RESILIENT INFRASTRUCTURE
June 1–4, 2016

RESILIENT INFRASTRUCTURE LONDON 2016

WIND PRESSURE COEFFICIENT PROVISIONS FOR LARGE FLAT ROOFS

Hatem Alrawashdeh
PhD student, Concordia University, Canada

Ted Stathopoulos
Professor, Concordia University, Canada

ABSTRACT

The existing literature on wind-induced pressures on roofs of low-rise buildings is generally limited to regular-shaped, mostly rectangular roofs with relatively small dimensions, say less than 60 m. Large roofs for industrial and institutional buildings have not been considered in the formulation of wind code and standard provisions. Therefore, it is important to assess the efficiency of the current national building code/standard provisions as to their applicability for very large roofs. This paper presents experimental results of wind loads on flat roofs of low-rise buildings with large dimensions carried out in an atmospheric boundary-layer wind tunnel for different wind directions. Nine low-rise buildings (5, 7.5 and 10 m high) have been modeled and tested in open-country terrain exposure. The buildings have square plans with full-scale horizontal dimensions ranging from 60 to 180 m. Comparison of the results with respective provisions adopted by ASCE 7-10, NBCC 2015, EN 1991-1-4:2005 and AS/NZS 11702, 2011 indicates that some of the current provisions may lead to considerably conservative designs by increasing the size of the edge and corner zones. A variety of approaches were considered in order to redefine the size of the edge and corner zones with respect to the magnitude of the pressure coefficients provided for all roofs in the different codes/standards when dealing with large roofs of low-rise buildings.

Keywords: design, edge and corner zones, large roofs, wind codes and standards, wind pressures, wind tunnel

1. INTRODUCTION

Historically, significant contributions have been made by several studies to describe the wind pressures on low-rise buildings and codify the results such as the comprehensive research conducted in the mid-seventies to investigate various geometries of low-rise buildings by means of atmospheric wind tunnel tests (Davenport et al. 1977, 1978) and the study on the estimation of instantaneous area-averaged pressure coefficients by the pneumatic-averaging method (Surry and Stathopoulos, 1978).

A number of wind-engineering investigators have also presented wind measurement results in the form of wind loads and reviews for low-rise buildings, e.g., Stathopoulos (1984-B); Holmes (1993); Krishna (1995); Kasperski (1996); Stathopoulos et al (1996); Uematsu and Isyumov (1999); Ho et al (2005); and St. Pierre et al (2005).

Over the past several years the wind load on interior areas of flat roofs of low-rise buildings has been intensely investigated by wind tunnel and full-scale experiments. For instance, Gerhardt and Kramer (1992); Milford et al (1992); Lin et al (1995); Lin and Surry (1998); and Morrison and Kopp (2007). However, these studies were restricted to the simple shapes of low-rise buildings with common, relatively small, dimensions.

Recently, the characteristics of mean and peak wind pressure on flat roofs of large low-rise buildings have been described by (Alrawashdeh and Stathopoulos, 2015). The study found that although building height plays a key role in impacting the values of pressure coefficients, the distribution patterns of roof wind pressures are mainly affected by building plan dimensions. The impact of horizontal plane dimension on the flow patterns is presented in Figure 1, which shows the wind flow patterns over roofs of different dimensions for wind direction normal to the building edge.

Figure 1 (a) represents the general simplified trace of pressure distribution over relatively small roofs - for this group of buildings the pressure distribution collapses slowly; moreover, the reattachment (if any) occurs further away from the leading edge. Figure 1(b) represents the general trend of pressure distribution over relatively large roofs. For this case, the pressure distribution collapses rapidly up to the point of first reattachment and thereafter the flow is retreated close to the surface and runs away smoothly.

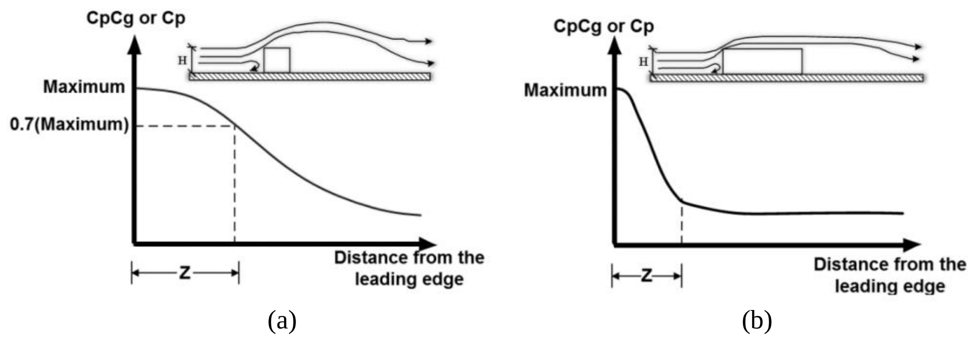


Figure 1: Mean or peak negative pressure distributions over roofs of different sizes:
(a) Smaller roofs (b) Larger roofs (Alrawashdeh and Stathopoulos, 2015)

The loading zones of large roofs have been generated by (Alrawashdeh and Stathopoulos, 2015) along with their wind loads and compared with respective provisions adopted by North American wind codes and standards (ASCE 7-10 and NBCC 2015).

The aim of the current paper is to extend the scope of the previous work. Thus, this paper presents a comparative study, which consists of two parts. The first part includes comparisons of application of current national wind building codes and standards, namely: ASCE 7-10 (USA), NBCC 2015 (Canada), EN 1991-1-4:2005 (Europe) and AS/NZS 11702, 2011 (Australlia/New Zealand), provisions for flat roof zone systems and design wind pressures. The second part of the paper compares the present experimental results with those specified in the current codes/standards to assess their suitability for roofs of large buildings.

