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Local wind pressures acting on walls of low-rise buildings and comparisons to the Japanese and US wind loading provisions

Eri Gavanski*, Yasushi Uematsu

Department of Architecture and Building Science, Graduate School of Engineering, Tohoku University, Sendai, Miyagi 980-8579, Japan

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ABSTRACT

This paper examines peak external wind pressures acting on walls of low-rise buildings using various parameters. Results indicate that positive pressure distribution is relatively uniform regardless of parameters considered and its magnitude decreases as averaging area size becomes larger. Large suction pressure distribution occurs at lateral edges of walls and its magnitude does not average out with increasing averaging area size as rapidly as for positive pressure. Based on these observations, we find that zoning of wall area for design purposes is only necessary for wall suction pressures. We further find that it is more suitable to base zoning on building height to some extent. When the present results are compared with the design values in the AIJ Recommendations for Loads and Buildings in Japan, the design values significantly underestimate positive wall pressures for small averaging areas, but the degree of underestimation diminishes as area becomes larger. Similarly, design values underestimate negative wall pressures up to an area of 10 m^2, but begin to overestimate past that point. A similar observation was made for a comparison with ASCE7-10; however, the degree of overestimation of negative code values at larger areas was smaller than the one observed in the comparison with the AIJ Recommendations.

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1. Introduction

Although wall systems of low-rise buildings in both commercial and residential uses have frequently sustained damage during severe wind events, they have received little attention compared to roof systems. This may simply be because the magnitude of wind pressures induced on wall surfaces is smaller than that on the roof, and because wall aerodynamics are believed to be less complicated on account of a wall system's lesser dependence on building shape.

In previous wall structure studies, researchers have actively focussed on wall resistance capacities, especially in the field of pressure equalization performance of multi-layer wall systems, which affect both water and wind resistance capacities (recent studies are summarized in Kumar (2000)). In addition, investigations pertaining to wall wind resistance capacity without pressure equalization have also lately begun to gain some attention (e.g. National Association of Home Builders (NAHB) Research Center, 2008; Kopp and Gavanski, 2012). In terms of wind loading on walls, almost no studies focus exclusively on wall loading characteristics to the authors' knowledge.

Generally speaking, if researchers mention the characteristics of wind loads acting on walls at all, it is tangentially and by comparison to the main subject of loads acting on roofs. These researchers' main findings on wall loadings may be summarized as follows: (1) Positive wind pressure is insensitive to the roof slope (Stathopoulos, 1984; Reardon and Holmes, 1981; Holmes, 1983); (2) Probability density function (PDF) of pressure on windward walls is non-Gaussian (Stathopoulos, 1980; Uematsu and Isyumov, 1999); (3) Large peak factors are obtained for windward walls (Apperley et al., 1979; Stathopoulos, 1980; Okada and Ha, 1992); (3) Building geometry affects pressure coefficients on walls, especially on leeward walls (Hoxey and Moran, 1983; Hoxey and Robertson, 1994); (4) Wind pressure coefficients referenced to eave height are similar regardless of the model height (Stathopoulos, 1980). However, both the number of studies and the range of parameters considered are rather limited compared to the abundance of studies dealing with wind loads acting on roofs. In addition, the authors consider that certain observations that vary among researchers, such as wind directions causing large wind pressures and the uniformity of the wind pressure distributions, should be discussed in greater detail.

Moreover, it is uncertain whether current zoning specified in design codes is adequate for wall loadings. The design wall loads in the current design code in the United States (ASCE7-10) and the Recommendations for Loads on Buildings of the Architectural

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* Corresponding author. Tel. +81 22 795 7869; fax. +81 22 795 7875.
E-mail address: egavanski@m.tohoku.ac.jp (E. Gavanski).

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Institute of Japan (AIJ Recommendations, 2004) are likely to have been designated based on the work of Stathopoulos (1979) and Kanda and Maruta (1993), respectively. In both norms, wall area is divided into end and interior zones only for negative pressures, and the parameter defining the zones is determined based on the roof pressure distribution, rather than the wall pressure distribution. Likely, this result is a simplification made by the drafters for the purposes of the code. The parameter in question is the distance from the edge that is required for pressures of up to 70% of the peak pressure exerted on the roof, normalized by roof width and height (Stathopoulos, 1979; Morrison and Kopp, 2007) for ASCE7-10. In the case of the AIJ Recommendations, the zoning regulations were first codified more than 30 years ago, and as a result the concrete reason behind the zoning is not clear. Therefore, it is uncertain whether zoning based on roof pressure distribution is an adequate approximation of wall loadings.

Considering the above reasons, this study exclusively examines peak local wind pressure coefficients acting on walls of low-rise buildings, using wind tunnel data obtained on testing models, with various building eave heights, roof slopes, and plan dimensions. Internal wind pressure falls outside of the scope of the present study. Comparisons with the AIJ Recommendations and ASCE7-10 are introduced in the last section of the present paper.

