A review of the wind loading zones for flat roofs in code provisions

Chris P.W. Geurts[1,2], Gregory A. Kopp[3] and Murray J. Morrison[4]

[1]Department of Built Environment, TU Eindhoven, the Netherlands

[2]TNO, Delft, the Netherlands

chris.geurts@tno.nl

[3] Boundary Layer Wind Tunnel Laboratory, University of Western Ontario, Canada

[4]Insurance Institute for Business & Home Safety, United States

Abstract

The provisions for wind loads on flat roofs differ considerably between current wind loading standards in different jurisdictions. For a number of major wind loading codes, both the definition of roof zones, and the values applied to determine the wind loads are discussed. This paper concentrates on the wind loading zones near edges and corners, with special emphasis on local loads on low-rise buildings. Differences in sizes for edge and roof zones of a factor 2 occur when comparing some of the major wind loading standards. Based on recent wind tunnel results, recommendations are given for further development of these codes.

1 Introduction

Despite many decades of code development worldwide, storm damage to flat roofs still accounts for large losses. In Europe, the national standards have been replaced by the Eurocodes. In 2005, the new European wind loading standard, EN 1991-1-4, was published. It was the result of many years of development and discussions, and inevitably contained compromises between calculation models in the former national documents.

To define the wind loads, a peak dynamic pressure is multiplied by one or more pressure or force coefficients. In the Eurocode, figures and tables with pressure coefficients on the surfaces of buildings are provided. The coefficients are given as local coefficients, representing the loads on 1 m^2, typically used to design fixings of roofing and cladding; and global coefficients, representing the loads on 10m^2 or more, used to design the load-bearing structure of the building. These coefficients are given as a function of location on the roofs or walls, represented by wind loading zones. To determine the loads on flat roofs, in EN 1991-1-4, a flat roof is divided into four zones, representing corner loads, edge loads, and two zones in the middle area of the roof. The definition of the roof zones, and the values taken for the loading coefficients originate from different sources. A quick comparison with some of the former national standards showed that considerable differences occurred. This may lead to unsafe choices, or on the contrary, to larger costs for fixing of roofs and roof coverings.

This paper discusses the backgrounds of the values and zones given in EN 1991-1-4, it compares the rules in EN 1991-1-4 with other codes worldwide, and defines possible improvements necessary for a safe design of roof coverings, based on results of wind tunnel experiments.

2 Background

The wind loads on the exterior of buildings are determined by the upstream wind and by the extent this wind is disturbed by the building itself. The building causes the wind to separate at the edges and to reattach downstream. At oblique angles of attack, conical vortices are formed, giving rise to increased wind loads. These two phenomena are illustrated in figure 1.

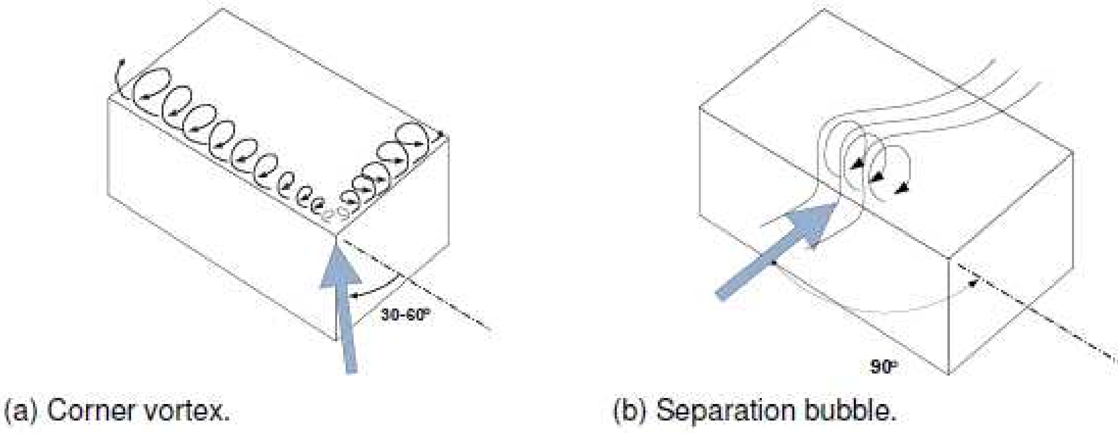

Figure 1: Schematic view of flows over flat roofs.

