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Wind loads on buildings: A code of practice perspective

Ted Stathopoulos, Hatem Alrawashdeh*

Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Quebec, Canada

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ABSTRACT

The paper reviews the wind loading of buildings from a code perspective. The Canadian wind load provisions for buildings, due primarily to the ingenuity of Alan G. Davenport, have gained an international reputation after recognition for their innovative and pioneering character by researchers and practitioners across the globe. In this regard, these provisions have been influential in the development and evolution of various national and international wind load standards, including the ASCE 7, the ISO wind load standard, the Eurocode, the China standard for wind loads on roof structures and others. The paper provides first an overview of ASCE 7 (USA), NBCC (Canada) and GB 50009 (China) to gain some insight into the extent to which the external pressures, internal pressures, exposure issues and topography - among others - are currently being addressed through these provisions. The current similarities and differences among wind load provisions for buildings are outlined and attempts are made to resolve some of the apparent discrepancies leading to possibly non-conservative results. Ultimately, innovative codification approaches and trends currently under discussion, development and consideration are also presented.

1. Introduction

The response of buildings to wind impact largely depends on the structural characteristics of the building. The key characteristics involve the natural frequency of the first few modes of vibration and the height of the building. Accordingly, buildings are classified as rigid (stiff) and flexible (aeroelastic). Only the response of rigid buildings will be discussed in this paper. Rigid buildings, such as low-rise buildings that form the majority of the buildings on earth, have a high natural frequency of vibration and respond to the wind loads experienced by them without magnification. Such buildings are described as static for wind loading design purposes, although they experience highly fluctuating (dynamic) loads during strong wind events.

Evaluation of wind loads on low-rise buildings has been the subject of many review studies, relevant examples include: Stathopoulos (1984), Holmes (1993), Krishna (1995), Kasperski (1996), Stathopoulos et al. (1996), Uematsu and Isyumov (1999), Ho et al. (2005), St. Pierre et al. (2005), Alrawashdeh and Stathopoulos (2015) and others have also provided state-of-the-art papers on wind loads on low-rise buildings. Although wind pressures on buildings reported prior to the postulation of Jensen's law (Jensen, 1958) may not be representative, some of the early ideas hold well up to date.

Further, the evolution of research and thinking in the formulation of wind loading provisions has been very remarkable during the closing decades of the last century or so. For instance, Krishna (1995) compared mean pressure coefficients (C_p) on a gable roof building with a roof angle of 30° and wind normal to the ridge, as they appear in code provisions of twelve different countries, and found significant differences: for example, C_p values on the windward part of the roof reportedly range from −0.5 to +0.2 while those on the leeward part range from −0.4 to −0.7.

Extensive research has led to the postulation of design pressure coefficients more consistent with building aerodynamics considerations and the loading mechanisms of low-rise buildings with various roof geometries. Although these provisions have found their way in the North American wind standards and codes of practice, to which this paper particularly refers, they have also influenced and continue to play a significant role in the development of other national and international standards. The level of confidence and the reliability in the wind codes and standard provisions have always been accorded a very high priority, with bearing in mind the simplicity of these provisions.

The paper will discuss the current wind provisions of the American Society of Civil Engineers (ASCE 7, 2016), the National Building Code of Canada (NBCC, 2015) and the National Standard of the People's Republic of China (GB 50009, 2012) with reference to their developments in recent years. Definitely, issues about how design wind loading procedures related factors have been handled through the considered wind codes and standards will be discussed, including among others: the effects of upstream roughness, topography and geometry of building on both external and internal pressures.

* Corresponding author.
E-mail address: h_alraw@encs.concordia.ca (H. Alrawashdeh)

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However, the objective of this paper is not a direct comparison of wind codes and standards, i.e. a simple comparative exercise but to show the differences over the years and countries in terms of philosophies, design procedures, approaches and assumptions made or followed by code committees in the development of simple technical provisions necessary for design practice. In this regard, some historical development in terms of technical procedures and approaches was particularly necessary to include in order to show the evolution of procedures, their similarities and differences without, again, attempting to compare the current provisions in terms of saying that design pressure is presently higher or lower in different codes, as a mere comparison would imply. Ultimately, this paper will refer to some particular vital issues of the current interest of both wind engineering researchers and code/standard committees (wind loading on roofs and building attachments, artificial intelligence, non-synoptic winds and CFD).

2. Procedures of assessing wind loads on low-rise buildings

The interaction between wind flow and structures is inherently very complicated. Thus, the pressure on any surface of the exposed structure is spatially heterogeneous from point to point, depending on the shape and size of the structure, the speed and direction of the wind, and on the surrounding environment such as the nearby obstacles. In aerodynamics, this interaction must be quantified at both the impact of the accelerated flow on the surface pressures and their distribution, as they are characteristic of such interaction. The induced surface pressure (p) at any point can be expressed in terms of the dynamic velocity pressure (q) by the use of a pressure coefficient C_p, as follows:

$$p = C_p q \tag{1}$$

At the outset, the national wind codes and standards were typified by being simple and similar in following the design guidance. Indeed, the wind pressure defined by Eq. (1) was the nucleus within which the historical development of the formulas currently adopted by wind codes and standards. Table 1 summarizes the present procedures used by national wind codes and standards of ASCE 7 (2016), NBCC (2015) and GB 50009 (2012). As illustrated, although these procedures in various wind codes and standards seemingly show similarity to some extent, in reality they are quite different when dealing with wind-induced pressure determinants. Indeed, the design procedures presented in Table 1 will be traced, with particular reference to terrain, topography and pressure coefficients considerations.

For instance, directionality effects, which are apparently quantified in ASCE 7 (2016), are also taken into account implicitly in the Canadian Code (NBCC, 2015). Thus, the values of pressure coefficients adopted by NBCC (2015) implicitly reflect the directionality effects. Also, the ground elevation factor (K_e) of ASCE 7 (2016) is an adjustment factor for the reference velocity pressure to consider changes in air density with height. However, ASCE 7 (2016) permits users to neglect this variation and take $K_e = 1.0$.

Table 1
Wind code and standard procedures for deriving external surface pressure.

