ABL flow. The calculations are based on the material summarized herein.

Estimation of Peak Force F_{peak} Induced by the Atmospheric Boundary Layer Flow on the Windward Building Face

1. The spectral density of the longitudinal flow fluctuations u is described by the expression for the modified Kaimal spectrum (Simiu 2011)

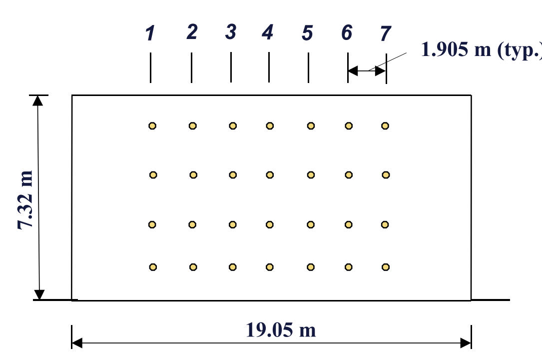

Fig. 1. Tap layout: a building (width 19.05 m, elevation 7.32 m)

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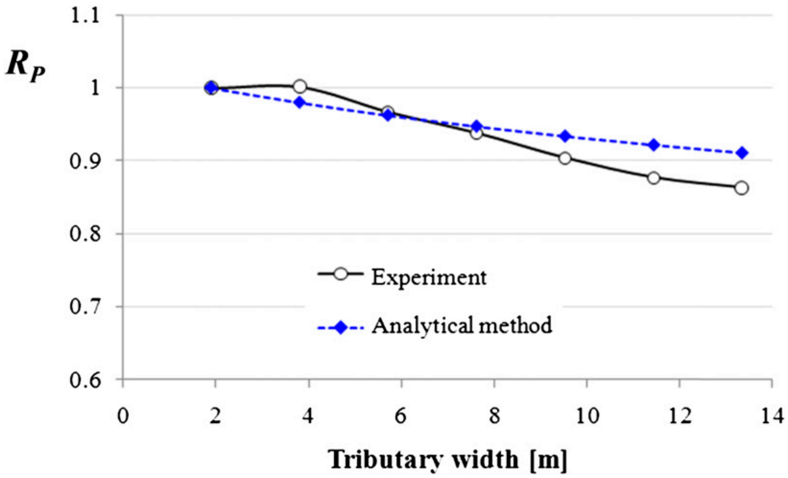

Fig. 2. Ratio R_p

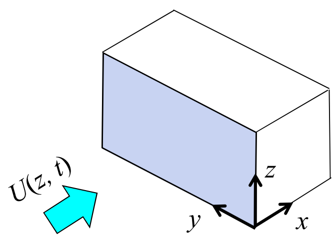

Fig. 3. Schematic of the building (height h, width b)

$$\frac{n\,S_u(z,n)}{{u_*}^2} = \frac{200\,f}{(1\,+\,50\,f)^{5/3}} \tag{1}$$

where $f = nz/U(z)$ = reduced frequency and u_* = friction velocity. This expression is valid for frequencies $0 < f \leq f_c$. It is reasonable to assume a cut-off frequency $f_c = 10$ [i.e., $S_u(z,n) = 0$ for $f > f_c$]. If appropriate, different expressions for the spectrum may be used.

2. The expression for the spatial coherence of the longitudinal wind velocity fluctuations u is

$$\mathrm{Coh}(y_1, y_2, z_1, z_2, n) = \exp\left\{-\frac{n\left[C_y^2(y_1-y_2)^2 + C_z^2(z_1-z_2)^2\right]^{1/2}}{\frac{1}{2}[U(z_1)\,+\,U(z_2)]}\right\} \tag{2}$$

where n = frequency, $C_y = 16$ and $C_z = 10$ = estimates of exponential decay coefficients in the y- and z-directions, respectively, and (y_1, z_1) and (y_2, z_2) = coordinates of two points on the windward wall.

