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Wind pressure provisions for gable roofs of intermediate roof slope

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Abstract. The paper addresses the suitability of wind pressure coefficients specified in contemporary design standards and codes of practice for gable roofs of intermediate slope (roof angle 10^o-30^o). In a recent research study, a series of low building models with different roof slopes in this intermediate range were tested in a boundary layer wind tunnel under simulated open country terrain conditions. This was different from the original study in the 70's, which produced the current provisions on the basis of a model tested only for a single roof slope (4:12) in this range. The results of the study suggest that a modification to the American wind provisions would be warranted to make them more representative of the true local and area-averaged wind loads imposed on gable roofs of intermediate slope.

Key words: building; code; design; load; pressure; roof; standard; wind.

1. Introduction

Wind loading provisions in building codes of Canada (NBCC 1995), the United States (ASCE 7-98) and other countries have continuously been updated during the past 20 years, following research findings from wind-tunnel experimentation and full-scale investigation. The gable roof was the first geometry to be considered in these wind codes and standards for low buildings. Design wind pressure coefficients were typically provided for three roof slope ranges, namely, quasi-flat (0^o-10^o), intermediate (10^o-30^o) and high-pitched (30^o-45^o). This was primarily decided on the basis of the systematic wind-tunnel research on gable-roof buildings by Davenport *et al*. (1977) as well as several other studies.

Wind loading on a gable roof building depends upon the flow pattern around the building, which, in turn, depends on building geometry, dimensions, surroundings and wind flow characteristics. When the wind flow is normal to the ridgeline of a gable roof building, quasi-flat roofs in the range of 0^o-10^o create a similar flow pattern of separation, entrainment and reattachment (if applicable); a high negative pressure (suction) prevails, especially at the windward edges and corners. On the other hand, if the roof angle is greater than 30^o, wind flow will generally strike on the windward roof prior to separating from the windward edge or ridge. This induces a positive pressure region on

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most part of the windward slope and a negative region on the leeward slope. These flow patterns and pressure distributions may vary with the wind direction, but they remain comparable in respective roof slope ranges. Therefore, the simplification by grouping the roof slope into 0^o-10^o and 30^o-45^o has been justified and accepted.

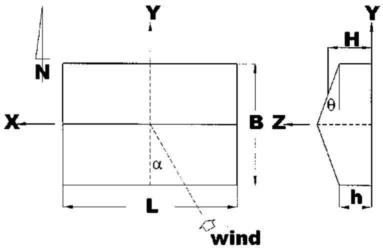
In contrast, over the roof angle range of 10^o-30^o, the wind flow over the building roof may change drastically between the two typical flow patterns described above. Depending upon the exact value of roof slope, a given roof region could be subjected to either negative or positive pressures, and some wind standards, e.g., the Australian wind code (AS 1170.2 1989), recognize this element, by providing different sets of pressure coefficients for various roof slopes within this range. However, both the Canadian building code and the American wind standard treat roofs within this large slope range by the same provisions originated mainly by testing a single model with a roof slope of 4:12 (18.4^o). Therefore, the current study investigates the wind pressures on gable roofs of intermediate slope, to examine the suitability of the current design wind pressure coefficients and the definition of the slope range. Based upon the results, simple modifications are proposed that could be considered by the code and standard committees for implementation. This paper concentrates on the American wind standard (ASCE 7-98) provisions.

2. Experimental

The study was experimental and was carried out in the boundary layer wind tunnel of the Building Aerodynamics Laboratory of the Centre for Building Studies, Concordia University. The wind tunnel is 13 m long and 1.8 m wide, with an adjustable roof height between 1.6 m and 2.0 m at the test section. The wind speed at gradient height was set at 12.5 m/s. Wind profiles of the mean speed and turbulence intensity were generated by screens, spires and carpet upstream. The power-law exponent was equal to 0.14 and the turbulence intensity at the building eave height was 16%. These parameters, together with measurements of the gradient height, the roughness length, the wind spectrum and the integral length scale of turbulence, indicate an adequate simulation of a typical open country exposure with a geometric scale of 1:400.

Five building models of gable roof angles equal to 10^o, 15^o, 20^o, 25^o and 30^o were designed with the same eave height of 27.5 mm and the same length of 150 mm. Keeping the same gable roof dimensions made it possible to interchange a single instrumented roof panel (52×150 mm) from building to building. A total of 45 pressure taps have been installed over half of the single roof panel, with high concentration near roof edges and corners. Figs. 1 and 2 show the building models with full-scale dimensions and the roof panel details, respectively. All five models have been investigated for all azimuths. However, detailed data measurements were made for 18 wind directions, namely $\alpha = 0^o$, 15^o, 30^o, 45^o, 55^o, 60^o, 65^o, 70^o, 90^o, 120^o, 130^o, 135^o, 140^o, 150^o, 180^o, 225^o, 270^o and 315^o. A high-speed scanivalve system (Hyscan 1000) with 16 transducers was used for data acquisition with a sampling rate of 256 Hz.

