Testing of Residential Homes under Wind Loads

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Abstract: Aerodynamic testing of low-rise structures is fraught with difficulties that can be the cause of large measurement errors, resulting in the underestimation of aerodynamic pressures by a factor of as much as two. The errors are primarily attributable to the inadequate knowledge and simulation of wind flows affecting low-rise buildings, especially residential homes in suburban environments. A type of aerodynamic testing of sufficiently small low-rise structures is explored that does not entail the simulation of the turbulence intensity and integral turbulence scales. That type of testing would offer several advantages: eliminating a major cause of discrepancies among measurements conducted in different laboratories, allowing the use of larger model scales, and allowing testing in both typical commercial wind tunnels and in open jet facilities of the Wall of Wind (WoW) type. Preliminary tests based on data obtained at the University of Western Ontario wind tunnel and the Florida International University large-scale six-fan WoW facility suggest that the proposed type of testing yields systematically conservative results for the specialized type of measurements considered herein. In most cases, but not all, the degree of conservatism is modest. The results appear to be of sufficient interest to warrant additional research. **DOI: 10.1061/(ASCE)NH.1527-6996.0000034.**

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Introduction

An international round-robin set of wind tunnel tests of a low-rise structure conducted at six reputable laboratories produced the result that wind-induced internal forces in structural frames, and pressures at individual taps, can differ from laboratory to laboratory by factors larger than two (Fritz et al. 2008). Owing in part to such differences, aerodynamic pressures on low-rise structures specified in the ASCE 7 Standard can be smaller by as much as 50% than pressures measured in the wind tunnel (Surry 2003; St. Pierre et al. 2005; Ho et al. 2005; Coffman et al. 2010).

Among the reasons for the nonrepeatability of wind tunnel tests across laboratories (i.e., for the dependence of wind tunnel test results on the laboratory in which they are conducted) are two facts. First, the low-frequency fluctuations of the oncoming flow turbulence in the atmospheric surface layer are difficult to simulate, and second, the techniques for their production in the wind tunnel are not standardized. Because those fluctuations contain the bulk of the turbulent energy, they contribute overwhelmingly to the turbulence intensity and the integral turbulence scale. This paper is concerned with the question of whether improvements in repeatability of wind-induced pressures on small structures can be achieved by subjecting models to flows that do not attempt to reproduce atmospheric turbulence intensity and integral turbulence scales.

The paper is organized as follows. Within the framework of a general discussion on the aerodynamic testing of civil engineering structures, the writers will show why it is reasonable to hypothesize that results obtained in flows that do not contain low-frequency fluctuations are typically conservative and may be acceptable when testing sufficiently small buildings. This hypothesis appears to be supported by preliminary wind tunnel and Wall of Wind (WoW) test results. The paper is concluded with suggestions for future research.

Boundary Layer Flows and their Laboratory Simulation

In the 1970s it was believed that faithful laboratory simulations of atmospheric boundary layer flows could be achieved by allowing a boundary layer to grow naturally by friction at the wind tunnel floor over a sufficiently long development distance (30 m, for example). However, depths of the boundary layers so achieved turned out to be insufficient for the testing of tall buildings. Even if longer development lengths were allowed for, the simulations could not reproduce atmospheric boundary layer flows faithfully for two reasons. First, high-frequency turbulent fluctuations, corresponding to the prototype inertial subrange, are not correctly reproduced in the wind tunnel owing to energy dissipation by internal friction within small eddies at small model scales. This limitation can be significant insofar as high-frequency turbulent fluctuations promote transport of free-stream particles with high momentum across separation

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layers, a phenomenon that affects flow reattachment and, therefore, the magnitude of negative pressures in separation zones. Second, the mechanisms of boundary layer formation are different in the wind tunnel and in the atmosphere. For example, in large-scale extratropical storms the depth of the atmospheric boundary layer, rather than being independent of flow velocity, as is implicit in the power law description of the wind profile, is inversely proportional to the Coriolis acceleration and proportional to the wind speed. It follows from this relation that the range of validity of the logarithmic law, rather than being approximately 50 m, regardless of flow velocity (Davenport 1965), as was commonly believed before the development of atmospheric boundary layer similarity theory, is also proportional to the wind speed (Csanady 1967; Simiu and Miyata 2006), and can be as high as 400 m for strong winds (Powell et al. 2003).