3. The longitudinal flow fluctuations and the flow-induced forces on the windward wall are approximately Gaussian.

Using these assumptions, the total wind-induced peak force F_{peak} on the windward wall can be expressed as the sum of the mean force and the peak force as the result of all fluctuation components:

$$F_{\text{peak}} \approx F_U \,+\, \kappa_{Fp}\,\sigma_{Fp} \tag{3a}$$

$$\text{where } F_U = \int_0^h \int_0^b \frac{1}{2}\rho\, C_p U^2(z)\; dy\; dz \tag{3b}$$

where b = width of building, h = height, ρ = air density, $C_p = p(z)/[1/2\rho U^2(z)] \approx 0.8$ = mean pressure coefficient, $p(z)$ = mean pressure at height z, κ_{F_p} = peak factor based on Davenport (1964), and σ_{F_p} = RMS of fluctuating force F_p.

The peak factor for a flow with a duration of T seconds is approximately (Davenport 1964)

$$\kappa_{Fp} \approx \sqrt{2\,\ln\,(\nu_{Fp}T)} \,+\, \frac{0.577}{\sqrt{2\,\ln\,(\nu_{Fp}T)}} \tag{4a}$$

$$\nu_{Fp} = \left[\frac{\int_0^{n_c} n^2 S_{Fp}\; dn}{\int_0^{n_c} S_{Fp}\; dn}\right]^{1/2} \tag{4b}$$

where ν_{F_p} = expected frequency of the peak force, n_c = dimensional cut-off frequency corresponding to f_c, and S_{F_p} = spectral density of the fluctuating force F_p on the windward wall. The RMS of the fluctuating force F_p is obtained by integration

$$\sigma_{Fp} = \left[\int_0^{n_c}\int_0^h\int_0^h\int_0^b\int_0^b \rho^2 C_p^2 U(z_1)U(z_2)\, S_u^{1/2}(z_1,n)\, S_u^{1/2}(z_2,n) \times \mathrm{Coh}(y_1,\, y_2,\, z_1,\, z_2,\, n)\, dy_1\, dy_2\, dz_1\, dz_2\, dn\right]^{1/2} \tag{5}$$

Estimation of Peak Force F_{peak1} Induced by the Simplified Flow

The estimation process is similar to the estimation of F_{peak}, except for the following:

1. The mean speed is cU $(c > 1)$; and
2. The spectral density of the longitudinal velocity fluctuations u in the simplified flow is

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$$S_u(z,n) = 0 \qquad \text{for} \quad 0 < f \leq f_{\text{low}} \tag{6a}$$

$$\frac{n S_u(z,n)}{u_*^2} = \frac{200f}{(1 + 50f)^{5/3}} \quad \text{for} \quad f_{\text{low}} < f \leq f_c \tag{6b}$$

where f_{low} can be selected near the lower limit of the interval within which the Kolmogorov inertial subrange hypothesis holds in the ABL wind, and $f_c = 10$ is as indicated earlier. For small structures, it is reasonable to assume, approximately, $f_{\text{low}} = 0.1$. Numerical calculations based on equations presented in this section can be used to assess the effect of using alternative values of f_{low}. The reduced frequency f is based on the mean wind speed $U(z)$. Note that high-frequency fluctuations affect the shape of separation bubbles and should therefore be simulated in the simplified flow.

The mean force induced on the windward face by the simplified flow is denoted by $F_{cU} = c^2 F_U$. The corresponding peak force is

$$F_{\text{peak1}} \approx c^2 F_U + \kappa_{Fph}\sigma_{Fph} \tag{7}$$

where κ_{Fph} and σ_{Fph} = counterparts of κ_{F_p} and σ_{F_p} in Eq. (3).

Estimation of the Upper Limit of Low-Frequency Fluctuations Flow

Method a

Given f_{low}, the increased mean wind speed, denoted by $cU = U + \Delta U$, is determined from the relation $F_{\text{peak}} = F_{\text{peak1}}$. It follows from Eqs. (3) and (7) that

$$c = \sqrt{\frac{\kappa_{Fp}\sigma_{Fp} - \kappa_{Fph}\sigma_{Fph}}{F_U} + 1} \tag{8}$$

