**WIND LOADS ON LOW-RISE BUILDINGS: UPSTREAM EXPOSURE EFFECT**

Ioannis Zisis\(^1\) and Ted Stathopoulos\(^2\)

\(^1\) Research Assistant, Building Aerodynamics Laboratory, Concordia University
Montreal, Quebec, Canada, i_zisis@live.concordia.ca

\(^2\) Professor and Associate Dean, Concordia University
Montreal, Quebec, Canada, statho@bcee.concordia.ca

**ABSTRACT**

An experimental test house has been constructed in Fredericton (NB, Canada) and both envelope pressures and its wind-induced structural response have been monitored during the last three years. In addition, a 1:200-scaled model of the house was tested at the boundary layer wind tunnel of Concordia University. Acquired field data have been analyzed to evaluate the exposure characteristics for different wind angles of attack. Upstream terrain characteristics variations with respect to wind direction are presented. These data are also considered to properly simulate the upstream terrain in the wind tunnel. Mean and peak pressure coefficient distributions are evaluated and the impact of a varying exposure on the overall structural wind-induced load is discussed.

**KEYWORDS:** FULL SCALE WIND MONITORING, WIND TUNNEL TESTS, UPSTREAM EXPOSURE, PRESSURE DISTRIBUTION, OVERALL WIND LOAD

**Introduction**

Wind-induced loads on low-rise buildings are evaluated based on a set of parameters, such as dynamic velocity (\(q\)), exposure factor (\(C_e\)) and gust pressure coefficient (\(C_pC_g\)). The importance of accurate representation of upstream terrain characteristics during wind tunnel tests has been widely addressed (Stathopoulos 1984, Levitan et al. 1990, Mehta and Smith 2004). The success of wind tunnel experiments is directly related to the availability of accurate upstream terrain characteristics such as wind speed, direction, power spectra, roughness length etc. The impact of different upstream exposures on the gust pressure values was until recently addressed by various codes through the conservative approach of open terrain simulation properly factored for directionality effects. Current interest of the American and Canadian code committees initiated a new potential for studies where a more efficient and rigorous definition of upstream exposure and roughness is intended (Stathopoulos et al 2009). Currently both the American (ASCE 7-05) and the Canadian (NBCC 2005) provisions use the suburban velocity profile for cases in which the exposure is classified in accordance with the code definition as suburban.

Of special interest to the present study is the experimental work conducted by Wang and Stathopoulos (2006). A low building model was tested for a total of 66 fetch cases and 13 wind angles of attack to evaluate the effect of upstream exposure on the wind loading. The different upstream configurations revealed that peak wind loads are basically affected by short distance roughness characteristics rather than further terrain properties. In most cases these loads can be determined by considering a fetch of 300-400 meter since lengths greater than that seem not to affect the wind-induced response. Moreover, the study carefully addresses the impact of “rougher” patches located on the proximity of the examined building and the importance of such variations to both mean and peak wind loads. The findings are closely

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related to the objectives of the current study where full-scale findings in conjunction to wind tunnel experiments are coupled to evaluate upstream terrain characteristics and their influence on local pressures and total response of the building.

**Field Facilities**

The experimental house is located in Fredericton (New Brunswick, Canada), in a relatively open-suburban area. The test building is a single storey typical North-American residential house with a rectangular layout, external dimensions of 8.6x17.2x5.6 meter (WxLxH) and a duo-pitch roof of 4/12 slope. More details about the test house and the instrumentation can be found in Doudak (2005) and Zisis (2006).