For these reasons, long development distances have no longer been considered necessary for the simulation of atmospheric flows. To make up for insufficient boundary layer depth, it has been proposed that spires be placed upwind of the test section. The spires, in conjunction with roughness elements placed on the wind tunnel floor, create turbulent shear flows deemed to be adequate if the development lengths over which elements may be placed are approximately 15 m, for example. This technique is now being widely used in commercial wind tunnel testing.

For the testing of tall building models, the justification for the requirement that the atmospheric turbulence intensity and the integral turbulence scale be simulated in the wind tunnel is that the spatial coherence of the turbulent fluctuations in the incoming flow is imperfect. This means that if the peak velocity of the oncoming flow at a point A in space occurs at a time t_A, at any other point B of a vertical plane normal to the mean speed the peak velocity will occur at a time $t_B \neq t_A$. The along-wind force on a large structure will therefore be smaller than if the flow were perfectly coherent spatially (i.e., if it were true that $t_A = t_B$). The justification for that requirement is far less compelling if the building being tested is small in relation to the integral turbulence scale. Indeed, the coherence of the oncoming flows over lengths comparable to the building dimensions is in this case relatively large. It may therefore be hypothesized that peak aerodynamic effects experienced by a small building subjected to a flow whose velocities have significant low-frequency fluctuations are not substantially different from the aerodynamic effects induced by flows with (1) negligible low-frequency content, and (2) mean velocity equal to the sum, in the flow with significant low-frequency content, of (1) the mean velocity, and (2) the peak fluctuating velocity induced by the low-frequency fluctuations. However, for this hypothesis to be warranted the mean flow must, in both cases, simulate reasonably well the atmosphere's mean shear flow. This can be achieved by a variety of techniques that can be independent of wind tunnel configuration and are therefore capable of being standardized, a task that has not been achieved so far in the U.S. and Canada for wind tunnels using spires and roughness elements. One such technique, used in Florida International University's (FIU) six-fan WoW, is described by Huang et al. (2009), and is adaptable for wind tunnel use.

A second argument may be invoked in favor of resorting to flows with little or no low-frequency content. The ASCE 7 Standard (2005) requires that the ratio between integral length scales and building dimensions be the same in the wind tunnel and in the prototype. The fact that integral length scales typically achievable in wind tunnels are relatively small imposes, for typical commercial wind tunnels, geometric model scales of the order of 1:100. At such scales, model dimensions for a residential home are of the order of 0.1 m, i.e., not much larger than those of a match box. This renders measurements difficult and prone to significant errors. Freeing the geometric scale from constraints associated with the integral turbulence scale offers the significant advantage of allowing the use of considerably larger geometric scales than are now possible, without violating standard blockage requirements.

Wind Tunnel Test Results

Consider the pressures induced on the windward face of a relatively small building by a flow with mean speed described by a power law and normal to that face. Consider two theoretical cases: (1) The low-frequency turbulence is approximately similar to its counterpart in the atmosphere, and (2) the low-frequency content of the flow is negligible, whereas the mean velocity is equal to the sum, in the flow with significant low-frequency content, of (1) the mean velocity, and (2) the peak fluctuating velocity induced by the low-frequency fluctuations. The hypothesis is tested in that the peak pressures on the windward face do not differ significantly in the two cases, provided that the horizontal distance between the outermost taps being considered is not too large. For this purpose, a 1:100 model of a building was chosen with a 1:12 slope gable roof and with dimensions 3.66 m eave height and 12.20 × 19.05 m in plan, for which measurements performed in the wind tunnel of the University of Western Ontario (UWO) were incorporated in the NIST aerodynamic database (NIST 2003). The wind tunnel tests were conducted in flow with significant low-frequency content simulating atmospheric flows. Pressure taps on the 3.66 × 19.05 m wall were located on two rows: one row at 0.6 m below the eave, and one row at 1.52 m above ground level. Fig. 1 shows an elevation of the 19.05 × 3.66 m building face and the taps of interest in this study. The following sets of taps were considered: (1) the pair of taps located on line 4 of Fig. 1 (i.e., at the center line of the face of the building); (2) the two pairs of taps located on axes 4 and 5; (3) the three pairs of taps located on lines 3, 4, and 5; (4) the four pairs of taps located on lines 3, 4, 5, and 6; and (5) the five pairs of taps located on lines 2, 3, 4, 5, and 6. The horizontal distances tributary to the sets of taps 1, 2, 3, 4, and 5 are 1.905, 3.81, 5.715, 7.62, and 9.525 m, respectively.