Method b

An alternative estimate of the increased mean speed, denoted by $c'U = U + \Delta U'$, can be performed by equating the peak wind speeds in the simulated ABL flow and the simplified flow, that is, $U + \kappa_u\sigma_u = c'U + \kappa_{uh}\sigma_{uh}$. The result is

$$c' = \frac{\kappa_u\sigma_u - \kappa_{uh}\sigma_{uh}}{U} + 1 \tag{9}$$

In the preceding expressions, κ_u and σ_u = peak factor and RMS, respectively, of the longitudinally fluctuating wind speed corresponding to all frequency fluctuations $0 < f \leq f_c$ in the ABL flow, and κ_{uh} and σ_{uh} = their counterparts in the simplified flow corresponding to flow with frequencies $f_{\text{low}} < f \leq f_c$. The calculated $\Delta U'$ is slightly more conservative (i.e., larger) and less accurate than the value ΔU calculated by Method a. The larger the building, the less accurate is the simplified calculation.

Analytical Results

We considered rectangular buildings with height $h = 12$ m and various widths ($b = 6-22$ m) with open terrain exposure. First, we investigated the extent to which the imperfect coherence of the low-frequency pressures induced by the ABL flow is significant in practice. The investigation was performed by calculating the ratio

$$R_{\text{low}} = \frac{\kappa_{Fpl}\sigma_{Fpl}\big|_{C_y = 16,\ C_z = 10}}{\kappa_{Fpl}\sigma_{Fpl}\big|_{C_y = 0,\ C_z = 0}} \tag{10}$$

where the numerator and the denominator, respectively, = peak force resulting from the low-frequency fluctuating flow fluctuations based on the use of exponential decay coefficients $C_y = 16$, $C_z = 10$ and $C_y = 0$, $C_z = 0$. The various terms in Eq. (10) are calculated for the frequency range $0 < f \leq f_{\text{low}}$. We emphasize that the exponential decay coefficients exhibit significant variability in nature, so the values selected for this study are illustrative.

Fig. 4 is a plot of R_{low} as a function of b and f_{low}. As expected, for lower f_{low} and b values, the value of R_{low} is closer to unity. A lower f_{low} results in better pressure simulations in the simplified wind; however, a higher f_{low} is more desirable from an experimental as well as computational viewpoint. In this study, $f_{\text{low}} = 0.1$, which is the approximate practical lower limit of the frequency range within which the Kolmogorov's hypothesis concerning the inertial subrange holds.

We estimated the additional increment in mean wind speed required for the simplified wind model with $f_{\text{low}} = 0.1$ for open terrain to obtain the equivalent peak force of the conventional ABL flow. As shown in Fig. 5, the increment in the mean speed does not change significantly as the width b increases. For $f_{\text{low}} = 0.1$, for open terrain

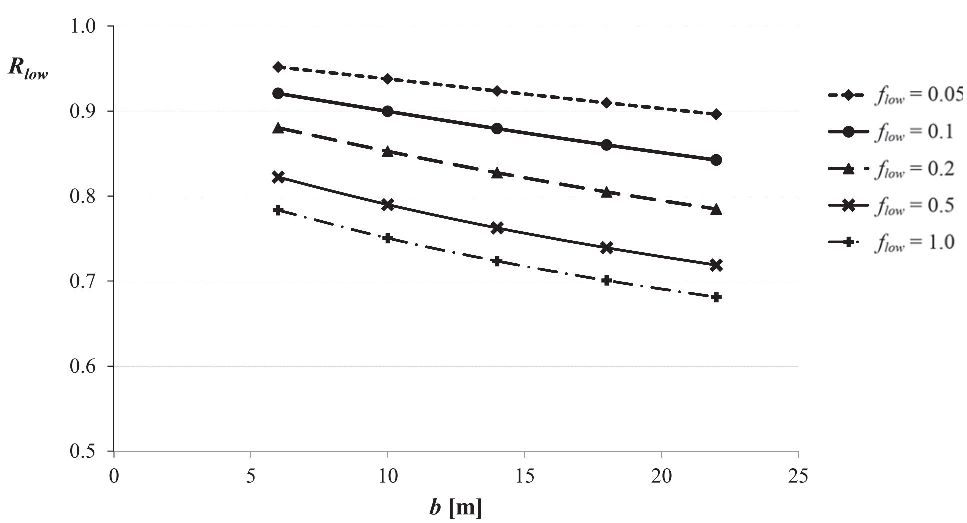

Fig. 4. Spatial coherence of peak force as the result of low-frequency fluctuations

