WIND EFFECTS ON MONOSLOPED AND SAWTOOTH ROOFS

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ABSTRACT

Wind is one of the significant forces of nature that must be considered in the design of buildings. The actual behavior of wind is influenced not only by the surface (or boundary-layer) conditions, but also by the geometry of the building. All sorts of turbulent effects occur, especially at building corners, edges, roof eaves. Some of these effects are accounted for by the wind pressure coefficients. Wind pressure coefficients are determined experimentally by testing scale model buildings in atmospheric boundary layer wind tunnels.

In this study, a series of wind tunnel tests with scaled building models were conducted to determine the wind pressure coefficients that are applicable to monosloped and sawtooth roofs. In the estimation of wind pressure coefficients, the effects of building height, number of spans and terrain exposure are considered and analyzed in detail. Both local and area-averaged wind pressure coefficients are calculated and compared with values in ASCE 7 design load guidelines.

Wind pressure coefficients on “special” sawtooth roof buildings (sawtooth roof monitors separated by horizontal roof areas) are also investigated. It is found that increased separation distances result in increased peak negative wind pressures on the sawtooth roof monitors that exceed the wind pressures determined on a classic sawtooth roof building.

Analysis of the test results show no significant difference between the extreme wind loads on monosloped roofs and sawtooth roof buildings and by implication, current design provisions in ASCE 7 for monosloped roofs may be inadequate. The author-defined pressure zones for the windward span, middle spans and leeward span of sawtooth roofs based on wind tunnel tests allow more accurate determination of different levels of suction on the roofs.

Finally, the author proposes the design wind pressure coefficients and wind pressure zones for these two types of roofs and suggests future enhancement to existing ASCE 7 design load provisions for sawtooth roof systems.

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CHAPTER 1

INTRODUCTION

1.1 Background

Since the 1960s, atmospheric boundary layer wind tunnel studies on building models have been the primary source of determining wind design loads. Due to the cost of full scale tests, engineers must rely upon the continuing development of wind tunnel tests for new building shapes, which has been the primary method for determining wind design codes that contain wind pressure and force coefficients for several generic building shapes. Early studies focused on the gable-roof shaped structure (Davenport et al., 1977[a,b]) and the monosloped roof structure (Surry et al., 1985), and subsequent to those efforts, studies were done to investigate hipped-roof building loads (Meecham, 1992). These were particularly important for assessing wind loads on low-rise building structures. As building styles change, further wind tunnel studies are necessary to update wind load provisions and to validate existing provisions as new information becomes available.

1.1.1 Extreme Wind Effects on Low Rise Buildings

In North America, hurricanes, tornadoes and winter storms generate the extreme winds for which roof designs must be created. Hurricanes, with winds of at least 33 m/s, cause most of the extreme wind loads on buildings in coastal states of the US. Recent severe wind events such as Hurricane Andrew in 1992, Hurricane Charley in 2004 and Hurricane Katrina in 2005 have highlighted the devastating effects of these storms on coastal communities. In fact, FEMA (Reid, 2006) estimates that approximately $5 billion in wind-related damage annually occurs in the United States, much of which occurs to low-rise buildings, defined as any building having a mean roof height of less than or equal to 18 m in the ASCE (American Society of Civil Engineers) 7-02 Minimum Loads for Buildings and Other Structures (ASCE, 2002).

Experimental investigations by Schiff et al. (1994) at Clemson University showed that the roof sheathing attached to wood roof rafters or trusses using 8d nails at 0.15 m spacing on center can fail from wind-induced negative pressures of as low as 3.35 kN/m^2. In comparison, a strong hurricane with 71.5 m/s gust wind speed can exert wind uplift pressure as high as 4.79 kN/m^2 at a corner location of a 9.1 m tall residential building with a flat roof (William et al., 2002). As a result, continuing investigation of the wind effects on building sheathing systems is still necessary and important.

1.1.2 Typical Terrain Exposures

Atmospheric wind velocity varies with height above ground and the wind speed fluctuation (or turbulence intensity) also varies with height. The turbulence intensity of the wind is a measure of the departure of instantaneous wind speed from the mean wind speed and it is defined as the ratio of the longitudinal standard deviation or roof root mean square (RMS) wind speed to the mean wind speed as shown in Eq. 1.1.

$$T.I. = \frac{U_{rms}}{\overline{U}} \tag{1.1}$$

where T.I. denotes the turbulence intensity; U_{rms} denotes the RMS wind speed and $\overline{U}$ denotes mean wind speed.

Buildings are affected by winds flowing within the atmospheric boundary layer, which is the lowest part of the atmosphere. Winds within this atmospheric region are directly influenced by contact with the earth's surface. The surface roughness is a measure of small scale variations on a physical surface. As the earth surface becomes rougher there is a commensurate increase in turbulence intensity and a reduction in the mean wind velocity with height increasing. The roughness of the earth's surface causes drag on wind, converting some of this wind energy into mechanical turbulence. Since turbulence is generated at the surface, the surface wind speeds are less than wind speed at higher levels above ground. A rougher surface causes drag on wind more than a smoother surface, which makes the mean wind speed increase more slowly and generates higher wind turbulence. This variability of wind speed with height is illustrated in Fig. 1.1.

For engineering design purposes, the earth's surface can be divided into several categories of terrain characteristics which dictate how the wind speeds and velocities vary within the atmospheric boundary layer. Wind speed profiles are defined by two methods; the log-law and power-law which provide approximate estimates of wind velocity changes with height for any specific terrain. The log-law velocity profile, defined in Eq. 1.2, relates to roughness length, z_0 which is a measure of the size of obstructions in a particular terrain.

Boundary Layer

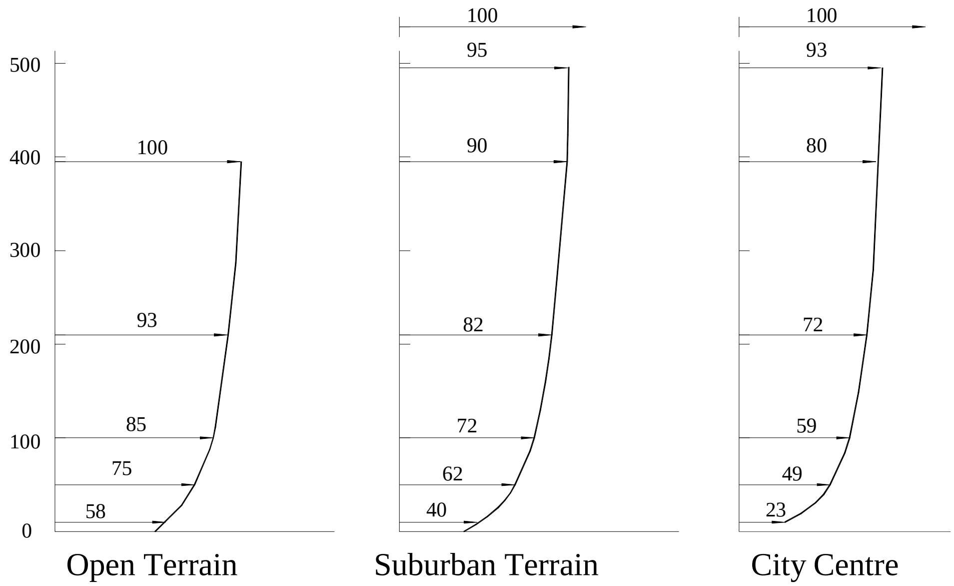


Figure 1.1 Mean Wind Speed Profiles for Various Terrains
(Height Unit : m)

$$\frac{\overline{U}_z}{\overline{U}_{ref}} = \frac{\log_e\left(\frac{z}{z_0}\right)}{\log_e\left(\frac{z_{ref}}{z_0}\right)} \tag{1.2}$$

where, $\overline{U}_z$ denotes the mean wind speed at height of z m above ground; $\overline{U}_{ref}$ denotes the mean wind speed at the reference height.

The log-law equation accurately represents the variation of wind over heights in a fully developed wind flow over homogeneous terrain.

$$\overline{U}(z) = \frac{u_*}{k}\log_e\left[\frac{z - z_h}{z_o}\right] \tag{1.3}$$

u_* is the friction velocity; k denotes von Karman's constant (0.4); z_h is the zero-plane displacement.

The power-law wind profile is used more widely than the log-law wind profile. There are three reasons to account for this fact.

1. In the atmosphere, the criteria of neutral stability condition necessary for applying the log-law equation are rarely met; the neutral condition requiring the temperature profile in the surface layer to be always close to adiabatic is not easy to maintain in natural conditions.
2. The log-law equation cannot be used to determine wind speeds near to the ground or below the zero-plane displacement. The zero-plane displacement is the height in meters above the ground at which zero wind speed is achieved as a result of flow obstacles such as trees or buildings. It is generally approximated as 2/3 of the average height of the obstacles.
3. The complexity of the log-law equation makes it difficult to integrate over a building height, which in turn makes the determination of wind load on the whole building height very difficult.

For typical engineering design calculations, the power law equation is often preferred. The power law shown below in Eq. 1.4 is particularly useful when integration is required over tall structures:

$$\bar{U}(z) = \bar{U}_{10}\left(\frac{z}{10}\right)^{\alpha} \tag{1.4}$$

where, z is the height above the ground; $\overline{U}_z$ denotes the mean wind speed at the height of z meter above ground and $\overline{U}_{10}$ denotes the mean wind speed at the reference height of 10 m above ground;

$$\alpha = \left(\frac{1}{\log_e \left(z_{ref} / z_o \right)} \right) \tag{1.5}$$

Simiu and Scanlan (1996) recommended the power-law constant α = 0.15 and log-law typical roughness length = 0.02 m for open country exposure. Using the mean wind speed at 10 m above ground as the reference wind speed, non-dimension wind profiles based on power-law and log-law can be obtained (Fig. 1.2). It can be seen that wind speeds based on the power-law and the log-law for heights below 40 m are very close to each other.

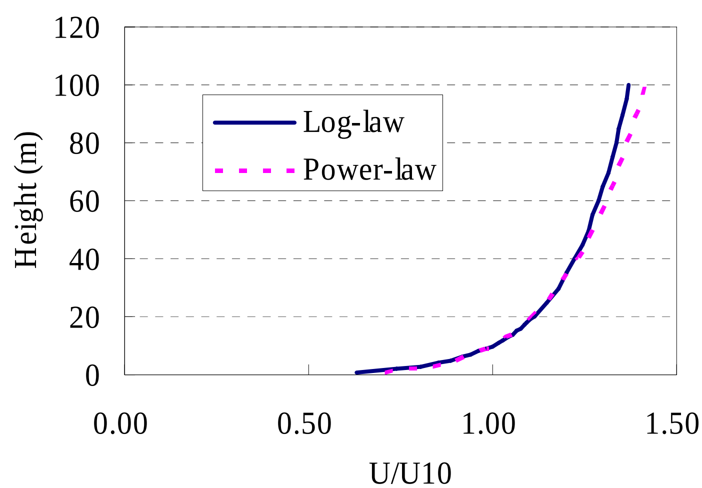


Figure 1.2 Log-law and Power-law Wind Profiles for Open Country

The ASCE 7-02 standard divides exposures into three categories of Exposure B, C and D (in earlier versions of the Standard Exposure A was used for city centers but this has been removed in the ASCE 7-02 edition). The exposure categories correspond to terrains with different characteristics. For example, Exposure B represents the urban and suburban terrain and wooded areas with numerous closely spaced obstructions having the size of single family dwellings or larger. Exposure C describes areas with open terrain and scattered obstructions of height generally less than 9.1 m. Exposure D describes an area which is flat, unobstructed or a water surface. The log-law and power-law coefficients estimated by Simiu and Scanlan (1996) for open country and suburban exposures are shown in Table 1.1.

Table 1.1 Coefficients for Log-law and Power-law Wind Profiles

Exposure	Log-law Coefficient z_0 (m)	Power-law Coefficient
Suburban	0.15 ~ 0.7	0.22 ~ 0.28
Open Country	0.01 ~ 0.15	0.1 ~ 0.16

1.1.3 Estimation of Design Wind Loads

It is known that wind forces vary both in space and in time over a building’s surface. Because of their stochastic nature, peak wind loads are difficult to estimate, and it is not yet possible to determine the wind loads analytically through any known mathematical methods. Wind tunnel studies make it possible for engineers and scientists to provide a relatively complete assessment of the wind-induced loads on a building, including their spatial and time-varying components.

The design wind pressures on buildings in the United States are determined using ASCE 7-02 provisions. The Analytical Method (called Method 2 in ASCE-7) is used to estimate the wind velocity pressure *q* using Eq. 1.6 first, then using Eq. 1.7 to determine the design wind pressure *p*.

$$q_z = 0.00256 K_z K_{zt} K_d V^2 I (lb/ft^2) \tag{1.6}$$

$$p = qGC_p - q_i (GC_{pi}) \tag{1.7}$$

where p denotes the wind pressure occurring on a building location; GC_p and GC_{pi} denote the external and internal wind pressure coefficient respectively; q_z denotes the wind velocity pressure at height z; V denotes the basic wind speed, defined as the three-second gust wind speed in miles per hour at 10 m above the ground in Exposure C; K_z is the velocity pressure exposure coefficient; K_d is the wind direction factor; K_{zt} is the topographic factor, and I is the structural importance factor.

Thus, the determination of wind loads on a building is directly dependent on experimentally determined pressure coefficients from previous wind tunnel tests. If these pressure coefficients for a particular building shape do not exist, engineers must perform new wind tunnel tests to estimate design wind loads. While the existing winds load design guides provide wind pressure coefficients for some building shapes (gabled, hipped, monosloped etc.) the range is limited by previous experiments. In addition, improvements to the current building codes can only be achieved through further testing and verification of past results.

1.1.4 Development of Wind Tunnel Experiments

By the 1950s atmospheric studies of the Earth's turbulent boundary layer had led to a greater understanding of its complexity and the establishment of a better set of modeling criteria. Cermak (1958) demonstrated the criteria for the independence of Reynold's Number effect when modeling an atmospheric boundary layer flow at a reduced scale. Davenport (1961) developed the application of statistical concepts to physical modeling in wind engineering. Cermak's and Davenport's work was instrumental in establishing the basis for contemporary boundary layer wind tunnel studies of wind loads on buildings. By the end of 1960s, such wind tunnel studies were routinely performed on buildings, particularly high-rise structures.

Cermak (1971, 1981) completed the extensive theoretical justification for the similarity requirements of wind tunnel scaled model test. It was observed that the dependence of drag on the Reynolds number for bluff, sharp edged bodies (and the boundary layer itself) was small when performed above a critical Reynolds number. The insensitive nature of load coefficients to the Reynolds number meant that boundary-layer wind-tunnel modeling was viable at moderate wind speeds.

1.1.5 Full Scale Wind Pressure Measurements

Full scale wind load measurements are needed to confirm the results of wind tunnel test procedures. Major studies on full scale wind loads on three well known buildings are reviewed below.

1. In the late 1970s, the Aylesbury experimental building in the United Kingdom was constructed (Eaton and Mayne, 1975). This gabled-roof building had an adjustable roof slope, and overall width of 7 m, length of 13.3m and height to eave of 5 m.
2. In the late 1980s, the Silsoe Building, also in the United Kingdom, was constructed with a fixed 10^o gable roof, 12.93 m wide, 24 m long and 4 m high (Richardson et al., 1990).
3. Also in the late 1980s, the Texas Tech University (TTU) experimental building (Levitan and Mehta, 1992[a,b]) was constructed at Lubbock, Texas. This structure had a near-flat roof and rectangular plan, with 9.1 m wide, 13.7 long and 4.0 m high.

In his paper, Holmes (1982) discussed some of the full-scale results from the Aylesbury building experiments and the subsequent international wind tunnel model studies. Holmes concluded that the turbulence intensity must be scaled correctly in the wind tunnel in order to generate realistic wind loads on buildings.

Based on a comparison between full-scale and wind tunnel measurements Sill et al. (1989, 1992) indicated that the similarity parameter h/z_0 (building height/roughness length) is not sufficient to ensure similarity when significant isolated local roughness elements such as trees and hedges are present. Furthermore, it was founded that the large laboratory-to-laboratory variations in wind pressure coefficients was attributable to experimental differences in data acquisition methods and in the location of measuring points of the reference static and dynamic pressures (Sill et al., 1992).

1.1.6 ASCE 7 Specifications

Although there have been several wind tunnel studies investigating wind loadings on low-rise buildings, most studies focused on gable roofed buildings (Uematsu and Isyumov, 1999). As a result, several common building shapes lack reliable wind load design pressure coefficients, i.e. single-family residential structures and L-shaped and T-shaped buildings. In addition, some structures for which design values are provided, i.e. the sawtooth roof buildings, there are sufficiently wide variations in architectural and construction practices that the design wind load assumptions may not always be appropriate.

A sawtooth roof building consists of a series of single pitch roof monitors forming a roof shape that resembles the sharp teeth of a saw. This roof shape is found in industrial buildings and factories, in which the vertical face of the roof monitor contains window glazing that allows light to enter the building. To maximize this ambient light, sawtooth roofs typically have roof slope angles between 15^o and 25^o. The research on sawtooth roof systems is not as extensive as the research on gable roof buildings. Current wind design parameters were derived from a single building model with a fixed aspect ratio and roof slope based on Saathoff and Stathopoulos' work (1992[a,b]). It has yet to be established if the results can be extrapolated to other building dimensions.

The ASCE-7 has provided design wind pressure coefficients for sawtooth roofs since 1995. Table 1.2 presents wind pressure coefficients provided by the ASCE 7-02 for typical roof shapes including gable roofs, monosloped roofs, sawtooth roofs and multi-span gable roofs. In the critical suction zones, wind pressure coefficients for monosloped roofs exceed the wind pressure coefficients for gable roofs by 12%. Critical wind pressure coefficients for sawtooth roofs exceed those for gable roofs by 57% in corners and by 88% in edge zones. In addition, the design wind pressure coefficients for the corner zone of monosloped roofs are 41% less than those for sawtooth roofs, despite the obvious similarity of geometric characteristics between these two building types.

Table 1.2 External Pressure Coefficients for Gable, Monosloped and Sawtooth roofs in ASCE 7-02

Roof slope	$10 < \theta < 30$ (degrees)								
Zone / Roof Shape	Area $\leq$ 10ft^2			Area = 100ft^2			Area $\geq$ 500ft^2		
	1	2	3	1	2	3	1	2	3
Sawtooth (Span A)	-2.2	-3.2	-4.1	-1.6	-2.3	-3.7	-1.1	-1.6	-2.1
Sawtooth (Span B, C, D)	-2.2	-3.2	-2.6	-1.6	-2.3	-2.6	-1.1	-1.6	-1.9
Monosloped	-1.3	-1.6	-2.9	-1.1	-1.2	-2.0	-1.1	-1.2	-2.0
Gable ($27 \geq \theta > 7$)	-0.9	-1.7	-2.6	-0.8	-1.2	-2.0	-0.8	-1.2	-2.0
Multi-Gable	-1.6	-2.2	-2.7	-1.4	-1.7	-1.7	-1.4	-1.7	-1.7
Note: Wind pressure coefficients are normalized to 3-second Gust Wind Speed at Mean Roof Height; 1 ft^2 = 0.09 m^2									

It should be noted that prior to the 1995 version of the wind design standard (ASCE 7-95), wind loads on buildings with sawtooth roofs were estimated using the design wind load criteria for gable roofs, which makes the estimated wind loads for sawtooth roofs far lower than the design wind load estimated based on the current ASCE 7-02 provisions. For example, a sawtooth roof building under open country exposure with standard 3-s gust wind speed 49.2 m/s has a wind load on the corners of 7.5 kN/m^2 , based on ASCE 7-02 provisions. With the same terrain and wind speed conditions, the wind pressure on corners of gable roofs is 4.7 kN/m^2 based on ASCE 7-02 provisions for gable roofs. If the difference of wind pressures between sawtooth roofs and gable roofs is really so large, it should be the case that these buildings are more likely than gable roofed structures to suffer damage during extreme wind events. However, forensic investigations of two roofing systems installed on sawtooth buildings in Massachusetts (Fig. 1.3) found no signs of increased wind uplift failure of the roofing systems. This fact motivates further research on wind pressure distribution on sawtooth roofs.