Wind Code/Standard	ASCE 7(2016)	NBCC(2015)	GB 50009(2012)
Basic Wind Speed	V	V	V
Velocity Pressure, q_h (N/m ^{2})	$0.5\rho V^2 K_h K_{ht} K_d K_e$	$0.5\rho V^2 C_e C_t$	$0.5\rho V^2 \mu_h$
Design Building Pressure, P	$q_h G C_p$	$q_h C_g C_p$	$q_h C_{pe}$
Terrain Factor	K_h	C_e	μ_h
Topography Factor	K_{ht}	C_t	–
Directionality Factor	K_d	–	–
Ground Elevation Factor	K_e	–	–
Basic Wind Speed Averaging Time (sec)	3	3600	600

2.1. Reference velocity pressure

Reference velocity pressure (q) is defined as a function of the square of the basic wind speed V, which depends upon several conditions, mainly including reference height, averaging time and return period. Table 2 summarizes the conditions of the reference velocity pressure adopted by the wind codes/standards, which consider a unified reference height (10 m) and reference region of flat open terrain (Exposure C in ASCE 7, 2016; Open in NBCC, 2015; and B in GB 50009, 2012) for the basic wind speed of the velocity pressure. Nevertheless, pronounced differences still exist, clearly upon the averaging time and the return period in which the design pressure coefficients and the mean wind speed are respectively referenced, thus necessitating the uniformity of the averaging time for consistency reasons. The well-known Durst curve (Durst, 1960), which charts the relationship between the probable maximum wind speed averaged over a variety of periods ($1.0 = t \leq 3600$ s) and the mean wind speed over 3600 s (hourly wind speed), can be used to adjust from one averaging time to another.

It should be noted that the American Standard (ASCE 7, 2016) has recently considered 4 return periods for analyzing the basic wind speed according to the category of risk. However, it should be made clear that the high return periods of the American standard do not imply more conservative loads but reflect a different approach to design. Indeed, the return period for each risk category is defined on the basis of a target reliability level established on the basis of load combination considerations. As an example, the NBCC (2015) considers a 50-year return period for the basic wind speed but with a wind load factor of 1.4 while the ASCE 7 (2016) provides the basic wind speed maps of return periods ranging between 300 and 3000 years based on four risk categories with a wind load factor of 1.0.

2.2. Terrain factor

Two expressions are utilized by the national wind codes and standards to represent the mean wind profile, namely: Power Law and Logarithmic Law. The wind profiles of the wind codes/standards considered are fitted by the power law. Exceptionally, the profile of the American standard can be provided by power and logarithmic laws. As shown previously in Table 1, wind codes/standards adopt the so-called terrain factor for different terrain categories to address the effects of the upstream exposure conditions in calculating the design wind load. Exposure (terrain) factors are called K_z (ASCE 7, 2016), C_e (NBCC, 2015) and μ_z (GB 50009, 2012). Generally, the exposure factor of the codes/standards considered has the following universal expression:

Table 2
Characteristics of velocity pressure of wind codes/standards.

Wind Code/Standard	Air density (kg/m ^{3})	Reference height (m)	Averaging time	Return period (years)
ASCE 7 (2016)	1.226	10	3 s	300 700 1700 3000
NBCC (2015)	1.2926	10	1 h	50
GB 50009 (2012)	1.225	10	10 min	10 50 100

$$\text{Exposure Factor } = a\left(\frac{Z}{Z_{ref}}\right)^{\alpha} \quad (2)$$

in which a, Z_{ref} and α are parameters dependent on the upstream terrain exposure.

In the current national wind codes and standards, the upstream exposures are somewhat vaguely and differently defined. Thus, the characterization of upstream exposures in the wind codes/standards is still simple and provided in rough descriptive terms. For instance, ASCE 7 (2016) and GB 50009 (2012) identify four categories for upstream exposures; NBCC identifies three upstream exposure categories A, B and C and more recently only two (open and rough).

Table 3 presents the exposure categories provided by the considered wind codes and standards along with the recommended key determinants (α, a and Z_{ref}) referred to in Eq. (2), of each exposure profile. It should be noted that exposure A is the rougher category (urban core) of ASCE 7 (2016) and has been eliminated from the past editions of ASCE 7, for which currently only the wind tunnel procedure is recommended. Also, each of the exposure categories (A, B, C and D) of ASCE 7 (2016) is in conformity with a range of values of roughness length (z_o) for implementation of the logarithmic law.

Fig. 1 shows the variation of exposure coefficient values with height provided by ASCE 7 (2016), NBCC (2015) and GB 50009 (2012). For the evaluation of these curves, the recommended terrain category variables (α, a and Z_{ref}) prescribed in Table 3 were used. Certainly, the exposure coefficients among the considered wind codes and standards cannot be compared, since they refer to different terrain conditions. However, it is important to recognize that within the individual wind code/standard there is a significant increase in exposure coefficient values among the exposure categories and thus an increase in the design wind pressure. It turns out that a more detailed definition of upstream conditions of the building site is indispensable since it will significantly lead to enhancing the credibility of the design pressure.

In the past, less attention has been allotted to examine the effect of exposure on the wind loading of low-rise buildings compared to that given to the evaluation of pressure coefficients. However, the reliable description of the upstream exposure is of practical importance. Indeed, accurate estimation of the vertical profile of mean wind speed, turbulence and wind direction for the site of interest will lead to a more realistic prediction of wind-induced pressures on buildings.

Furthermore, additional issues are needed to be addressed in the context of the exposure coefficient reform process. Wind codes/standards of practice provide various minimum fetch lengths required for a particular characterization of an upstream exposure. The transition between exposures has received little attention despite its significance. An experimental study was conducted by Wang and Stathopoulos (2006) to examine the effect of upstream exposure on the wind loading of low-rise buildings. The study has concluded that the upstream terrain configurations only in a short distance upwind the site have a direct bearing on peak wind loads measured on the building envelope.

A renewed interest in a more rigorous definition of upstream exposure and roughness associated with it has dominated the discussions of the American Wind Standard (ASCE-7) Committee. The objective is to include in the Standard clearer definitions of the exposure includ-

Table 3
Exposure categories of ASCE 7 (2016), NBCC (2015) and GB 5009 (2012).
Expand

Wind Code/Standard	Number of categories	Exposure Class	Exposure Parameters of Equation (2)			Roughness length
			Z_{ref} (m)	A	a	z_o(m)
ASCE 7 (2016)	4	A: City	–	–	–	2.00
		B: Urban/ Suburban	366	0.15	2.01	0.30
		C: Open	274	0.11	2.01	0.02
		D: Flat	213	0.09	2.01	0.005
NBCC (2015)	2	Open	10	0.20	1.0	–
		Rough	10	0.30	0.7	–
GB 50009 (2012)	4	A: Flat	10	0.24	1.4	–
		B: Open	10	0.32	1.0	–
		C: Urban	10	0.44	0.6	–
		D: City	10	0.60	0.3	–