the wind speed factors (c for Method a and c' for Method b; i.e., the ratios at eave height of the augmented mean speed to the original wind speed) are approximately 1.30. The figure also shows that the difference between the factors calculated by Method a and Method b (i.e., 1.29 and 1.33, respectively) is small. Method b provides a less accurate and more conservative ratio than Method a, because it is based on the equality between the peak wind speeds in both wind models, rather than on the equality between the respective peak forces. The difference between the increments in the wind speeds is ∼10%, meaning that the corresponding differences between the respective estimated peak forces are less than 5%. Both methods, therefore, are acceptable; however, Method b is more practical and straightforward.

All results reported so far correspond to open terrain exposure (roughness length $z_0 = 0.03$ m). The increased mean wind speeds in the simplified wind flow were also estimated for open water exposure ($z_0 = 0.005$ m), suburban exposure ($z_0 = 0.3$ m), and urban terrain exposure ($z_0 = 0.7$ m). Fig. 6 shows that for open water surface exposure the factors are 1.22 (corresponding to estimates based on equivalent peak forces, Method a) and 1.25 (corresponding to estimates based on equivalent peak speeds, Method b). For urban terrain, the factors are 1.64 and 1.69, respectively. It is clear that both methods can be used, regardless of terrain exposure.

The analytical approach presented in this paper can be used to provide approximate estimates of the augmented mean wind speeds cU or $c'U$ to be used in experimental work. Refinements of these estimates would depend on experimental results similar to those reported by Simiu et al. (2011).

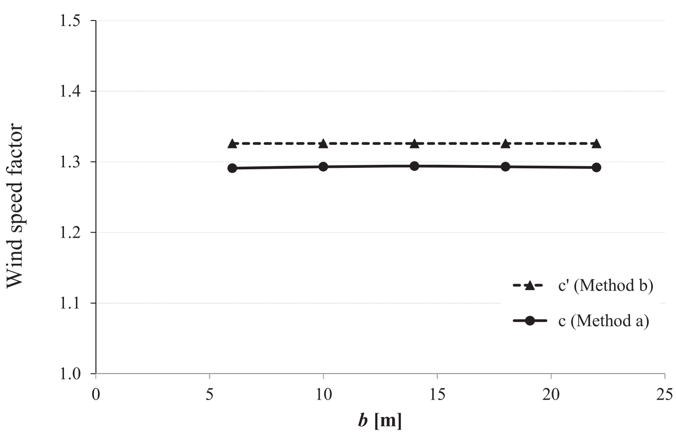

Fig. 5. Wind speed factor ($f_{low} = 0.1$)

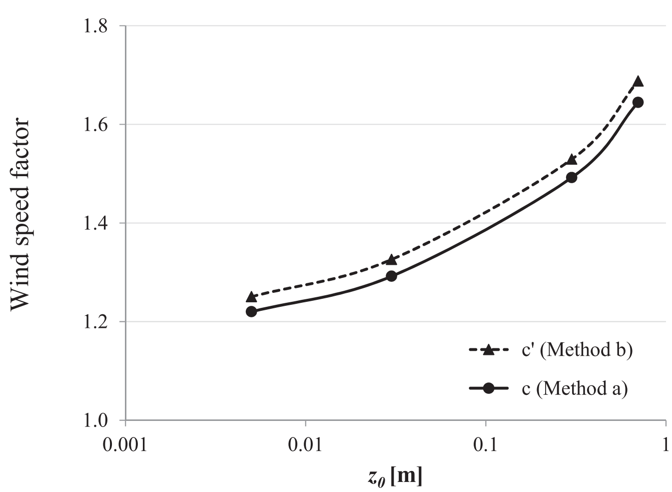

Fig. 6. Wind speed factor as a function of terrain conditions

Laboratory Testing

Description of Experiments

The experiments were conducted using the 12-fan small-scale Wall of Wind (WoW), an open jet test facility at Florida International University (Aly et al. 2011; Chowdhury et al. 2010; Fu et al. 2012). The models tested (Fig. 7) were as follows:

1. Silsoe cube: 89 × 89 × 89 mm (length scale 1:67.5); and
2. Texas Tech University (TTU) building: 175 × 260 × 77 mm (length scale 1:52).