2. OVERVIEW

This section presents a concise overview of the methodologies used by current wind standards and codes of practice. The description includes the recommended external design wind pressures and the flat roof zones given by ASCE 7-10, NBCC 2015, EN 1991-1-4:2005 and AS/NZS 11702 (2011), for low-rise buildings.

2.1 Design wind pressures on external building cladding

The methodologies used by the four codes/standards mentioned above, for calculation of wind pressures of enclosed rectangular buildings are summarised in Table 1. The basic wind speed used in NBCC 2015 has a longer averaging time (1-hr) compared with the 3-sec averaging time used in ASCE 7-10. Therefore, since the gust factors for computing pressure coefficients used in ASCE 7-10 will be lower than those in NBCC 2015, the current values of the gust pressure coefficients used in the ASCE7-10 will be lower than those in NBCC 2015 in order to yield comparable design wind pressures.

2.2 Zonal systems for flat roofs

Wind standards and codes of practice divide the entire flat roof of the building into at least three loading zones, namely: corner, edge and interior. The loading zones of the current wind codes and standards are defined as a function of different parameters such as building plan dimensions and building height. The detailed definitions for the zonal system recommended by the wind codes/standards for large flat squared roofs are presented in Figure 2.

Also, design local peak pressure coefficients for each respective zone are provided. As shown in Figure 2, NBCC 2015, ASCE 7-10 and AS/NZS 11702, 2011 use square corner zone, whereas EN 1991-1-4:2005 recommends L-shape corner zones. Also, AS/NZS 11702, 2011 divides the roof interior zone into subzones of width Z2 and Z3 on the basis of H, which is the roof height.

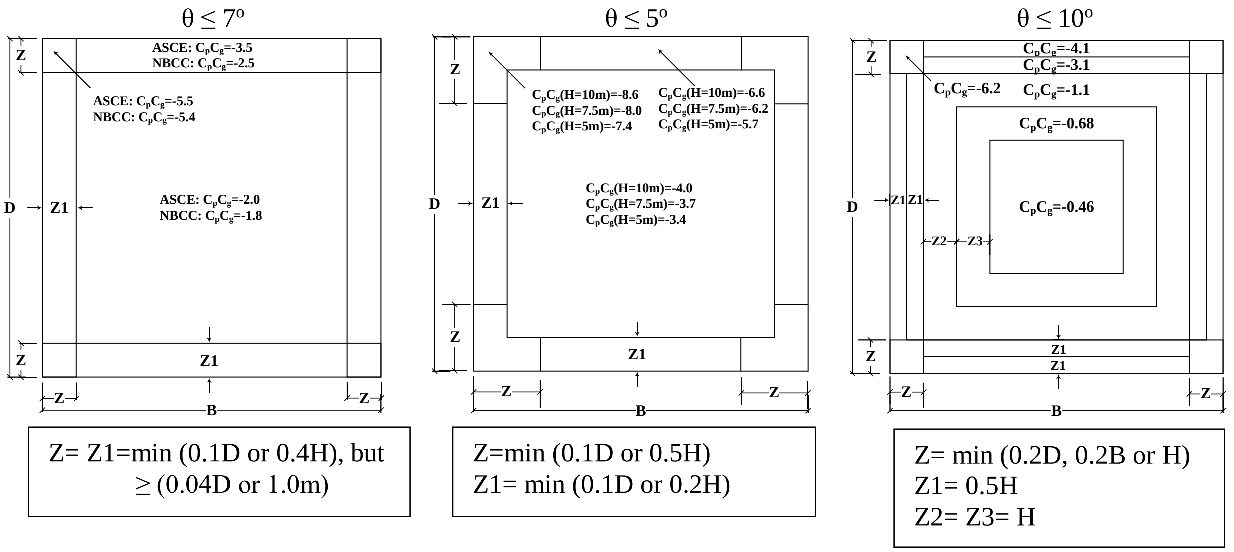
The local external peak pressure coefficients of ASCE 7-10 (GC_p) and NBCC 2015 were obtained directly from simple graphs versus the tributary area. These values are the envelope from all wind directions. It should also be noted that the directionality factor, $K_d = 0.85$, has already been applied to GC_p values of ASCE 7-10.

The local external peak pressure coefficients of EN 1991-1-4:2005 are the equivalent values for $C_eC_{p,e1}$. EN 1991-1-4:2005 specifies two values for external pressure coefficients on building envelope. The first is assigned for loading area 1 m^2 or smaller and represented by $C_{pe,1}$ as a local coefficients, whereas the second is for loading area of 10 m^2 or larger and represented by $C_{pe,10}$ as overall coefficients. The values of $C_{pe,1}$ for the corner, edge and interior zones of flat roofs are -2.5, -2.0 and -1.2, respectively. However, these values are the most critical from all wind directions in the range between 45^o to the left and right of the orthogonal wind direction to the roof edge. This is equivalent to all wind directions for the case of square roofs, which are dealt with in this paper. The exposure factor, C_e, is given as a function of height above the terrain and the terrain category. For the three heights considered in this study (10, 7.5 and 5 m) and open exposure, the values of exposure factors are 3.0, 2.8 and 2.6 and, therefore, the values of the $C_eC_{p,e1}$ for the corner zones are -7.5, -7.0 and -6.5, respectively.