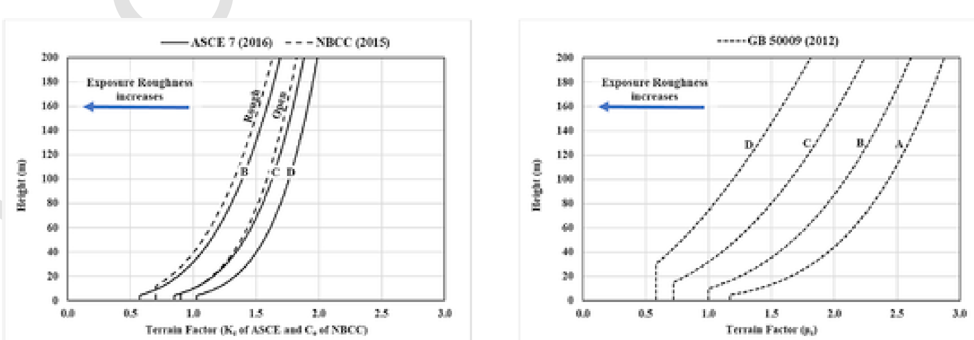


Fig. 1. Exposure coefficient values with height for different upstream conditions: K_z of ASCE 7 (2016), C_e of NBCC (2015) and μ_z GB 50009 (2012).

ing the transition cases by specifying appropriate values for the exposure coefficient. A detailed elaboration of the exposure effects will increase the complexity of the design process but may lead to more adequate and economical wind provisions.

It should be mentioned that several current wind pressure coefficient provisions in codes and standards including ASCE 7 (2016) and NBCC (2015) used to be based on a conservative open country exposure regardless of the actual situation and the prevailing wind direction. The American standard ASCE 7 (1998) has proceeded to permit the use of coefficients similar to those implicitly used in the Canadian Code - but with a 0.85 directionality factor instead of the 0.80 reduction factor - with the velocity profile of a suburban exposure if the actual building is indeed exposed to a suburban corresponding roughness. This reflects the great majority of cases of low-rise buildings. St. Pierre (2002) has compared experimentally-measured vertical uplift and horizontal thrust coefficients on an end bay of gabled roof of low-rise buildings in suburban terrain roughness with the Canadian (NBCC, 1995), American (ASCE 7, 1998) and European (ENV, 2005) corresponding provisions. Fig. 2 shows typical results from this study. It was shown that the American provisions underestimate the measured data, distinctly more than the other specifications. It appears that the ASCE 7 (1998) coefficients may have been reduced more than warranted when the building design case under consideration is indeed in a suburban type of upstream terrain for all wind directions.

Current efforts related to this area address the necessary roughness fetch requirements for the characterization of the exposure and examine the transition equations in order to provide exposure coefficients appropriate for cases of upstream terrain roughness changes. The intent is to allow interpolation in exposure transition zones near changes in ground surface roughness. In another study (Yu et al., 2019), a different approach based on the details of the upstream exposure identifies the particular directional roughness length leading to the appropriate exposure factor more expeditiously and accurately.

2.3. Topographic factor

When the path of the airflow is crossed by topographical features such as escarpments or hills, the flow will be blocked by the windward escarpment contributing to reducing its mean wind speed. With the uphill, the airflow begins to accelerate resulting in a speed up wind profile in comparison with that of the flat terrain.

The considered wind codes and standards provide too idealized and standardized provisions to assess the design wind speed over isolated and symmetric hills and escarpments, as illustrated in Fig. 3. Certainly, these cases of earth surface topography are rarely given the extent of the reliability of the earth's surface topography. Generally, the assessment of the interaction between the wind and the topographical features is mainly governed by the shape of the hill or escarpment (size and slope) and the distance from the summit. The anticipated speed-up is usually referred to as "fractional speed-up ratio, ΔS″, which can be defined as (Miller and Davenport, 1998):

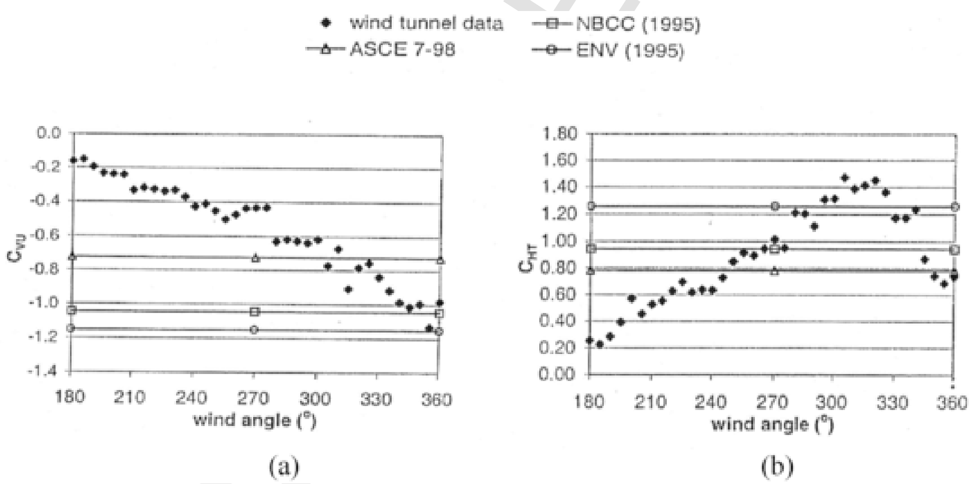


Fig. 2. Minimum vertical uplift (C_{VU}) and maximum horizontal thrust coefficients (C_{HT}) for the end bay of a gabled roof building in suburban terrain exposure, (a) eave height: 9.75 m; roof slope: 3:12 (b) eave height: 7.32 m; roof slope: 1:12 (after St. Pierre (2002)).

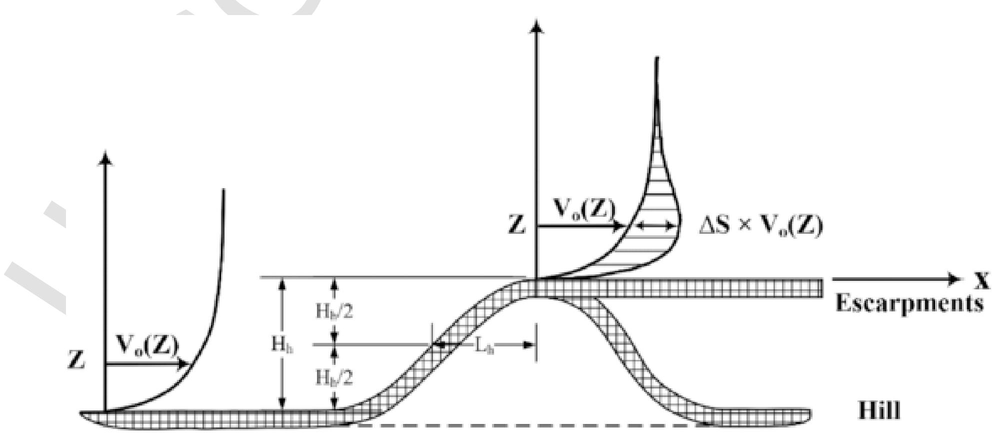


Fig. 3. Illustration of mean speed-velocity on a hill or escarpment (Modified from NBCC, 2015).

$$\Delta S = \frac{V(Z) - V_O(Z)}{V_O(Z)} \tag{3}$$

in which V is the velocity at height Z above the hill summit surface, V_o is the reference upstream wind velocity at the same height as V above the ground.