Figure 1.3 A Building with Sawtooth Roof Located in Wellesley, MA

A comparison of wind pressure coefficients in Saathaff and Stathopoulos' study (1992a) for monosloped and sawtooth roofs with similar geometric characteristics showed that the extreme peak wind pressure coefficients on the two roofs are very similar, with difference in values of less than 5%. However, in ASCE 7-02, there is a 41% difference in extreme wind pressure coefficients for monosloped roofs and sawtooth roofs (-2.9 versus -4.1). Interestingly, for the sawtooth roof building there is virtually no difference between the ASCE 7-02 design wind pressure coefficient (-4.1) and the extreme wind pressure coefficient determined by Saathoff and Stathopoulos (-4.2). The rationale for the discrepancy of wind pressure coefficients between the Saathoff and Stathopoulos' results and ASCE 7-02 wind design provisions for the monosloped roof is a question that has yet to be determined.

There are two fundamental questions regarding the wind loading on sawtooth and monosloped roofed buildings that this dissertation seeks to investigate:

1. Are wind-induced loads on sawtooth roofs higher than loads on gable-roofed buildings?
2. How much do wind-induced loads on monosloped roof buildings differ from loads on a similarly-proportioned sawtooth roof building?

This study seeks to elucidate the effects of several parameters on wind-induced pressures on monosloped and sawtooth roofs. Those parameters thought to be of significance include building height, terrain exposure and localized roughness around the building.

1.2 Objectives

This section presents the main objectives of the research on wind effects on monosloped and sawtooth roofs.

1. To investigate the effects of number of sawtooth roof spans, building height, surface roughness and wind direction on wind pressure coefficients for monosloped and sawtooth roofs.

2. To compare wind pressure coefficients between monosloped roofs and sawtooth roofs which have similar geometric configurations.
3. To investigate the relationship between peak wind pressure coefficients and corresponding root mean square (RMS) wind pressure coefficient.
4. To investigate wind pressure coefficients for a separated sawtooth roof, having flat-roof separations between pitched roof portions.
5. To propose modifications to ASCE 7 wind design standard for monosloped and sawtooth roof buildings.

1.3 Outline

A brief overview of each chapter is given as follows:

Chapter 2 presents a literature review of major research works on wind tunnel testing and the design wind pressure coefficients for monosloped and sawtooth roofs. Chapter 3 describes the simulated boundary layers in the wind tunnel, construction of the test models and test cases.

The wind tunnel test results and analysis are presented in Chapter 4, including the extrapolation method used to estimate the peak wind pressure coefficient from one pressure coefficient time history measured in the wind tunnel. Parameter effects, such as number of spans, building height and terrain, on wind pressure coefficients are investigated. Pressure zone definition, critical wind directions for monosloped and sawtooth roofs, and RMS wind pressure coefficient distributions are also studied. The results are presented in terms of both local and area-averaged wind pressure coefficients.

The comparison of the wind pressure coefficients derived from test results with design wind pressure coefficients from ASCE 7-02 are discussed in Chapter 5. Finally, conclusions based on this research work are presented in Chapter 6. Proposed recommendations for modifying the design wind pressure zones for monosloped and sawtooth roofs are suggested as a potential change to the current wind loading design standard.

CHAPTER 2

LITERATURE REVIEW

This chapter reviews relevant literatures on wind pressure coefficients for monosloped and sawtooth roofs. The literatures on peak value estimation of measured wind pressure time series for low rise buildings in wind tunnel tests are also specifically reviewed. Finally, current ASCE 7-02 provisions for wind pressure coefficients for monosloped and sawtooth roofs are introduced and compared with previous researches.

2.1 Peak Estimation of Wind Pressure Time Series

The wind pressure coefficients available in current building codes, such as the ASCE specification of wind loads, are all based on extensive wind tunnel tests described in Chapter 1. The procedures used to obtain these pressure coefficients are from extreme value analysis of the measured data. However, there is no explicit probability distribution applicable to wind pressure time series and the largest peak pressure on a model varies by 30% from one measurement to another due to a natural variation in the largest peak during a measurement period (Tieleman, 2006). The following peak value estimation methods are commonly used to calculate local wind pressure coefficients:

1. Averaging peaks from several measurement records;
2. Extrapolating the peak values obtained from a number of sub-records to the full record;

3. Obtaining the distribution of the largest peak by measuring all independent peaks observed from a large number of sample records.

2.1.1 Averaging Direct Peak Method

To obtain more stable peak values, the method of averaging peak pressures from several measurement records is used. This method has been widely used by wind engineers and researchers for the estimation of peak wind pressure values. Holmes (1983) used this peak estimation method to determine design wind pressures on a 5-span sawtooth roof model. However, that paper did not indicate how many test runs were used to obtain the average peak values.

In another experiment, Saathoff and Stathopoulos (1992a) obtained the estimates of peak wind pressure coefficients in critical suction regions (corners) by averaging the peaks of ten 16-s pressure samples.

2.1.2 Extrapolation Method

The peak pressure value occurring during one wind tunnel run not only depends upon the upstream wind flow, building geometric information, pressure tap location on the model but also upon pressure sampling length. The probability of a larger peak value occurrence is higher for the wind tunnel run with longer sampling time. This extrapolation method (2004, Geurts et al.) is based on the assumption that the peak value and sampling time follow a theoretical relationship which can be analyzed by dealing with peaks of sub-records with varying sampling length. The peak value for a whole record is obtained by extrapolating the peaks of sub-records using the analyzed relationship function between peak value and sample length. Since the direct peak value for whole record is unstable, this method is used to increase the stability of the peak estimation.

2.1.3 Lieblein BLUE Method

A statistical average peak value estimation method was applied by Kopp et al. (2005) in which wind pressures were sampled on the 1:50 scale building model for 120 seconds at a rate of 400 samples per second. Kopp et al. instead of using the absolute peak pressure coefficient recorded within the sample period, they used the Lieblein-BLUE fitted statistical peak value (Lieblein, 1974). The Lieblein-Blue procedure is used for estimating the two parameters (shape parameter and scale parameter) of a Type I extreme value distribution. For small group samples (samples numbering less than or equal to 16), Lieblein provided the coefficients of Best Linear Unbiased Estimators (BLUE) for Type I Extreme-Value Distribution in his report. Kopp et al. undoubtedly assumed that the peak value of wind pressure time series follows the Type I extreme value distribution. They divided the recorded time series into ten equal segments and arranged the 10 peaks of these segement in ascending order. The expected wind pressure coefficient was the sum of these ten peaks weighted by corresponding Lieblein BLUE coefficients. The method makes more statistical sense than the averaging direct peak method.

2.2 Wind Pressure Coefficients for Monosloped Roofs

2.2.1 Jensen and Franck's Experiments

Jensen and Franck (1965) investigated the influence of the ratio of building width/length/height and of roof slope on the mean wind pressure on monosloped roofs. They used various simulated upstream wind terrains for wind tunnel model tests in a boundary layer wind tunnel with a working section 7.5 m long and 0.6 m square. Their study showed that the mean wind pressure distributions were affected by roof slope and the ratio of width/length/height. The model roof slopes ranged between 6^o to 15^o. The extreme mean wind suction coefficient occurred on the building with roof slope 15^o at an oblique cornering wind direction under open country exposure. However, since peak pressures were not measured in the study, these results cannot be used in developing wind load specifications for monosloped roofs.

2.2.2 UWO Wind Tunnel Experiments

Wind tunnel experiments were conducted at the University of Western Ontario (UWO) to investigate the effects of roof slope, building height and terrain exposure on the wind pressures occurring on monosloped roof buildings (Surry and Stathopoulos, 1985). The tests used 1:500 scale monosloped roof models constructed with plan dimensions of 100 mm by 40 mm and low eave heights of 10 mm and 15 mm. The model's roof angle was adjusted in the range of 0^o to 18.4^o. There were 78 pressure taps installed on the model roof with smallest tributary area being 18 m^2 at full scale as shown in Fig. 2.1. The wind tunnel was used to simulate 1:500 scale open country and suburban terrain velocity profiles. The results included the local and area-averaged wind pressures coefficients for seven wind directions (0^o, 40^o, 60^o, 90^o, 120^o, 140^o and 180^o). The model's dimensions and wind directions are shown in Fig. 2.2, where 0^o represents wind blowing perpendicularly to the higher edge.

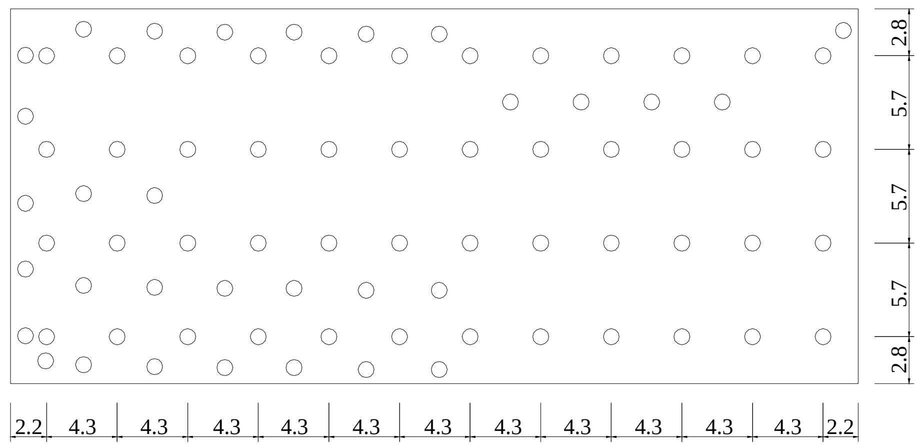


Figure 2.1 Taps on Roof of UWO Model (Full Scale; unit: m)

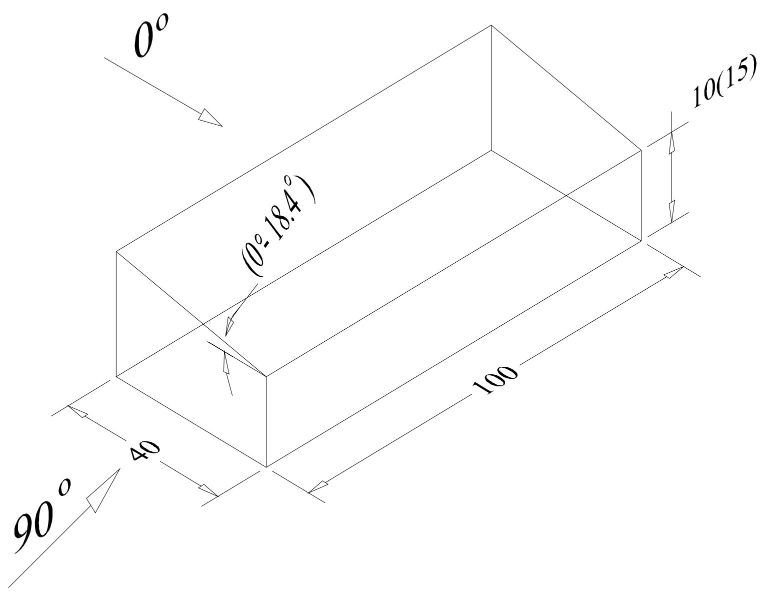


Figure 2.2 Dimensions of UWO Monosloped Roof Model and Test Wind Directions (Unit: mm)

This study indicated that rougher terrain led to similar or slightly smaller peak loads and much lower mean loads on monosloped roofs. For buildings with the same low eave height, higher suction occurred on the building with a larger roof slope angle. For example, the most critical wind suction coefficients, referenced to mean wind speed at gradient height in open terrain, for a building with roof angle 18.4^{o} exceeded the value for flat roof by 85% (-1.84 versus -0.99).

The study also proved that averaging area played a strong role in wind pressure coefficients. Area-averaged pressure coefficients had sharply reduced values compared with local or point pressure coefficients. The difference between the local and area-averaged wind pressure coefficients with a tributary area of 74 m^2 was more than 40% in the critical suction zone (high corner).

By comparing wind pressure coefficients for monosloped roofs and gable roofs, Surry and Stathopoulos found that the most critical wind pressure coefficients for monosloped roofs were slightly higher than those for gable roofs. The extreme wind pressure coefficient with a tributary area of 74 m^2 occurring on the 7.62 m high, 1:12 roof slope monosloped roof under open country exposure was -2.75. The extreme value for a gable roof building with a similar height and roof slope was -2.60. Here the wind pressure coefficients were referenced to the mean wind speed at the mid-roof height.

The UWO research results showed that the worst negative wind pressure coefficients came from quartering winds (wind direction 45^{o}) onto the high eave corners. It was also demonstrated that the effect of roof slope on wind suction coefficients varied depending on the pressure zone location on the roof. Pressure taps on the low side of the roof showed that peak suctions decreased with increasing roof slope. However, pressure taps near the high edge of the roof showed monotonically increasing suctions with increasing roof slope. The extreme negative wind pressure coefficient always occurred at the high corner of monosloped roofs. While little difference was found in wind pressure coefficients between flat and 1:12 roofs, there was a large increase in wind pressure coefficients from the 2:12 to the 4:12 roof slope. Table 2.1 presents the peak negative wind pressure coefficients for various monosloped roofs in open terrain exposure. The pressure coefficients in Table 2.1 were referenced to the mean gradient wind pressure.

Table 2.1 Extreme Wind Pressure Coefficients for Monosloped Roofs in Open Terrain

Building Height	7.62 m (Full Scale)				
Roof Slope	flat	1:24	1:12	2:12	4:12
Extreme wind pressure coefficient	-1.01	-1.01	-1.16	-1.25	-1.84
Note: The wind pressure coefficients are referenced to the mean wind speed at gradient height in open terrain					

2.2.3 Concordia University Wind Tunnel Experiments

Stathopoulos and Mohammadian (1985[a,b]) conducted wind tunnel tests on a 1:200 scale monosloped roof models and previously tested 1:500 scale UWO model described above. The tests were conducted at the boundary layer wind tunnel of the Centre for Building Studies Laboratory (CBS) at Concordia

University. The Concordia model and pressure tap arrangement are shown in Fig. 2.3. The Concordia model had a constant roof slope of 4.8 degrees and overall full-scale dimensions of of 61 m in length by 12.2 m and 24.4 m widths resepctively. The full scale heights to the low eaves were 3.66 m, 7.62 m, or 12.20 m. Wind pressures on the models were measured in simulated open country exposure, having a power law exponent of 0.15 for eight wind directions, 0^o, 30^o, 45^o, 60^o, 90^o, 120^o, 150^o and 180^o, where 0^o degree indicated wind blew perpendicular to the lower eave. Wind pressure coefficients were referenced to the mean wind pressure at mean roof height.

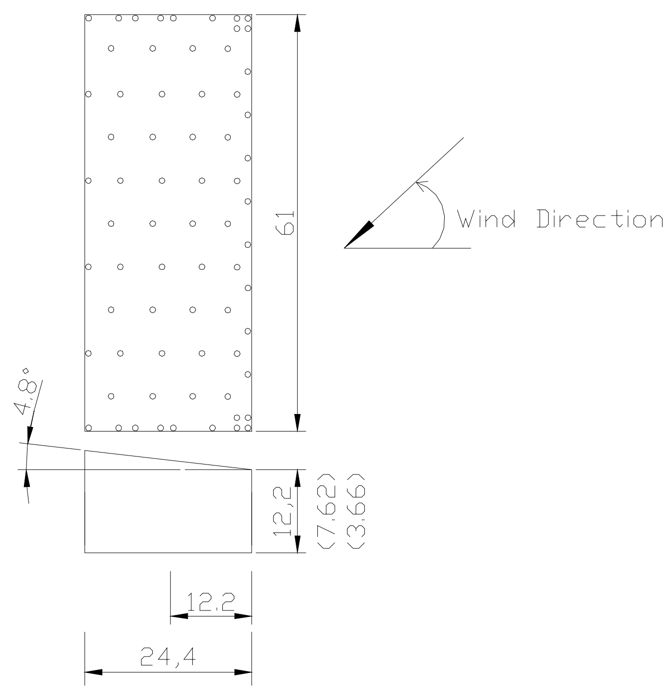


Figure 2.3 Concordia Basic Model and Pressure Tap Arrangement
(Full Scale, unit: m)

Stathopoulos and Mohammadian also investigated the averaging area effect on wind pressure coefficients for the Concordia models. The averaging area at full scale was 74.4 m^2 which was 1/20 of the whole roof area of the 24.40 m wide model and 1/10 of the 12.20 m wide model. The tested full scale model heights were 3.66 m, 7.62 m for both narrow and wide model and 12.2 m only for narrow model.

Stathopoulos and Mohammadian investigated the influence of roof slope, aspect ratio (width/length), building height and wind direction on the wind pressure coefficients. These pressure coefficients in their report were referenced to the mean wind pressure at the low eave height of the building. They concluded that, although the wind pressure coefficients for the monosloped roofs were referenced to the mean wind pressure at the building height, building height still affected those pressure coefficients, particularly for roof corner points and for critical wind directions. Test results showed that the mean and peak wind pressure coefficients on monosloped roofs, increased as the height increased for critical wind directions.

The building height effect on area-averaged wind pressure coefficients showed different characteristics from the effect on local wind pressure coefficients. It was found that area-averaged wind pressure coefficients for the higher building were not always higher than those for the lower building. The extreme area-averaged wind pressure coefficient for the 7.62 m model was higher than the values for the models with 3.66 m and 12.2 m low eave height models. The most critical area-averaged wind pressure coefficient for the 12.2 m wide monosloped roofs was -3.92 which occurred on the 7.62 m high model, and the critical values for the 3.66 m high and 12.2 m high models were -3.11 and -3.60 respectively.

The extreme local and area-averaged wind pressure coefficients for the 24.4 m wide monosloped roof were higher than the comparable values for the 12.2 m wide monosloped roof with similar building height and roof angle. The critical local wind pressure coefficients for the 24.4 m and 12.2 m wide monosloped roofs were -7.14 and -6.30 respectively. The critical area-averaged wind pressure coefficient with a tributary area of 74.4 m^2 for the 24.4 m wide monosloped roof was -4.19 compared to the value of -3.92 for the 12.2 m wide one. Table 2.2 shows the critical wind pressure coefficients for Concordia models.

Table 2.2 Critical Wind Pressure Coefficients for Concordia Models

Model (roof slope, length/width, height)	High Corner		Low Corner	
	Local Cp	Area Cp	Local Cp	Area Cp
Wide Model (24.4 m)				
4.8^o, 24.4 / 61,12.2	-6.1		-5.15	
4.8^o, 24.4 / 61, 7.62	-5.7	-4.19		-2.05
4.8^o, 24.4 / 61, 3.66	-4.95	-3.67		-1.85
Narrow Model (12.2 m)				
4.8^o, 12.2 / 61 ,12.2	-6.30	-3.60	-4.77	-1.70
4.8^o, 12.2 / 61 ,7.62	-5.6	-3.92		-2.33
4.8^o, 12.2 / 61 ,6.1	-4.9			
4.8^o, 12.2 / 61 ,3.66	-3.7	-3.11		-2.73
Note: wind pressure coefficients were referenced to mean wind pressure at building height.				

The lower suctions generally occurred between azimuth angles of 0^o and 90^o. Critical wind directions for high suction ranged between 130^o and

150^{o}. The roof slope effect on the peak and mean wind pressure coefficients for varying regions of monosloped roof are summarized below.

- Mean negative wind pressure coefficients decreased at the lower eave and increased at the ridge with increasing roof slope.
- The peak wind pressure coefficients for the low eave were unaffected by roof slope. However, the peak wind pressure coefficients for the high ridge increased with the increasing roof slope.
- Wall suction appeared unaffected by the roof slope.