Six segments of pressure data were recorded with a sampling time of 6 seconds for each segment. Assuming a 1:4 ratio of wind-tunnel speed to full-scale speed, the duration of 6 seconds in the wind tunnel corresponds to 600 seconds or 10 minutes in full scale. Using the data recorded, mean, rms, and peak values were calculated not only for local, but also for area-averaged pressures. Local peak values were obtained by averaging each of the peaks of the six data segments and increasing the averaged value by 8%. This extreme data analysis approach was originated from that proposed by Peterka (1983), following a detailed comparison of peaks obtained from records of different length



θ	L (m)	B (m)	h (m)	H (m)
10°	60	40.8	11	12.8
15°	60	40.2	11	13.7
20°	60	39.1	11	14.6
25°	60	37.7	11	15.4
30°	60	36.0	11	16.2

Fig. 1 Diagrammatic presentation of the model buildings with full-scale dimensions

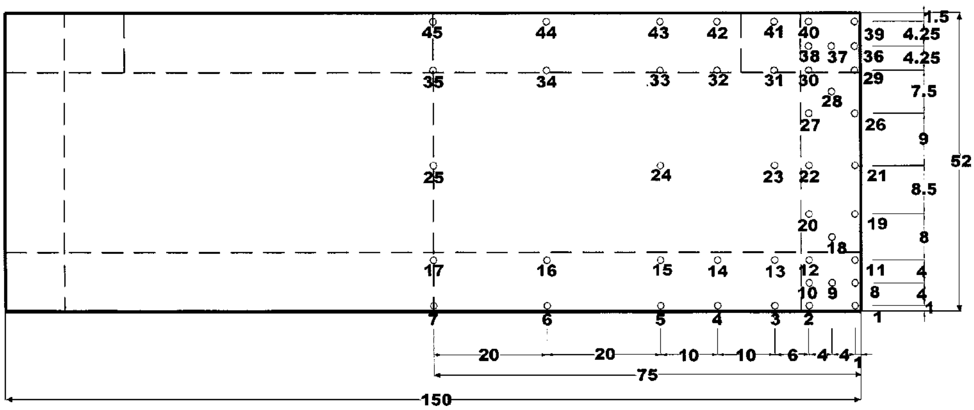


Fig. 2 Illustration of the pressure taps and the regions delimited on the interchangeable roof panel (unit : mm)

corresponding to pressure taps at various locations. Area-averaged pressures have been derived from the simultaneously recorded time histories of local pressures and were based upon a series of tap combinations representing different areas of different zones on the roofs. For interior, edge/ridge and corner zones, 3, 19 and 15 sets of tap combinations have been considered; these corresponded to equivalent full-scale areas ranging from 1.9 m^2 to 99.8 m^2. The reference pressure used for the calculation of wind pressure coefficients was the total velocity pressure at mid-roof height (H), which varied slightly with the different roof slopes of the building models tested.

3. Results and discussion

3.1. Local pressures

Instantaneous peak pressures and suctions obtained from different wind directions have been analyzed and the most critical values for each tap have been retained to form the most critical

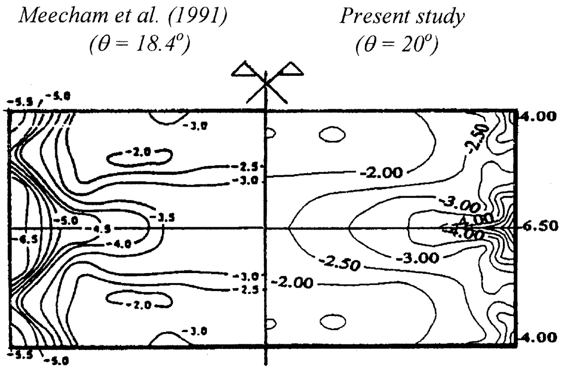


Fig. 3 Comparison of the most critical local peak pressure coefficients measured by Meecham *et al*. (1991) with the present results

pressure coefficients applied to each point of the roof envelope for each roof configuration. These data have been validated by comparison with results obtained from previous studies to ascertain their effectiveness to be used for codification purposes.

Fig. 3 presents a comparison of wind tunnel data of Meecham *et al*. (1991) measured on a 4:12 roof slope ($\theta = 18.4^{\circ}$) with the present data measured on the 20°-roof model. Although the data of Meecham *et al.* (1991) appear somewhat higher than those of the present study for some locations, such as those for eave corners, data from these two studies agree reasonably well. The difference is likely due to the differences in wind simulation and model configuration, as Meecham *et al.* (1991) used a rougher terrain exposure, with a power-law exponent equal to 0.19 versus 0.14 in the present study. It should be recalled that rougher terrain generally induces higher peak pressure coefficients.