ASCE 7 (2016) and NBCC (2015) provide the values of ΔS for three topographic features: 2-dimensional hill, 2-dimensional escarpment and 3-dimensional axisymmetric hill. These provisions were based on the work performed by Lemelin et al. (1988). On the other hand, the Chinese code (GB 50009, 2012) does not involve specific guidance on this issue but simply recommends considering Exposure B (See Table 3) in case of an existing hill for the design of roof pressures.

In the literature, both numerical and experimental approaches have been utilized to study the topography potential on the wind speed and to examine the credibility of the wind codes/standards, where the computational studies accounted for the bulk of the literature (i.e., Carpenter and Locke (1999); Ishihara et al. (1999); Bitsuamlak et al. (2004); Tamura et al. (2007); Dupont et al. (2008); Berg et al. (2011); Wan and Porté-Agel (2011); Diebold et al. (2013); Abdi and Bitsuamlak (2014); Weerasuriya et al. (2016); and Shamsoddin and Porté-Agel (2017)). However, most of the previous studies tend to consider idealized geometries.

Several studies, for example, Finnigan et al. (1990), Miller and Davenport (1998), Carpenter and Locke (1999), Takahashi et al. (2005) and Lubitz and White (2007), have been carried out in atmospheric boundary layer wind tunnels to measure the speed-ups over single and multiple hills of different dimensions (H_h/L_h = 0.08 to 0.4). Previous studies indicate that the velocity speed-ups in multiple hills are low compared to single hills and lowest over complex terrain.

Therefore, application of the current procedure available in the wind codes and standards for idealized topographies may lead to conservative design wind speed, and therefore conservative design wind loads. Further studies would still be necessary to obtain unequivocal provisions about topography impact on wind-induced loads on surface pressure, in particular, experiments and discussions on the direct impact of the topography on the pressure coefficients to ensure better predictability of wind loads.

2.4. Directionality factor

It was clearly Alan Davenport's idea to introduce the previously-mentioned and well-known 0.8 factor in order to account for a variety of alleviating effects such as the variation in terrain roughness and wind direction in the codification process. Open country terrain exposure was giving generally the highest pressures but the great majority of low-rise buildings were in suburban terrain exposure and since the design pressure coefficients were provided regardless of wind direction (i.e., envelope approach), it would be rather unlikely to expect the most critical wind speed to originate from the most critical wind direction for a particular building orientation. Therefore, codified wind pressure coefficients were formulated by considering the most critical measured values factored by 0.8.

It is interesting to know that the introduction of this factor has generated a major controversy in the history of wind engineering. However, subsequent studies, such as that of Ho (1992), have justified Davenport's original approach not only regarding the selection of this factor but also regarding the rationale and reliability analysis that Davenport carried out (Davenport et al., 1985), which comprised statistics of exposure factors, pressure coefficients, gust factors and those of the wind dynamic velocity pressures.

Currently, ASCE 7 (2016) tabulates several values for the directionality coefficient ranging between 0.85 and 1.0 according to the structure type. For instance, the directionality factor of values 0.85 and 1.0 is recommended in determining the wind loads on buildings and circular domes, respectively. However, this is still an open discussion matter within wind code committees.

3. Design pressure coefficients for typical buildings

Realistically, the wind load induced on cladding and components of an enclosed or semi-open building is the net combination of the external and internal pressure coefficients (i.e., the difference between the wind pressure on both surfaces). Therefore, the external and internal pressure coefficients assigned for building components and cladding will be tackled at greater length in the following sections.

3.1. External pressure coefficients

The design external pressure coefficients of low-rise buildings depend primarily on geometric dimensions, shape of the building and the angle of wind attack. In addition, the induced wind pressures are unevenly distributed both spatially and in terms of time.

The Canadian wind load provisions for low-rise buildings have earned high international marks, following the recognition of their innovative and pioneering character by researchers and practitioners across the globe. In this regard, these provisions have been influential in the development and evolution of various national and international wind load standards, including the ASCE 7 and the China Standard for Wind Loads on Roof Structures.

Fig. 4 shows the pressure coefficients for buildings with gable roofs as specified in the 1975 edition of the Commentaries of Part 4 of the National Building Code of Canada (NBCC, 1975). The coefficients vary with the slope of the roof: suction dominates for roof angles lower than 22° and pressure for roof angles greater than about 39°. Roofs with angles between 22° and 39° have to be designed for both pressures and suctions. Although there were provisions to increase values of suctions acting on roof edges and corners, the increased pressures at the ridges and ridge corners of intermediate or high roof slopes were not there. In contrast, typical provisions for the design of gable roofs of intermediate and high slopes included in the User's Guide (Structural Commentaries, Part 4) of the 2015 National Building Code of Canada (NBCC, 2015) show the dominant effect of the tributary area (particularly for roof corners, edges and ridges of intermediate slopes) and the critical suction values for specific roof areas and different ranges of roof slopes, in comparison with the 1975 data.

In more detail, a set of experimental studies on low-rise buildings with different dimensions, heights, roof slopes (1:12 (4.8°), 4:12 (18.4°) and 12:12 (45°)) and upstream exposures were considered in an extensive experimental program at The University of Western Ontario (Davenport et al., 1977, 1978). Subsequent codification work, to extend the experimental results was undertaken for more comprehensive wind-induced loads assessments, thereby enhancing the development and progress of the wind codes/standards. Detailed information about these experimental studies is provided by Alrawashdeh and Stathopoulos (2015).