2.2.4 Previous Recommendations for ASCE 7 Provisions

Surry and Stathopoulos (1985) reviewed papers of previous research results for wind loads on low buildings with monosloped roof, and specifically compared wind pressure coefficients for monosloped roofs with those for gable roofs with similar roof angles. Their review yielded the following conclusions:

- Local positive wind pressure coefficients were consistent with those found for gable-roofed buildings having similar roof slopes.
- Local negative wind pressure coefficients on monosloped roof followed distinctly different trends from those of gable roofs. The area and boundary of wind pressure zones on monosloped roofs differed from the pressure zones for gable roofs. The wind suction, occurring at the high corner of monosloped roofs, was significantly higher than at the low corner.

- Area-averaged wind pressure coefficients with a large tributary area, such as 74 m^2, for monosloped roofs were consistent with those measured on gable roofs, although they did tend to be slightly larger.
- Roof slope had a significant effect on wind pressure coefficients for monosloped roofs. Different values were recommended for 0^o ~ 10^o slope and 10^o ~ 30^o slope monosloped roofs.
- The effect of terrain roughness on monosloped roofs was similar to that on gable roofs. Rougher terrain generally gives lower wind loads.

Finally, Surry and Stathopoulos (1985) provided recommendations of wind pressure coefficients for monosloped roofs. They sorted monosloped roofs into two categories based on roof angles. The monosloped roofs with roof angles between 0^o to 10^o have identical wind pressure coefficients as well as the monosloped roofs with roof angles between 10^o to 30^o. Two groups of pressure zones (Version 1 and Version 2, as shown in Fig. 2.4 and Fig. 2.5) for monosloped roofs were provided, and associated wind pressure coefficients were recommended based on different pressure zone definitions. The main difference between the two groups of pressure zones lay in the area of the corner. The corner area in Version 1 is larger than that in Version 2. However, the corner zones in both versions defined by Surry and Stathopoulos are larger than the corner zones used on the gable roofs.

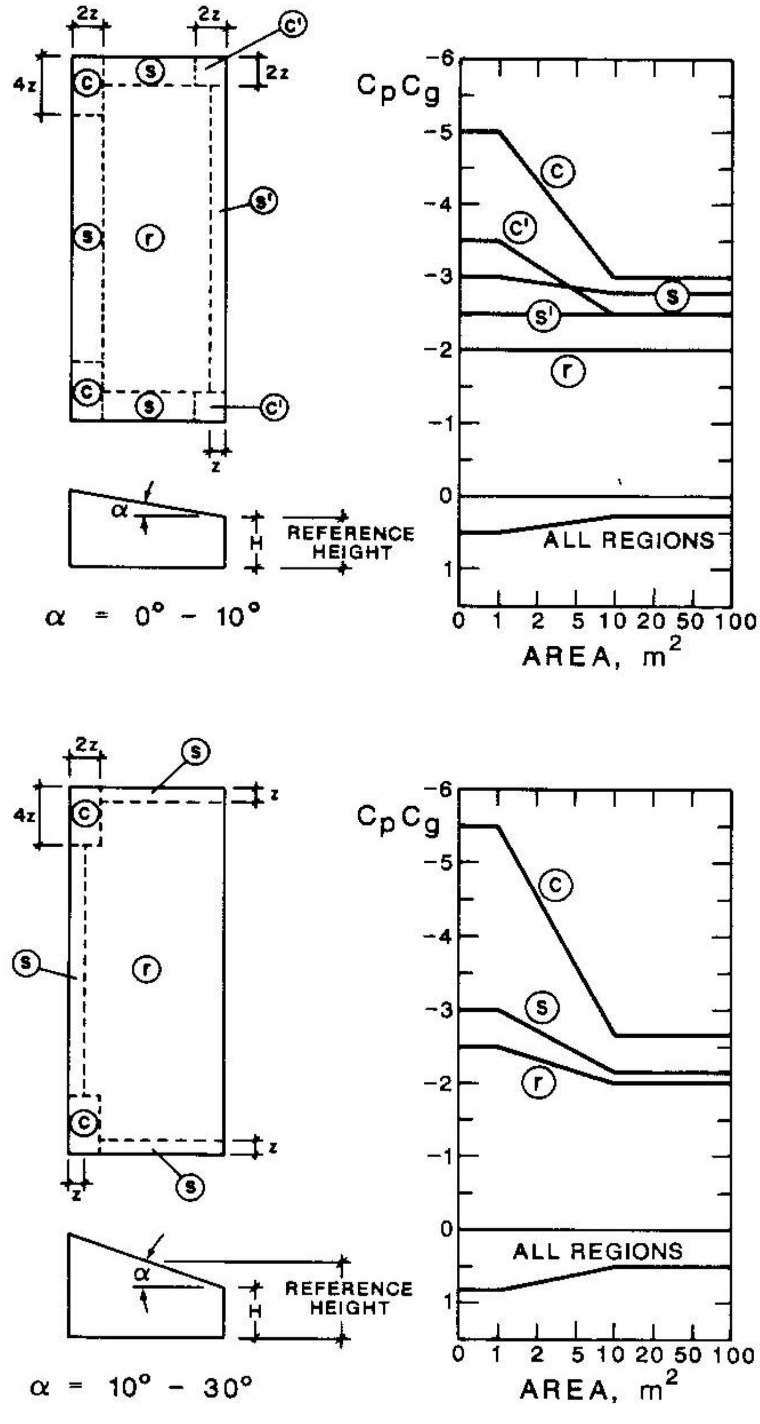


Figure 2.4 Recommendations for Wind Pressure Coefficients for Monosloped Roof – Version 1 (Surry and Stathopoulos, 1985)

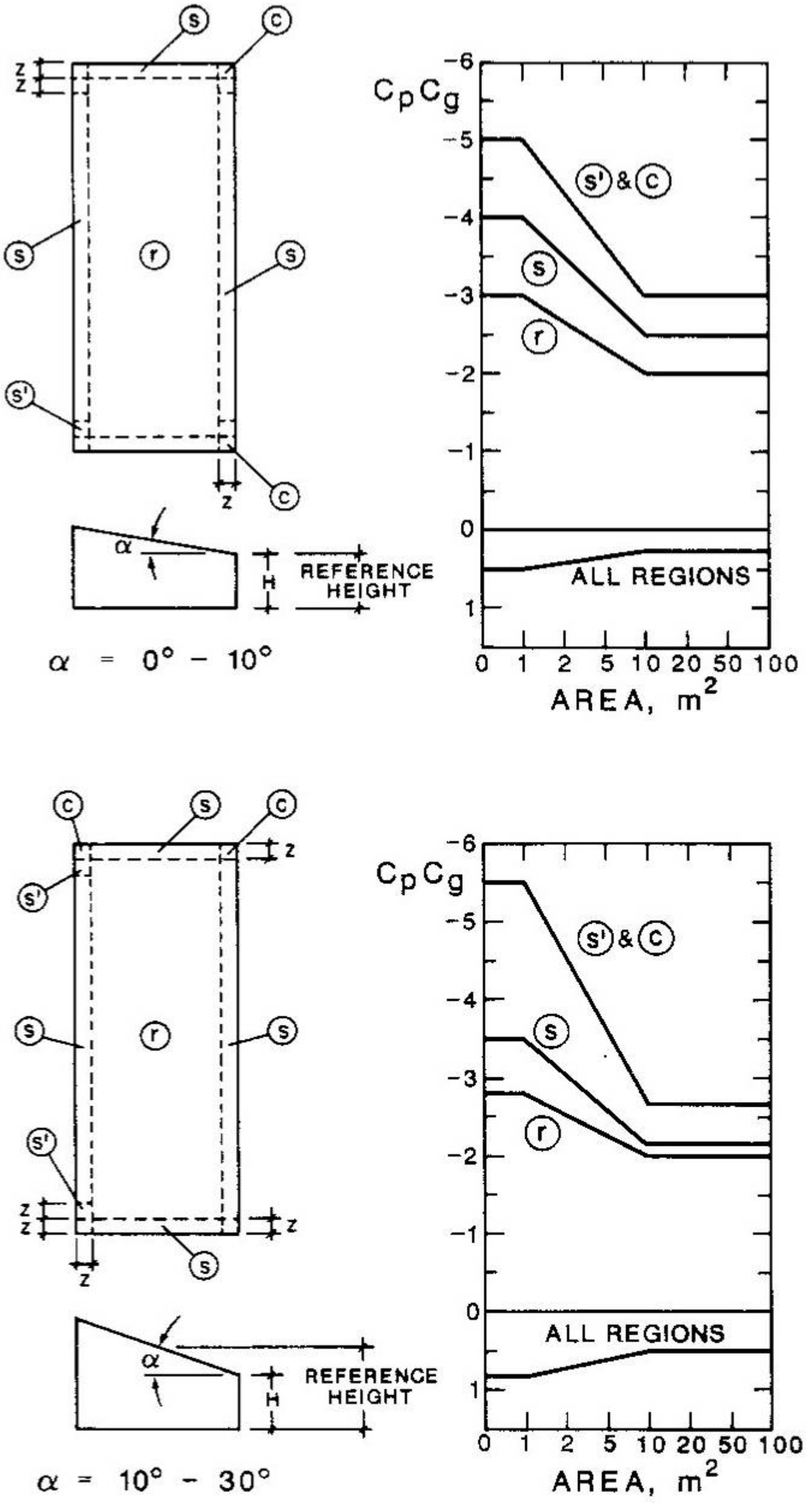


Figure 2.5 Recommendations for Wind Pressure Coefficients for Monosloped Roof – Version 2 (Surry and Stathopoulos, 1985)

2.3 Wind Pressure Coefficients for Sawtooth Roofs

This section reviews the studies of the wind pressure coefficients for sawtooth roof buildings.

2.3.1 Wind Tunnel Tests on a Five-span Sawtooth Roof

Holmes (1983, 1987) investigated local and area-averaged wind pressures on a 5-span sawtooth building with a roof angle of 20°. The building dimensions, illustrated in Fig. 2.6, shows that the single span building has plan dimensions of 39 m long by 12 m wide at full scale. The building low eave height is 9.6 m. Local and area-averaged wind pressures were measured on the 1:200 scaled model under simulated open country exposure in a boundary layer wind tunnel. The turbulence intensity of wind speed for the simulated open country terrain is 0.20 at a height of 9.6 m.

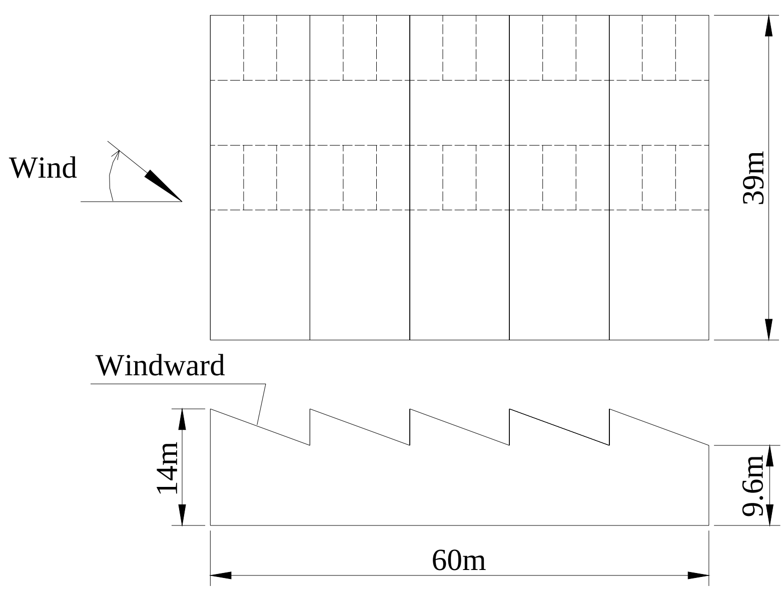


Figure 2.6 Layout and Elevation of Holmes' Sawtooth Model at Full Scale

Local wind pressures were measured for wind directions between 20^o and 60^o at 5^o increments and area-averaged wind pressures were measured for wind directions between 0^o and 360^o at 45^o increments. The non-dimensional pressure coefficients were referenced to mean wind pressure at the eave height in the free stream, away from the influence of the building model. The most extreme local wind pressure coefficient measured by Holmes was -7.6, occurring on the tap most close to the high corner of windward span of the sawtooth roof at wind direction 35^o.

Holmes measured area-averaged wind pressure coefficients using the pneumatic technique for panels on the sawtooth roof model. The panel's locations, shown in Fig. 2.6, can be divided into 6 pressure zones, (e.g. high corner, low corner, sloped edge, high edge, interior and low edge). All panels have an identical area of 31.2 m^2. The extreme area-averaged wind pressure coefficient was -3.86, which occurred on the panel on the high corner of windward span of the sawtooth roof model. This extreme wind pressure coefficient exceeded the values for other area-averaged wind pressure coefficients by at least 46% in magnitude.

Except for the wind pressure coefficient for the panel in the high corner of the windward span, other wind pressure coefficients for the high corner, sloped edge and low edge for all spans of the sawtooth roof ranged from -2.13 to -2.63. Holmes' study showed that the extreme area-averaged wind pressure coefficient for the high edge, low edge and interior zones was -2.24, occurring on the interior panel of the windward span. The wind pressure coefficients for the low edge and interior zones of all roof spans except windward span were substantially lower than those for other zones. The peak wind pressure coefficient for these regions was less than -1.58 in magnitude.

2.3.2 Varying Span Sawtooth Roofs

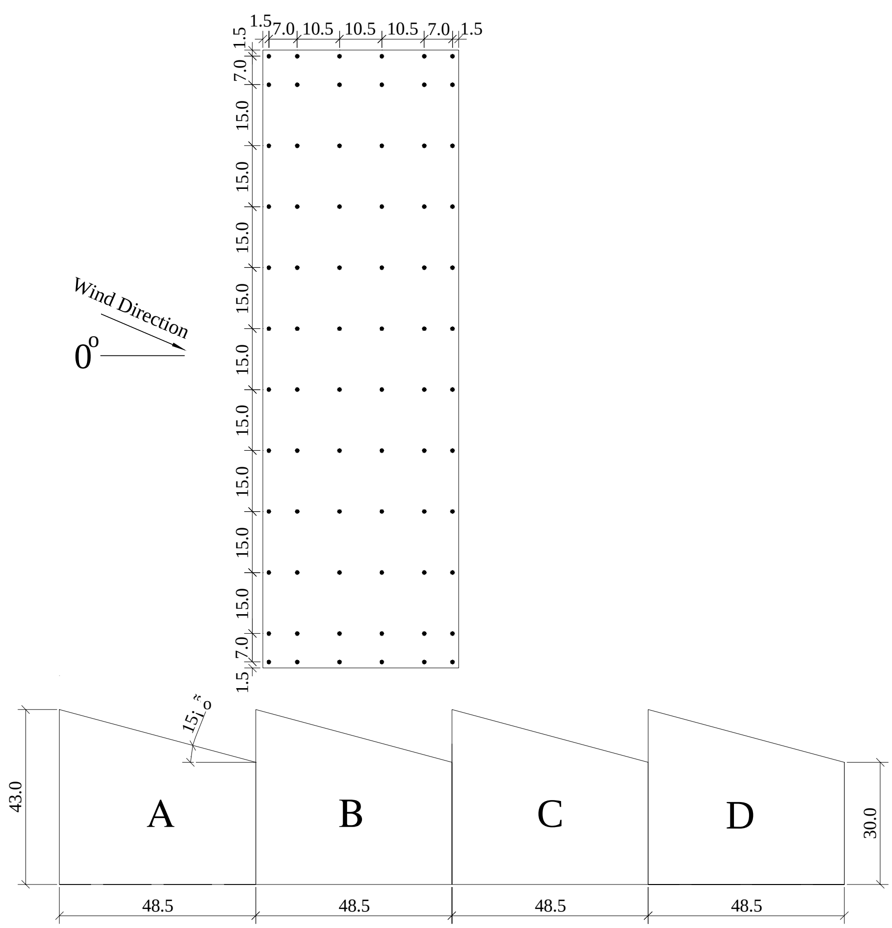


Figure 2.7 Saathoff and Stathopoulos' Model and Tap Arrangement
(Unit: mm; 1:400 Scaled)

Saathoff and Stathopoulos (1992[a,b]) conducted wind tunnel tests on building models with a monosloped roof and 2 and 4 spans sawtooth roofs to investigate wind pressure distributions. The roof slope of all tested models was

15 degrees. Models were at a scale of 1:400 and were exposed to eleven different wind directions with open country boundary layer flow, i.e., 0^o, 30^o ~ 150^o at 15^o increments and 180^o. Fig. 2.7 shows the wind direction corresponding to the configurations of models. Each single-span model had full-scale dimensions of 19.4 m wide, 61 m long and a 12 m height to low eave. Local and area-averaged wind pressures were sampled at a rate of 500 samples per second. Pressure coefficients were obtained from one 16-s sample, and the wind pressure coefficients for pressure taps in the corner zones were obtained by averaging peak values of ten 16-s samples.

Saathoff and Stathopoulos divided the roof into six zones, high corner, sloped edge, low corner, high edge, interior and low edge. The pressure zones are shown in Fig. 2.8. Saathoff and Stathopoulos discussed local and area-averaged wind pressure coefficients on each pressure zone. They concluded that the highest negative wind pressure occurred on the high corner of the monosloped roof model and on the high corner region of the windward span of the two-span and four-span sawtooth roof models. They also observed that the high suction occurred in the low corners of the windward span and in the middle spans of the 4-span sawtooth roof. Suctions on the interior and low edge zones were significantly less than on the other zones. Table 2.3 presents the zonal peak negative wind pressure coefficients obtained from Stathopoulos test results and Holmes' test results.

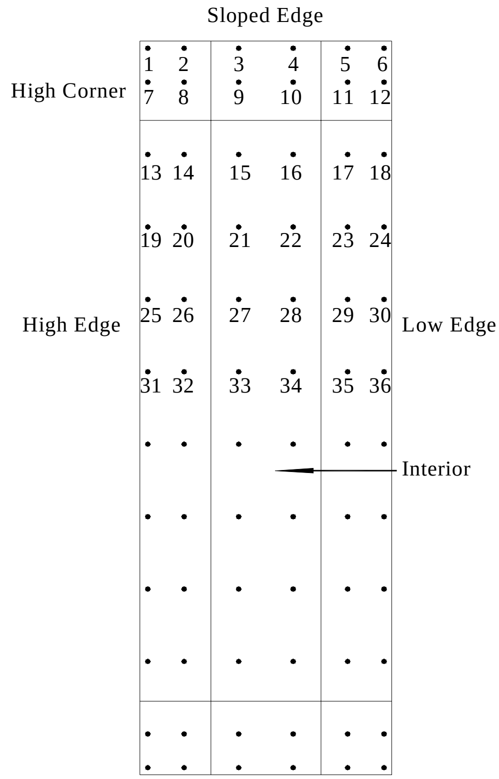


Figure 2.8 Pressure Zones Defined by Saathoff and Stathopoulos

Table 2.3 Local Wind Pressure Coefficients from Saathoff and Stathopoulos' and Holmes' Results

Pressure Zone	Monosloped Roof[1]	Sawtooth Roofs						
		2-span[1]		4-span[1]				5-span[2]
		A	D	A	B	C	D	A
High corner	-9.8	-10.2	-6.4	-10.2	-5.6	-5.5	-4.8	-7.6
Low corner	-4.7	-6.3	-5.3	-7.9	-7.7	-7.3	-6	-5.9
Interior	-3.3	-3.8	-3.2	-4.1			-3.2	/
High edge	-4.2	-6.2	-5.8	-5.5	-4.5	-3.8	-3.6	/
Lowe Edge	-3.2	-3.2	-3.2	-3.7	/	/	-2.9	/
Slope edge	-3.8	-5.1	-4.9	-5.8	-5.4	-4.7	-4.3	/

[1]Saathoff and Stathopoulos' results; [2]Holmes' results;
The pressure coefficients are referenced to mean wind pressure at the low eave height of the building.