The difference could also be attributed to the slight difference in the roof slopes of the models of these studies. Further comparison of the data with the most critical local peak coefficients of Case and Isyumov (1998) shows similar results.

Fig. 4 presents the experimental pressure coefficients measured at 0° wind direction along the mid-length line for each of the five roof models. For comparison purposes, data from previous wind tunnel and full-scale studies (Holmes 1981, Hoxey and Moran 1983, Richardson and Surry 1991) are also included in this figure. For the 10°-roof, the present results show good agreement with both wind tunnel and full-scale data measured by Richardson and Surry (1991). For the 15°-roof, the full-scale data from Hoxey and Moran (1983) agree well with the wind-tunnel data from Richardson and Surry (1991), but both are higher than the present results, particularly on the windward side of the roof.

Agreement is better among the present data and the results of Holmes (1981). For the 20° and 30° roofs, the present data have been compared with data of Holmes (1981); the latter appear somewhat lower. It could be noted that only mean pressure coefficients are available from these previous studies presented in Fig. 4. The discrepancies found can be attributed to the differences among wind tunnel simulations and model configurations.

Data presented in Fig. 4 are also instructive in demonstrating the significant differences in wind loading occurring on roofs in the intermediate roof range, for which at present, there is a single set of provisions in the North American wind load specifications. On the other hand, it should be taken

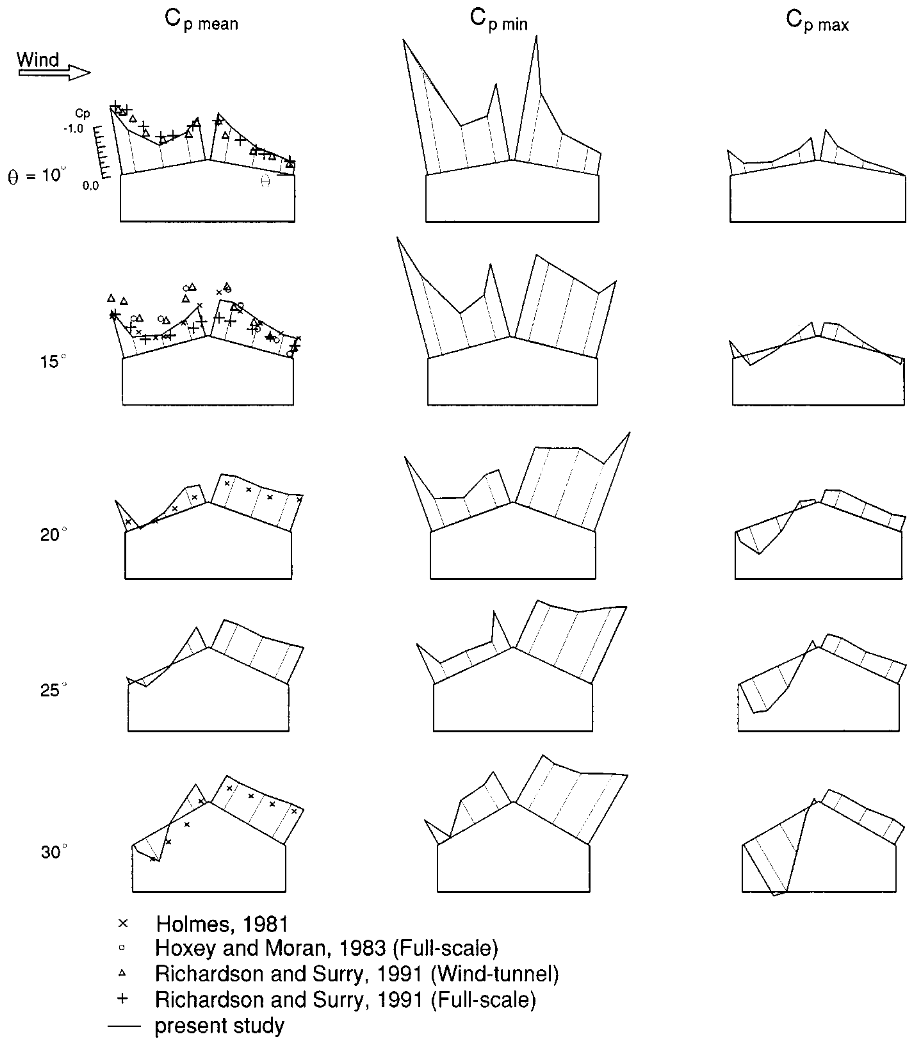


Fig. 4 Mean and peak pressure coefficient profiles along the mid-length lines of the roofs, $\alpha = 0^{o}$

into account that these data have been produced by a single wind direction, namely 0^{o}. Therefore, conditions may be different when data from various wind directions are combined in order to produce the envelope of the most critical pressure coefficients.