Currently, national wind codes and standards address a wide range of common and regular geometries and configurations. Table 4 summarizes the building geometries for which extensive studies have been carried out and their results have been adopted in the considered wind codes and standards. As an illustrative example, Figs. 5 and 6 respectively show the loading zones of quasi-flat and gable roofs accompanied by the design pressure coefficients of ASCE 7 (2016), NBCC (2015) and GB 50009 (2012). It should be noted that the values of the pressure coefficients of NBCC (2015) and GB 50009 (2012) were converted and provided following the same definition of ASCE 7–16, i.e. referenced to the dynamic velocity pressure (q) based on 3-sec basic wind speed. Although the pressure coefficients shown in these figures are technically comparable, no comparison of pressures should be at-

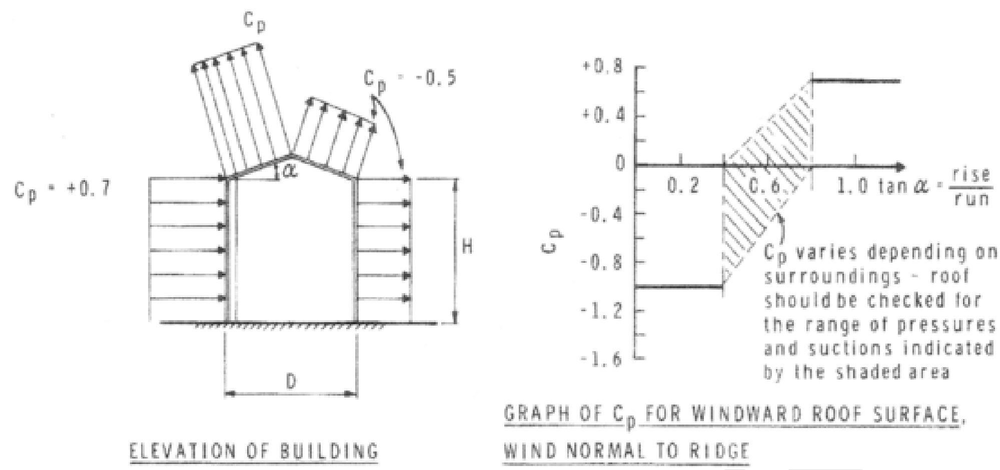


Fig. 4. Gable roof design pressure coefficients, after NBCC (1975).

tempted due to the different frameworks of each code provision development, as discussed previously in this paper.

The importance of the tributary area has an additional dimension when wind pressure loads affecting systems covering more than one surface of the building envelope are considered. A typical example is the frame of a low metal building. The lack of correlation of wind pressures acting on different building surfaces, in addition to the averaging effects of tributary areas, are significant factors to be considered in the evaluation of the actual wind load seen by the structure and, consequently, used in its design. Notwithstanding the difficulties due to the experimental limitations at the time, this rather sophisticated part of the research determined values of structural actions, such as total uplift, horizontal shear and bending moments at various points of the indirectly-loaded primary structural systems with a variety of influence lines corresponding to various structural systems and utilized on-line during the experiments.

An optimization software routine was subsequently used to develop sets of pseudo pressure coefficients to generate loading conditions which would envelope the maximum induced force components to be resisted for the wind directions and exposures tested. The set of coefficients provided represents fictitious loading conditions, which conservatively envelop the maximum values of induced force components to be resisted independent of wind direction. It is of interest that it took almost 20 years to persuade the ASCE-7 wind load committee to accept this approach and introduce a similar set of coefficients in the American wind standard. Details of this process can be found in Shoemaker (2014).

Although wind codes and standards refer currently to several common building configurations, some buildings such as those of irregular roof shapes (T, L and U shapes), complex geometry, gambrel and turret roof have not yet been addressed. Wind studies on these geometries are still scarce, or even absent from the literature, and the achievement of having wind codes/standards regulations remains a necessary objective.

A recent study conducted by Shao et al. (2018) and Shao et al. (2019) represents a unique attempt to examine the wind pressure on 4:12-sloped hip roofs of L- and T-shaped low-rise buildings. Several models of rectangular, L- and T-shaped roofs have been tested for open-country exposure. The study highlighted the fact that the local and area-averaged pressure coefficients are affected by the building shape (gable or hip) and geometry (rectangular or L- and T-shaped). It was found that L-shape and T-shape buildings have experienced similar wind pressure but different from those of regular rectangular buildings.

3.2. Internal pressure coefficients

Wind-induced internal building pressures can greatly affect the net loading of the building envelope. Since buildings are very rarely airtight, the wind loading in design is taken as the difference between loadings acting on the external and the internal sides of the building envelope. In enclosed buildings, the internal pressures are relatively small compared with the external pressures but their magnitude becomes comparable to that of external pressures for partially enclosed buildings. There has been a renewed interest in wind-induced internal pressures, resulting in numerous publications and possible revisions of relevant provisions of building codes and standards (Holmes, 1979; Stathopoulos et al., 1979; Vickery and Bloxham, 1992; Irwin and Dunn, 1994; Beste and Cermak, 1996; Ginger et al., 1997; Wu et al., 1998; Ginger and Letchford, 1999; Jian et al., 2003; Kono et al., 2005; Karava et al., 2006; Ginger et al, 1997, 1997, 2008, 2010).

Internal pressure loads depend on the distribution of the external pressures and the location of building openings, if any, along with the magnitude and variability of the porosity of the building envelope. Fig. 7, taken from Whittemore et al. (1948), shows internal pressure coefficients specified about 70 years ago. Clearly, for buildings with 30% or more of the wall surface open, or subject to being opened or broken open, an internal pressure coefficient near +0.8 or −0.6 is specified for windward or leeward/parallel wall openings respectively.

Subsequent research studies carried out by Stathopoulos et al. (1979), Beste and Cermak (1996), Vickery and Bloxham (1992) and Irwin and Dunn (1994) have been critical in the formulation of the current provisions for internal pressures, as they appear in ASCE 7 (2016). The provisions are much more detailed, although they preserve the physical reality of pressurization and depressurization phenomena. As illustrated in Table 5 (after ASCE 7, 2016), four sets of internal pressure coefficients for four types of buildings specified, namely: enclosed, partially enclosed, partially open and open.

The Canadian provisions for internal pressure coefficients also recognize that due to the variability and uncertainty of the size and distribution of building openings, their values can be influential and wide-ranging. However, the Canadian approach is less prescriptive. There are three design categories of buildings, defined as follows (NBCC, 2015):

Category 1 (C_{pi} = -0.15 to 0; C_g = 1.0): Buildings without large openings but with small uniformly distributed porosity, less than 0.1% of total surface area;

Table 4
Roof shapes addressed in wind codes and standards with some example studies.