Pressure coefficients are defined for a range of approach flow directions, thus implicitly taking the relevant phenomena into account. Typically, the local wind loads are highest in corner regions and lowest at zones in the middle of the roof. For fixings of roofs, the most unfavourable load for all approach flow directions, is needed.

In the process of drafting the Eurocodes, two main datasets have been used as the basis (Geurts et al, 2001). First, the work done by Cook and co-workers in the 1980's, reported in many papers and technical reports, has been used. An overview of this work and a translation into code coefficients is given in (Cook, 1986). The values obtained by defining so-called pseudo-steady pressure coefficients, have been applied as c_{pe} values for loads on 10m^2 or more. These values are typically used to design the overall structural system. These are related to a loading duration in full-scale of about 1 second, and have been defined by the 78% probability of non-exceedence of the peak values occurring in 10 minutes. These values have been determined for a range of wind directions, with increments of 30 degrees. Per direction, Cook defines regions near the corners and edges where higher loads are experienced. The values in the codes are the worst values found for wind directions normal to the roof edge +/- 45 degrees. The values and zones have been used first in the British Standard BS 6399. Later, these data have been used to define the pressure coefficients in the prestandard ENV 1991-2-4 (1995) and the current EN 1991-1-4. These values have been used as c_{pe10} values, representing loaded areas of 10 m^2 or more. The database of Cook does not provide values for smaller loaded areas, however the definitions of the roof zones in the Eurocode is the same for local and global loads.

A second dataset, which is being used to define local loads, is based on the work of Stathopoulos, published in 1979, and referred to in later overviews (Stathopoulos 1984, Stathopoulos 2003). Peak wind loads have been determined as a fraction of the measured maximum peak for any wind direction. Based on these peak measurements, Stathopoulos defined a pattern of zones on roofs, also depending on building height and width. This pattern of zones differs from the zones defined by Cook.

Values and definitions of these zones have been adopted and applied in a number of codes, e.g., the Canadian NBCC building code and the ASCE 7 for the USA. These peak loads have also been applied in the Eurocode as values for local loads, on loaded areas of 1 m^2 or less. However, the definition and sizes of the roof zones have not been taken from the work of Stathopoulos. Instead, the zone dimensions of the work given by Cook are used in EN 1991-1-4. To examine the validity of these choices, and the consequences in design, the US and EN code are compared with each other, with some other wind loading codes, and with experimental work.

3 Comparison of roof zones wind loading codes

The size and shape of the roof zones in building codes are defined as function of building height, depth and width, and in some codes also related to the loaded area (the zones differ for local loads and global loads). The definitions of the corner and edge zones for a rectangular plan building, for local loads are given in Figure 2.

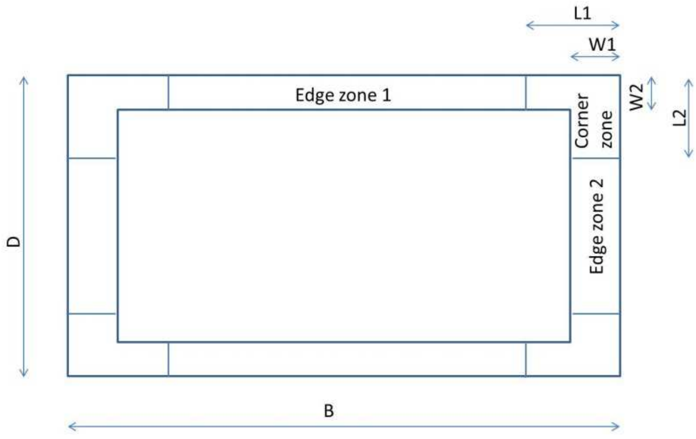

Figure 2: Definitions used in this paper for sizes of roof and corner zones. Note that B ≥ D.