The distributions of the most critical mean, rms and peak local pressure coefficients measured for the five roof models are shown in contour form in Fig. 5. It should be noted that all these contours have taken advantage of the symmetry of the roofs, thus the contours on a quartering roof can reflect those for the entire roof. The dashed lines superimposed delimit the zonal areas in accordance with the North American standards, which define the width of each pressure zone in terms of building width or building height, namely 10% of minimum horizontal dimension of the roof or 40% of mid-roof height, whichever is less. Fig. 5 shows that the most critical values are higher near gable ends and ridge, particularly for ridge corners, but lower close to eaves. On the other hand, on the region of ridge near apex which is specified by NBCC 1995 but not in ASCE 7-98, the most

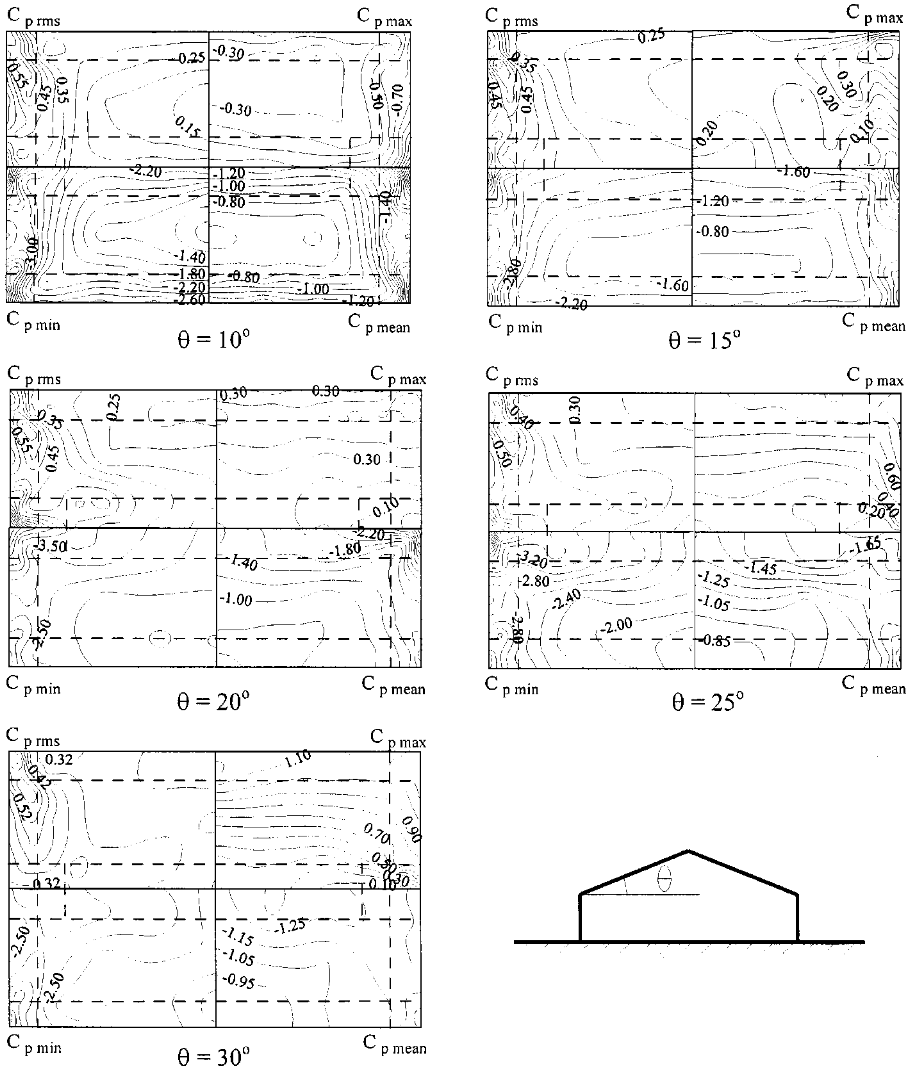


Fig. 5 Most critical local pressure coefficients measured on the five roofs for all wind directions

critical local pressure coefficients do not have higher values in comparison with those in its neighborhood, at least in most of the measurements, which is in agreement with ASCE 7-98 but against NBCC 1995.

3.2. Area-averaged pressures

Area-averaged loads have been derived for areas of different sizes and the extreme values of their coefficients from their variations with azimuth have also been obtained. The variation of suction coefficients with each roof angle is hard to be classified, although positive pressure coefficients seem to increase gradually with the increase of roof angle. Area-averaged pressure coefficients as function of wind azimuth for the entire area of the ridge corner are shown in Fig. 6. Further