High-frequency cobra probes were used for wind speed measurements and set at a 625-Hz sampling rate. A 64-channel pressure transducer was used at a 100-Hz sampling rate. Pressures were measured for 0 and 45° angles of attack. To simulate the simplified flow a flat waveform signal was input into the WoW controller. For the simulation of the ABL flow the input consisted of a quasi-periodic waveform signal based on the spectrum of the longitudinal velocity fluctuations for real hurricanes (Yu et al. 2008). The peak of the input signal for the quasi-periodically driven fans simulating ABL flows was equal to the constant input signal for the uniformly driven fans generating simplified flows. The increased mean wind speed $c'U(z)$ for uniform flow was estimated by using Method b, explained in the previous section. The optimal distance between the exit of the WoW and the windward wall surface of the test models was 22.0 cm (8.6 in.).

For the TTU model, the full-scale wind speed was assumed to be 50 m/s. A passive device, consisting of a set of horizontal planks with inclinations adjusted by trial and error, was used to generate a mean wind speed profile typical of open terrain (Chowdhury et al. 2010; Huang et al. 2009). The measured mean wind speed and turbulence intensity at 89 mm (3.5 in.) above ground were about 24.8 m/s and 6% for the simplified flow, and 16.9 m/s and 26% for the simulated ABL flow. This choice ensured that the simplified flow had a mean velocity equal to the sum, in the simulated ABL flow, of the mean velocity and the peak fluctuating velocity induced by the low-frequency fluctuations. The duration of the tests was 5 min. The prototype duration of the tests is given by the relation

$$\frac{T_p U_p}{L_p} = \frac{T_m U_m}{L_m} \tag{11}$$

where T, U, and L = time, mean wind speed, and characteristic length, respectively, and subscripts p and m refer to prototype and model, respectively. For the TTU test

$$T_p = \left(\frac{L_p}{L_m}\right)\left(\frac{U_m}{U_p}\right)T_m = (52)\left(\frac{16.9\,\text{m/s}}{50\,\text{m/s}}\right) \times 5\,\text{min} = 87.9\,\text{min} \tag{12}$$

For the Silsoe test, $T_p \approx 2$ h.

Test Results

To remove the uncertainties inherent in the randomness of the peaks, probabilistic analyses were performed using a procedure for estimating statistics of pressure peaks from observed pressure time histories (Sadek and Simiu 2002; www.nist.gov/wind). Because