For the case of mean flow normal to the windward wall represented in Fig. 1 the total load associated with set 1 is equal to the sum of the loads associated with the upper tap and the lower tap. The total load associated with set 2 can be calculated in the following alternative ways. First, by adding to the load associated with set 1, the load, obtained in a similar manner, associated with the taps located on line 5. This type of calculation accounts for the imperfect coherence between the pressures acting at on lines 4 and 5. Second, by multiplying by two the load associated with the taps located on line 4. The latter type of calculation assumes perfect coherence between pressures on line 4 and their counterparts on

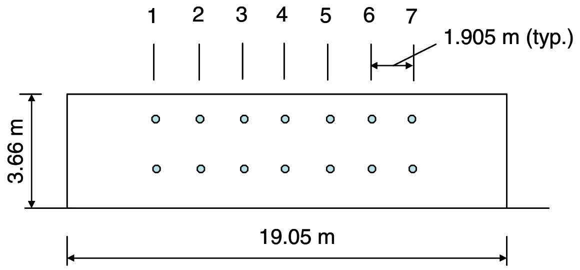

Fig. 1. Elevation of 19.05 × 3.66 m building face, and location of taps of interest

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Table 1. Ratio L_1/L_2 of the Total Load L_1 for Sets 1, 2, 3, 4, and 5

Set of pressure taps	Tributary horizontal distance	L_1/L_2
1	1.91	1.00
2	3.81	1.03
3	5.72	1.05
4	7.62	1.12
5	9.53	1.21

Note: Ratios were calculated by assuming perfect spatial coherence, to the corresponding total load L_2 calculated by accounting for imperfect spatial coherence.

line 5 and mimics the case in which low-frequency fluctuations are replaced by an increment in the mean load, as described in the previous section. Because the pressures in the atmospheric flow are not perfectly coherent, the second calculation would be conservative. Similar considerations apply to sets 3, 4, and 5, in which the second type of calculation would entail the factors three, four, and five, instead of the factor two, as for the load associated with set 2. It is clear that the approximation inherent in the assumption that the pressures are perfectly coherent is closer, because the horizontal distance between the outermost taps is smaller. Table 1 shows the ratios between the total loads obtained by calculations of the second type and of the first type. The ratios are a direct measure of the degree to which the assumption of perfect coherence overestimates the total load.

The imperfect spatial coherence of the pressures depends on the quality of the wind tunnel simulation of the flow, and may be different from the spatial coherence in actual atmospheric flows. Indeed, it is not uncommon that in the wind tunnel the integral turbulence scale is smaller than its scaled prototype counterpart. If this was the case, the prototype counterparts of the ratios L_1/L_2 would be closer to unity than those of Table 1. The ratios of Table 1 only provide information on loads induced on the windward building face, far enough from the corners, by wind with mean speed normal to that face. Table 1 offers the conclusion that for buildings or portions with dimensions on the order of 10 m, the errors inherent in the use of flows with little or no low-frequency turbulence content are relatively modest.