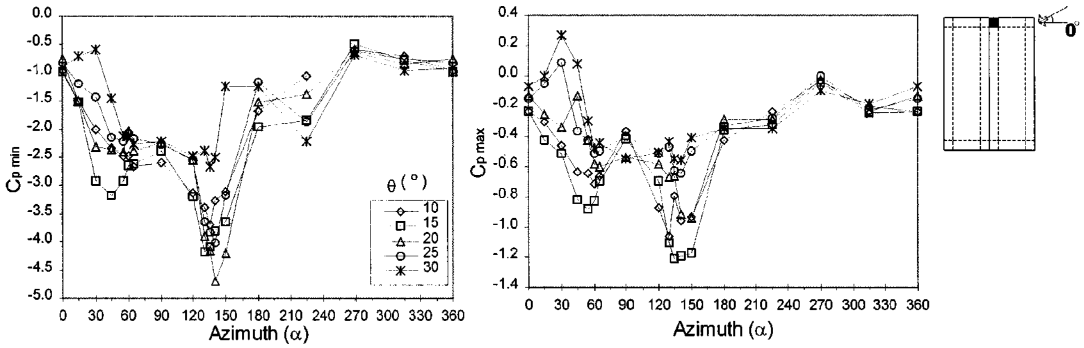


Fig. 6 Area-averaged pressure coefficients as function of wind azimuth for the entire area of ridge corner of the roof

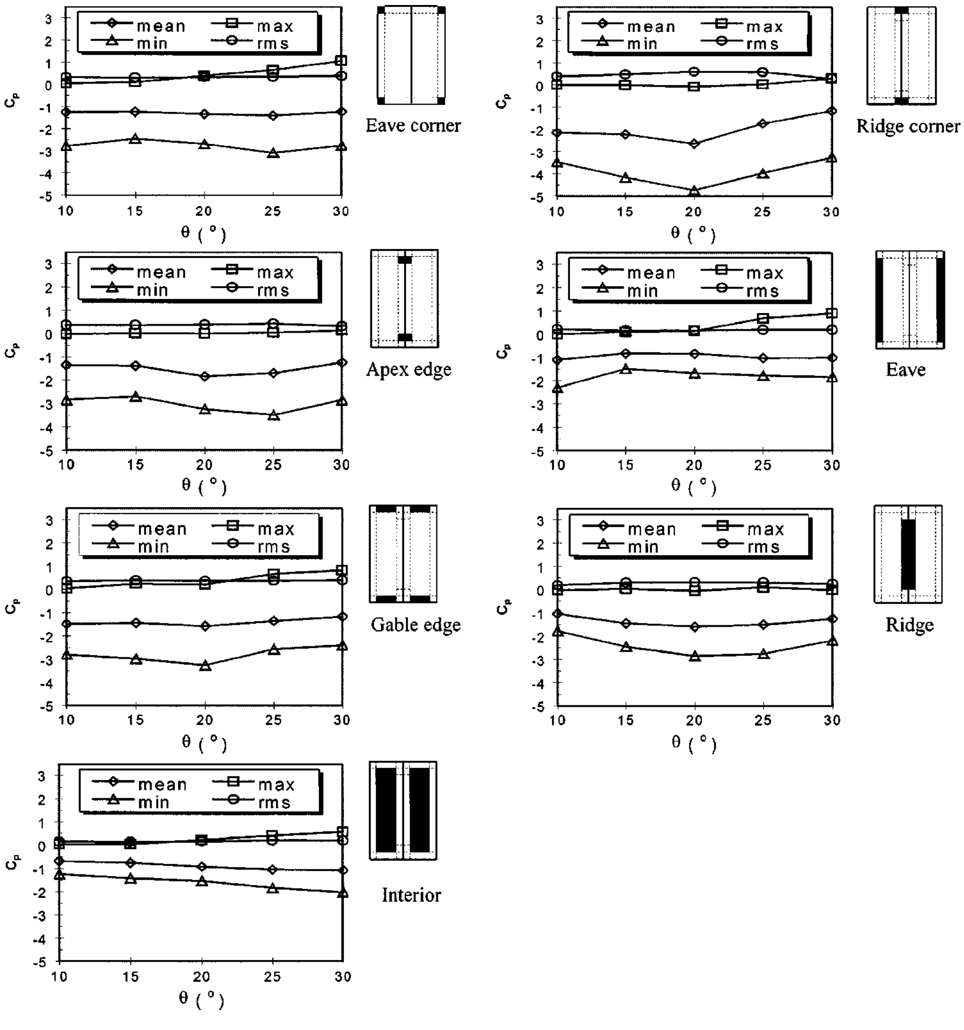


Fig. 7 Most critical area-averaged pressure coefficients as function of roof angle for all roof regions

examination of the data from the other regions indicates similar results, but data measured on the 30°-roof can be distinctly different from those for the other roofs in the intermediate slope range.

The most critical area-averaged pressure coefficients in form of mean, rms. and peak values for all roof regions considered have been presented as function of roof angle in Fig. 7. The effect of roof angle on wind loads for the intermediate roof slope appears rather weak, with the exception of suction on ridge corners, which is higher on the 20°-roof than on the other roofs. This indicates that the most critical suction coefficients are likely to occur when the roof angle approaches 20°. However, this is not the case for other roof areas. Generally, the variation of area-averaged pressure coefficients with roof angle is clearly non-monotonic, as also found for local pressure coefficients.