The wind loading codes that are being considered here are the Eurocode (EN 1991-1-4;2005), The US standard ASCE 7-10, the Japanese standard (AIJ; 2004), and the ISO standard ISO 4354, which is similar to the provisions in the Australian standard AS/NZ 1170. The definitions in these codes are compared in table 1.

Table 1: definitions of sizes of edge and corner zones in different building codes

	L1	**L2**	**W1**	**W2**
Eurocode EN 1991-1-4;2005	min(0,25B;0,5H)	min(0,25D;0,5H)	min(0,1D;0,2H)	min(0,1B;0,2H)
ASCE 7-10	min (0,1D;0,4H) > 0,04H > 3 ft (0,9 m)	min (0,1D;0,4H) > 0,04H > 3 ft (0,9 m)	min (0,1D;0,4H) > 0,04H > 3 ft (0,9 m)	min (0,1D;0,4H) > 0,04H > 3 ft (0,9 m)
AIJ ; 2004	min (0,2D;0,2H)	min (0,2D;0,2H)	min (0,1D;0,4H)	min (0,1D;0,4H)
AS/NZS 1170.2;2002 ISO 4354	Min (0,1D,0,5H)	Min (0,1D,0,5H)	Min (0,1D,0,5H)	Min (0,1D,0,5H)

H = height, B = width, D = depth of building, B being the longest side.

Although the definitions of the roof zones in different wind loading codes should be similar, since these represent the same phenomena, a number of differences occur. These are related to a number of issues regarding the definitions in major wind loading codes, which will be discussed below.

The Eurocode and AIJ guideline use L-shaped zones for the corners. Both the ASCE 7-10 and ISO 4354 define square sized corner zones. The Eurocode has different sizes for the edge zones when the sides of the building are different, because the sizes of the zones are defined for different approach flow angles. The other codes considered use the same size for all sides.

In the Eurocode, the zones defined are the same regardless of loaded areas (both local and global loads apply the same zones). The other codes distinguish between loads to calculate the load bearing system and local loads. In this paper, only the local loads are examined.

To illustrate these differences between the codes, table 2 gives the values for the zones for a series of buildings with 10 metres of height.

Table 2: width of the edge zones in Eurocode and ASCE for some building dimensions, local loads.

Building #	Height in m	Width in m	Length in m	Width of edge zone, in m				
				Eurocode	Eurocode	ASCE 7-05	AIJ 2004	ISO 4354
				W1	W2	W1=W2	W1=W2	W1=W2
1	10	6	30	0,6	2	0,91	0,6	0,6
2	10	10	30	1	2	1	1	1
3	10	15	30	1,5	2	1,5	1,5	1,5
4	10	20	30	2	2	2	2	2
5	10	30	30	2	2	3	3	3
6	10	30	80	2	2	3	3	3
7	10	60	80	2	2	4	4	5
8	9,8	30,5	45,7	1,95	1,95	3,05	3,05	3,05
9	12,2	12,2	19,1	1,22	1,91	1,22	1,22	1,22
10	9,8	24,4	38,1	1,95	1,95	2,44	2,44	2,44
11	7,3	48,8	76,2	1,46	1,46	2,93	2,93	3,66

For relatively small sized buildings, the sizes of the roof zones are in the same order of magnitude. However, when the footprint of the roof becomes relatively large compared to the height, the sizes of the edge zones in the Eurocode are smaller than in the other loading codes. In the Eurocode, these dimensions are determined by the height, where for the other codes, the sizes are determined by the width of the building.