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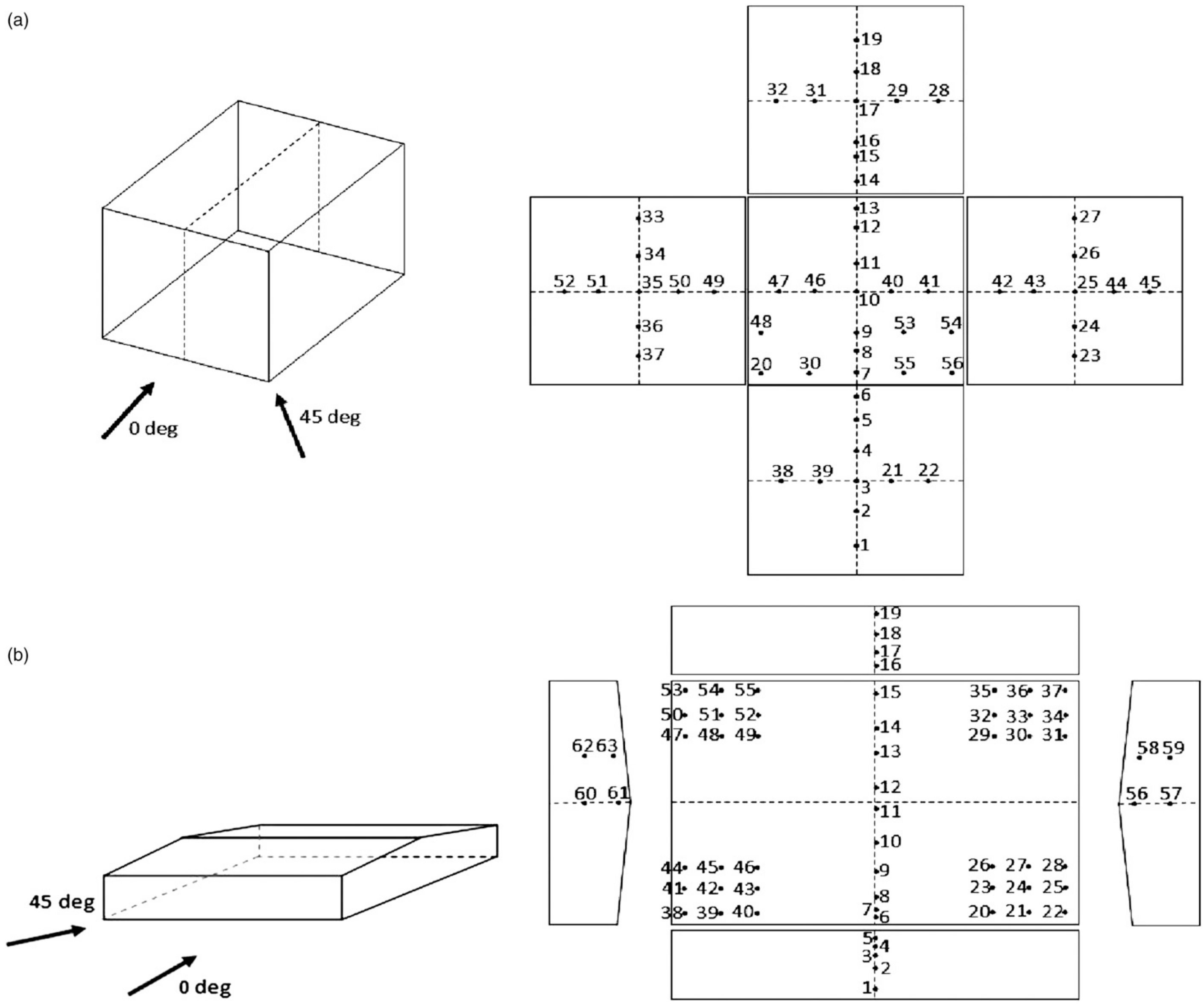

Fig. 7. Tap layout: (a) Silsoe; (b) TTU building

estimates obtained by this procedure are based on the entire information contained in the time series, they are more stable than estimates based on observed peaks, and provide a more meaningful basis for the comparisons. The comparisons were in all cases based on the 95th percentile of the estimated distributions of the peaks.

The test results are summarized in Table 1 and Fig. 8. For both the Silsoe and the TTU models, the ratios R of the estimated peak pressures measured under the simplified flow to peak pressures measured in the simulated ABL flow were found to exceed unity by at most 20% and be lower than unity by at most 15%. This is true not only for the windward wall when the wind direction is normal to that wall (as was previously shown by the analytical approach), but also for roof and leeward wall pressures, as well as for the case in which the wind direction is skewed with respect to a building face. This means that the same conclusion obtained for pressures on the windward wall by using the theoretical methodology described previously in the section Requisite Increase of the Mean Wind Speed in Simplified Flows: Rectangular Buildings, Mean Wind Normal to a Building Face are approximately applicable to other parts of the building as shown by the experimental results.

Table 1. Peak Pressure Ratios $R = a/b$ under Mean Wind Speed at 90 and 45° (Simiu et al. 2011)

	Tap					
Angle of attack (degrees)	1	3	5	7	15	17
90	1.07	1.21	0.9	1.26	1.01	1.13
45	1.18	1.25	1.15	1.06	0.98	1.08

Note: a and b are 95th percentile peak pressures in flows with no low-frequency content and with low-frequency content, respectively.