A 12-meter high mast located approximately 20 meters west of the house was used to mount three propeller anemometers at heights of 5.0, 6.5 and 10.0 meters. A second smaller mast was added on the east side of the test house equipped with one anemometer at a height of 5.0 meters. An aerial view of the area with the actual building and the meteorological towers is shown in Figure 1. The test house was equipped with 27 foundation and 6 roof load cells. Moreover, 40 pressure taps were distributed on the wall and roof surface, as shown in Figure 2.

\[Figure 1: Test House and Meteorological Tower Location\]

\[Figure 2: Load Cell and Pressure Tap Location on the Experimental House\]

**Wind Tunnel Simulation**

The wind tunnel tests were conducted at the Building Aerodynamics Laboratory located in the Engineering Complex at Concordia University. A geometric scale of 1:200 was selected for the wind tunnel study. The metallic model has external dimensions of 86.5 mm by 42.5 mm (length – width) and a total height of 24.35 mm (ridge height – excluding concrete foundation wall). The model is equipped with 126 pressure taps located on the wall and roof surface respecting the full-scale tap distribution. In addition to the building model, a proximity model of was constructed at the same 1:200 scale. Considering the scale of the test model and the size of the wind tunnel test section, a circular wood base of 1.60-meter diameter and 3.0 mm thickness was used to place all surrounding structures and tree elements on it, as shown in Figure 3.
Results and Discussion

Full-scale Terrain Data

The reliability of the weather tower results was validated through comparison to the closest weather stations operated by Environment Canada, i.e. Fredericton Airport and CDA station. Wind speed and direction comparison charts are shown in Figures 4a and 4b respectively. Records acquired from the 6.5 and 10.0-meter anemometers in the period October 21-31, 2008 were used for this comparison. The agreement between the two sources validates the accuracy of the test facility instrumentation results.
Of great interest was to evaluate the basic exposure characteristics (power law exponent, turbulence intensity and roughness length) using the available field data. Wind data collected from two anemometers (at 6.5 and 10.0-meter height) during October to December 2008 and April to June 2009 were analyzed and power law exponent, turbulence intensity and roughness length values were calculated. Due to a sensor malfunction the third anemometer (5.0 meter height) could not be used reducing, to some extent, the accuracy of the derived characteristics. The results are based on 10-minute averaged statistical values (mean and standard deviation) and were filtered for wind speeds over 10 km/h (at 6.5-meter height). The distribution with respect to direction is shown in Figures 5a, 5b and 5c. The power law exponent ranges from 0.05 to 0.50, the turbulence intensity from 20 to 50% and the roughness length from a few millimeters up to 1.2 meters. It is quite interesting how these properties vary considering that the test house is located in a relatively open area with only few low-rise buildings and medium height trees in the proximity. Following current wind provision guidelines and “common” wind engineering sense, the terrain would be classified in the open to sub-urban region expecting a power law exponent in the range of 0.20. The higher variations should be clearly attributed to the influence of adjacent buildings (north and south sides) and forestry area (east side) located inside the radius of the 300-400 meter fetch. These deviating terrain properties indicate that complex terrains need to be examined carefully in order to properly conduct scaled model tests and successfully compare full-scale to wind tunnel results.

![Figure 5a: Power Law Exponent for Field Data](image)

![Figure 5b: Turbulence Intensity for Field Data](image)
Wind Tunnel Experiments

Currently, two sets of wind tunnel tests have been completed. These tests have been conducted using a power law exponent of 0.16 and 0.21. The turbulence intensity levels at the roof height were approximately 17 and 20% respectively. The complete properties for the two cases are presented in Table 1. In both tests a total of 36 wind directions have been examined (see Figure 3). A more detailed discussion and presentation of each individual wind tunnel experimental approach will be presented as soon as the remaining terrain categories (sub-urban and urban) will be completed.

<table>
<thead>
<tr>
<th>Power Law Exponent (a)</th>
<th>Turbulence Intensity (%)</th>
<th>Roughness Length ($z_o$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Wind Tunnel (m)</td>
</tr>
<tr>
<td>Test A 0.16</td>
<td>17</td>
<td>0.00023</td>
</tr>
<tr>
<td>Test B 0.21</td>
<td>20</td>
<td>0.00045</td>
</tr>
</tbody>
</table>