For the L-shaped zones applied in Eurocode and AIJ guideline only, the differences are given in table 3:

Table 3: Sizes of corner zones in different wind loading codes

Building #	Height in m	Width in m	Length in m	Length of corner zones, in m		
				Eurocode	Eurocode	AIJ 2004
				L1	L2	L1 = L2
1	10	6	30	5	1,5	1,2
2	10	10	30	5	2,5	2
3	10	15	30	5	3,75	2
4	10	20	30	5	5	2
5	10	30	30	5	5	2
6	10	30	80	5	5	2
7	10	60	80	5	5	2
8	9,8	30,5	45,7	4,88	4,88	1,95
9	12,2	12,2	19,1	4,76	3,05	2,44
10	9,8	24,4	38,1	4,88	4,88	1,95
11	7,3	48,8	76,2	3,66	3,66	1,46

The differences in sizes for corner and edge zones have an effect for the number of fixings required for roof coverings. For building number 9, Eurocode puts 18% of the area in the corner region and 22% in the edge, whereas on the other end, ASCE and ISO only have 3% in the corner and 28% in the edge.

For building 11, with large footprint, Eurocode puts 1% of the total area in the corner and 9% in the edge, where the other codes have edge zones which are at least 16% of the area, and corner zones are 1 to 3% of the total area.

Experimental work

To further investigate the pressure coefficients in edge and corner zones of flat roofs, measurements on a building about 10 m high, with plan dimensions of about 30 x 45 metres have been performed in Boundary Layer Wind Tunnel 2 at the University of Western Ontario. A total of 700 pressure taps, covering a full-scale area of about 4 x 8 metres have been used; the high resolution module has a nominal tap spacing of 15 cm at full scale, the full tap layout can be found in Kopp et al. (2005). This high resolution module has been placed at three locations on the roof, nominally corresponding to the corner, edge and interior regions as defined in the ASCE7-05. Experiments were conducted in several terrain categories simulating varying roughness lengths ranging from open sea to urban boundary layers. Complete details of the measurements are not provided here, for length, but some aspects of the data set are available in Morrison and Kopp (2010), who examined clip loads on standing seam metal roofs. These data are used in the current work to precisely define the variation of pressure coefficients as a function of area, for a building of one particular size.

In addition, wind tunnel data obtained from the NIST aerodynamic database is also used in the present study. Details on these experiments can be found in Ho et al. (2005) and analysis of wind-induced structural loads in St. Pierre et al. (2005). The NIST database contains wind pressure data for over 30 gable-roofed, rectangular plan dimensioned building with a lower tap resolution than with the high resolution module described above. Despite the lower tap resolution the range of building sizes (plan dimensions and height) allow us to investigate the effects of building size on the aerodynamic coefficients and the effectiveness of each standard in accurately representing the true aerodynamic forces for different building shapes. In general, the buildings in the NIST database were tested under a open country and suburban terrain simulations. The current paper only presents results from the open country terrain simulation from each database. While the model scale for each wind tunnel database is different (1:50 for the high resolution data versus 1:100 for the NIST database) the roughness lengths for each terrain simulation is identical (z_o=0.03). In addition, the turbulence intensity at roof height are similar being approximately 18-20%.