Relevance of Proposed Approach to Computational Wind Engineering Pressure Simulations

One of the barriers to performing CWE simulations of wind effects on bluff bodies, such as typical buildings, is the difficulty of

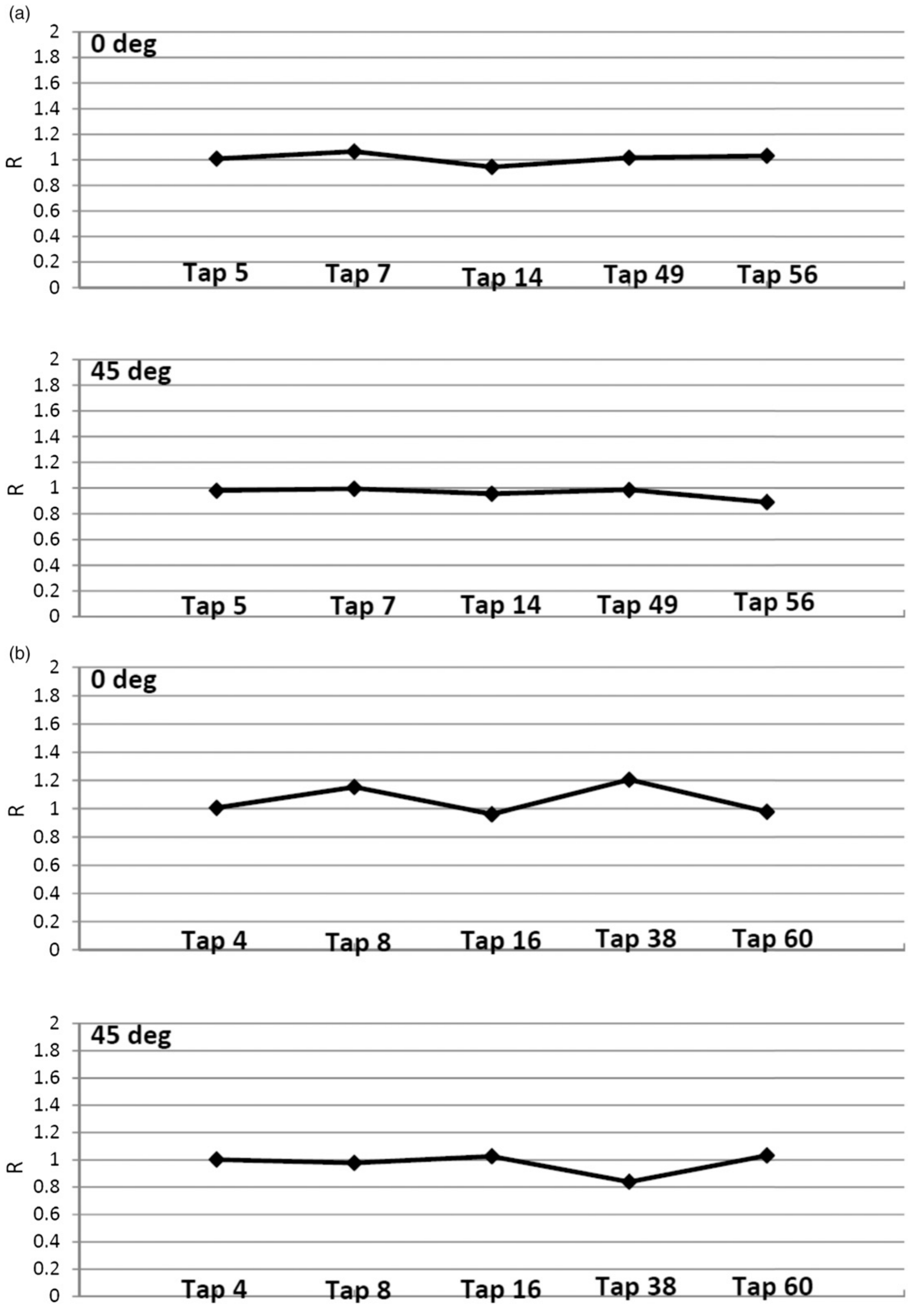

Fig. 8. Peak pressure ratio R of simplified ABL and full ABL: (a) Silsoe cube; (b) TTU building

simulating ABL flows with imperfect spatial coherence of the low frequency turbulent fluctuations. It is anticipated that the suppression of such fluctuations in simplified flows would make it possible to perform CWE simulations efficiently. NIST is currently engaged in studies aimed at achieving such simulations.