Table 1: Wind Code and Standard Approaches for Design Wind Pressure. (Alrawashdeh and Stathopoulos, 2015)

	ASCE 7-10	NBCC 2010	EN 1991-1-4 2005	AS-NZS 1170-2 2011
Basic wind speed	V	V	$V = V_{b,o}C_{dir}C_{seas}$	$V = V_R M_d M_{z,cat} M_s M_t$
Velocity pressure, q	$0.5\rho V^2 K_z K_{zt} K_d I$	$0.5\rho V^2 I$	$0.5\rho V^2$	$0.5\rho V^2$
Design building pressure	$q(GC_p)$	$qC_e(C_gC_p)$	$qC_eC_{p,e}$	$qK_aK_{c,e}K_lK_p(C_{p,e})$
Terrain factor	K_z	C_e	C_r	$M_{z,cat}$
Topographic factor	K_{zt}	C_e^*	C_o	M_t
Directionality factor	K_d	-	C_{dir}	M_d
Basic wind speed averaging time	3 s	1 h	10 min	3 s
Wind velocity profile	Logarithmic law Power law	Power law	Logarithmic law	Logarithmic law

When the topographic factor is used in NBCC, C_e^* is placed instead of C_e.
C_e: Exposure factor defined as follows: $C_e = [1 + 7I_V]C_r^2C_o^2$, in which I_V is the turbulence intensity.
C_p and $C_{p,e}$: External pressure coefficient. C_{seas}: Seasonal factor.
G and C_g: Gust effect factor.
I : Turbulence intensity.
K_a: Area reduction factor. $K_{c,e}$: Combination factor for external pressures.
K_l: Local pressure factor.
K_p: Porous cladding reduction factor. M_s: Shielding multiplier.
$V_{b,o}$: Fundamental value of the basic wind velocity (10 minutes mean wind velocity at 10 m above ground level open country terrain). V_R: Regional 3 seconds gust wind speed.



(a) (b) (c)

θ: Roof slope
D: minimum horizontal dimension
H: Eave height

Figure 2: Zonal systems of large flat roofs recommended by wind codes and standards: (a) ASCE 7-10 and NBCC 2015, (b) EN 1991-1-4:2005 and (c) AS/NZS 11702, 2011. All pressure coefficients were referenced to $q = 0.5\rho\overline{V}^2$, where: $\overline{V}$ is the mean hourly wind speed.

AS/NZS 11702 provides the values of external mean pressure coefficients, $(C_{P,e})$, for flat roofs as a function of the distance from the windward roof edge and the ratio of the roof height to the width. For the roofs shown in Figure 2, $C_{p,e}$ for the corner and edge zones is -0.9, for the interior zones $C_{p,e}$ values are -0.5, -0.3 and -0.2. The area reduction factor (K_a) depends on the tributary area (A), such that it has a maximum value of 1.0 for A ≤ 100 m^2, 0.9 for A = 25 m^2 and 0.8 for A ≥ 100 m^2. The combination factor, $K_{c,e}$, is not applied for roof cladding, thus it is taken as 1.0 in case of wind pressures acting alone. The local pressure factor (K_I) on flat roofs is applied to the cladding elements within a distance of Z from the leading edge. Thus, the values of (K_I) are 3.0, 2.0 and 1.5 for small cladding area on the corner, exterior edge and interior edge zones, respectively. For the interior zones $K_I = 1$. Permeable cladding reduction factor (K_P) accounted for the effect of surface permeability on the negative pressure is taken as 1.0. For example, the value of $K_a K_{c,e} K_I K_P (C_{P,e})$ of the corner zones is $1 \times 1 \times 3 \times 1 \times 0.9 =$ -2.7.

Finally, in order to take into account the different averaging time for the basic wind speed the values of GC_p (ASCE 7-10), $C_e C_{p,e1}$ (EN 1991-1-4:2005) and $K_a K_{c,e} K_I K_P (C_{P,e})$ (AS/NZS 11702, 2011) have been multiplied by 2.31, 1.14 and 2.31 respectively using Durst (1960).

3. EXPERIMENTAL PROCEDURE

All experiments have been carried out in the boundary layer wind tunnel at the Building Aerodynamics Laboratory, Concordia University. The wind tunnel has a length 12.20 m and working section with 1.80 m wide with an adjustable roof height ranging between 1.40 m and 1.80 m. At the test section, the tunnel is provided with a turntable of 1.60 m diameter, which allows the tested model to rotate at different wind directions. The floor of the tunnel is covered by carpet to generate the required velocity and turbulence profiles of open-country exposure.
The variation of the mean wind speed with the height above the floor was generated with power law index (α) of 0.15, matching the exposure B of ASCE 7-10 and open terrain exposure of NBCC 2015, exposure II of EN 1991-1-

4:2005 and exposure 2 of AS/NZS 11702, 2011. Therefore, CpCg values of EN 1991-1-4:2005 shown in Figure 2 will be modified by a reduction factor 0.80 to make them compatible with the exposure used in this study.

A geometric scale of 1:400 has been used for all experiments of this wind tunnel study as recommended by Stathopoulos (1984). A Plexi-glass model of full-scale equivalent plan dimensions of 60 m has been used as a basic model in the simulation. The roof of the basic model is equipped with 127 roof pressure taps. Models of larger plan dimensions are composed of the basic model and similar geometry wooden blocks, which can be removed or placed to create varying building dimensions i.e. buildings of plan dimensions of 120 m and 180 m. Three full-scale heights of 5.0, 7.5 and 10.0 m are considered in this study. Totally, nine configurations of large low-rise buildings have been tested for this study (B1:60X60X10 m to B9: 180X180X5 m).