The current analysis focuses on the local load coefficients in the corner zone as defined by W1 and W2, for the ASCE7 and ISO standards. In total 4 different buildings are considered, buildings 9-12 as defined in tables 2 and 3. Within the corner zone defined by W1 and W2 both the ISO and ASCE7 standard provide different external pressure coefficients based the size of area considered. In the case of the ISO the local pressure coefficient is constant for areas less than 0.25*$W1^2$ and for areas between 0.25*$(W1=W2)^2$ and $W1^2$. In contrast, the local pressure coefficients reduce linearly as a function of area between 0,93 and 9,3 m^2. For each building peak pressure coefficients are calculated for areas ranging from 0,09 m^2 to $W1^2$. Rather than taking the absolute peak value the wind tunnel time series was divided into 3 sections, corresponding to 768 seconds for the NIST database and 600 seconds for the high resolution data. The peak from each section are fit using a Gumbel distribution using the formulation presented by Lieblein (1974). The 50th percentile peak from this distribution is then reported as the peak wind tunnel coefficient. The peak wind tunnel coefficients are converted into equivalent pressure coefficients that are directly comparable to the ASCE7 and ISO standard, using the method described by St. Pierre et al. (2005). For each area size, the peak pressure coefficients for all possible permutations of that area size with the area defined by $W1^2$ are calculated, using a 0.3m length increment. The peak coefficients for each area size is then chosen. Figure 5 presents the peak external pressure coefficients for each building for different size areas. Also shown in Figure 3is the external pressure coefficients specified for each are size in the corner zone region from the ASCE7. Since the reduction of external pressure coefficients in the ASCE7 is based solely on area the x-axis of Figure 1 is shown in dimensional units of m^2. Similarly the results for the corner zone using the ISO standard are shown in Figure 4. Unlike the ASCE7 standard the pressure coefficients in the ISO standard vary based on a percentage of $W1^2$. Therefore the x-axis in Figure 4is presented as a non-dimensional area normalized by $W1^2$.

In general, both the ASCE7 and the ISO underestimate the peak pressure coefficients in the corner zone of the roof, especially for every small areas. The degree of the under estimation is reduced as the areas get larger. In fact, the reduction of the pressure coefficient in the ASCE7 between areas of 3 and 7 m^2 seems to fit the data from buildings 9, 11 and 12. At areas approaching 9 m^2 the data from these 3 buildings appear to asymptotically approach a value of approximately -1.5. At areas greater than 9.3 m^2 the ASCE7 pressure coefficient is constant with a value of -1.1 appearing to take this asymptotic behaviour into account. However, as the current results indicate the reduction may be slightly too large, with a more appropriate value perhaps being -1.5. Compared to the wind tunnel results the ISO appears to under-estimate the peak pressure coefficients for areas less than approximately 0.7 $W1^2$. However, at areas larger than $0.7W1^2$, the wind tunnel data appears to asymptotically converge to the ISO prescribed pressure coefficient of -1.35.