2. Dataset

2.1. Database and building models

All the wind tunnel measurement data employed in the present analysis are from the National Institute of Standards and Technology (NIST) aerodynamics database. The NIST database consists of wind-induced pressure time series data acquired from the roof and wall surfaces of various generic low-rise building models measured at the Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario (UWO). The wind tunnel has a working cross section of 3.4 m wide, a variable height of between 1.8 m and 2.7 m, and an upstream fetch of 39 m. The boundary layer simulations were designed to create wind speed and turbulence intensity profiles matching those of the Engineering Science Data Unit (ESDU) (1982), with $z_0=0.03$ m for open country and $z_0=0.3$ m for suburban terrain at a scale of 1:100. Further details on boundary layer simulation can be found in Ho et al. (2005) and are not repeated herein.

From several model configurations listed in the NIST database, 15 model configurations were selected for the present analysis and the details of each model are presented in Table 1. All models have a geometric scale of 1:100, and gable roofs with no overhang. Although overhang is likely to affect external wall pressures, this effect is not considered in this study due to the limitations of the available database. Surface pressures on all the selected models were measured in suburban terrain ($z_0=0.3$ m). The basic model (ef2) has a plan dimension of 38.1 m × 24.4 m with an eave height, h_{eave}, of 7.3 m, and a roof slope, β, of 5°. Other model configurations were selected in order to examine the effects of roof slope ($\beta=1°$–$7°$), eave height ($h_{\mathrm{eave}}=4.9$–12.2 m), and plan dimension (half and twice the size of the basic model). Thus, the contemplated dimensions correspond mostly to industrial buildings.

Building models have pressure taps on all 4 walls, but their location and density vary depending on the model configurations and walls. In general, more pressure taps are located on the northern and eastern walls than on the southern and western walls. Examples of pressure tap layout for the basic model appear in Fig. 1. The measurements were taken starting at various wind directions (θ) and spanning in a range of 180° in increments of 5°, $\theta=0°$ corresponding to the direction normal to the north wall, with θ increasing in a clockwise direction (Fig. 2).

2.2. Wind pressure coefficients

The wind tunnel measurements are performed with a nominal mean hourly wind speed at an upper level in the wind tunnel where the flow is uniform with low turbulence levels (i.e., reference height), V_{ref}, of 13.7 m/s, and with a sampling rate of 500 Hz for 100 s. Assuming a velocity scale of 1:3.2, with a geometric scale of 1:100, gives a time scale of 1:31; and thus a testing time of 100 s corresponds to 52 min in full scale. All measured surface pressure time histories, $P(t)$, are converted into pressure coefficient time series, Cp_{ref}, referenced to the dynamic pressures taken at the reference height with:

$$Cp_{ref}=\frac{P(t)-P_o}{q_{ref}}=\frac{P(t)-P_o}{0.5\rho\ V_{ref}^2} \tag{1}$$

where P_0 is the static pressure at the reference height, ρ is the air density and q_{ref} is the dynamic pressure at the reference height. Cp time series referenced at eave height, Cp_{eave}, are obtained using the following expression: $Cp_{\mathrm{eave}}=Cp_{ref}\times(q_{ref}/q_{\mathrm{eave}})$ where the conversion factor corresponding to the ratio of the eave height to reference height dynamic pressures is provided in the NIST database for each model configuration. These Cp_{eave} time series are further re-referenced to the model mean roof height (as defined by the AIJ Recommendations (Architectural Institute of Japan (AIJ), 2004)), h_{mean}, using mean hourly velocity profile models in the ESDU item 82026 (1982). Thus, unless specifically explained, the results of wind pressure coefficient time series re-normalized by a “common velocity reference” of a 60-min averaging speed at the mean roof height in model suburban terrain are presented as Cp in the following sections.

2.3. Area-averaged pressure coefficients

The area-averaged pressure coefficients, Cp_A, referenced to a “common velocity reference (60-min, h_{mean}, suburban terrain)” were calculated by simultaneously averaging the single tap Cp time series at multiple surrounding taps. The tributary area, which was not necessarily a square, for each wall pressure tap was created by tracing lines parallel to the wall edges through midpoints between adjacent taps. The smallest side of tributary area on any model wall (however oriented), $l_{\min}$, was selected and used as the side length of the square-shaped basic averaging area for the Cp_A calculation for the given model. The basic averaging area was the smallest averaging area, A $(=l_{\min}^2)$, considered in this study. The 2nd smallest averaging area was created by lengthening the sides of the base averaging area by $l_{\min}$ (i.e., the 2nd smallest averaging area was $(2l_{\min})^2$). Larger averaging areas were created by repeating this process until the side length reached either the eave height of the model (h_{eave}) or the horizontal width of the walls (in other terms, either W or L).

For each averaging area size, Cp_A time series were calculated at different locations on the model walls. The location of the averaging area for the Cp_A calculation were decided as follows. Initially, the averaging area was placed at the bottom corner of the wall and then shifted horizontally and vertically by a predetermined increment until it reached the other end of the wall or the full wall height (eave height for east and west walls, height from gable end rafter to the ground for north and south walls). This increment equalled half of the side of the smallest tributary area on the given wall. Consequently, the increment varied for each wall of a model. Cp_A time series were calculated at each location for each size of averaging area with respect to each model.

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