The extreme wind pressure coefficient for monosloped roofs or sawtooth roofs always occurs in the high corner. Therefore, the critical wind direction for the most extreme wind pressure coefficient usually occurs at the critical wind direction of the peak wind pressure coefficient in the high corner. The most critical wind pressure coefficient for the monosloped roof occurred at a wind direction of 45. For sawtooth roofs the critical wind direction was between 30^o and 40^o. The extreme area-averaged wind pressure coefficient for the monosloped roof occurred in the high corner at the critical wind direction of 45^o, which was identical to the wind direction for the local extreme value. The critical wind direction for the area-averaged wind pressure coefficient for the sawtooth roofs shifted from 30^o to 45^o. From these measurements, the critical wind direction for the high corner of the monosloped roof and the sawtooth roofs fell in a narrow range. Saathoff and Stathopoulos also investigated the critical wind direction for wind pressure coefficients in the low corner of both the monosloped and sawtooth roofs. They concluded that the critical wind direction for the low corner had a relatively wider range from 60^o to 105^o which is different from that for the high corner of monosloped roofs and sawtooth roofs.

Tributary area also plays an important role in determining wind pressure coefficients. Using the pneumatic technique, Saathoff and Stathopoulos investigated the area-averaged wind pressure coefficients by measuring pressures on panels with a number of tap combinations. Saathoff and Stathopoulos also concluded that the reduction ratio for wind pressure coefficients for the high edge, low edge and interior is less than that for the corners and the sloped edge for the monosloped and sawtooth roofs. The reduction rate of wind pressure coefficient for the high corner from local value to the value with an averaging area of 10 m^2 was less than the reduction rate with tributary area increasing from 10 m^2 to 36 m^2. For the most critical wind pressure coefficient on the sawtooth roofs, the local pressure coefficient exceeded the 10 m^2 area-averaged pressure coefficients by 10%. However, the local wind pressure coefficient exceeded the 36 m^2 area-averaged wind pressure coefficient by 40%.

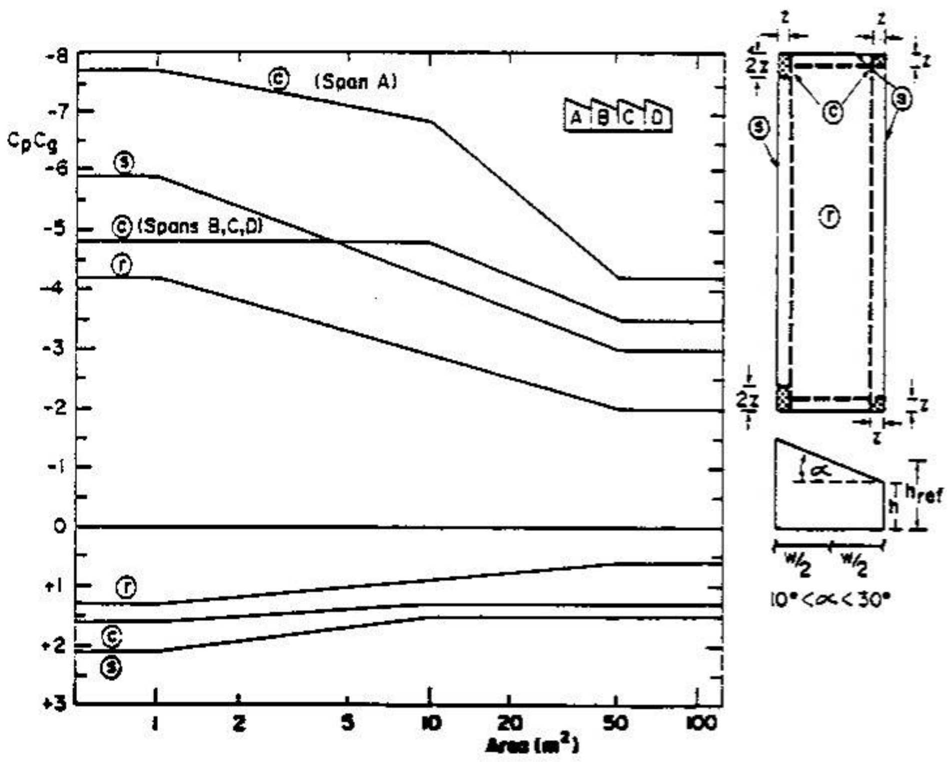


Figure 2.9 Proposed Design Pressure Coefficients for Sawtooth Roofs by Saathoff and Stathopoulos

Saathoff and Stathopoulos (1992b) proposed design wind pressure coefficients based on their study on wind effects on sawtooth roofs as shown in Fig. 2.9. In their recommendation, pressure coefficients are based on the mean wind speed at the mean roof height. The characteristic length *z* is defined as the less value of 10% of the least horizontal dimension, or 40% of building height, and z is larger or equal to 1 m and not less than 4% of least horizontal dimension. The results of Saathoff's and Stathopoulos' study were incorporated into the 1995 ASCE-7 and in subsequent revised editions of ASCE-7.

2.3.3 Comparisons of Previous Research Results and ASCE 7 Provisions

As mentioned above after 1995, ASCE-7 used Saathoff and Stathopoulos' results as a major reference for design wind pressure coefficients for sawtooth roofs. Fig. 2.10 presents the ASCE 7-02 wind pressure coefficients for sawtooth roofs, in which the wind pressure coefficients are referenced to the three-second gust wind speed at mean roof height. It is worth noting that in Fig. 2.9 the wind pressure coefficients are referenced to the mean wind speed at the mean roof height. A comparison of these two figures revealed that the pressure zones defined by Saathoff and Stathopoulos were adopted in the ASCE 7-02 building design standard. The wind pressure coefficients in the ASCE 7-02 were also determined based on Stathopoulos' values by multiplying by an adjustment factor which is approximately 0.54.

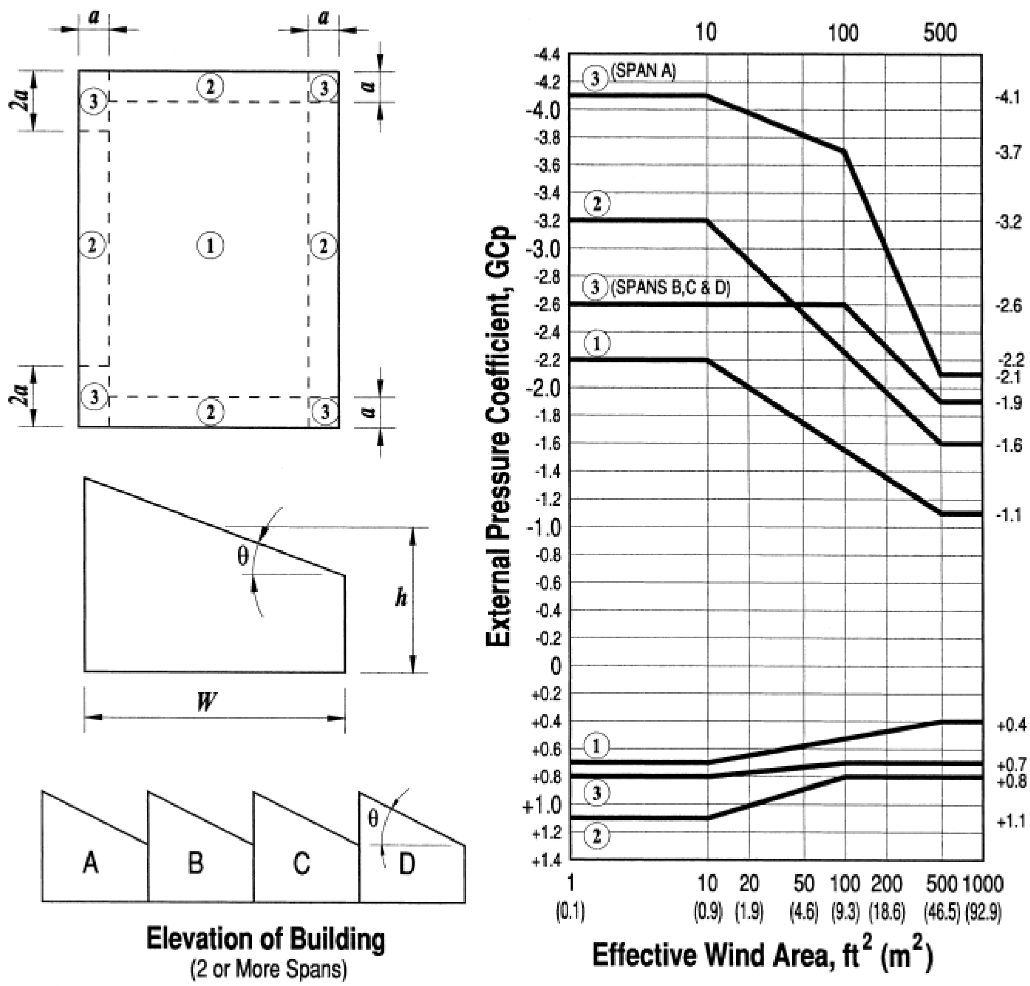


Figure 2.10 ASCE 7-02 Design Wind Pressure Coefficients for Sawtooth Roofs

CHAPTER 3

WIND TUNNEL TESTS

Wind tunnel tests were performed for monosloped and sawtooth roofs at Clemson University's Wind Load Test Facility (WLTF). This chapter briefly introduces the wind tunnel utility at WLTF. Simulated terrains including open country and suburban terrains applying for wind tunnel tests are introduced. The wind tunnel test set up, construction of scaled models and test cases are introduced as well.

3.1 Boundary Layer Wind Tunnel

Clemson University's Wind Load Test Facility houses an open return boundary layer wind tunnel powered by two 1.8 m diameter fans, controlled by a variable frequency drive. The wind tunnel consists of settling chamber, contraction cone, and a test section. The settling chamber and contraction are used to produce wind flow that is nearly uniform across the tunnel and with low turbulence intensity. The test section of the wind tunnel is 3 m wide, 2.1 m tall and 18 m long. Wind tunnel elements such as trip plates and spires are set up at the entrance to the test section, and slant boards and roughness boards are arranged along the test section to initiate the growth of a thick atmospheric boundary layer. Models are mounted on the 2.7 m diameter turntable which can rotate a full 360^{o} to enable the models to be tested for any desired wind direction.

Pressure data are collected from each model pressure tap location using an electronic Scanivalve pressure scanner system. The base of this pressure scanning system holds eight scanner units; each unit, or module, can hold 64 data channels. Because this pressure scanning system can sample pressure data for 512 channels during one wind tunnel run, it is possible to increase the efficiency of the wind tunnel test by simply installing as many pressure taps as necessary. In fact, the number of pressure taps installed on a residential building model during any given test rarely exceeds 500. Even for a 1:50 scaled residential building model, 500 pressure taps can ensure the necessary resolution to observe the extreme wind pressure occurring on the model. Therefore this system is more than adequate for ensuring that accurate wind tunnel measurements can be taken on respective residential building models during a wind tunnel run.

A reference Pitot tube stationed near the top of the wind tunnel is used to provide reference static and dynamic pressures for normalizing the pressures measured on the model surface. At this reference height, the highest wind speed occurs in the wind tunnel and the wind speed will be unaffected by the tested models. The mean wind pressure measured by the reference channel connected to Pitot tube is a standard velocity pressure, which enables a good comparison of pressure coefficients from one model to another.

Each test run in the wind tunnel collect data from the pressure taps for a sample period of 120 seconds at a rate of 300 samples per second. Applying this sampling rate to collect wind pressure data enables a stable estimation to the peak wind pressure. It was proved by the observed stable mean wind pressure at the reference height in the wind tunnel.

In this study, test wind pressures are referenced to mean wind pressure measured at a Pitot tube installed at the height of 300 mm below the tunnel ceiling. However, the design pressure coefficients provided by ASCE-7 are referenced to the three-second gust wind speed at the mean height of the roof. In order to compare the test wind pressure coefficients with those provided in ASCE-7, an adjustment factor is needed to convert the test wind pressure coefficients to pressure coefficients referenced to the 3-second gust wind speed at mean roof height of the model. The ratios between mean wind speeds at the reference Pitot location and the 3-second gust wind speed at the mean roof height are used to calculate the adjustment factor between test wind pressure coefficients and ASCE values. This adjustment factor is presented in Section 4.4.2 below.

Most wind speed measurements are made using a wind speed data acquisition system consisting of a hot film anemometer and computer aided data acquisition system. The system is used to measure both wind speed and turbulence intensity at any height above ground by adjusting the hot film position. The wind speed is usually sampled at a rate of 2000 samples per second for 60 seconds at every chosen height above ground to determine the wind speed and turbulence intensity profiles.

3.2 Simulated Terrains

In order to determine the effects of terrain roughness on wind pressure coefficients open country and suburban terrains are simulated by combining various sizes of roughness elements, spires and trip boards within the wind tunnel test section. Fig. 3.1 and 3.2 show the roughness elements used to develop the wind profiles for the open terrain and suburban terrain applied in the tests. Details of the wind tunnel arrangement for two simulated terrains are shown in Fig. 3.3 ~ Fig. 3.4.

Figure 3.1 1:100 Open Country Terrain

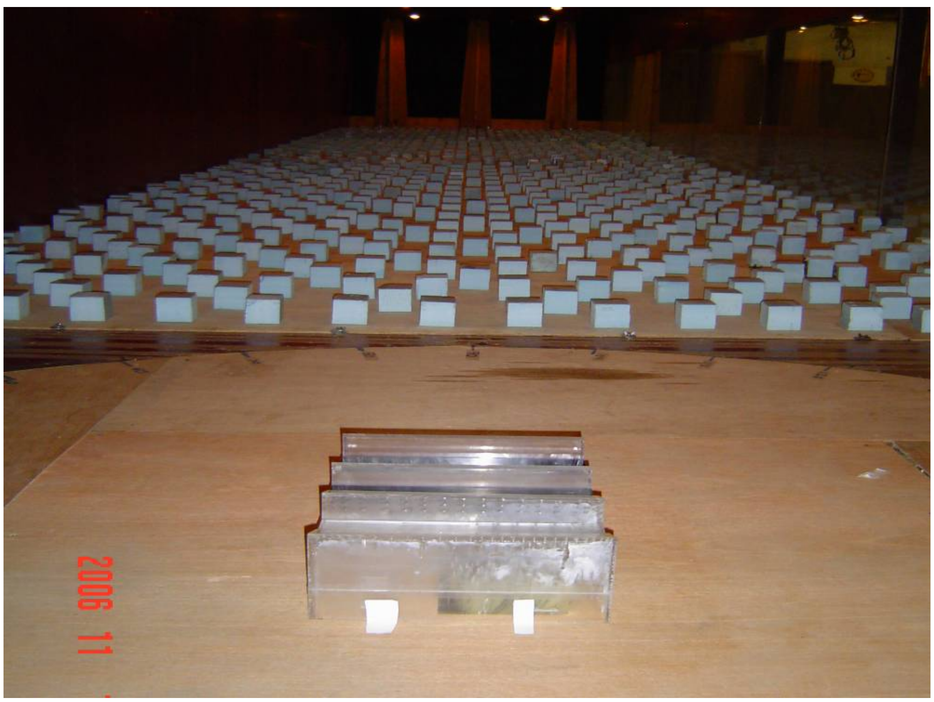
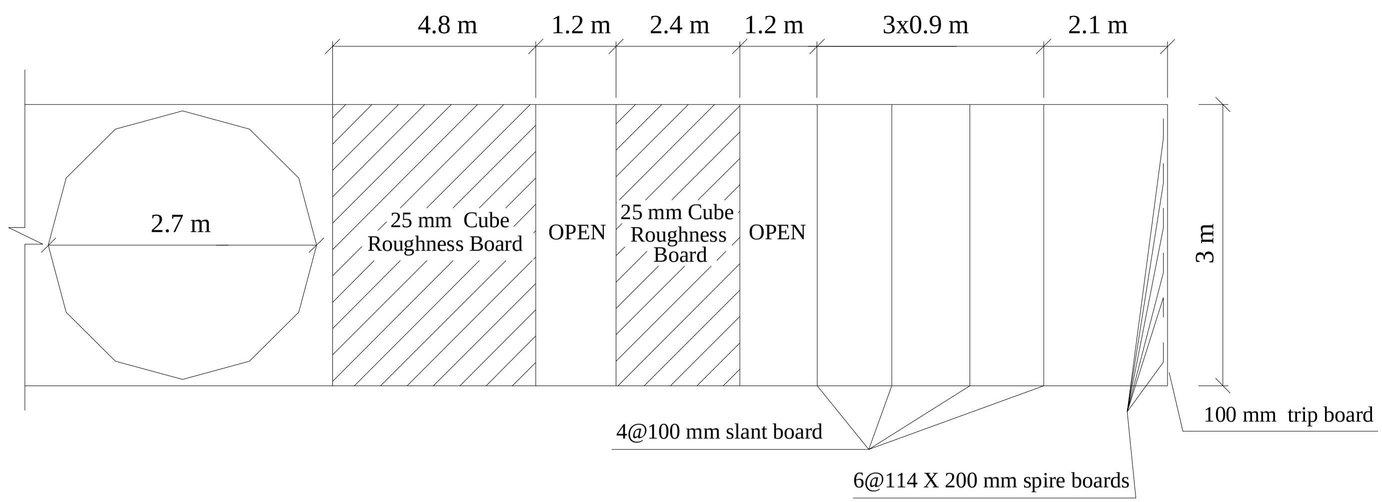


Figure 3.2 1:100 Classic Suburban (Smooth Local Terrain)



1:100 Open Country Terrain

Figure 3.3 Wind Tunnel Arrangement for 1:100 Open Country

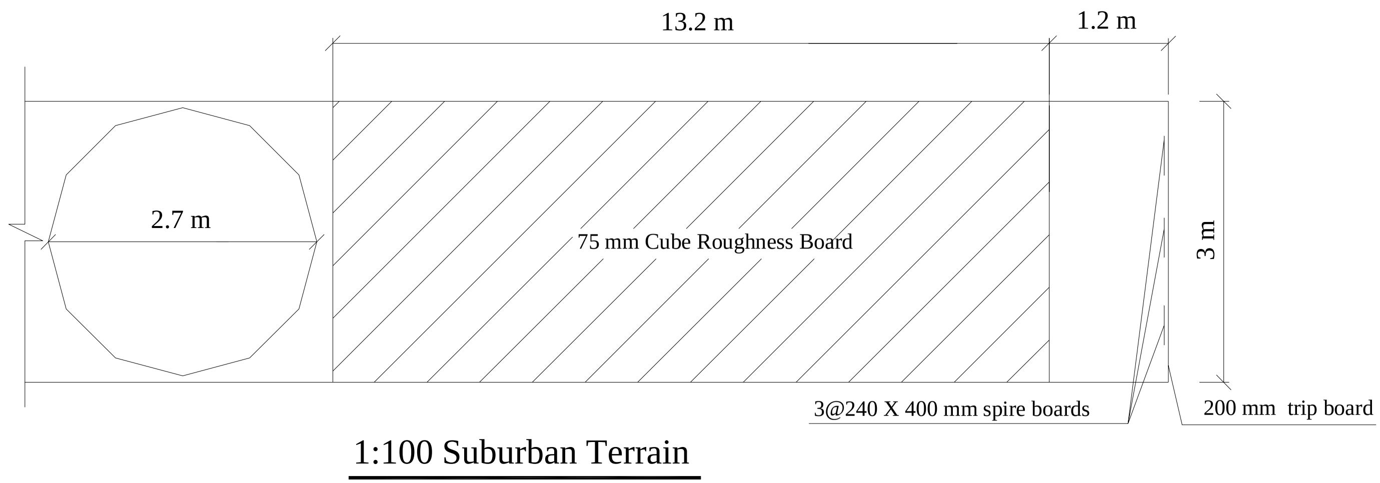


Figure 3.4 Wind Tunnel Arrangement for 1:100 Suburban

The effect of near field roughness on wind pressures are investigated by including local roughness elements and surrounding house models on the turntable around the test model. The modified suburban terrain (Fig. 3.5) is used in order to evaluate the effect of small roughness changes on wind pressures in the immediate vicinity of the building. The wind field near the test building was changed by using different arrangements of randomly distributed 25 mm high wood blocks. Fig. 3.6 shows the detail arrangement of turntable roughness board in the wind tunnel for the modified suburban terrain.