Pressure Coefficient Comparison

Representative full-scale pressure data from two records (May 14, 2009 and June 1, 2009) were used to verify the agreement of each of the two available wind tunnel tests (Test A and B). For this comparison two pressure taps were selected, one on the wall (Figure 6a) and one on the roof surface (Figure 6b). The mean and peak pressure coefficient was plotted with respect to direction using Eq. (1):

$$
\frac{c_{p, \text{mean/peak}}}{p_{\text{mean/peak}}} - p_a = \frac{1}{2 \rho V_{BH}^2}
$$

where $\rho$=air density (kg/m$^3$); $\bar{V}_{BH}$=mean wind speed at the building height (m/s); $p_a$=ambient atmospheric pressure (Pa), and $p_{\text{mean/peak}}$=actual surface pressure (Pa). It should be noted that for the full-scale calculations the mean values where based on a 10-minute average and the instantaneous peak on a 3-second average (full-scale time scale). The dynamic pressure was always averaged on a 10-minute basis and was referenced to the mean roof height. Moreover field data were integrated over a wind angle of attack of 10-degree range to account for the higher standard deviation values and to be directly compared to wind tunnel tests carried out using intervals of 10 degrees. To better represent the varying characteristics of the full-scale results the minimum and maximum integrated values of each set of data were considered in addition to the mean values.

The agreement for both mean and peak pressure coefficients is good. Wind tunnel values are in most cases within the range of the field results. The discrepancies are somewhat

![Figure 5c: Roughness Length for Field Data](image)
Figure 6a: Mean and Peak Pressure Coefficient Comparison (Wall Pressure Tap)

Figure 6b: Mean and Peak Pressure Coefficient Comparison (Roof Pressure Tap)
higher for the peak pressure coefficient for which the effect of the different simulation profile is also pronounced (a=0.16 versus a=0.21). These discrepancies also coincide with the region where the upstream terrain data were disturbed resulting into higher power law exponent and roughness length (240-290 degrees). This particular case also demonstrates the impact and importance of varying upstream terrain properties to the resulting wind-induced local pressures.

**Force Coefficient Comparison**

A unique characteristic of the experimental house is that it is structurally isolated from the foundation. The total uplift force was recorded and normalized in accordance to the approaching wind characteristics. Moreover data from the wind tunnel experiments were used to assess the equivalent total uplift force coefficient using Eq. (2):

\[
C_{f,\text{mean/peak}} = \frac{F_{z,\text{mean/peak}}}{(1/2 \rho V_{BH}^2)A}
\]

where \(\rho\)=air density (kg/m^3); \(V_{BH}\)=wind speed at the building height (m/s); \(F_{z,\text{mean/peak}}\)=total uplift force (N), and \(A\)=building area (m^2). The full-scale force coefficient was based on field-recorded data, whereas the wind tunnel force coefficient was the result of the integration of the vertical component of all pressures. Similar to the pressure coefficient analysis, both mean and peak components were considered (Figure 7). The field data were collected during May and June of 2009 and were filtered for wind speeds over 10 km/h. The mean values were averaged over a period of 10 minutes and the peaks on a 3-second basis (full-scale time scale).

![Figure 7: Mean and Peak Force Coefficient Comparison (Total Uplift)](image-url)
The effect of adequate upstream simulation in the wind tunnel experiments is even more pronounced on this case. The two different wind tunnel tests (Test A and B) resulted into two discrete trends which for some critical wind directions differ up to 25% for the mean and 40% for the peak values. Results from both wind tunnel tests are within the range of the field data but seem to underestimate the averaged (integration of different full-scale records) peak component, which can be partially justified by the lower level of turbulence. Higher fluctuations of the wind direction should also be addressed and considered accountable for the above mentioned discrepancies.

Conclusions

Field data from two anemometers were used to define the exposure characteristics of a full-scale testing facility. The data interpretation showed higher than expected variations for power law exponents and roughness lengths; the variation for wind turbulence intensity was relatively small. Two sets of data from wind tunnel tests have been compared with the field results in the form of pressure and total uplift force coefficients. The comparisons indicate discrepancies between the two different wind tunnel terrain configurations, which in some cases could be considered critical for the agreement between the field and the simulation studies.

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