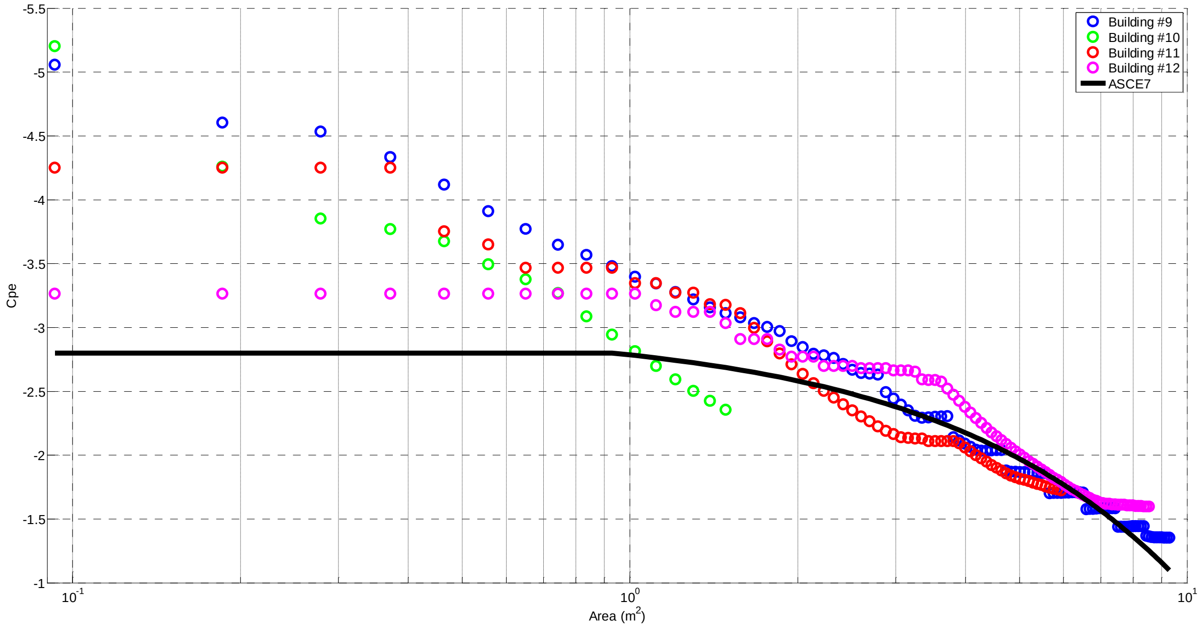

Figure 3 Comparison of local external pressure coefficients from buildings 9-12 to those specified by ASCE7 for different areas

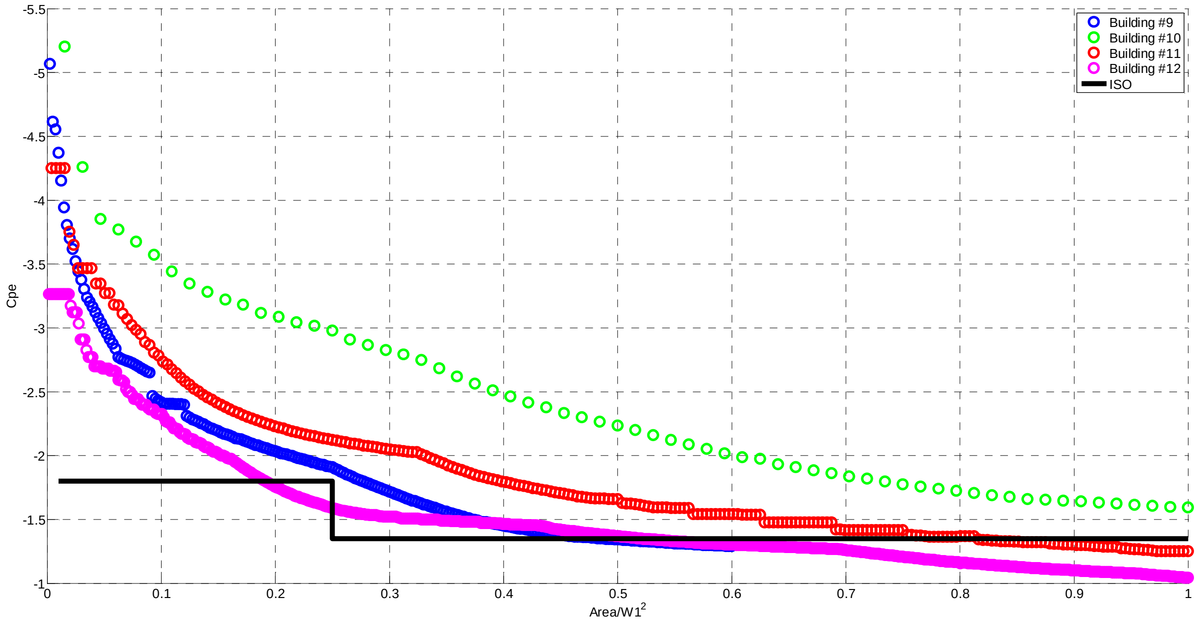

Figure 4 Comparison of local external pressure coefficients from buildings 9-12 to those specified by ISO for different areas