4. ASCE-7 pressure coefficient provisions

4.1. Comparison with current provisions

In order to compare the measured peak pressure coefficients with the most recent provisions of the American wind standard (ASCE 7-98), the most critical local and area-averaged values have been re-referenced to the dynamic velocity pressure at mid-roof height corresponding to the 3-second gust reference speed. The latter was assumed to be equal to 1.53 times the mean hourly wind speed.

Fig. 8 compares the measured peak pressure coefficients (GC_p) of the 10°-roof with the current ASCE 7-98 provisions specified for both the quasi-flat roof range ($0° < \theta \leq 10°$), in which they are supposed to belong, and the intermediate range ($10° < \theta \leq 30°$). However, the experimental data fit much better with the provisions for the intermediate slope range, particularly for those measured on the edge, ridge and corner regions. This is against the current codal definition. Similarly, considering the upper end of the intermediate slope range, the experimental data of the 30°-roof have been compared with the ASCE 7-98 provisions for both the intermediate roof range ($10° < \theta \leq 30°$), in

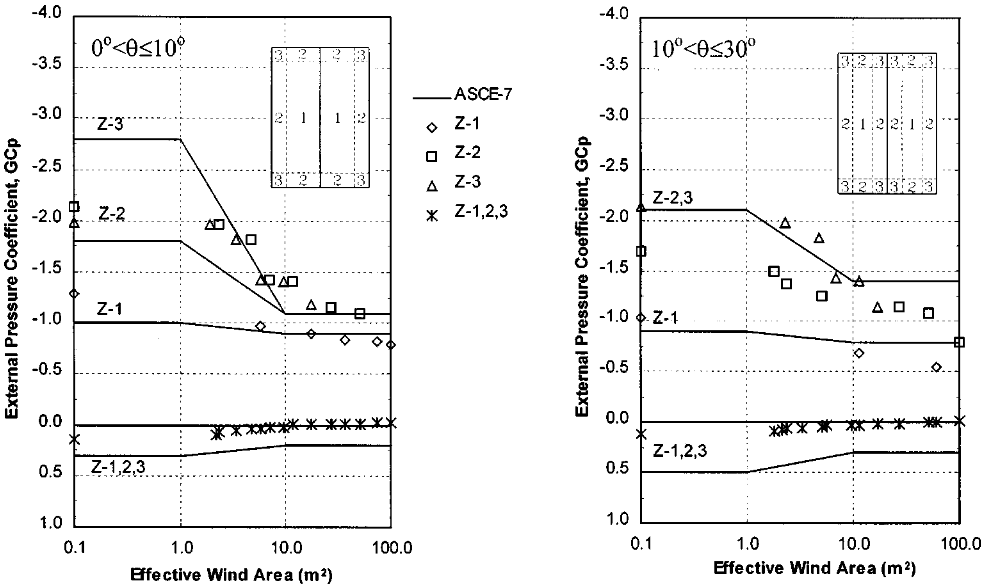


Fig. 8 Comparison of the 10°-roof experimental data with the corresponding ASCE 7-98 provisions

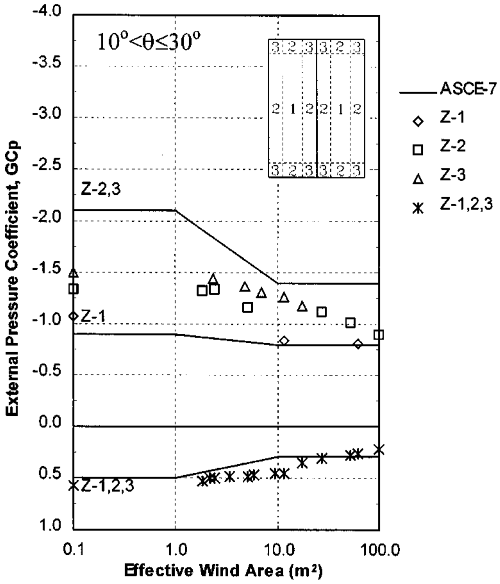


Fig. 9 Comparison of 30°-roof experimental data with the corresponding ASCE 7-98 provisions

which they are supposed to belong, and the high-pitched roof range (30°< $\theta \leq$ 45°). The results are shown in Fig. 9. Once again, it appears that the experimental data fit better with the provisions for the high-pitched slope range, but contrary to the current code definition; the latter could be modified as follows: 10° roof and 30° roof could be taken out of the quasi-flat roof range (0°< $\theta \leq$ 10°) and intermediate roof range (10°< $\theta \leq$ 30°), and relocated into the intermediate and high-pitched roof range, respectively. Through extrapolation and interpolation of the measured data, both present and past, and by using good engineering practice, the gable roof slopes could be rearranged as quasi-flat (0°< θ <7°), intermediate (7° $\leq \theta$ < 27°) and high-pitched (27° $\leq \theta \leq$ 45°).