The instantaneous surface pressures over the entire roof have been measured for wind directions between 0° and 90° at increments of 15°. The measured pressures have been normalized by the mean dynamic pressure measured at reference height to express them as non-dimensional pressure coefficients, $C_{pi}(t)$ defined as

[1] $$C_{Pi}(t)=\frac{P_i(t)-P_s}{\bar{q}_z}, \qquad \bar{q}_z=\frac{1}{2}\rho\bar{V}_H^2$$

in which $P_i(t)$ is the wind pressure at pressure tap (i), P_s is the static pressure at reference location, $\bar{q}_z$ is mean value of the dynamic velocity pressure at height Z_{ref}, ρ is the density of the air and $\bar{V}_H$ is mean value of the wind velocity at roof height, H.

4. COMPARISON OF ZONAL SYSTEMS FOR FLAT ROOFS

In this section, zonal systems of current national wind codes and standards considered in this study are compared. Moreover, experimental results of the large roof zones are compared with respective values from current wind codes/standards.

4.1 Current wind codes and standards for large roofs

It is well known that the provisions of the current wind codes and standards were established mainly based on wind tunnel experiments of model configurations with relatively small dimensions. Therefore, it would be of interest to apply the provisions of these codes/standards on flat roofs of low-rise buildings with large dimensions. A comparison of roof zone patterns and sizes of ASCE 7-10, NBCC 2015, EN 1991-1-4:2005 and AS/NZS 11702, 2011 was made for the nine building geometries considered in this study.

It has been noted that differences in terms of zonal system sizes are significant among the four national codes/standards considered in this study. For instance, ASCE 7-10 (NBCC 2015) edge/corner zone sizes are determined by the design criterion of 4% of the least horizontal dimension (0.04Ds) for most geometries. According to EN 1991-1-4:2005, the sizes of the edge zone for all geometries are governed by the design criterion of 20% of the roof height (0.2H) and sizes of the corner zone are defined by 50% of the roof height (0.5H); whereas, the width of edge and corner zones of AS/NZS 11702, 2011 are determined by the roof height (H); the sub-zones within the edge zones are governed by (0.5H), while the interior sub-zones are created by (H) for all geometries considered in this study; see Figure 2.

Clearly, it can be noticed that the smallest corner and edge zone sizes are those provided by EN 1991-1-4:2005. For relatively high buildings ($H \geq 7.5$ m), the largest corner zones are created by AS/NZS 11702, 2011 provisions. Also, for buildings with relatively low height ($H \leq 7.5$ m) the largest edge zones are those created by the provisions of ASCE 7-10 (NBCC 2015).

4.2 Experimental data and current wind codes/standards

Edge and corner zones have been created by following the same methodology and patterns implemented for ASCE7-10 and NBCC 2015. Detailed information about this methodology is provided by Alrawashdeh and Stathopoulos (2015).

Comparison of the roof zone sizes of the experimental results with those created by the current guidelines of ASCE 7-10 and NBCC 2015 shows that for buildings with low height and large size (B ≥ 120 m and H ≤ 7.5 m), the edge and corner zones are considerably smaller than the sizes governed by ASCE 7-10 (NBCC 2015) guidelines. The disagreement between the experimental results and the respective code values is due to the zoning parameter 4% of the least horizontal dimension (0.04Ds). For instance, the edge zone size of ASCE 7-10 (NBCC 2015) for building (B9) is found to be twice as large as the actual (experimental) size. On the contrary, for relatively high and large roof buildings, the sizes of the edge and corner zones created by this investigation are comparable to the current ASCE 7-10 (NBCC 2015) provisions.

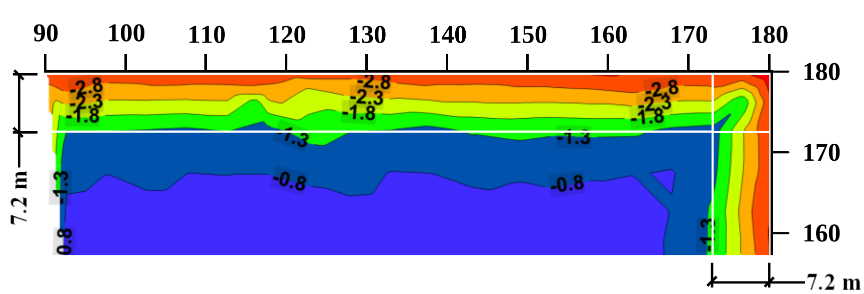
The experimental sizes of the corner zone (Z) are found to larger than those created by EN 1991-1-4 (0.5H). For all tested roofs, the experimental width of the edge zone (Z1) are a factor of 2.7 to 3.6 larger than those provided by (0.5H) of EN 1991-1-4. In addition, the experimental sizes of the corner and edge zones (Z and Z1, respectively) are approximately 1.5 to 2.0 times smaller than those created by the design criterion (H and 0.5H, respectively) of AS/NZS 11702.

The methodologies followed for the development of current wind code and standard provisions are different. For instance, the smallest sizes of the corner and edge zones are provided by EN 1991-1-4, which also gives the highest local peak pressure coefficients among the other codes and standards; see Figure 2. Therefore, quantitative comparisons of the roof zone sizes separately may not be sufficient to describe the adequacy of these codes and standards. In this regard, the suitability of the code/standard roof systems should be equally examined with the design wind pressure coefficients.