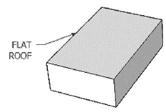
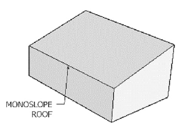
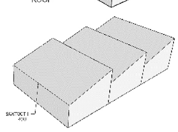
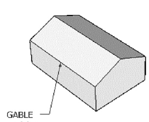
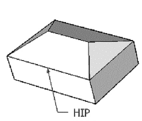
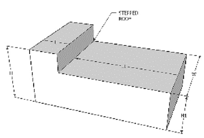
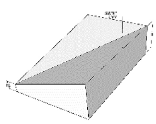
Building	Study	Terrian Exposure	Building dimensions (FS, m)				
			Roof Slope		Width	Length	Eave Height
	Stathopoulos and Dumitrescu-Brulo (1989)	Open country (α = 0.15)	0		61	61	12, 25,
		Suburban (α = 0.21)					55, 100, 45
	Lin and Surry (1998)	Open country	0		80 18	80, 27	8, 16, 24
	Alrawashdeh and Stathopoulos (2015)	Open country (α = 0.15)	0		60, 120, 180	60, 120 180	5, 7.5, 10
	Kopp and Morrison (2018)	Open country (z_o = 0.03)	<1:12		12, 24,	19, 38	3.7, 5.5, 7.3,
		Suburban (z_o = 0.3)			36, 48	57, 61, 76	12.2
	Stathopoulos and Mohammadian (1991)	Open country (α = 0.15)	1:12–4:12		12–24	61	3.6–12.2
	Saathoff and Stathopoulos (1992)	Open country (α = 0.15)	4:12	1 Span	20	60	12
				2 spans	40		
				4 spans	80		
	Meecham et al. (1991)	Open country (α = 0.19)	4:12		100	200	30
		Suburban (α = 0.32)					
	Stathopoulos et al. (2000)	Open country (α = 0.14)	2:12, 3:12, 4:12, 6:12, 7:12		36–41	60	11
	Case and Isyumov (1998)	Open country (α = 0.15)	4 : 12		32	32–96	16
		Suburban (α = 0.24)					
	Ginger and Holmes (2003)	Open country	9:12		40	96, 160 240	7.5, 15
	Meecham et al. (1991)	Open country (α = 0.19)	4:12		100	200	30
		Suburban (α = 0.32)					

Table 4 (*Continued*)

Building	Study	Terrian Exposure	Building dimensions (FS, m)			
			Roof Slope	Width	Length	Eave Height
	Xu and Reardon (1998)	Open country (α = 0.14)	3:12, 4:12, 7:12	7	16	2.9
	Ahmad and Kumar (2001)	Open country (α = 0.15)	7:12	7	16	2.9
	Stathopoulos and Luchian (1990)	Open country (α = 0.15)	0	40	41(L) 19(L1),	30 (H1)
					30(L) 30(L1), 41(L), 19(L1) 19(L), 41(L1)	
	Dong and Ye (2012)	Open country (α = 0.16)	varies	120	120	0 (H1)
						20, 40 (H0)

Category 2 (C_{pi} = -0.45 to 0.3; C_g = 1.0): Buildings with significant openings expected to be closed in storms and with non-uniformly distributed porosity; design should cover the entire range of Cpi's provided; and

Category 3 (C_{pi} = -0.7 to 0.7; C_g = 2.0): Buildings with large openings expected to transmit gusts to the interior; structures of post-disaster services are included in this category.

In some very concise form, GB 50009 (2012) provides only internal pressure coefficients for enclosed buildings (C_{pi} = −0.3 and + 0.2). Positive internal pressure coefficients are applied to the cladding elements subjected to negative external pressure; and negative internal pressure coefficients are applied to the cladding elements subjected to positive external pressure.

Notwithstanding the sound intent of these provisions, their interpretation and application in practice have caused and continue to cause problems to practicing engineers. For instance, when dealing with the ASCE-7 provisions, the internal pressure for a building goes from moderate (enclosed) to high (partially enclosed), back to moderate (partially open), and to negligible (open). However, most engineers do not expect that the internal pressure goes back to a moderate level if the building does not meet the enclosed or partially enclosed requirements – they tend to go directly to the open classification. The suggestion to add the fourth category of buildings (partially open) has created additional problems because part of the difficulty in transferring the knowledge to the practitioners is associated with the terminology used. As an example, a rectangular hangar with at least a door opening in the windward wall may be considered “partially enclosed” as long as the windward wall width is less than half of the other building plane dimension; otherwise, it might be treated as “partially open” since the building does not qualify to be an “enclosed” or “open” classification! This is a critically sensitive area requiring additional work for a satisfactory solution. Consequently, there is an ongoing effort to clarify issues and better organize these provisions.

4. Ongoing active issues

Several issues related to wind loads of buildings and their attachments remain under consideration of the current wind codes and standards. These include but are not limited to: wind loads on large roofs, wind loads on solar panels, wind loads on building attached canopies, artificial intelligence, non-synoptic winds and last but not least, Computational Fluid Dynamics.

4.1. Large roofs

The characteristics of mean and peak wind pressures on flat roofs of large low-rise buildings (width > 60 m) have been studied by Alrawashdeh and Stathopoulos (2015). The study found that although building height plays a dominant role in impacting the values of pressure coefficients, the distribution patterns of roof wind pressures are also affected by building plan dimensions. For codification purposes, the roof zones of large low-rise buildings were created following the same approach used for ASCE 7 (2010) and NBCC (2015). It was found that the area-averaged pressure coefficients prescribed by ASCE 7 (2010) and NBCC (2015) are relevant to large roofs, but the edge and corner zones shall be limited to the 80% of the building height.

4.2. Rooftop solar panels and building canopies

The latest edition of ASCE 7 and NBCC have included provisions for wind design of roof-mounted solar panels and wall canopies. Conceivably, current wind standards and code of practice provide emerging design provisions for limited configurations of roof-mounted solar panels. The provisions of ASCE 7 (2016) for solar panels inclined on flat roofs were created from studies carried out on low-tilt solar arrays by Kopp (2013). Also, the provisions for solar panels parallel to gable and hip roofs are based on the results of a study by Stenabaugh et al. (2010). The provisions of these wind codes and standards are mainly for a sys-