Fig. 10 compares the most critical data measured for θ = 10°, 15°, 20° and 25° with the current ASCE 7-98 design pressure coefficients for intermediate slope. Comparisons are generally good with the exception of the data measured on roof corner, which seem to be higher than the current design pressure coefficients. This can be explained by considering the multitude of wind directions investigated in the present study in comparison with the limited number of azimuths examined in the original study (Davenport *et al.* 1977) that led to the generation of the current provisions of ASCE 7-98. This is particularly critical to roof corner pressures due to their well-known sensitivity to wind directionality. In contrast, edge/ridge pressure coefficients measured are somewhat lower than the corresponding design values in the current provisions of ASCE 7-98. Furthermore, it also becomes evident from Fig. 10 that, the higher the roof slope, the larger the gap between the data measured on roof corner and the data measured on edge/ridge. In other words, with increasing the roof angle in the intermediate range, the pressure coefficients measured on roof corners are higher while the data measured on edge/ridge are lower than the current ASCE 7-98 provisions common for corner/edge/ridge. Thus, it becomes apparent that safety and economy dictate to distinguish the provisions for these two zones into two separate sets, one for corners and the other for edges and ridge.

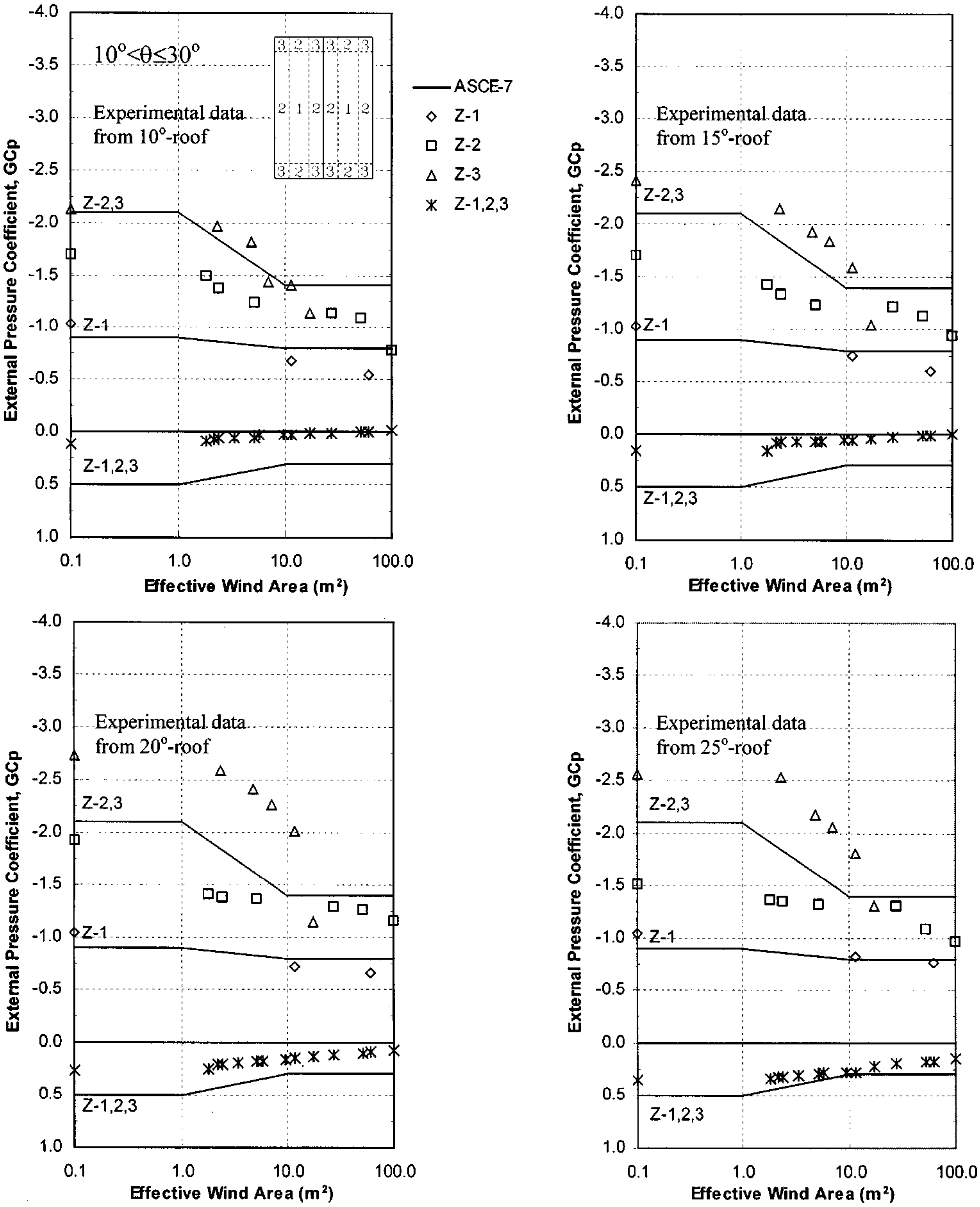


Fig. 10 Comparison of data measured on the 10°-, 15°-, 20°- and 25°-roofs with the current ASCE 7-98 provisions for gable roofs of intermediate slope (10°< $\theta \leq$ 30°)