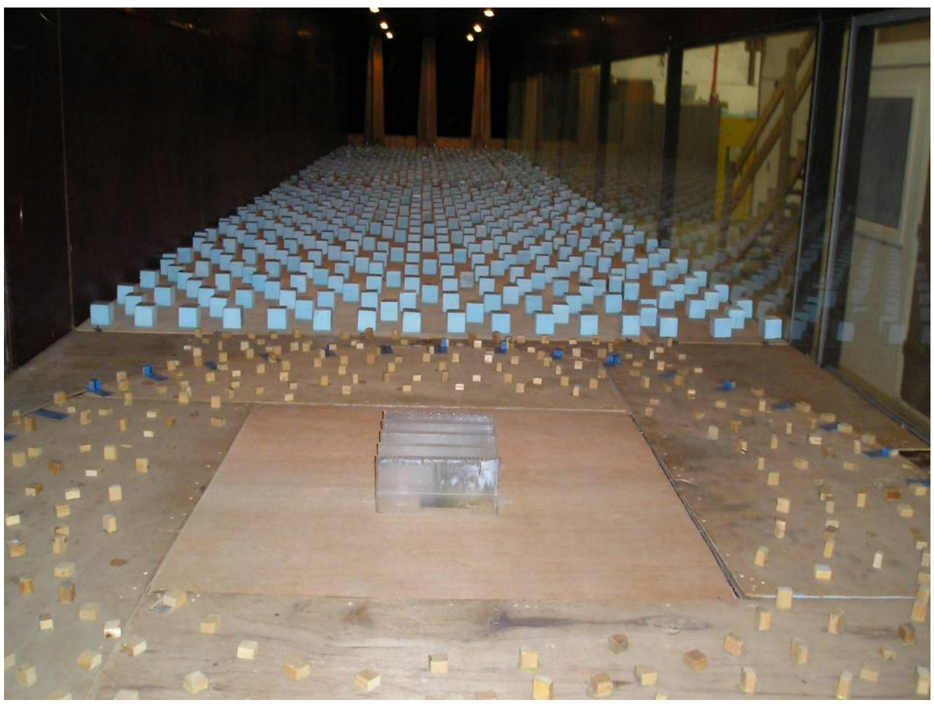
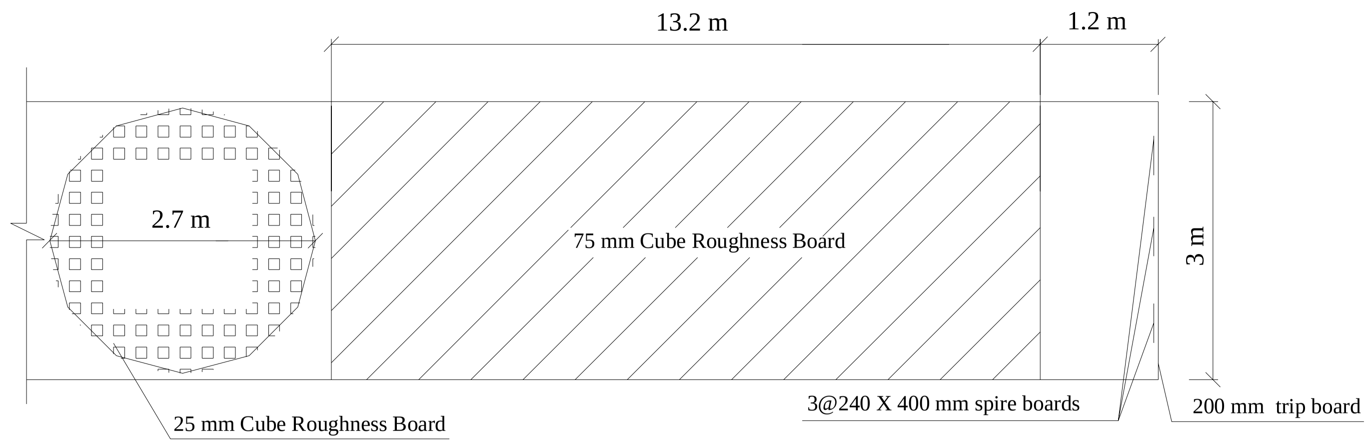


Figure 3.5 1:100 Modified Suburban (Rough Local Terrain)



1:100 Modified Suburban Terrain

Figure 3.6 Wind Tunnel Arrangement for 1:100 Modified Suburban

Fig. 3.7 shows the arrangement of the surrounding house models around the test model. These surrounding houses have similar sizes with the test models and are uniformly arranged around the test building.

Figure 3.7 Test Model with Surrounding Residential Houses

3.3 Wind Profiles for Simulated Terrains

Wind speeds at a series of heights ranging from full scale 2 m ~ 100 m above ground were measured for the open country, classic suburban and modified suburban terrains. The wind speeds at the reference height of full scale 180 m were also measured for these three terrains. Table 3.1 shows measured wind speeds, turbulence intensities (Urms/U).

Table 3.1 Measured Wind Speeds and Turbulence Intensities

Terrain	Open Country		Classic Suburban		Modified Suburban	
Height (m) Full Scale	U (m/s)	Urms/U	U (m/s)	Urms/U	U (m/s)	Urms/U
2.5	7.1	0.19	5.5	0.29	5.5	0.30
5.1	7.6	0.18	6.0	0.27	5.8	0.30
7.6	7.9	0.18	6.5	0.28	6.4	0.29
10.2	8.3	0.19	6.7	0.27	6.7	0.30
12.7	8.5	0.17	7.1	0.26	7.2	0.27
15.2	8.7	0.18	7.2	0.27	7.6	0.27
20.3	9.1	0.18	7.8	0.27	8.1	0.25
25.4	9.6	0.16	8.6	0.22	8.3	0.24
30.5	9.9	0.15	8.6	0.23	9.0	0.21
35.6	/	/	9.1	0.22	9.2	0.21
38.1	10.0	0.15	/	/	/	/
40.6	/	/	9.6	0.19	9.4	0.19
50.8	10.6	0.14	9.9	0.18	10.1	0.18
63.5	11.1	0.13	10.5	0.16	10.6	0.17
76.2	11.3	0.13	10.9	0.16	11.1	0.15
88.9	11.9	0.12	11.3	0.14	11.3	0.14
101.6	12.3	0.10	11.6	0.14	11.7	0.13
180	13	0.05	13	0.08	13	0.08

The measured wind speeds are normalized to non-dimensional values by reference to the measured wind speed at the full scale height of 10 m for each simulated terrain. The function between the normalized wind speeds and the heights can be determined by a logarithmic profile as shown in Eq. 3.1.,

$$\frac{\overline{U}_z}{\overline{U}_{ref}} = \frac{\log_e\left(\frac{z}{z_0}\right)}{\log_e\left(\frac{z_{ref}}{z_0}\right)} \tag{3.1}$$

where z_0 denotes the roughness length of the surface; $\overline{U}_z$ denotes the mean wind speed at height z m above ground; $\overline{U}_{ref}$ denotes the mean wind speed at the reference height z_{ref}. Here, the reference wind speed is defined as the wind speed at 10 m above ground. For a given z_0, the calculated wind speeds for each height can be determined based on Eq. 3.1. By comparing the calculated wind speed profile and the measured wind speed profile, the sum of difference square between the two sets of wind speeds can be calculated. By trying a series of z_0 values in the given range, a series of sums of wind speed difference square are obtained. The z_0 with the least square sum is the best fit roughness length for the simulated terrain. The ASCE 7-02 recommended typical roughness length for open country terrain is 0.02 m with acceptable values ranging between 0.01 m and 0.15 m. The recommended typical roughness length for suburban exposure is 0.3 m with a range from 0.15 m to 0.7 m. So the trial z_0 values can be chosen in the range of these roughness length ranges for open country and suburban terrains. The best fit roughness lengths for the simulated terrains are determined based on the above mentioned procedures. Table 3.2 shows the best fit roughness lengths, the ASCE 7-02 recommended roughness length limitations and the referenced wind speeds for the open country, classic suburban and modified suburban terrains.

The power law profiles are described by the following equation Eq. 3.2.

$$\frac{\overline{U}_z}{\overline{U}_{ref}} = \left(\frac{z}{z_{ref}} \right)^{\alpha} \tag{3.2}$$

α is the power-law constant. The wind speed at the height of 10 m is also determined as the reference wind speed. Based on the least square method mentioned above, by trying a series of α values, the power-law constants for the three simulated terrains were also obtained as shown in Table 3.2.

Table 3.2 Roughness Lengths and Power-law Constants for Measured Wind Profiles

Terrain	Open Country	Classic Suburban	Modified Suburban
Best Fit Test Roughness Length	0.036 m	0.42 m	0.42 m
Best Fit Test Power-law α	0.15	0.25	0.25
ASCE 7-02 Typical Roughness Length (m)	0.02	0.3	0.3
ASCE 7-02 Roughness Length Limitation (m)	0.01 ~ 0.15	0.15 ~ 0.7	0.15 ~ 0.7
Reference Wind Speed at 10 m (m/s)	8.3	6.7	6.7

Fig. 3.8 ~ Fig. 3.10 show the wind speed and turbulence intensity profiles for the three simulated terrains, in which the Log-Law wind speeds are calculated based on the best fit roughness length and measured wind speed at the height of 10 m.

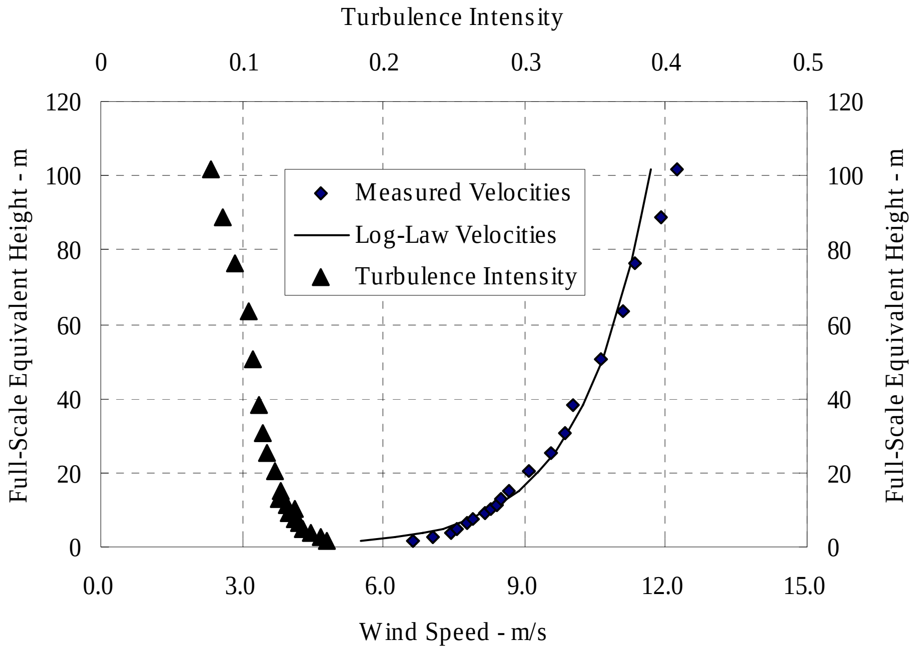


Figure 3.8 Wind Speed and Turbulence Intensity Profiles for Open Country

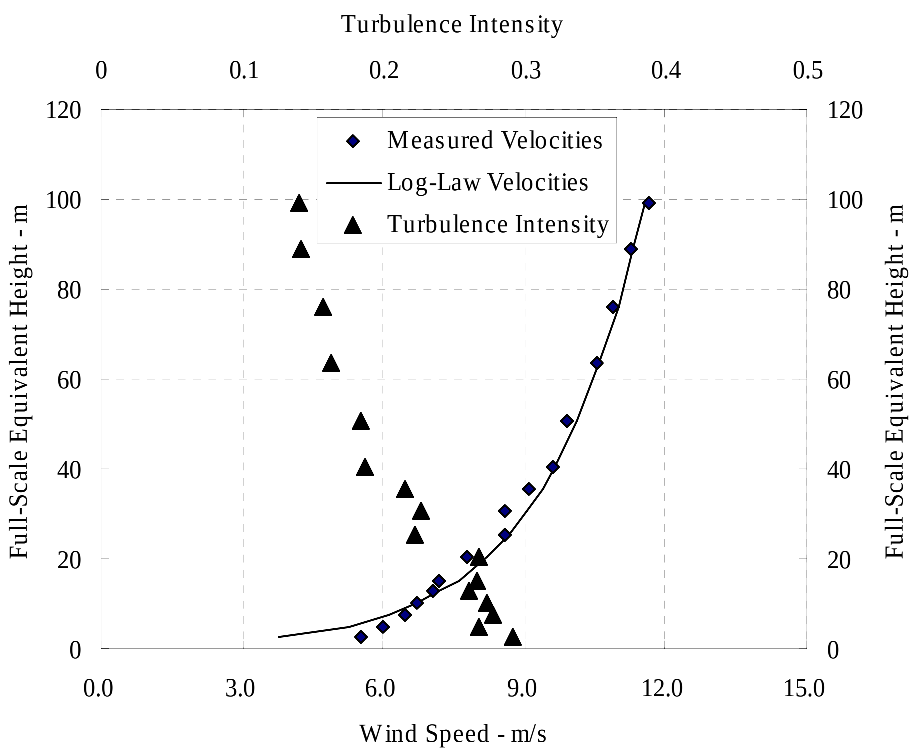


Figure 3.9 Wind Speed and Turbulence Intensity Profiles for Classic Suburban

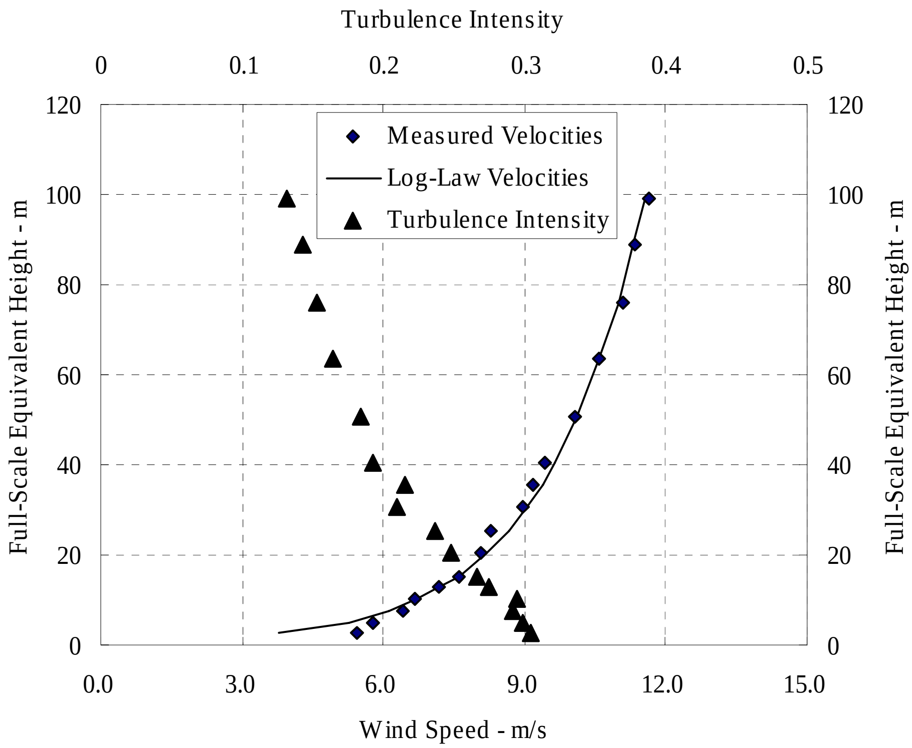


Figure 3.10 Wind Speed and Turbulence Intensity Profiles for Modified Suburban

A comparison of the suburban and modified suburban wind velocity profiles illustrates the effect of the small roughness elements placed on the turntable around the building on the wind speed profile. The wind speed profiles for both terrains are essentially identical with a maximum wind speed difference of 5%, or less at any elevation. A more natural (or gradual) decrease of the turbulence intensity with height increasing compared with the suburban terrain was also observed at lower elevations (below 20 m full-scale height) in the modified suburban terrain. The turbulence intensity is approximately 27% for the classic suburban terrain for heights between 5 m to 20 m. For the modified suburban, the turbulence intensity values vary from 25% to 30% between the heights ranging from 5 m to 20 m and the turbulence intensity decreases as the height increases.

3.4 Construction of Scaled Models

This study made several improvements in technique over earlier wind tunnel studies on sawtooth roof buildings, one of these improvements is the larger model scale (1:100) that is used, resulting in a denser distribution of pressure taps than were used in either the Holmes' (1:200 scale) or the Saathoff and Stathopolous' (1:400 scale) model studies. These changes resulted in improved accuracy of wind pressure distributions on these roof shapes.

The multi-span building models were constructed by combining several single pitched roof models with a roof slope of 21^o. In this wind tunnel test studies, monosloped roof, 2-, 3-, 4-, and 5-span sawtooth roof models were formed. The model height could be adjusted to correspond to three full-scale mean roof heights of 7 m, 11.6 m and 16.1 m. For ease of identification of the sawtooth roof spans they were designated to conform to the naming system used by ASCE-7 for sawtooth roof spans. For example, the windward span of a 5-span sawtooth roof is called 'Span A', the middle spans, 'Spans B, C and D' and the leeward span is called 'Span E'.

The five single pitched models were constructed using Plexiglas sheet. On one of these models, 290 pressure taps were installed on the roof and this model was used as the instrumented model in all experiments. The models are 79 mm wide by 299 mm long and 177 mm high at the ridge. By changing the instrumented span location and repeating the tests, the wind pressure distribution on the whole sawtooth roof can be measured in the wind tunnel. Fig. 3.11 and Fig. 3.12 show these sawtooth roof models with the respective model geometry information. Fig. 3.13 shows the detail tap location on the instrumented model.