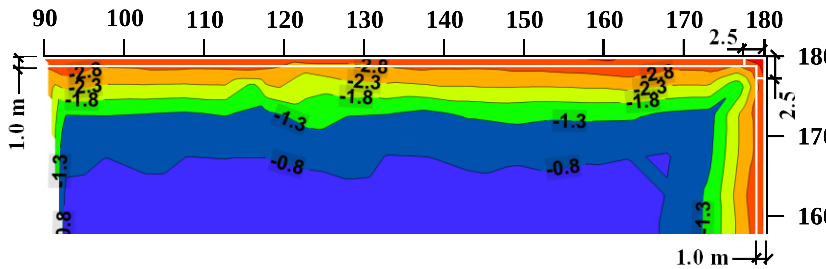
The current wind codes/standards roof zones and the experimental roof pressures are investigated together by projecting the wind codes/standards zone layouts on the roof distribution of most critical peak pressure coefficients. For example, Figure 3 shows the contour distribution of most critical peak pressure coefficients over the perimeter of the building B9: 180X180X5 m with roof zones of current wind codes/standards. It should be noted that these contours on a quarter of the roof reflect the pressure distribution on the entire roof perimeter by taking advantage of the symmetry of the roof models. The summary of this investigation is presented in Table 2, in which the range of most critical pressure coefficients captured by corner and edge zones of current provisions are provided.

Based on the results shown in Table 2, it can be concluded that the current provisions of ASCE 7-10 and NBCC 2015 have a tendency to provide very conservative corner and edge zones. These results have been demonstrated by Alrawashdeh and Stathopoulos (2015) during their investigation to the current ASCE 7-10 and NBCC 2015 provisions for flat roofs.

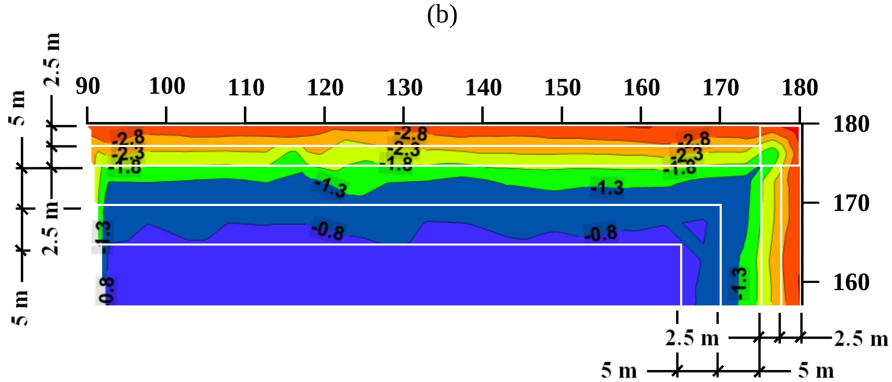
Corner and edge zones of EN 1991-1-4:2005 capture the local pressure coefficients higher than -3.0 and -2.5, respectively. These values, which represents the local boundary pressure coefficients between edge/corner zones and the interior zone, are found to be in agreement with design pressure coefficients for the interior zones (-3.3, -3.0 and -2.7, see Figure 2). Accordingly, current edge and corner zones of EN 1991-1-4:2005 on the one hand are suitable for large roofs, and on the other hand very conservative design pressure coefficients are provided for edge and corner zones.



(a)



(b)



(c)

Figure 3: Most critical negative peak pressure coefficient contours (envelope values for all wind directions) with roof zones for building B9: 180X180X5 m of the current provisions of: (a) ASCE 7-10 (NBCC 2015), (b) EN 1991-1-4 and (c) AS/NZS 11702, 2011

Corner zones of AS/NZS 11702 capture local boundary pressure coefficients higher than -1.8, -1.7 and -1.5 for all roofs of heights 10, 7.5 and 5 m, respectively. Comparison of these boundary pressure coefficients with those provided by AS/NZS 11702 for the first interior zone (-1.1, see Figure 2) shows that the design pressure coefficients of AS/ (2011) 11702 for interior zones are insufficient and indeed lower than the actual wind pressure. This implies that sizes of the corner zone and total edge zones (two sequential) created by design criterion eave height (H) for large flat roofs are less than desired. Thus, these zones should be extended for larger sizes to capture lower pressure coefficients. Accordingly, the size of the interior zones will be reduced and the maximum local pressure coefficients captured by these zones will be decreased too.

Table 2: Minimum Values (in Absolute Sense) of Most Critical Pressure Coefficients Captured by Current Wind Code/Standard: ASCE 7-10 (NBCC 2015), EN 1991-1-4:2005 and AS/NZS 11702, 2011– see Figure 3 for B9.

Corner Zone			
Building	ASCE 7 (NBCC)	EN 1991-1-4	AS/NZS 11702
	C_pC_g	C_pC_g	C_pC_g
B1	> -2.5	> -3.0	> -2.0
B2	> -2.0	> -2.8	> -1.8
B3	> -2.0	> -3.0	> -1.8
B4	> -2.2	> -2.7	> -1.6
B5	> -1.9	> -2.7	> -1.7
B6	> -1.3	> -2.8	> -1.3
B7	> -2.0	> -3.0	> -1.4
B8	> -1.5	> -2.8	> -2.0
B9	> -1.3	> -2.8	> -1.3
Edge Zone			
Building	ASCE 7 (NBCC)	EN 1991-1-4	AS/NZS 11702

	C_pC_g	C_pC_g	C_pC_g	C_pC_g
B1	> -2.5	> -2.5	> -2.5	-2.5> C_pC_g >-1.8
B2	> -2.3	> -2.8	> -2.3	-2.3> C_pC_g >-1.8
B3	> -2.0	> -2.5	> -2.3	-2.3> C_pC_g >-1.8
B4	> -2.5	> -2.7	> -2.4	-2.4> C_pC_g >-1.6
B5	> -2.3	> -2.7	> -2.5	-2.5> C_pC_g >-1.7
B6	> -1.8	> -2.5	> -2.3	-2.3> C_pC_g >-1.8
B7	> -2.5	> -3.0	> -2.5	-2.5> C_pC_g g>-1.5
B8	> -1.5	> -2.5	> -2.5	-2.5> C_pC_g >-1.8
B9	> -1.3	> -2.8	> -2.3	-2.3> C_pC_g >-1.8