4.2. Recommendations

Following the observations discussed in section 4.1, Fig. 11 shows the proposed provisions as well as the current ASCE 7-98 for gable roofs of intermediate slope. Roof edge/ridge design pressure coefficients are reduced while corner design pressure coefficients are increased. The proposed design pressure coefficients encompass the great majority of the experimental data. Some variation

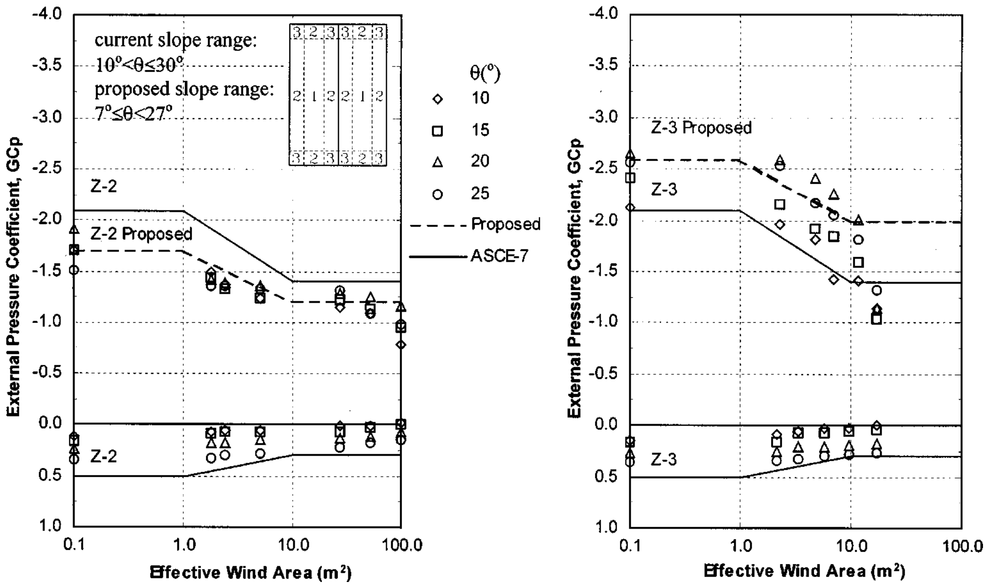


Fig. 11 Proposed and current ASCE 7-98 design pressure coefficients for edge/ridge and corner zones

Table 1 Comparison of the proposed design pressure coefficients with the current ASCE 7-98 provisions as well as some previous findings

	Local GC_p values	
	Zone 2	Zone 3
Proposed ASCE 7-98 provisions	-1.7	-2.6
ASCE 7-98 provisions	-2.1	-2.1
Case and Isyumov (1998)	-2.1	-2.8
Holmes (1981)	2.0	2.8
Meecham *et al.* (1991)	-2.0	-2.8

between the experimental data and proposed design pressure coefficients still exists. This is normal and occurs within other studies, the results of which have been used for codification purposes. Table 1 compares the proposed provisions for local pressure coefficients with the current ASCE 7-98 values and some findings from previous studies as well. Data are shown only for local GC_p values given the lack of relevant results for area-averaged loads. The comparison shows that the proposed provisions, which increase the roof corner suctions and decrease those in edges and ridges, are an improvement in comparison with those currently used. In addition, considering that areas of roof edges and ridge are significantly larger than those of corners, the proposed provisions will be more economical than the current provisions as well. As previously mentioned, the definition of the intermediate slope range could be modified into $7^\circ \leq \theta < 27^\circ$ from the current $10^\circ < \theta \leq 30^\circ$ for a more accurate representation of the roof slope ranges in accordance with the experimental results. Finally, if this recommendation is adopted, the other two roof angle ranges will also be modified to $0^\circ \leq \theta < 7^\circ$ and $27^\circ \leq \theta < 45^\circ$ accordingly.

5. Conclusions

A wind tunnel study has provided detailed extreme local and area-averaged pressure coefficients for low-building roofs with several roof slopes in the intermediate range, exposed to an open-country upstream terrain. The results have been compared with those from previous studies and have also been used as the basis to suggest modifications to the current American wind provisions (ASCE 7-98) to be considered for the wind design loads of gable roofs of intermediate slope. The proposed provisions appear to be simple and economical.

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