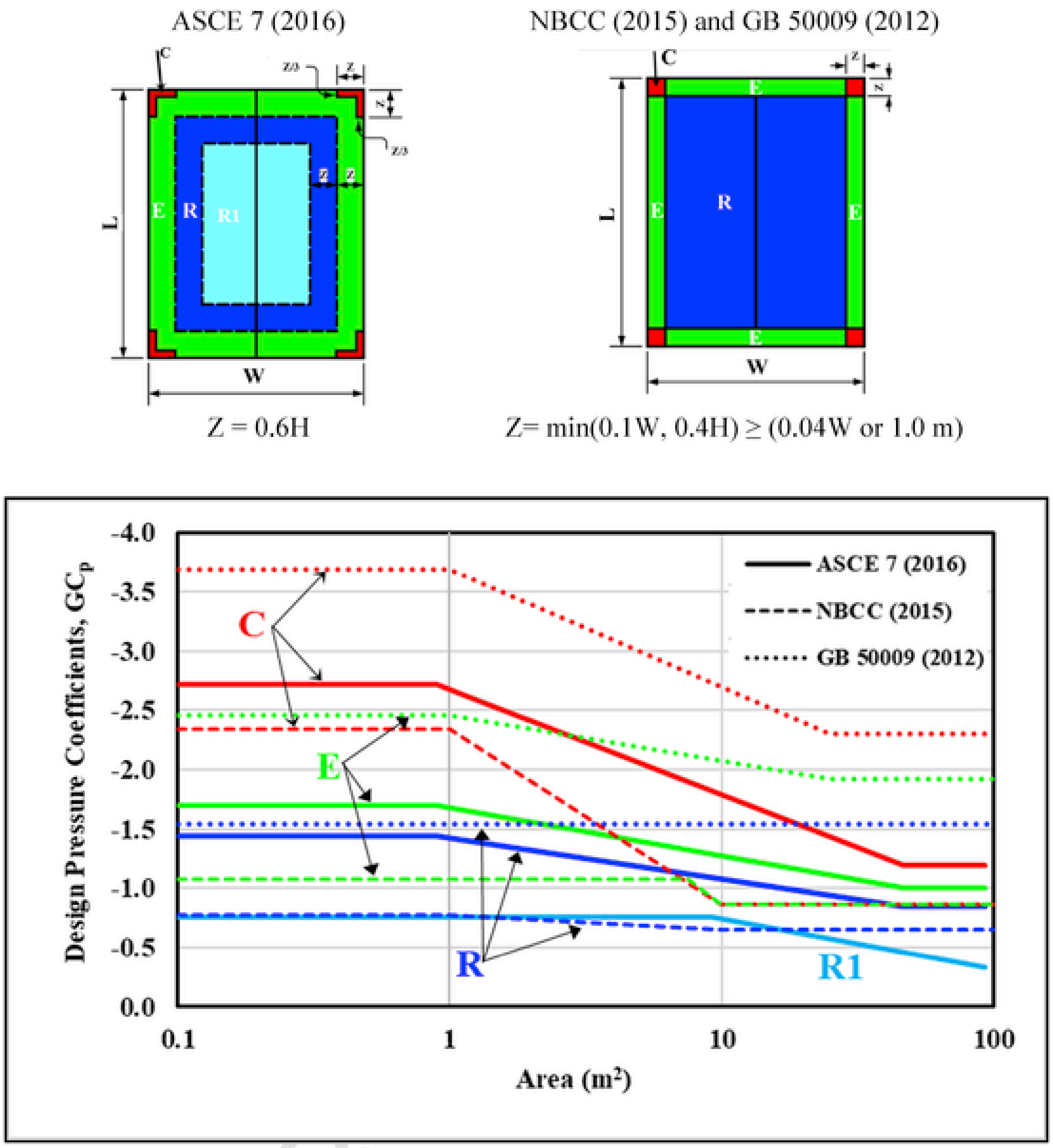


Fig. 5. Loading zones layout and design pressure coefficients of Flat Roofs ($\theta \leq 7^{\circ}$).

tem of multi-array solar panels mounted on building roofs and have many limitations that may restrict the scope of their applications. It should be mentioned that none of the mentioned wind codes and standards provide design guidelines for ground-mounted solar panels, an item currently being addressed.

Further, ASCE 7 (2016) and NBCC (2015) provide design pressure coefficients of the canopies on the basis of building height and canopy height. These provisions were developed relying upon the experimental work conducted by Candelario et al. (2014). These provisions were obtained on canopies attached to low-rise buildings of relatively low eave height (i.e., $3.5 < H < 10.5$ m).

More comprehensive parametric studies on wind loads on solar panels and wind loads on canopies are needed to provide additional results for codification purposes. In particular, more experiments are needed on a preliminary basis to validate wind tunnel requirements for accurate simulating solar panel models in atmospheric flow, such as geometric test scaling which has been disregarded in previous studies. Also, the impact of some geometric parameters on wind-induced pressure, such as building size, roof slope, array inclination and array spacing, is still equivocal and further studies on these issues would be of interest. For provisions of canopies, more experiments are necessary to primarily validate the impact of building height on wind-induced pressures on building attached canopies, involving medium-and high-rise buildings.

4.3. Artificial intelligence

Incorporating artificial intelligence technologies, embodied by: Knowledge-Based Expert Systems (KBES), Deep Neural Networks (DNNs), Machine Learning (ML) and Deep Learning (DL) for wind engineering data with respect to either structural or environmental applications has become more deliberative and reflective.

There are intensive attempts to apply these intelligence technologies for several situations, such as the design of buildings for serviceability requirements and safety evaluations against the wind (Oh et al., 2019), wind-induced damage estimations (Unanwa and McDonald, 2000), design loading predictions (Hu and Kwok, 2019; Hu et