Fig. 2. 6-fan WoW and 2.9 m testing cube (image by A. Gan Chowdhury)

Wall of Wind Test Results

A new full- and large-scale testing apparatus generically named the WoW has been built at the International Hurricane Research Center (IHRC), FIU. The 6-fan WoW (Fig. 2) is capable of testing large-scale building models and full-scale portions of buildings. To develop flow management devices efficiently, a small-scale (1:8) WoW model was built and used for a series of tests conducted with a view to replicating tropical cyclone (TC) wind characteristics based on Florida Coastal Monitoring Program (FCMP) data analyses (Yu et al. 2008). To achieve the target flows, both passive devices and active controls were employed. The passive devices included an outer frame, a contraction, and inclined horizontal planks. The active controls were used to subject the fans to quasi-periodic rotations (i.e., rotations driven by signals consisting of sums of harmonics) that successfully replicated the low-frequency turbulence characteristics of the target TC flow. Following intensive experimentation, a combination of passive devices and active controls was achieved that resulted in atmospheric boundary layer-like profiles, turbulence intensities, power spectral densities, and gust factors (Huang et al. 2009). Two fluctuating waveforms, W1 and W2, were created and used in the small-scale WoW, corresponding, respectively, to one sinusoidal signal and three sinusoidal signals (Huang et al. 2009). The knowledge gained from the small-scale WoW tests was successfully applied to the full-scale WoW. The passive devices used in the full-scale WoW consisted of five plates (with −0.5°, 17°, 17°, 0°, and 0° inclination) placed inside the contraction. Two waveforms, W3 and W4, were developed that were the scaled counterparts of the waveforms W1 and W2, respectively. The resulting flow achieved in the full-scale WoW satisfactorily replicated the target TC flow. The results for the flat waveform (with no low-frequency content) and for the quasi-periodic fluctuating form W4 are shown in Table 2.

The full-scale WoW passive devices and the W4 waveform (additional details can be found in Huang et al. 2009) were used for the testing reported in this paper. Time histories of pressures on a cube with dimensions 2.9 × 2.9 × 2.9 m were measured in flows simulating winds over terrain with suburban exposure. Pressure taps were placed at the intersection between the cube's exterior surface and a vertical plane passing through the center of the roof and normal to a face, as shown in Fig. 3. To reduce the cost of running the tests, the test duration was 3 min. Two types of flow were used in each test. The first type of flow (flow 1, referred to as "flow with no low-frequency content") was generated using the flat waveform. For the second type of flow (flow 2, referred to as "flow with low-frequency content"), the low-frequency velocity fluctuations were obtained by imparting to the fans quasi-periodic rotational speeds generated by the W4 waveform, which is consistent with the low-frequency content of the atmospheric longitudinal velocity fluctuations at an elevation approximately equal to the eave height (Fig. 4). A comparison between gust factors is shown in Fig. 5. With the application of the W4 waveform, the estimated turbulence intensity value at 3.0 m elevation (the average roof eave height for

Table 2. Comparison of 6-Fan WoW Flow Characteristics for Flat and Quasi-Periodic Waveforms

Case (waveform; mean rpm)	Wind speed (m/s)	TI_u (%)	$GF(T,t)$	L_u^x (m)
Flat waveform	37 (1-min mean speed) 38 (3-s peak gust)	5	$GF\,(6\,\text{min}, 3\,\text{s}) = 1.06$ $GF(1\,\text{min}, 3\,\text{s}) = 1.04$	37
W4 quasi-periodic waveform	29 (1-min mean speed) 38 (3-s peak gust)	24	$GF(6\,\text{min}, 3\,\text{s}) = 1.42$ $GF(1\,\text{min}, 3\,\text{s}) = 1.33$	90