In both Figure 3 and Figure 4 there is not a good collapse of the external pressure coefficient between buildings, particularly Building #10. One possible reason for this poor collapse is that the parameter that determines the size of the corner zone, W1, can be different building to building. Such a parameter must be related to the size of the vortices or separation bubbles. For example, the conical vortices generated by oblique wind directions depend on the size of the wall, i.e., a normalizing area of DH, which has been shown to collapse the peak pressures on roof-mounted solar arrays for buildings of different size (e.g., Kopp, 2013). Figure 5 presents the peak pressure coefficients for each building normalized by B and H for each building. As shown, this normalization of the area provides an excellent collapse of the data for different building sizes and is much better collapse than using $W1^2$, as shown in Figure 4. This result indicates that defining the lengths of the wind zones on the roof as a percentage of BH may provide the best normalization for a universal set (for all building sizes) of external pressure coefficients. Note that further work is yet required to examine this in detail, particularly at small areas, where the breakdown of the this scaling likely has to do with the limitations (and significant differences) in the pressure tap resolution for these model buildings.

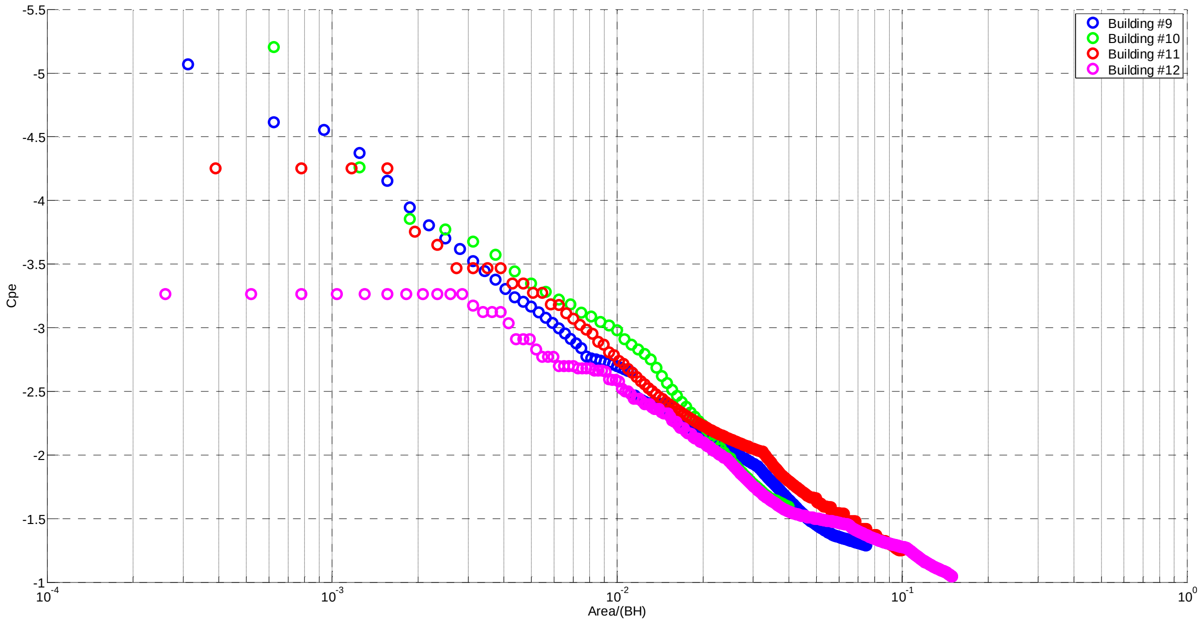

Figure 5 Peak pressure coefficients in the corner zone defined by W1 by the ISO for different areas normalized by BH.

4 Concluding remarks

The current rules in EN 1991-1-4 for determination of the sizes for roof zones on flat roofs lead to smaller edge and corner zones on the roofs compared to other major code provisions. Especially for low buildings with large footprint, these smaller zones lead to an underestimation of the loads in this region. Wind tunnel tests indicate that an alternative parameter could be defined to come to a uniform definition of corner and edge zones for flat roofs. Further analysis of the data will be done in the near future to refine this adapted approach.

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