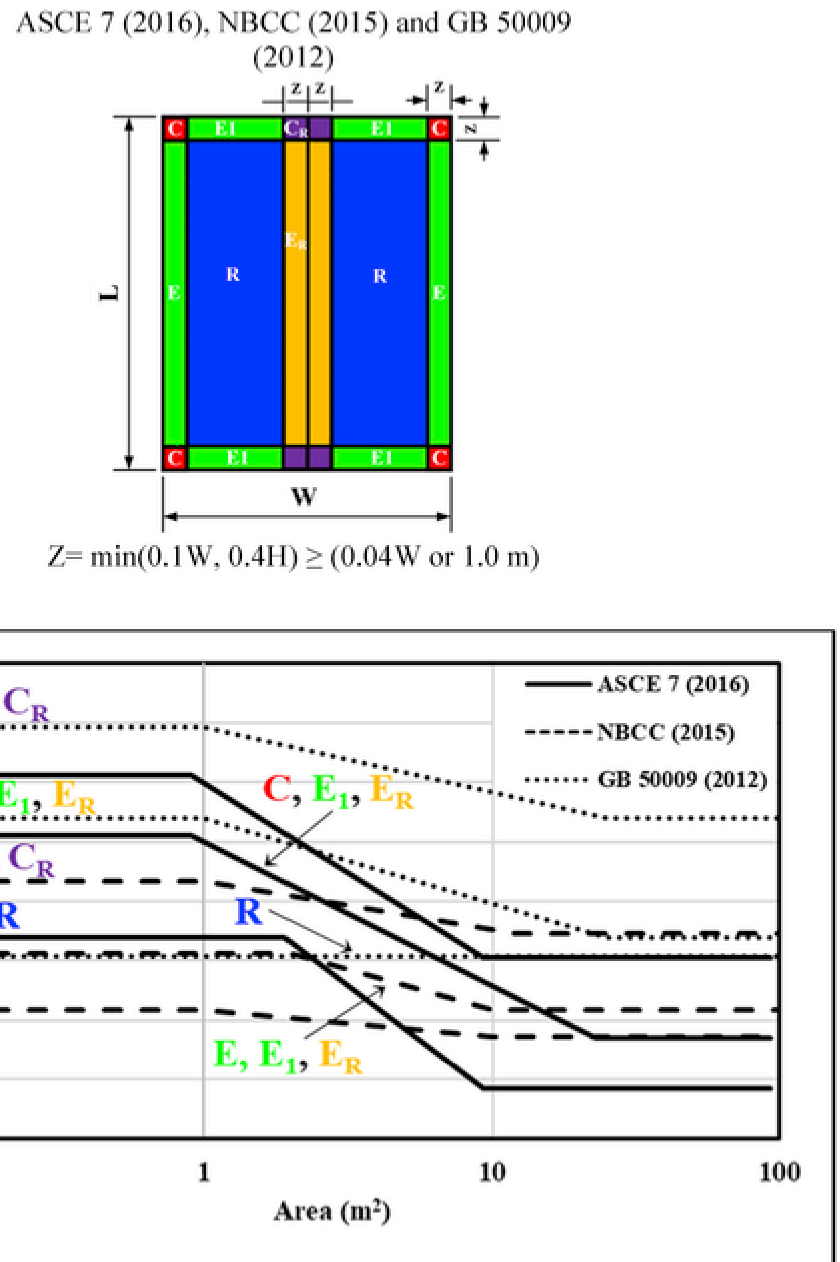


Fig. 6. Loading zones layout and design pressure coefficients of Gable and Hip Roofs (7° ≤ θ ≤ 20°).

al., 2019) and for applications of wind energy aerodynamics (Jursa and Rohrig, 2008).

4.4. Non-synoptic winds

The characteristics of wind for purposes of examining wind effects on structures, as reflected in international and national wind codes and standards, are for synoptic winds based on the assumption of the stationary atmospheric boundary layer. The significance of severe weather extreme events like downbursts, tornadoes, thunderstorms and other non-stationary winds was observed in costly damages notwithstanding their low probability of occurrence. In fact, climate change might also negatively affect the frequency and intensity of severe weather events; and thereby increasing their related disasters and compromising the safety of existing buildings (Auld, 2008; Wilby and Dessai, 2010).

There is a thrust to upgrade and develop wind engineering facilities that can produce downbursts and tornadoes, i.e. wind systems with profiles distinctly different from those of synoptic boundary layers, with the aim to better understanding the effect of non-synoptic winds on structures. Recently, some changes in the latest version of ASCE 7 (ASCE 7, 2016) and the Commentary of NBCC (2015) were made to include some general design guidance for tornadoes. The developments in this area are ongoing really fast. Indeed, more research and development for both wind code and standard provisions and engineering practice for construction and maintenance are urgently needed to achieve the desired level of safety.

4.5. Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) in the recent years has received growing attention. CFD is therefore used to a greater extent

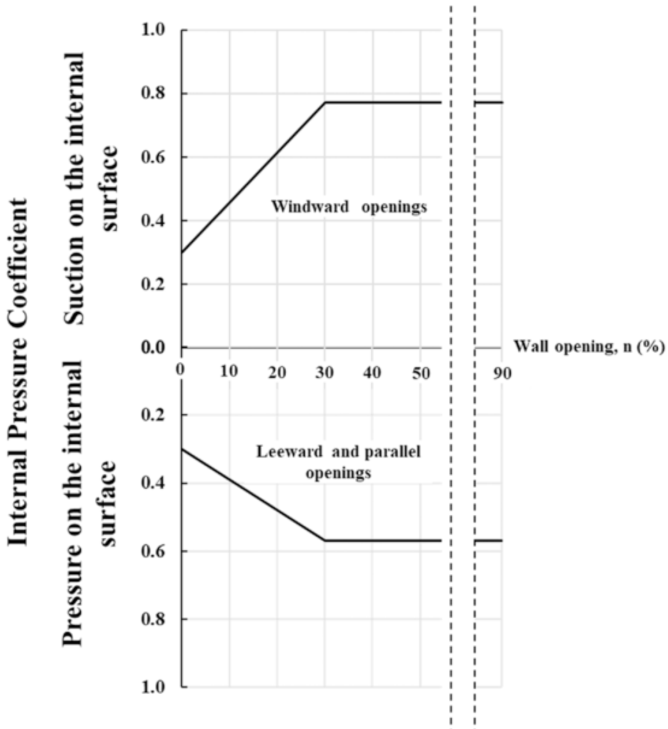


Fig. 7. Internal pressure coefficients, after US Department of Commerce (updated from Whittemore and Cotter, 1948).

than previously, especially for environmental applications; but for structural wind engineering, nonetheless, CFD does not yet fully attract the researchers' and wind/codes and standards' confidence.

Wind codes and standards strongly recommend the recourse to the wind tunnel approach to examine cases falling outside their scope, as evaluating wind loads on buildings. Moreover, wind codes and standards, with the exception of one statement in NBCC (2015), do not have any guidance for the CFD procedure. NBCC (2015) permits the use of CFD only in combination with the wind tunnel approach.

5. Conclusions

The paper has addressed some historical aspects of the development of wind loading provisions in wind standards and codes of practice. It has referred to current trends in further developments and enhancing their status. Clearly and in spite of the critical developments in the area of wind codes and standards, their provisions still require harmonization; and therefore, adoption of further work for that purpose is necessary.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table 5
Internal pressure coefficients, after ASCE 7 (2016).
Expand

Enclosure Classification for Buildings	Classification Criteria	Internal Pressure	Internal Pressure Coefficient(GC_{pi})
Enclosed	A_o < lesser of ($0.01A_g$, 0.37 m^2) and $A_{oi}/A_{gi} \leq 0.2$	Moderate	+0.18 −0.18
Partially enclosed	$A_o > 1.1A_{oi}$ A_o > the lesser of ($0.01A_g$ or 0.37 m^2) and $A_{oi}/A_{gi} \leq 0.2$	High	+0.55 −0.55
Partially open	A building that are not in conformity with the classifications of Enclosed, Partially Enclosed, or Open	Moderate	+0.18 −0.18
Open	Each wall is at least 80% open	Negligible	0

A_o: Total area of openings in a wall that receives positive external pressure.
A_g: Gross area of that wall in which A_o is concerned.
A_{oi}: Sum of the areas of openings in the building envelope (walls and roof) not including A_o.
A_{gi}: Sum of the gross surface areas of the building envelope (walls and roof) not including Ag.
1. Plus and minus signs signify pressures acting toward and away from the internal surfaces, respectively.
2. Two cases shall be considered to determine the critical load requirements for the appropriate condition: (i) a positive value of GC_{pi} applied to all internal surfaces. (ii) a negative value of GC_{pi} applied to all internal surfaces.

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