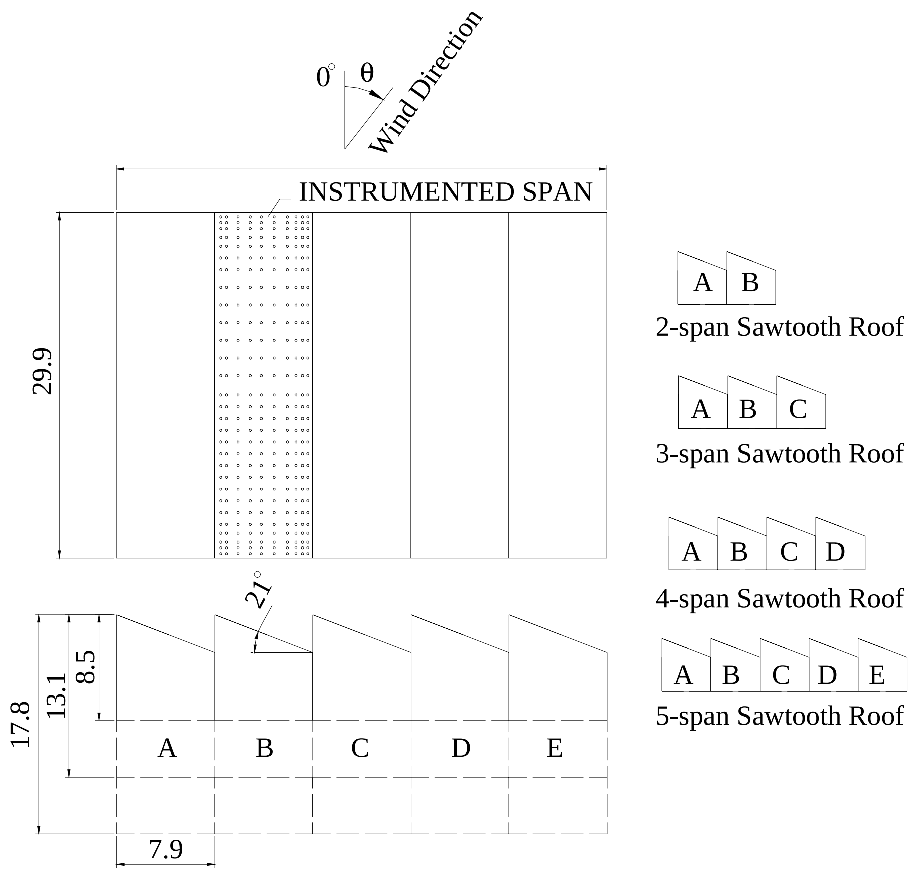


Figure 3.11 Sawtooth Models with Full-Scale Dimensions (unit: m)

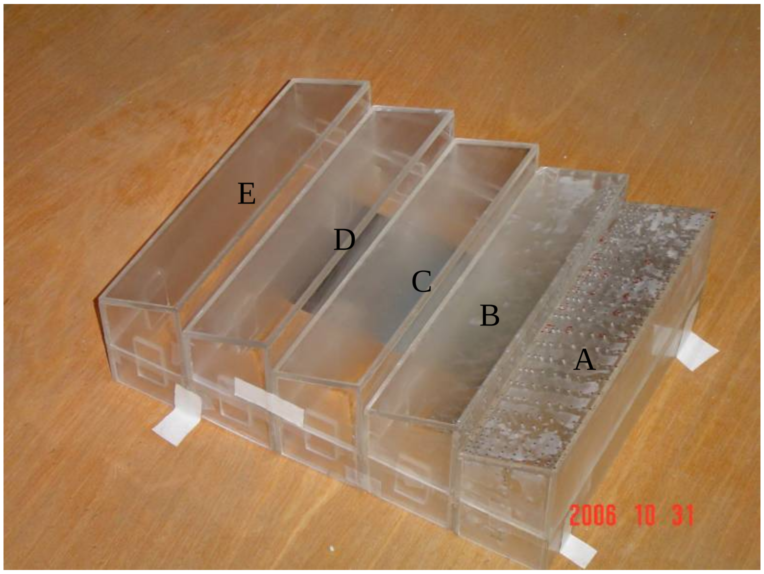


Figure 3.12 Five-span Sawtooth Roof Model

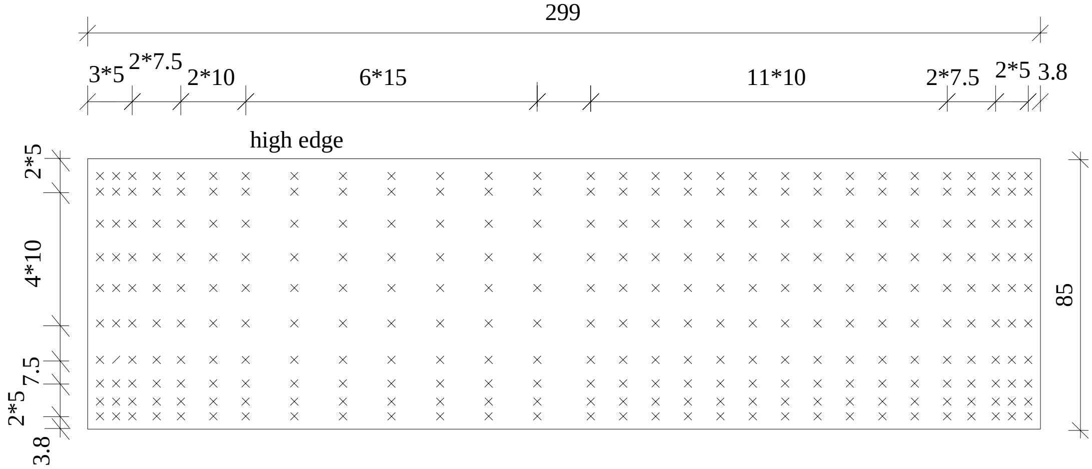


Figure 3.13 Tap Locations on Model Roof (unit: mm)

The larger scale models allow significantly increased tap density and therefore better resolution of the pressure contours. This configuration makes it possible to capture the high wind pressures occurring on test models and more accurately determine the wind pressure zone.

Because the highest suction occurs near the edge of roofs, more pressure taps were situated near the roof edge, thus increasing the likelihood of capturing the highest suction values that occur on the roof surface. For this study, pressure taps were installed as near as 0.4 m (equivalent full-scale) distance from the roof edge, which in turn enabled the observation of extreme suction during wind tunnel tests. In previous tests by Holmes (1983, 1987) the distance from roof edge to the nearest pressure tap was a full-scale distance of 2.0 m and in the Saathoff and Stathopoulos (1992[a,b]) tests, the distance was 0.6 m (equivalent full-scale). This difference in model construction may partially explain why the extreme wind pressure coefficient observed by Stathopoulos (-10.2) exceeded the peak pressure coefficients observed by Holmes (-7.6) by 34%.

Higher resolution of various taps placed on the model also provided a greater probability for determining the occurrence of real peak wind pressure on the models and makes it possible to study area-averaged wind pressure coefficients with a large amount of tributary areas. The smallest full-scale tributary area for one pressure tap in this study is equivalent to less than 1 m^2 which is approximately 25% of the smallest full-scale pressure tap tributary area used in the Saathoff and Stathopoulos' study (1992[a,b]). Table 3.3 compares the models of current research with the researches of Stathopoulos and Holmes.

Table 3.3 Comparison of Wind Tunnel Test Setup between Current Study and Prior Wind Tunnel Tests

	Saathoff and Stathopoulos (1992)	Holmes (1983, 1987)	Current Study (2007)
Model Scale	1:400	1:200	1:100
Prototype building dimension (Width/Length/Height)	19.4 m × 61m × 14.6 m	12 m × 39 m × 11.8 m	7.9 m × 30 m × 16.1 m × 11.6 m × 7.0 m
Model dimensions	48.5 mm × 152.5 mm × 36.5mm	60 mm × 195 mm × 59 mm	79 mm × 299 mm × 161.5 mm × 116 mm × 70 mm
Roof Slope (degrees)	15	20	21
No. of pressure taps	66	60	290
Minimum tributary area per pressure tap (equivalent full-scale)	5 m^2	3.2 m^2	0.4 m^2
Number of roof spans of tested model	1, 2 and 4	5	1 ,2 , 3, 4, & 5
Exposure Category	Open country	Open country	Open country/Suburban
Wind directions (degrees)	0^o, 30^o -150^o in 15^o increments & 180^o	20^o -60^o in 5^o increments	0^o–350^o in 10^o for 16.1 m 1-span & 5-span, 90^o-270^o in 10^o incr. other tests
Turbulence at low eave/mean roof height	0.2	0.2	0.18

3.5 Wind Tunnel Test Cases

A series of wind tunnel tests were conducted to investigate the effects of the major parameters such as number of spans, building height and terrain exposure on wind pressure coefficients. Each test run in the wind tunnel collected data from the pressure taps for a sample period of 120 seconds at rate of 300 samples per second. The reference height was 300 mm below wind tunnel ceiling where the mean wind speed is 13 m/s for both the open country and suburban terrains. The wind pressure data were collected nearly simultaneously at all pressure taps located on the roof.

Table 3.4 and Table 3.5 introduce the wind tunnel test parameters for the monosloped and sawtooth roof buildings.

Table 3.4 Wind Tunnel Test Parameters for Monosloped Roofs

Model	Height (m)	Exposure	Test Wind Directions (degree)	Wind Tunnel Runs
Monosloped Roof	16.1	Open Country	0 - 360 / 10	1
	16.1	Open Country	215, 220, 225	16
	11.6	Open Country	90 - 270 / 10	1
	11.6	Open Country	210 - 230 / 5	8
	7.0	Open Country	90 - 270 / 10	1
	7.0	Open Country	210 - 230 / 5	8
	11.6	suburban	90 - 270 / 10	1
	7.0	suburban	90 - 270 / 10	1
	11.6	Modified Suburban	90 - 270 / 10	1

Table 3.5 Wind Tunnel Test Parameters for Sawtooth Roofs

Model	Span	Height (m)	Exposure	Test Wind Directions (degree)	Wind Tunnel Runs
2-span Sawtooth Roof	A	16.1	Open Country	90 - 270 / 10	1
	B	16.1	Open Country	90 - 270 / 10	1
3-span Sawtooth Roof	A	16.1	Open Country	90 - 270 / 10	1
	B	16.1	Open Country	90 - 270 / 10	2
	C	16.1	Open Country	90 - 270 / 10	1
4-span Sawtooth Roof	A	16.1	Open Country	90 - 270 / 10	1
	B	16.1	Open Country	90 - 270 / 10	1
	C	16.1	Open Country	90 - 270 / 10	1
	D	16.1	Open Country	90 - 270 / 10	1
5-span Sawtooth Roof	A-E	16.1	Open Country	0 - 360 / 10	1
	A-E	7.0, 11.6	Open Country	90 - 270 / 10	1
	A	16.1	Open Country	235, 240, 245	16
	A	11.6	Open Country	170 - 260 / 10, 235, 245, 255	8
	A	7.0	Open Country	215 - 250 / 5	8
	B	11.6	Open Country	150 - 200 / 10, 175, 185, 195	8
	B	7.0	Open Country	155 - 175 / 5	8
	C	11.6	Open Country	150 - 200 / 10, 175, 185, 195	8
	C	7.0	Open Country	145 - 185 / 5	8
	D	11.6	Open Country	150 - 210 / 5	8
	D	7.0	Open Country	140 - 190 / 5	8
	E	7.0, 11.6	Open Country	125 - 145 / 5	8
	A-E	7.0, 11.6	Suburban	90 - 270 / 10	1
	A	11.6	Modified Suburban	90 - 270 / 10	1
	A,B	11.6	Suburban, with Surrounding Houses	90 - 270 / 10	1
Model	Span	Separation Width (m)	Exposure	Test Wind Directions	Wind Tunnel Runs
4-span Modified Sawtooth building	A,B, A1,B1	5.5 7.9 10.0	Suburban	90 - 270 / 10	1

CHAPTER 4

TEST RESULTS AND ANALYSIS

4.1 Peak Wind Pressure Coefficient Estimation

For the prediction of the extreme wind load on a building, it is essential to determine a stable estimate of the extreme wind pressure coefficient. Several methods have been used in wind tunnel studies, such as the extrapolation method (Geurts et al., 2004), the Lieblien BLUE statistical analysis method (Kopp, et al. 2005) and averaging peak method (Holmes, 1983). The latter two methods require that several repeats of wind tunnel data collection in order to make the estimate.

In this section, a comparison of three peak estimation methods are presented and data is given to establish the reasonableness and stability in results from the extrapolation method which is the method of choice to estimate the peak wind pressure coefficients in this study.

4.1.1 Averaging Direct Peak Method

Using averaging direct peak method to estimate the wind pressure coefficient many wind tunnel runs need to be conducted. The final estimate of the wind pressure coefficient for a pressure tap is the averaged peak value of these wind tunnel runs. The main purpose for using this method is to obtain stable estimates of the wind pressure coefficients. The estimation can be obtained by the following equation.

$$C_p = \frac{1}{N}\sum_{i=1}^{N} C_{p,i} \tag{4.1}$$

where C_p is the final estimate for the peak wind pressure coefficient for a pressure tap, $C_{p,i}$ is the direct peak wind pressure coefficient for the pressure tap from one wind tunnel run. N denotes the number of total wind tunnel runs.

4.1.2 Extrapolation Method

In the extrapolation method the peak wind pressure coefficient for a test time series is obtained using the following manner:

1. Divide the full time-history of measurements into several equal-length sub-records (such as 500, 1000, 2000 samples). Then, determine the peak (minimum or maximum) value of each sub-record and calculate the average peak value as the peak value with that sub-record length.
2. Repeat Step 1 for all other sub-record lengths and find the mean peak values for each sub-record length.
3. Develop a regression function of the mean peak value versus the sub-record length and extrapolate the regression function to the record length of the full time-history of the measurements.

The logarithmic regression is used to determine the function of peak value and its corresponding record length. The expression equation takes the general form that is given below:

$$Cp_N = a\log_{10}(N) + b \tag{4. 2}$$

where C_{pN} denotes the peak value for sub-record with the number of samples N; The parameters a and b in Eq. 4.2 can be obtained during logarithmic regression process.

Here is an example showing the application of the extrapolation method to estimate the peak negative wind pressure coefficient occurring at a pressure tap in the high corner of a monosloped roof. The full time history record consisted of 36,060 data samples. This total record was divided into nine sets of sub-records with lengths ranging from 500 up to 12000 samples, and nine mean sub-record peaks corresponding to the nine sub-record lengths were calculated which are shown in Table 4.1.

Table 4.1 Mean Sub-record Peaks for a Full Record of Wind Pressure Coefficient Measurement

Group	Length of Sub-record	No. of sub-records	Mean Sub-record Peak
1	500	72	-2.57
2	1000	36	-2.88
3	2000	18	-3.21
4	3000	12	-3.35
5	4000	9	-3.52
6	5000	7	-3.6
7	6000	6	-3.61
8	9000	4	-3.85
9	12000	3	-4.01

The regression equation based on this example is shown in Eq. 4.3:

$$y = -0.443\log(x) + 0.18 \tag{4.3}$$

where y denotes the expected peak value and x denotes the record length. Fig. 4.1 shows the sub-record peaks and regression line. The expected extrapolation peak for the full record with 36060 samples can be calculated based on this equation.

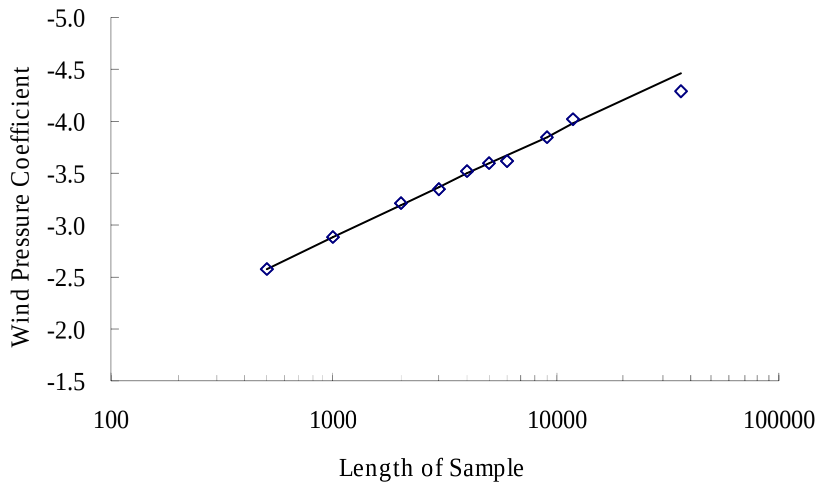


Figure 4.1 Peak Values versus Lengths of Sub-record

For this example the extrapolation peak is -4.46 as compared with the direct peak value -4.29 for this wind pressure coefficient time series. The closeness between the direct peak and extrapolated peak presents that extrapolation method works well for the prediction of peak values for a wind pressure coefficient time series. However, one thing that needs to be noted is that for different test records, the regression equations usually are different from each other; the equation should be determined for every test record.

4.1.3 Lieblien BLUE Method

Using the Lieblein BLUE method to estimate wind pressure coefficient data several wind tunnel runs are needed. This method is based on the study for the peak value distribution. The Extreme Value I distribution is considered as one of applicable distributions for the peak wind pressure coefficients. Based on this assumption that the peak wind pressure follows Extreme Value I distribution, Lieblein BLUE estimator (1974) is usually used to determine the statistical mean peak value.

In Lieblein BLUE estimation, the peak values are sorted in a ascending order and the statistical mean peak value is equal to the integration of these sorted peak values weighted by the corresponding Lieblein BLUE coefficients. The calculation is presented by Eq. 4.4.

$$C_{p,Sta} = \sum_{i=1}^{8} C_{p,i} \times a_i \tag{4.4}$$

where $C_{p,Sta}$ is the statistical mean peak wind pressure coefficient and a_i is the corresponding Lieblein BLUE coefficient.

To illustrate this method clearly, one example is provided. Table 4.2 shows the direct peak wind pressure coefficients for eight independent wind tunnel runs for a pressure tap on the 11.6 m high monosloped roof under open country exposure. In the table, the direct peak values are arranged in ascending order. The corresponding Lieblein BLUE coefficients are showed in Table 4.3. Using Eq. 4.4 statistical mean peak values are calculated based on the given data in Table 4.2. The statistical mean value for this example is -3.45.

Table 4.2 Direct Peaks from 8 Wind Tunnel Runs in Ascending Order

Sample	1	2	3	4	5	6	7	8
Direct Peak *Cp(i)*	-3.26	-3.42	-3.42	-3.5	-3.51	-3.53	-3.73	-4.36

Table 4.3 Lieblein BLUE Coefficients

Sample Size	8
Sample	Lieblein BLUE Coefficient (a_i)
1	0. 273535
2	0. 189428
3	0. 1502
4	0. 121174
5	0. 097142
6	0. 075904
7	0. 056132
8	0. 035485

4.1.4 Comparison of Peak Estimations

To evaluate the peak estimations based on the three methods, the wind pressure coefficients for eight pressure taps estimated from direct peak, extrapolation peak and Lieblein BLUE methods are compared with each other. These eight pressure taps are located in the high corner of the 5-span sawtooth roof with a height of 11.6 m. For the chosen model, eight wind tunnel runs were conducted for the critical wind direction of 240^o in open terrain. Fig. 4.2 shows the chosen pressure taps' location on the model roof.

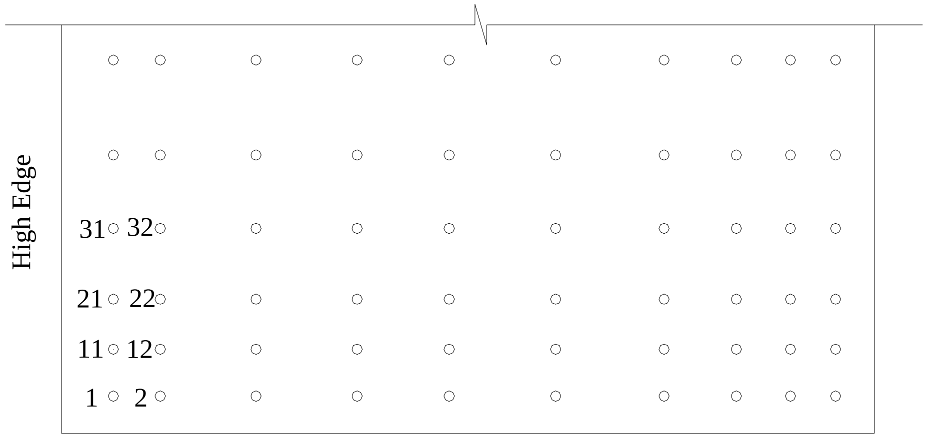


Figure 4.2 Locations of Chosen Pressure Taps for Peak Estimation Analysis

Table 4.4 shows the direct peaks, extrapolation peaks from the 8 wind tunnel runs. It can be seen than the mean value of extrapolation peaks is very close to the mean value of direct peaks with difference less than 4%. However the direct peaks vary much more than the extrapolation peaks. The standard deviation values from 8 direct peaks are higher than those for extrapolation peaks with more than 50%.