5. MODIFYING THE PROVISIONS OF CURRENT WIND CODES AND STANDARDS

A suggestion has been proposed by Alrawashdeh and Stathopoulos (2015) for the current statement of ASCE 7-10 (NBCC 2015) defining the roof zones of low-rise buildings for better evaluation of edge and corner zones of large roofs. A key limitation of this suggested exception is that the exception addresses the current roof zones sizes without modifying the structure of the guidelines defining the zone sizes, as well the design wind pressures of these zones. This suggestion is appropriate for buildings with mean roof height of 8 m or lower and least horizontal plan dimension greater than 90 m. Following this, during this section application of the proposed suggestion and its efficiency to current wind codes and standards will be discussed. The proposed suggestion is presented in Figure 4. Accordingly, Table 3 shows roof zones of the tested buildings obtained by experiments, current and modified provisions based on the suggested exception.

The current provisions of ASCE 7-10 (NBCC 2015) may lead to considerably conservative and uneconomic edge/corner zones for large and relatively low height roofs with sizes larger than the actual sizes. For these geometries the size of these zones should be decreased such that they will envelope higher range of pressure coefficients. This issue can be solved for the current roof system of ASCE 7-10 (NBCC 2015) by applying the suggested exception that presented in Figure 4. Application of this exception to the ASCE 7-10 (NBCC 2015) guidelines has led to more economic and adequate design for large roofs of large buildings.

Roof zones of EN 1991-1-4:2005 are found to be suitable in terms of sizes for large roofs with exaggerated design pressure coefficients for the small areas on the roof perimeter. In this case, increasing the size of the edge/corner zones is not compatible. Thus, interior zones with the exception will be designed for more conservative values of pressure coefficients compared with before (current system). As presented in Table 3, application of the suggested exception does not change the roof zones since the edge/corner zones are created by the design criteria 0.2H which is always less than (0.8H) of suggested by the exception.

<u>Exception:</u> for roofs of buildings with α = 0° to 7° and a least horizontal dimension greater than 90 m (300 ft) the width of the corner and edge zones (Z and Z1) shall be limited to a maximum of (0.8H) regardless of the zones shape.

Figure 4: Current guidelines specified in different wind codes/standards and the proposed suggestion.

Table 3: Size of Corner/Edge Zones of Present Study and Current Wind Code/Standard: ASCE 7-10 (NBCC 2015), EN 1991-1-4:2005 and AS/NZS 11702 (2011), compared with the proposed exception.

Corner Zone (Z, in m)							
Building	Experimental	ASCE 7 (NBCC)		EN 1991-1-4		AS/NZS 11702	
		Current	Modified	Current	Modified	Current	Modified
B1	5.3	4.0	4.0	5.0	5.0	10.0	10.0
B2	6.0	4.8	4.8	5.0	5.0	10.0	10.0
B3	6.9	7.2	7.2	5.0	5.0	10.0	10.0
B4	5.2	3.0	3.0	3.8	3.8	7.5	7.5
B5	5.3	4.8	4.8	3.8	3.8	7.5	6.0
B6	5.4	7.2	6.0	3.8	3.8	7.5	6.0
B7	3.3	2.4	2.4	2.5	2.5	5.0	5.0

B8	3.4	4.8	4.0	2.5	2.5	5.0	4.0
B9	3.4	7.2	4.0	2.5	2.5	5.0	4.0

Edge Zone (Z1, in m)

Building	Experimental	ASCE 7 (NBCC)		EN 1991-1-4		AS/NZS 11702			
		Current	Modified	Current	Modified	Current		Modified	
B1	5.3	4.0	4.0	2.0	5.0	5.0	5.0	5.0	5.0
B2	6.0	4.8	4.8	2.0	5.0	5.0	5.0	5.0	5.0
B3	6.9	7.2	7.2	2.0	5.0	5.0	5.0	5.0	5.0
B4	5.2	3.0	3.0	1.5	3.8	3.8	3.8	3.8	3.8
B5	5.3	4.8	4.8	1.5	3.8	3.8	3.8	3.8	3.8
B6	5.4	7.2	6.0	1.5	3.8	3.8	3.8	3.8	3.8
B7	3.3	2.4	2.4	1.0	2.5	2.5	2.5	2.5	2.5
B8	3.4	4.8	4.0	1.0	2.5	2.5	2.5	2.5	2.5
B9	3.4	7.2	4.0	1.0	2.5	2.5	2.5	2.5	2.5