The availability of CWE procedures for the efficient estimation of wind effects on tall buildings for design purposes would be highly desirable. In the present state of the art, rather than being used for estimating wind effects for final structural design purposes, such procedures could facilitate the ranking of alternative aerodynamic solutions at the preliminary design stage. This would preempt the need to resort to successive costly and time-consuming wind tunnel tests. In considering the possibility of achieving CWE estimates of wind effects on, say, tall buildings, it must be noted that, unless

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proper corrections are performed, simplified flows cannot reflect the load reductions inherent in the imperfect spatial coherence of pressures in ABL flows, as well as the effects of such imperfect coherence on the vorticity shed in the wake of the structure. Whether such corrections can be developed credibly is a topic that remains to be investigated. The authors believe that, for some types of tall buildings, research can lead to the development of correction algorithms that, in conjunction with CWE calculations performed for simplified flows, would allow practitioners to assess reliably the relative merits of alternative aerodynamic solutions. Numerical simulations of full-scale modeling and appropriate numerical methods, in combination with the use of a simplified ABL flow model, would reduce computational times for obtaining pressure time histories, and decrease inconsistencies among results obtained by different laboratories.

Conclusions

The adequacy of a simplified flow model used for estimating wind effects on relatively small structures was investigated by using an analytical approach, as well as experimental approaches based on pressure data measured in an ABL wind tunnel and in an open jet, 12-fan small-scale WoW facility. The investigation showed that the reduction of wind effects resulting from the imperfect spatial coherence of turbulence in the oncoming flow is small for buildings with relative small dimensions (up to approximately 20 m, e.g., single-family residential homes), and lends support to the hypothesis that it is in practice acceptable to substitute a simplified flow for an ABL-like flow.

We proposed an analytical approach to estimating the two parameters required to define simplified wind flows: (1) increment in mean wind speed ΔU, and (2) the upper limit of low-frequency fluctuations f_{low}. Because the analytical approach has limitations, it was used for the windward wall only and for wind direction being normal to that wall. The results of the study show that, for the simulation of wind forces on the windward face of small buildings normal to the direction of the mean wind speed, low-frequency fluctuations for which $f_{\mathrm{low}} \leq 0.1$ have sufficiently high spatial coherence to be replaceable, to within acceptably small errors, by an augmented mean wind speed. For a simplified flow with $f_{\mathrm{low}} = 0.1$ in open terrain exposure, the increment in mean wind speed is $\sim 30\%$ of the original reference mean wind speed.

To validate the adequacy of the simplified flow for the estimation of pressures on the roof and leeward and windward walls under normal and oblique angles of attack, an experimental approach was employed. Preliminary experimental results obtained at Florida International University suggest that the simplified flow model is also acceptable for pressures acting anywhere on the building surface, even under oblique wind. Although differences between experimental and analytical results exist, they are acceptably small compared with differences between results typically obtained in different wind tunnels, and can be explained by the variability inherent in aerodynamics affected by signature turbulence (i.e., turbulence created by the interaction between the structure and the oncoming flow, even if the latter were smooth).

Small-scale (i.e., high-frequency) turbulence, which plays a significant role in determining the position of the reattachment points, must be contained in the simplified flow. As far as wind tunnel testing is concerned, testing in simplified flows has the advantage of allowing geometric scales to be larger than is possible in ABL-like flows.

The use of the proposed simplified flow has also been proposed, and is currently being tested by the authors for application to CWE applications, in which it is likely to be useful given the fact that one of the major difficulties in achieving practical CWE calculations for buildings is the simulation of the lower frequency fluctuations of the boundary layer flow. Numerical simulations at full-scale and appropriate numerical methods, in combination with the use of a simplified ABL flow model, are expected to reduce computational time for pressure time histories on structures and to decrease inconsistencies of results observed among wind tunnel simulations.

The work reported in this paper is viewed as a first step in developing the proposed technique. Additional computational simulations are planned to further refine the technique and test the range of its applicability. Future experimental tests are planned to further validate the technique for a wide range of model-to-full-scale ratios.

Acknowledgments

The authors are indebted to A. M. Aly, G. Bitsuamlak, and T. C. Fu for contributions to the work reported in this paper. The topic discussed in this paper was suggested to the authors by E. Simiu.

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J. Eng. Mech. 2013.139:367-375.