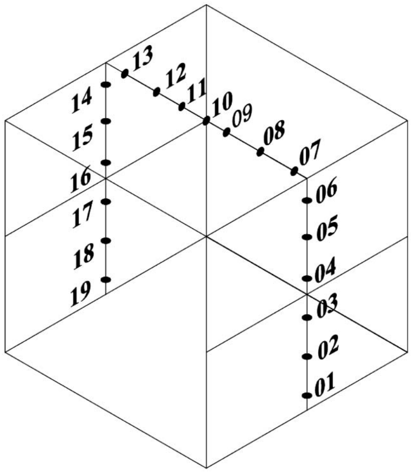

Fig. 3. 2.9 m cube tap layout

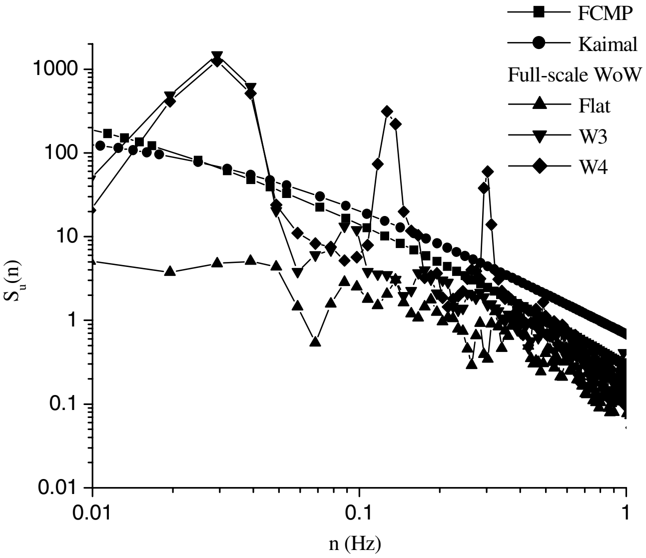

Fig. 4. Longitudinal power spectral density plots for WoW flow: Kaimal plot is described in Kaimal et al. (1972); FCMP plot is described in Yu et al. (2008)

typical low-rise residential buildings) was approximately 24%, versus 5% for the flat waveform. The 3-s peak wind speed for the flow with low-frequency content was 38 m/s, that is, the same as the 3-s peak (38 m/s) for the flow with no low-frequency content, for which the mean speed was 37 m/s.

Pressures were measured for the case of the mean flow speed normal to the face containing taps 1 through 6 and at a 45° angle to that face. The distance between the outermost plane of the WoW and the windward face of the cube was 2.74 m. The time history of the pressures over the 3-min duration was recorded at each tap. To achieve meaningful comparisons, the 95th percentile values of the peak pressures for a 60-min record were estimated from the 3-min time histories by using the method developed by Sadek and Simiu (2003). Software for the implementation of this method is available at www.nist.gov/wind.

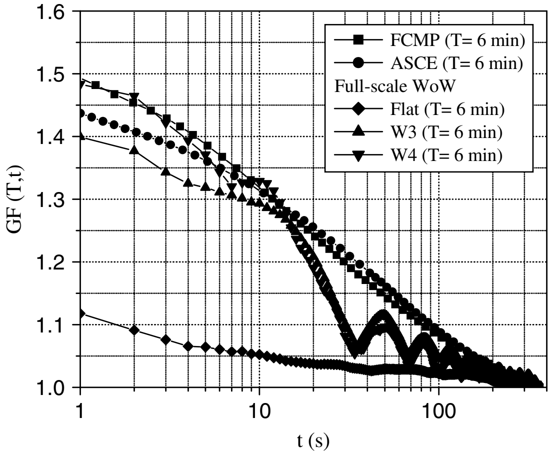

Fig. 5. Gust factors for WoW flow: FCMP plot is described in Yu et al. (2008); ASCE plot is described in ASCE Standard 7 (2006)

Table 3. Ratios $R = a/b$

	R-values	
Tap number	R (Case 90°)	R (Case 45°)
Tap #1	1.07	1.18
Tap #2	1.38	1.25
Tap #3	1.21	1.25
Tap #4	1.06	1.12
Tap #5	0.90	1.15
Tap #6	1.03	1.41
Tap #7	1.26	1.06
Tap #8	1.08	1.33
Tap #9	1.51	0.99
Tap #10	1.39	0.80
Tap #11	1.46	0.86
Tap #12	1.77	1.14
Tap #13	1.42	1.33
Tap #14	1.40	1.04
Tap #15	1.01	0.98
Tap #16	0.97	1.09
Tap #17	1.13	1.08
Tap #18	1.36	1.13
Tap #19	1.41	1.21

Note: *a* and *b* are 95 percentile peak pressures in flows with no low-frequency content and with low-frequency content, respectively. Mean speed at 90° and at 45° to windward face. Nominal flow duration: 60 min.