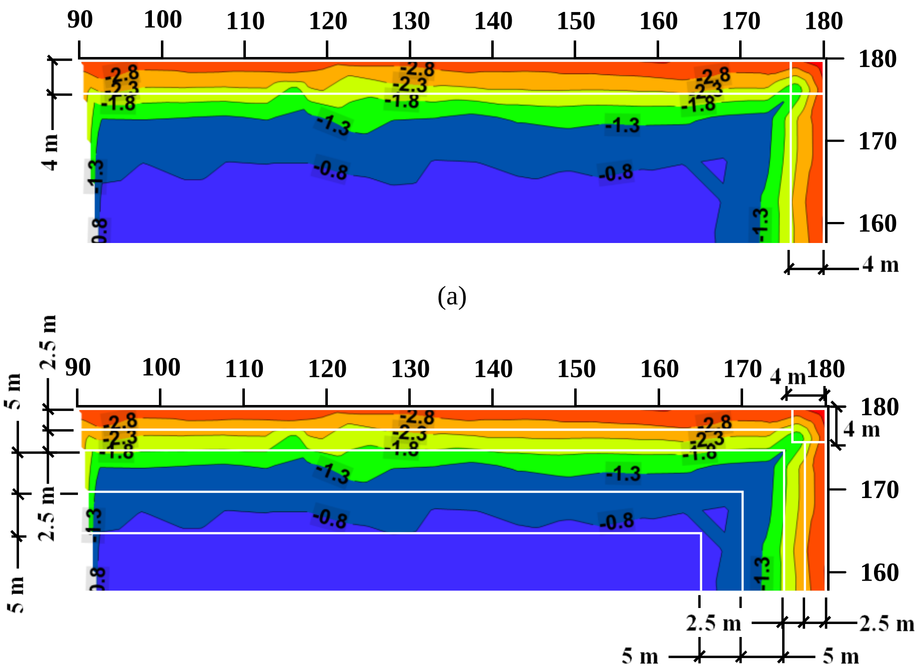
Current corner/edge zones of AS/NZS 11702 are found to capture experimental boundary pressure coefficients higher in values than those provided by the AS/NZS 11702 (2011) for the interior zone. Thus, current pressure coefficients of the first interior zone are not appropriate with the actual wind pressure coefficients. Therefore, decreasing the size of the edge zone will make the guidelines worse. Application of the suggested exception to the current guidelines of AS/NZS 11702 (2011) does not affect the size of the edge zone (Z1) since the edge zone size (0.5H) is less than the proposed size (0.8H), whereas application of the of the suggested exception has reduced the size of the corner zones, see Table 3. Thus, a part area of the corner zone will be a part of the edge zone (interior).

As a brief conclusion from the previous, the proposed exception has only effects on the guidelines of ASCE 7-10 (NBCC 2015) and AS/NZS 11702 (2011). As already noted, the current guidelines of ASCE 7-10 (NBCC 2015) overdesigning the corner/edge zones of large roofs and very low height ($H \leq 7.5$ m) by producing zones of width of 4% of the least horizontal plan dimension. AS/NZS 11702 (2011) underestimates the interior zone wind pressure or the guidelines of AS/NZS 11702 (2011) create edge zones of sizes less than required. In spite of that the authors believe that application of this practical exception will effectively improve the current provisions by decreasing the size of the unjustified areas under the conditions that the design wind pressure coefficients of ASCE 7-10 (NBCC 2015) and AS/NZS 11702 (2011) are kept as they are.

To verify this exception, the proposed roof zones are figured on the experimental contours of most critical pressure coefficients distribution of all tested buildings. Undoubtedly, the final outcomes of these code/standard provisions become more reliable against wind loading for low-rise buildings. As an illustration, proposed roof zones and the experimental pressure coefficients over the roof building B9: 180X180X5 m are shown in Figure 5.

Clearly, the gross area of the corner zones of ASCE 7-10 (NBCC 2015) and AS/NZS 11702 (2011) are reduced. The edge zones of ASCE 7-10 (NBCC 2015) are also decreased. These reductions in the sizes are treated for the overdesigning portion of the roof zones created by the current guidelines of these wind codes/standards. Thus, the corner zones of the modified provisions hold all local peak pressure coefficients higher than -1.8, whereas the corner zones of the current provisions hold all peak pressure coefficients higher than -1.3. In the same way, the edge zones of the modified provisions of ASCE 7-10 (NBCC 2015) hold all local peak pressure coefficients higher than -2.0 in comparison with the edge zones of the current provisions that hold all peak pressure coefficients higher than -1.3.

Moreover, the design wind pressure coefficients provided by ASCE 7-10 (NBCC 2015) and AS/NZS 11702 (2011) become more consistent with the actual pressure distribution on large roofs with the modified zonal system.



(a)

(b)

Figure 5: Most critical negative peak pressure coefficient contours (envelope values for all wind directions) with roof zones for building B9: 180X180X5 m of the proposed provisions: (a) AS/NZS 11702 (2011) and (b) ASCE 7-10 (NBCC 2015)

For instance, the maximum local peak pressure coefficients measured on the modified interior zone are found to be roughly -1.8, which are consistent with the respective design values -2.0 and -1.8 of ASCE 7–10 and NBCC 2015, respectively. Also, the local peak pressure coefficients measured on boundary of the modified corner zone of AS/NZS 11702 (2011) are found to be in range of -1.8 to -2.3, which will be overestimated by the AS/NZS 11702 (2011) design pressure coefficients -3.1 provided for the edge zone. Whereas in the case of the current provisions, these reduced parts of the corner zones are overestimated by the AS/NZS 11702 (2011) design pressure coefficients -6.2 provided for the corner zone.

6. SUMMARY AND CONCLUSION

This study has discussed roof zones of various wind codes/standards and their applicability for large low-rise buildings. A set of experimental results on large roofs have been acquired and applied for code comparisons, mainly including the roof wind pressures and roof zones. The main findings can be summarized as follows:

1. There are significant discrepancies in the definitions of edge and corner roof zones among current wind codes and standards, including the roof zone sizes and their design wind pressures. These discrepancies are due to the differences in their methodologies and sources at development.
2. The ASCE 7-10 and NBCC 2015 restriction (0.04Ds) may lead to oversized edge and corner zones for such buildings with large roofs and low heights ($H \leq 7.5$ m and $D \geq 120$ m).
3. Narrow corner and edge zones with high design pressure coefficients are introduced by EN 1991-1-4 for large flat roofs. This approach may be too conservative.
4. AS/NZS 11702, 2011 provisions overestimated the sizes of the roof corner zones.