Table 4.5 shows the comparisons of averaged direct peaks, averaging extrapolation peaks and Lieblein BLUE statistical mean peaks. The differences between averaging direct peaks and averaging extrapolation peaks are less than 4%. However, the statistical mean peaks are lower than the corresponding averaging direct peaks with 3.9% ~ 8.5%.

Table 4.4 Comparison of Peak Wind Pressure Coefficients Estimated by Direct Peak Method and Extrapolation Method

Pressure Tap No.	Run	1	2	3	4	5	6	7	8	***Mean***[1]	***STD***[2]	***Min***[3]	***Max***[4]
1	Direct Peak	-2.84	-3.31	-2.89	-2.92	-3.4	-4.86	-3.81	-2.88	***-3.36***	***0.69***	***-4.86***	***-2.84***
	Extrapolation	-2.88	-3.42	-3.04	-3.05	-3.54	-3.87	-3.7	-2.99	***-3.31***	***0.37***	***-3.87***	***-2.88***
2	Direct Peak	-2.88	-3.16	-2.69	-2.99	-3.45	-4.07	-3.15	-3.05	***-3.18***	***0.42***	***-4.07***	***-2.69***
	Extrapolation	-2.88	-3.14	-2.95	-3.2	-3.44	-3.4	-3.25	-3.04	***-3.16***	***0.20***	***-3.44***	***-2.88***
11	Direct Peak	-3.16	-3.64	-3.23	-3.93	-3.54	-2.96	-3.26	-3.18	***-3.36***	***0.32***	***-3.93***	***-2.96***
	Extrapolation	-3.41	-3.52	-3.45	-3.52	-3.51	-3.04	-3.35	-3.2	***-3.38***	***0.17***	***-3.52***	***-3.04***
12	Direct Peak	-3.3	-3.82	-3.14	-3.35	-3.72	-3.08	-3.84	-3.09	***-3.42***	***0.33***	***-3.84***	***-3.08***
	Extrapolation	-3.44	-3.6	-3.03	-3.38	-3.7	-3.07	-3.6	-3.33	***-3.39***	***0.25***	***-3.7***	***-3.03***
21	Direct Peak	-3.26	-3.73	-3.51	-3.42	-3.42	-3.53	-3.5	-4.36	***-3.59***	***0.34***	***-4.36***	***-3.26***
	Extrapolation	-3.22	-3.9	-3.39	-3.46	-3.45	-3.82	-3.74	-4.03	***-3.63***	***0.28***	***-4.03***	***-3.22***
22	Direct Peak	-3.02	-3.78	-3.15	-3.09	-3.2	-2.81	-4.58	-3.67	***-3.41***	***0.57***	***-4.58***	***-2.81***
	Extrapolation	-3.15	-3.49	-3.18	-3.33	-3.34	-3.1	-3.68	-3.29	***-3.32***	***0.19***	***-3.68***	***-3.1***
31	Direct Peak	-2.59	-3.04	-2.96	-2.61	-4	-2.86	-3.7	-3.18	***-3.12***	***0.50***	***-4***	***-2.59***
	Extrapolation	-2.83	-2.85	-2.84	-2.63	-3.42	-2.95	-3.59	-2.99	***-3.01***	***0.33***	***-3.59***	***-2.63***
32	Direct Peak	-2.86	-3.49	-2.77	-2.61	-3.58	-2.81	-3.23	-3.4	***-3.09***	***0.37***	***-3.58***	***-2.61***
	Extrapolation	-2.83	-3.04	-2.79	-2.86	-3.27	-2.82	-3.22	-3.16	***-3.00***	***0.20***	***-3.27***	***-2.79***

Note: [1]Mean value, [2]Standard deviation, [3]Min – minimum and [4]Max – maximum of all values shown in Columns 1 through 8.

Table 4.5 Comparisons of Averaging Peaks based on Three Methods

Pressure Tap	(1) Direct Peak Method	(2) Extrapolation Method	(3) Lieblen Blue Method	(4) [(2) – (1)]/ (1)	(5) [(3) – (1)]/ (1)
1	-3.36	-3.31	-3.08	-1.6%	-8.5%
2	-3.18	-3.16	-2.98	-0.6%	-6.2%
11	-3.36	-3.38	-3.21	0.4%	-4.6%
12	-3.42	-3.39	-3.26	-0.7%	-4.7%
21	-3.59	-3.63	-3.45	1.0%	-3.9%
22	-3.41	-3.32	-3.15	-2.7%	-7.7%
31	-3.12	-3.01	-2.88	-3.4%	-7.7%
32	-3.09	-3.00	-2.90	-3.1%	-6.2%

Two conclusions are drawn based on the above discussion::

1. For multiple wind tunnel runs, the three estimation methods work well for the estimation of wind pressure coefficients, and the methods all give similar results. The results from the Lieblein BLUE estimation method are lower than peak estimates obtained using the averaging direct peak method by 4% ~ 8.5%.

2. There is more scatter in the estimates of peak wind pressure coefficients using the direct peak method as compared with the the extrapolation method. The standard deviations of direct peaks are higher than those of extrapolation values by more than 50%.

Thus, it was shown above that a reasonable estimate of the peak wind pressure coefficient can be obtained using the extrapolation method. The results also show no bias in the extrapolation method estimates as compared with results from the more robust direct peak estimation method. In addition, because the extrapolation method using one wind tunnel run provides more stable peak estimation than direct peak method, it was selected as the method for determining peak wind pressure coefficients in this research. To establish greater reliability at the critical wind directions (for example cornering winds at 200^{o} ~ 240^{o} for the windward span of a sawtooth roof), multiple wind tunnel runs were conducted. The averaging value of extrapolation peaks from these wind tunnel runs is determined as the expected peak value where greater confidence in the extreme peak values is required.

4.2 Calculation of Area-averaged Wind Pressure Coefficients

Area-averaged wind pressure coefficients are important for the wind load design of components and cladding with larger tributary areas and secondary structural elements. In this section the numerical integraton method is used to calculate area-averaged wind pressure coefficients. This is different from the pneumatic test method of area-averaging used by Holmes (1983) and Saathoff and Stathopoulos (1992[a,b]), in which several pressure taps are physically connected to a single pressure tube through a manifold and the spatially averaged pressure coefficients are determined for the total tributary area of all the connected pressure taps. The numerical averaging method utilizes time histories of pressures on individual pressure taps in the tributary area. The time history of area-averaged wind pressure is mathematically created by combining the local pressure time histories weighted by the ratios of individual pressure tap tributary area to the whole tributary area. The numerical method is also very flexible as the pressure coefficient time series for any pressure taps can be combined together to form a new area-averaged wind pressure coefficient time series. Based on this method, the area-averaged wind pressure coefficient with any tributary area can be obtained and it does not need to do extra wind tunnel tests for different pressure tap combinations.

Area-averaged wind pressure coefficient analysis was applied to every test case. The instrumented roof area was divided into two group of panels as shown in Fig. 4.3. The tributary areas of the panels in Group I range from 1.86 m^2 to 5.6 m^2 and all panels have four pressure taps inside except A1 through A5 which have 6 pressure taps inside. The tributary areas of panels in Group II range from 7.4 m^2 to 15.8 m^2. In addition, more pressure tap combinations with tributary area ranging from 0.9 m^2 to 37.1 m^2 in the high corner and low corner zones are chosen. Fig. 4.4 presents the boundaries of the chosen tributary areas, in which the points represent the location of each pressure tap.

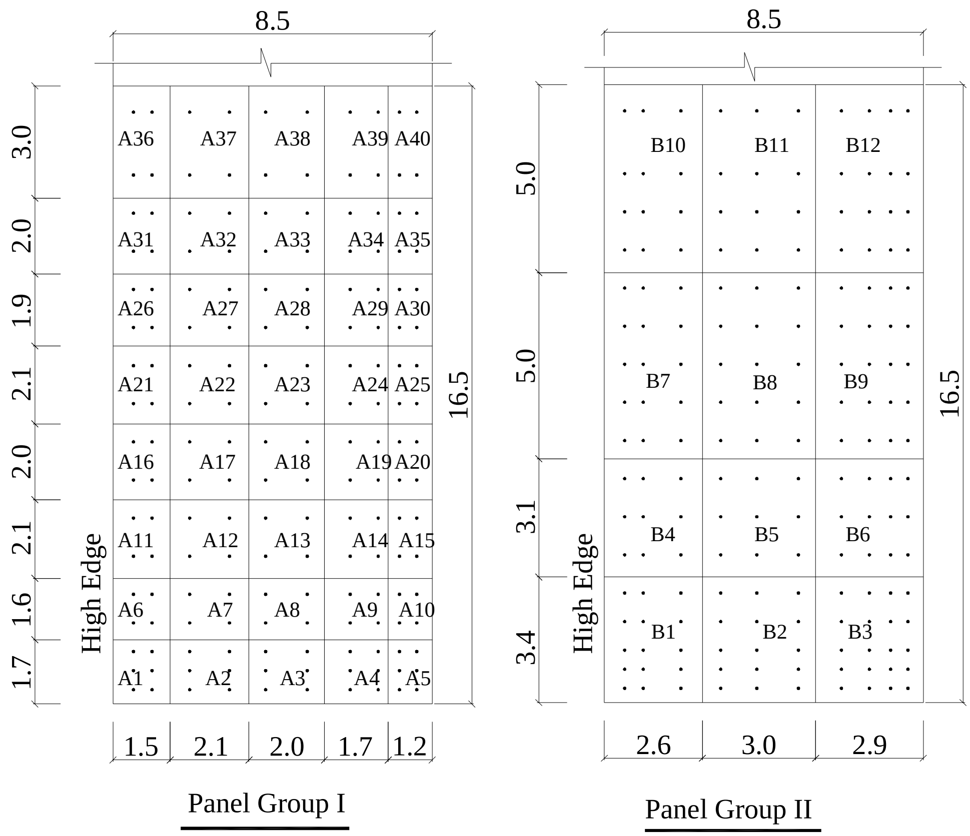


Figure 4.3 Pressure Panels on Roof with Full-Scale Dimensions (Unit: m)

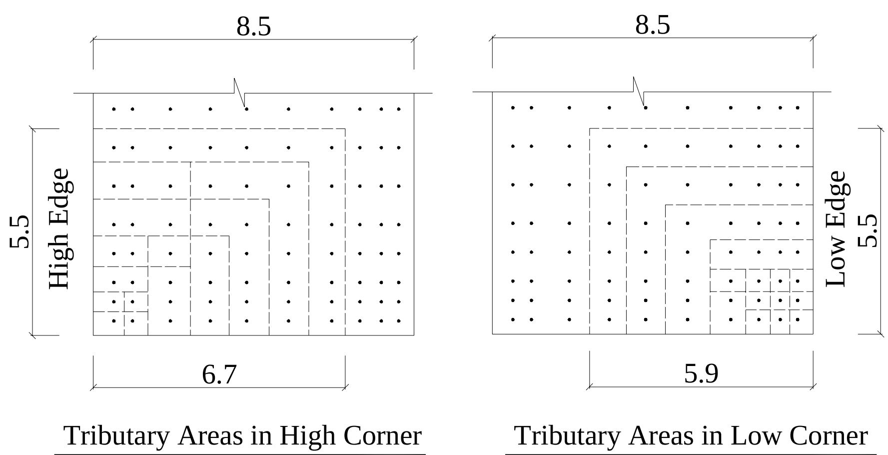


Figure 4.4 Boundaries of Tributary Areas at High Corner and Low Corner with Full-Scale Dimensions (Unit: m)

The time series of area-averaged wind pressure coefficients were determined by integrating the local wind pressure coefficients time series for pressure taps within the specified areas using the following equation:

$$C_{p(area,j)} = \frac{\sum_{i=1}^{n}\left(C_{p(i,j)} \times A_i\right)}{\sum_{i=1}^{n} A_i} \qquad (4.5)$$

where:

$C_{p(area,j)}$ denotes area-averaged wind pressure coefficient at time step j.

$C_{p(i,j)}$ = instantaneous local wind pressure coefficient of tap i at time-step j

n = the number of taps in the specified area

A_i = tributary area of the ith tap in the specified area

4.3 Pressure Zones on Monosloped and Sawtooth Roofs

The ASCE 7-02 recommendations for pressure zones on monosloped and sawtooth roofs are presented in Fig. 4.5. The characteristic length *a* is defined as the minimum value between 10 percent of the least horizontal dimension of the building or 40 percent of building height, and not less than 0.9 m and 4 percent of least horizontal dimension. Of particular note is that for multi-span gable roofs the least horizontal dimension is limited to one single-span module not to the whole building in the definition for characteristic length. However, this is not specified for the sawtooth roofs in the ASCE 7-02, although both multi-span gable roofs and sawtooth roofs consist of a series of same shape roofs.

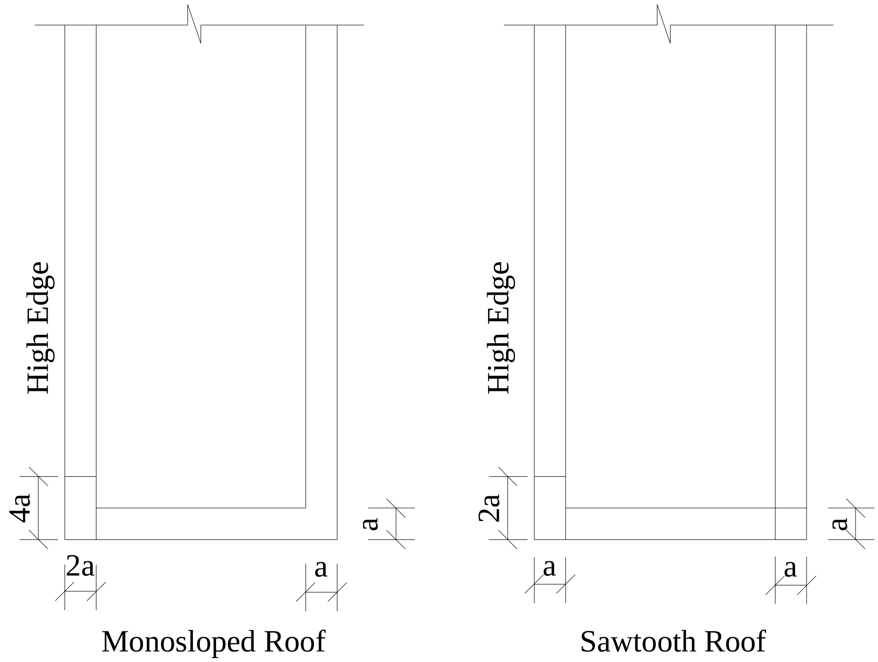


Figure 4.5 ASCE-7 Specification for Pressure Zones on Monosloped and Sawtooth Roofs

Table 4.6 Characteristic Lengths and Building Dimensions

Building	Overall Width (m)	Length (m)	Height (m)	*a* (m)
Monosloped Roof	7.9	29.9	16.1	0.9
2-span sawtooth	15.8	29.9	16.1	1.6
3-span sawtooth	23.8	29.9	16.1	2.4
4-span sawtooth	31.7	29.9	16.1	3.0
5-span sawtooth	39.6	29.9	16.1	2.8

Table 4.6 lists the respective characteristic lengths for the monosloped and sawtooth roof buildings, based on the least horizontal dimension of the whole building. The characteristic length values for the 16.1 m high monosloped, 2-, to 5-span sawtooth roof building differ from each other resulting in the pressure zone areas for these sawtooth roofs being different. But according to test pressure distributions, change of number of spans does not significantly affect the pressure

zone areas with similar pressure levels. For example, the pressure zone areas in the high corner on windward spans of 2- through 5-span sawtooth roofs appear quite similar when their configurations are based upon the pressure coefficients contours. To make the following comparisons of zonal wind pressure coefficients for monosloped roof and sawtooth roofs more reasonable, the same pressure zone areas are use in monosloped roof and 2- to 5-span sawtooth roofs. The pressure zones are defined based on characteristic length derived from the individual dimensions of a single-span module.

The new pressure zone definitions on monosloped and sawtooth roofs are based on the dimension of a single span of the sawtooth roof. This indicates the characteristic length, *a*, for the sawtooth roofs is same as that for the monosloped roof with same configuration characteristics. Fig. 4.6 shows the detail information about the defined pressure zones on the monosloped and sawtooth roofs. In these updated pressure zones, edge zone width is defined as '2a', and on the windward span of the sawtooth roofs, the high corner area is defined as the area with '4a' by '2a' which is same with the specification for the monosloped roof in the ASCE 7-02. The high corner areas on the middle and leeward spans in the sawtooth roofs are specified as the area with '2a' by '2a' as well as the area of the low corners for all spans. Zonal wind pressure coefficients are analyzed based on these preliminary pressure zones.

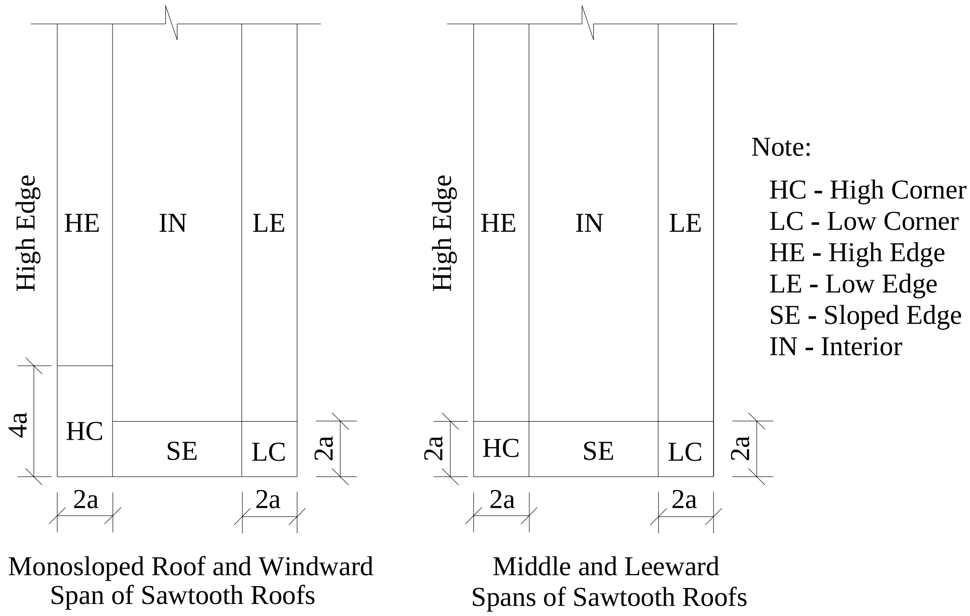


Figure 4.6 Preliminary Suggested Pressure Zones for Monosloped and Sawtooth Roofs

Table 4.7 lists the total number of pressure taps in each pressure zone on monosloped and sawtooth roofs. Only pressure taps of the half roof area are counted because of the symmetry of building roofs. Table 4.8 lists the panels of group I and group II in each pressure zone.