Table 3 lists the ratios *R* between (1) the maximum of the absolute value of the peak 60-min pressure obtained for flow 1 (flow with no low-frequency content) and (2) its counterpart for flow 2 (flow with low-frequency content). As expected, the results corresponding to flow 1 tend to be conservative. However, the conservative bias is not insignificant in some instances. For tap 12, the ratio is very large ($R = 1.77$); in this case, for flow with low-frequency content the peak pressures at tap 12 are small (approximately 20% of the peak windward pressure at tap 4), so the difference between the peak pressure in the two types of flow, while significant, is unlikely to influence the design. A judgment is required on whether the bias is acceptable in relation to errors, in many instances on the unconservative side, between results obtained in different wind tunnels or even in the same wind tunnel (Fritz et al. 2008; Surry et al. 2003), and between wind-tunnel based pressure estimates and pressures specified in the ASCE 7 Standard (St. Pierre et al. 2005; Ho et al. 2005; Coffman et al. 2010). Comparisons between conical vortices on a flat roof reported by Kawai (1997) showed that results for the smooth flow case were conservative in relation to those obtained in turbulent flows. The results of Table 3 suggest that testing in flow with no low-frequency fluctuations has the potential of yielding pressures that could be used for design purposes in lieu of pressures obtained in flow simulating atmospheric low-frequency velocity fluctuations. However, before a definitive assertion can be made to this effect, it will be necessary to subject the results reported herein to careful scrutiny via additional testing to be performed in the future.

Conclusions

The question arises whether it is desirable to use flows that attempt to simulate low-frequency fluctuations for the testing of residential homes and other low-rise buildings or portions thereof. The drawbacks of tests in such flows are the following. First, they induce errors in the estimation of the pressures. These errors tend to be significantly larger than the overall conservative bias inherent in the use of flows with no low-frequency fluctuations. Second, flows that attempt to simulate low-frequency fluctuations adversely affect the repeatability of the tests. To achieve repeatability across laboratories, a standard flow simulation protocol for low-rise buildings would have to be used. Because this would require uniformity not only in the roughness of the wind tunnel floor and the configuration of the spires, but also in the type and size of the wind tunnel facility, no such protocol has been established so far in the U.S. or Canada. On the other hand, standardization may be achievable for passive devices controlling the creation of mean wind speed profiles (e.g., devices such as those described in Huang et al. 2009). Third, the simulation of low-frequency turbulent fluctuations imposes severe constraints on the geometric model scale, which unavoidably entail additional errors in the estimation of aerodynamic effects. These constraints are eliminated for flows with no low-frequency fluctuations. Fourth, most residential homes are located in suburban environments, and the flows affecting a particular building are not textbook atmospheric boundary layer flows, but rather flows powerfully affected by the presence of other buildings, trees, and parked cars. Research on wind effects on low-rise buildings within such environments remains to be performed, and should be accounted for when making decisions on aerodynamic simulations of wind effects on low-rise structures. The nature of flows in such complex environments can be studied far more effectively at the larger scales allowed by simulations with no low-frequency flow fluctuations.

A debate on the issue of testing buildings with small dimensions for wind loads is warranted. This work is intended to be an exploratory contribution to such a debate. The test results reported in this paper suggest that the proposed type of testing wherein the flow has weak or no low-frequency content is conservative; the differences with pressures obtained in testing with conventional flows typically appear to be modest, but can in some instances be high, particularly for relatively small absolute values of the pressures. Such differences may be acceptable, but to reach definitive conclusions, more thorough testing than was conducted in this exploratory project will be necessary. Additional research will concentrate on the appropriate ratios between mean speeds in the flows with and without low-frequency content. In the writers' opinion, further research into the issue raised by this paper is warranted because current large differences between aerodynamic coefficients specified in standards on the one hand and those measured in the laboratory on the other can significantly affect the safety of residential homes and the estimation of wind-induced losses in strong winds.

Notation

The following symbols are used in this paper:

$G_{(T,t)}$ = gust factor, representing ratio of maximum wind speed averaged over t s to maximum wind speed averaged over T min;

L_1 or L_2 = total load;

L_u^x = integral turbulence length;

R = ratio between the maximum of the absolute values of the peak 60-min pressures for the flow with low frequency content to its counterpart for the flow without low frequency content;

TI_u = longitudinal turbulence intensity; and

t_A or t_B = time at point A or B.

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