Extending the scope of the work done by Alrawashdeh and Stathopoulos (2015), their proposed exception for large low-rise buildings has been applied to the general definitions of the size of edge and corner zones of ASCE 7-10 (NBCC 2015) and AS/NZS 11702 (2011). This exception reduced the sizes of the edge/corner zones of ASCE 7-10 (NBCC 2015) and the corner zones of AS/NZS 11702 (2011).

ACKNOWLEDGMENT

This work is sponsored by the Natural Sciences and Engineering Research Council of Canada (NSERC), financial support of which is gratefully acknowledged by the authers.

7. REFERENCES

Alrawashdeh, H., Stathopoulos, T. 2015. Wind Pressures on Large Roofs of Low Buildings and Wind Codes and Standards. *Journal of Wind Engineering and Industrial Aerodynamics*, 147: 212–225.

ASCE/SEI 7-10. 2010. Minimum Design Loads for Buildings and Other Structures. *Structural Engineering Institute of ASCE, Reston, VA*.

AS/NZS 1170.2. 2011. Australian/New Zealand Standard for Structural Design Actions, part 2: Wind Actions. Sydney, New South Wales, Australia: Standards Australia and Standards New Zealand.

Davenport, A.G., Surry, D., Stathopoulos, T. 1977. Wind Loads on *Low*-Rise Buildings, Final Report on Phases I and II. BLWT-SS7, *The University of Western Ontario, London, Ontario, Canada*.

Davenport, A.G., Surry, D., Stathopoulos, T. 1978. Wind Loads on Low-Rise Buildings, Final Report on Phase III. BLWT-SS8, *The University of Western Ontario, London, Ontario, Canada*.

EN 1991-1-4, 2005. Eurocode 1, 2005: Actions on Structures-General actions-Part 1-4: Wind Actions, European Standard.

Durst, C. S. 1960. Wind Speeds over Short Periods of Time. Meteor Magazine, 89, 181-187.

Gerhardt, H. J., Kramer, C. 1992. Effect of Building Geometry on Roof Wind Loading. *Journal of Wind Engineering and Industrial Aerodynamics,* 43: 1765–1773.

Ho, T.C.E., Surry, D., Morrish, D., Kopp, G.A. 2005. The UWO Contribution to the NIST Aerodynamic Database for Wind on Low Buildings: Part 1. Archiving Format and Basic Aerodynamic Data. *Journal of Wind Engineering and Industrial Aerodynamics*, 93: 1-30.

Holmes, J.D. 1993.Wind Loads on Low-rise Buildings - A Review. *CSIRO, Division of Building Research, Highett, Victoria, Australia*.

Kasperski, M. 1996. Design Wind Loads for Low-rise Buildings: A Critical Review of Wind Load Specifications for Industrial Buildings. *Journal of Wind Engineering and Industrial Aerodynamics*, 61: 169-179.

Krishna, P. 1995. Wind Loads on Low Rise Buildings - A Review. *Journal of Wind Engineering and Industrial Aerodynamics,* 54-55: 383-396.

Lin, J.X., Surry, D. 1998. The Variation of Peak Loads With Tributary Area Near Corners on Flat Low Building Roofs. *Journal of Wind Engineering and Industrial Aerodynamics*, 77-78: 185-196

Lin, J.X., Surry, D., Tieleman, H.W. 1995. The Distribution of Pressure Near Roof Corners of Flat Roof Low Buildings. *Journal of Wind Engineering and Industrial Aerodynamics*, 56, 235: 265.

Milford, R.V., Goliger, A.M., Waldech, J.L. 1992. Jan Smuts Experiment: Comparison of FullScale and Wind-Tunnel Results. *Journal of Wind Engineering and Industrial Aerodynamics,* 43: 1693-1704.

Morrison, M.J., Kopp, G.A. 2007. Evaluation of the ASCE 7-05 Definition of Edge and Corner Zones for Low-Rise Buildings. *The Boundary Layer Wind Tunnel Laboratory, The University of Western Ontario, Faculty of Engineering, London, Ontario, Canada N6A 5B9*.

NBC2015. 2015. User's Guide-NBC 2015, Structural Commentaries (Part 4). *Issued by the Canadian Commission on Buildings and Fire Codes, National Research Council of Canada*.

Stathopoulos, T. 1984-A. Design and Fabrication of a Wind Tunnel for Building Aerodynamics. *Journal of Wind Engineering and Industrial Aerodynamics*, 16: 361-376.

Stathopoulos, T. 1984-B. Wind Loads on Low-rise Buildings - A Review of the State of the Art. Engineering Structures, 6, 119–135.

Stathopoulos, T., Kumar, K.S., Mohammadiam, A.R. 1996. Design Wind Pressure Coefficients for Monoslope Roofs: A Time Series Approach. *Journal of Wind Engineering and Industrial Aerodynamics*, 65: 143-153.

St. Pierre, L.M., Kopp, G.A., Surry, D., Ho, T.C.E. 2005. The UWO Contribution to the NIST Aerodynamic Database for Wind on Low Buildings: Part 2. Comparison of Data with Wind Load Provisions. *Journal of Wind Engineering and Industrial Aerodynamics*, 93: 31-59.

Surry, D., Stathopoulos, T. 1978. An Experimental Approach to the Economical Measurements of Spatially Averaged Wind Loads. *Journal of Wind Engineering and Industrial Aerodynamics*, 2 (4): 385-97.

Uematsu, Y., Isyumov, N. 1999. Wind Pressures Acting on Low-Rise Buildings. *Journal of Wind Engineering and Industrial Aerodynamics*, 82: 1-25.