Table 4.7 Number of Pressure Taps in Each Zone on Monosloped and Sawtooth Roofs

Span	Zone	Number of Pressure Taps
Monosloped Roof and Windward Spans of Sawtooth Roofs	High Corner (HC)	10
	Low Corner (LC)	9
	High Edge (HE)	24
	Low Edge (LE)	42
	Sloped Edge (SE)	15
	Interior (IN)	70
Middle and Leeward Spans of Sawtooth Roofs	High Corner (HC)	6
	Low Corner (LC)	9
	High Edge (HE)	28
	Low Edge (LE)	42
	Sloped Edge (SE)	15
	Interior (IN)	70

Table 4.8 Panels in Each Pressure Zone

	For Panel Group I	
Pressure zones	Windward Span and Monosloped Roof	Middle and Leeward Spans
HC	A1, A6	A1
LC	A4, A5	A4, A5
HE	A(11,16,21,26,31,36)	A(6,11,16,21,26,31,36)
LE	A(9,10,14,15,19,20,24, 25,29,30,34,35,39,40)	A(9,10,14,15,19,20,24, 25,29,30,34,35,39,40)
SE	A2, A3	A2, A3
IN	A(7,8,12,13,17,18,22, 23,27,28,32,33,37,38)	A(7,8,12,13,17,18,22, 23,27,28,32,33,37,38)
Pressure zones	For Panel Group II	
HC	B1	
LC	B3	
HE	B(4,7,10)	
LE	B(6,9,12)	
SE	B2	
IN	B(5,8,11)	

4.4 Parametric Studies on Wind Pressure Coefficients

In this section, a series of parameter effects such as number of spans, building height, and terrain exposure, on wind pressure coefficients are investigated. The wind pressure coefficients are referenced to the mean wind speed at the reference height in the wind tunnel unless indicated otherwise. Patterns of wind pressure coefficient distributions are presented to provide an overall perspective for wind pressure coefficient distribution on roofs. Zonal local and area-averaged wind pressure coefficients are also presented to better understand the effect of these parameters.

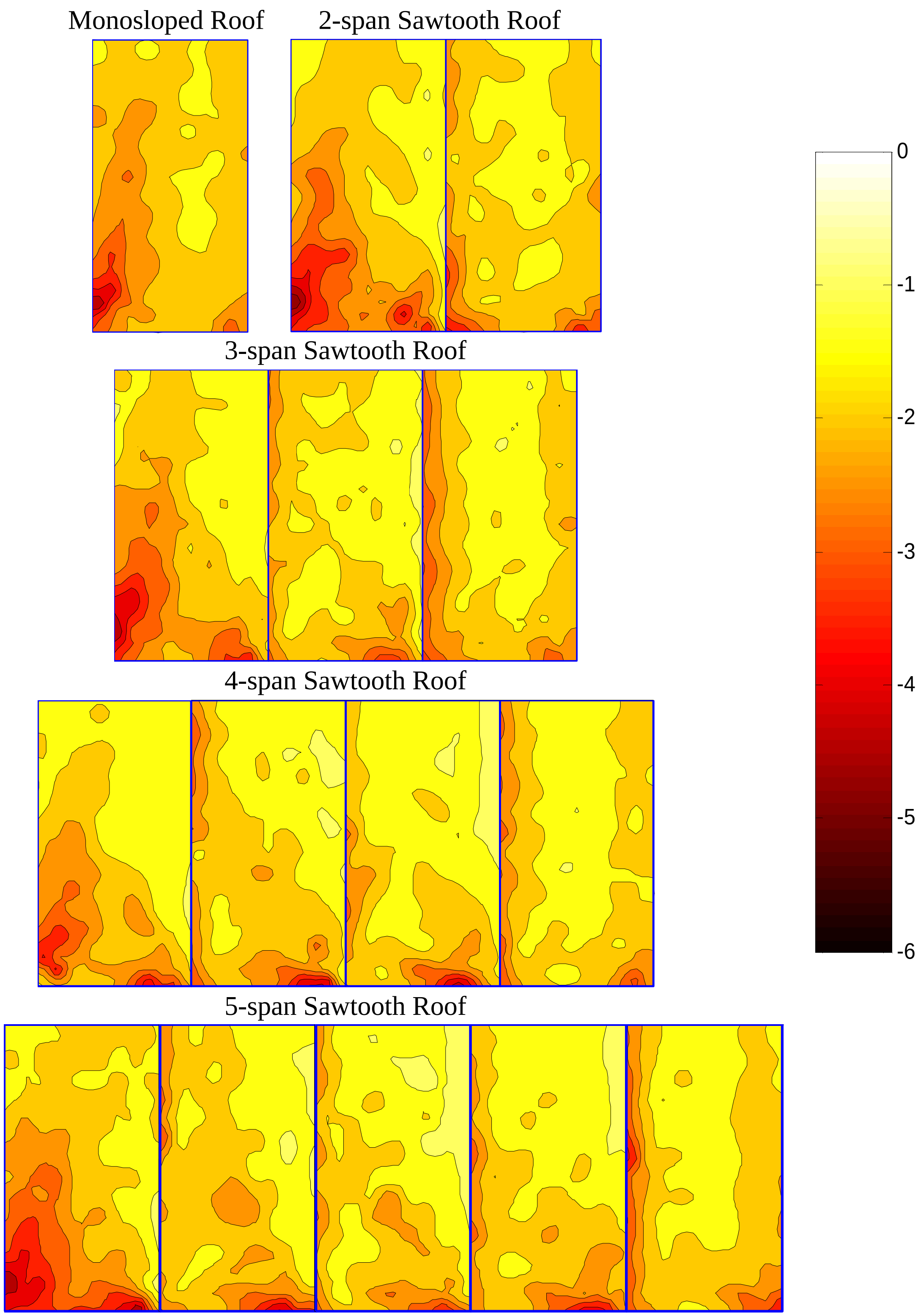
4.4.1 Varying Number of Spans

Wind tunnel tests were conducted for the monosloped roof model and four sawtooth roof models with 2-, 3-, 4-, and 5-spans under open country exposure. The mean roof height at full scale for these models is 16.1 m. Local and area-averaged wind pressure coefficients are calculated. Separate analyses for the windward spans (Span A), middle spans (Spans B, C and D) and leeward spans (Span E) of sawtooth roofed buildings are presented.

4.4.1.1 Patterns of Wind Pressure Coefficient Distribution

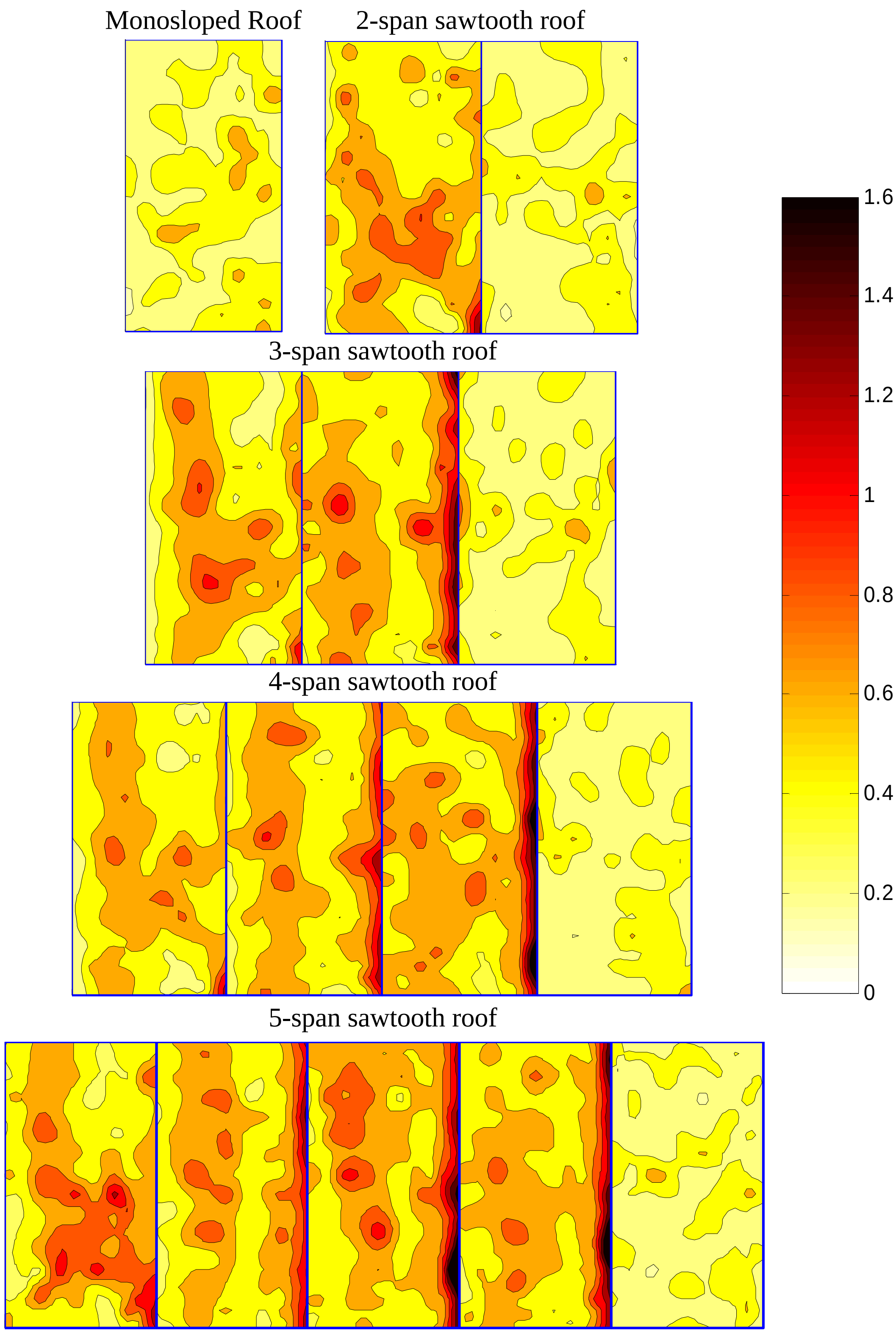
Peak negative and positive wind pressure coefficients for all wind directions were determined during the investigation of the wind pressure distributions on buildings. Contour plots are generated to visualize the wind pressure distributions on the monosloped and sawtooth roofs. All contour plots in this research are generated using the Matlab contouring sub-routine based on the

‘V4’ interpolation contour algorithm. This algorithm used the type of surface to fit to the data other than the ‘nearest’ or ‘linear’ interpolation method. Since the ‘linear’ and ‘nearest’ interpolations only use several data for the pressure taps around the interpolated point these interpolations will have discontinuities in the first and zero'th derivatives respectively, while the ‘V4’ interpolation creates the smooth surface. The contour plots are shown in Figures 4.7 and Figure 4.8.



(16.1m High; Open Exposure; Left Side is High Edge)

Figure 4.7 Contours of Peak Negative Cp for Monosloped and Sawtooth Roofs



(16.1m High; Open Exposure; Left Side is High Edge)

Figure 4.8 Contours of Peak Positive Cp for Monosloped and Sawtooth Roofs

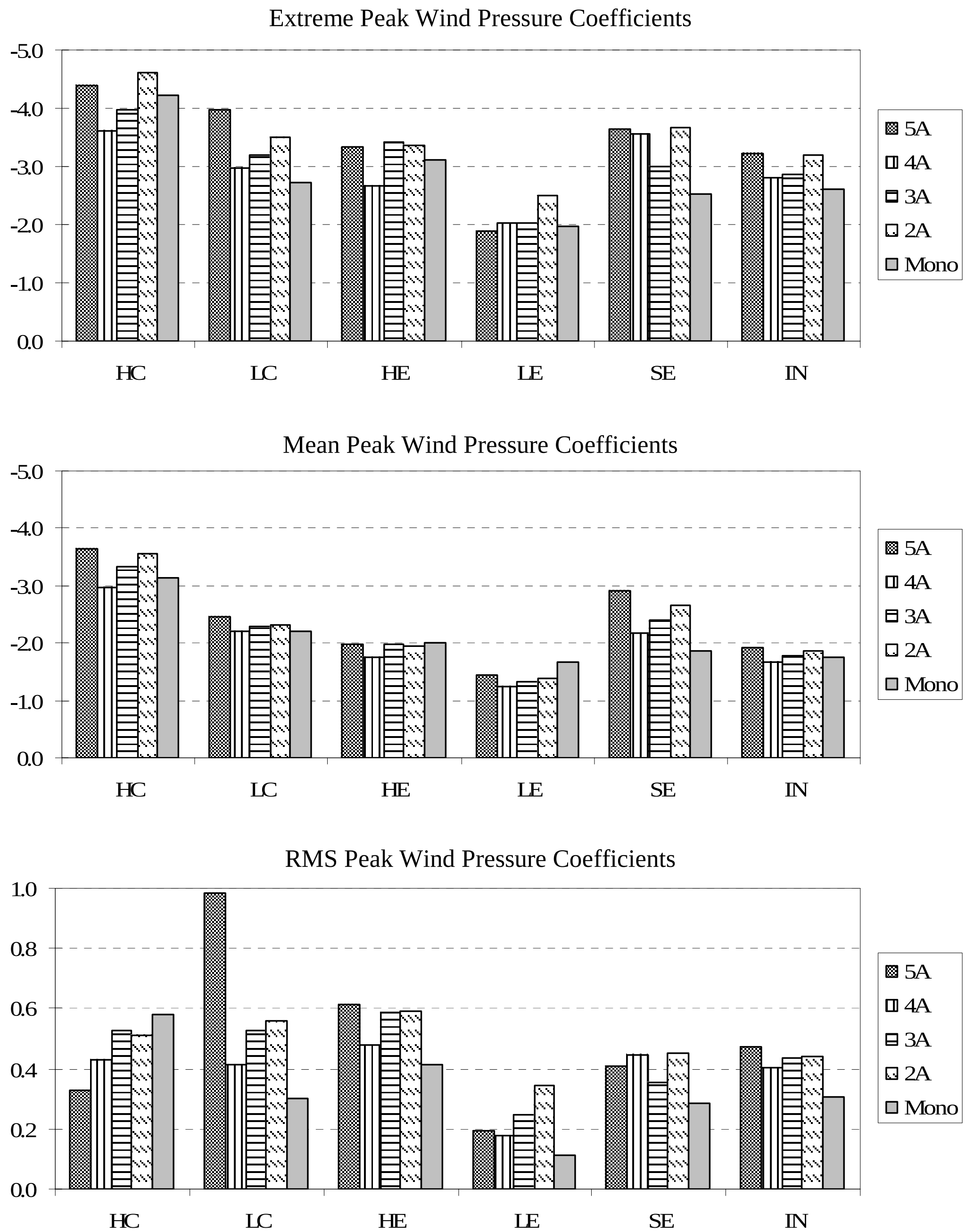
Wind pressure distribution patterns on sawtooth roofs can be divided into three categories - windward span, middle span, and leeward span. The peak negative and positive wind pressure coefficient distribution patterns are similar to each other for the windward spans of the four sawtooth roofs. The same can also be concluded for middle spans and leeward spans on sawtooth roofs.

The peak negative wind pressure distribution on the monosloped roof is similar to those on the windward spans of the sawtooth roofs. The peak positive wind pressure coefficient distribution on the monosloped roof is similar with those on the leeward spans of the sawtooth roofs.

4.4.1.2 Local Wind Pressure Coefficients

4.4.1.2.1 Monosloped Roof and Windward Span of Sawtooth Roofs

Extreme, mean and RMS values of peak negative wind pressure coefficients for pressure taps in each pressure zone on the monosloped roof and windward spans of sawtooth roofs are presented in Fig. 4.9. The corresponding statistical values are shown in Table 4.9.



(Building height: 16.1 m; Terrain: open country)

Figure 4.9 Comparisons of Statistical Values of Peak Negative Cp for Monosloped Roof and Windward Spans of Sawtooth Roofs

Table 4.9 Statistical Values of Peak Negative Cp for Monosloped Roof and Windward Spans of Sawtooth Roofs

Zone	Statistical Values	5A	4A	3A	2A	Mono
HC	Extreme	-4.38	-3.61	-3.96	-4.61	-4.22
	Mean	-3.63	-2.96	-3.33	-3.56	-3.13
	RMS	0.33	0.43	0.53	0.51	0.58
LC	Extreme	-3.97	-2.96	-3.20	-3.49	-2.73
	Mean	-2.46	-2.19	-2.28	-2.32	-2.21
	RMS	0.99	0.41	0.53	0.56	0.30
HE	Extreme	-3.32	-2.66	-3.42	-3.36	-3.11
	Mean	-1.99	-1.74	-1.99	-1.96	-2.01
	RMS	0.61	0.48	0.59	0.59	0.41
LE	Extreme	-1.88	-2.03	-2.02	-2.49	-1.97
	Mean	-1.44	-1.25	-1.33	-1.39	-1.67
	RMS	0.19	0.18	0.25	0.34	0.11
SE	Extreme	-3.65	-3.56	-3.00	-3.67	-2.54
	Mean	-2.92	-2.18	-2.39	-2.65	-1.85
	RMS	0.41	0.45	0.35	0.45	0.28
IN	Extreme	-3.23	-2.81	-2.86	-3.19	-2.61
	Mean	-1.93	-1.66	-1.77	-1.86	-1.75
	RMS	0.47	0.40	0.43	0.44	0.31
Note: Building height: 16.1 m; Terrain: open country						

The extreme peak negative wind pressure coefficients for each pressure zone on the windward spans vary significantly for sawtooth roofs with different number of spans. The discrepancy between the maximum and minimum peak values for 2- to 5-spans sawtooth roofs is more than 20% in zones of the high corner, low corner, high edge and low edge.

The highest suction always occurs in the high corner of monosloped roofs and of windward span of sawtooth roofs. The extreme peak negative wind pressure coefficient on the windward span of the 5-span sawtooth roof is -4.38, slightly higher than the value of -4.22 for the monosloped roof. The extreme values for the windward spans of 2-, 3- and 4-span sawtooth roofs are -4.61, -3.96 and -3.61 respectively, indicating a relatively large spread in peak pressure coefficients among the four sawtooth models. The largest difference among peak wind pressure coefficients for 2- to 5-span sawtooth roofs is more than 20% of the extreme peak value. Possible reasons may be the variation of critical wind directions and the difference of critical pressure tap locations. One interesting phenomenon found in this study is that the peak negative wind pressure coefficient increased with the horizontal dimension aspect ratio increasing, indicating aspect as another reason of high suction.

The aspect ratio values for the 2-, 3-, 4- and 5-span sawtooth roof models are listed in Table 4.10. Comparisons of the extreme peak negative wind pressure coefficients for sawtooth roofs show that the greater the aspect ratio the larger the extreme peak wind pressure coefficients.

Table 4.10 Aspect Ratios versus Extreme and Mean Peak Cp

Model	Aspect ratio (length/width)	Extreme Peak Wind Pressure Coefficients	Mean Peak Wind Pressure Coefficients
Monosloped roof	3.77	-4.22	-3.13
2-span sawtooth roof	1.88	-4.61	-3.56
3-span sawtooth roof	1.26	-3.96	-3.33
4-span sawtooth roof	1.06	-3.61	-2.96
5-span sawtooth roof	1.33	-4.38	-3.61

The mean values presented in Fig. 4.9 and in Table 4.9 are the average peak negative wind pressure coefficients for pressure taps in each pressure zone. The mean negative wind pressure coefficients for the high corner on the monosloped roof and the windward spans of 2- to 5-span sawtooth roofs range from -2.96 to -3.63 and the corresponding RMS values range from 0.33 to 0.58. The windward span of the 5-span sawtooth roof has the most negative mean peak value and smallest RMS value, indicating a larger high wind suction area on the windward span of the 5-span sawtooth roof than on either the monosloped roof or the windward spans of 2- to 4-span sawtooth roofs. The mean peak value for 2-span sawtooth roof is -3.53 which is closest to the value for 5A.

The suction occurring in the low corner of windward spans of the sawtooth roofs is less than the suction in the high corner. The highest suction coefficient is observed on the 5-span sawtooth roof with peak negative wind pressure coefficient of -3.97. The lowest suction is observed on the 4-span sawtooth roof with suction coefficient of -2.96. The wind suction for the low edge is lower than on either the high edge or the sloped edge, and the observed highest negative wind pressure coefficient for the low edge is -2.49, which occurs on the 2-span sawtooth roof.

The zonal wind pressure coefficients for some pressure zones in the monosloped roof are similar in magnitude to the zonal pressure coefficients on the windward spans of the sawtooth roofs. For the high corner and high edge zones, the difference of the peak negative wind pressure coefficients between the monosloped roof and windward spans of sawtooth roofs is less than 10%. However, for other pressure zones on the monosloped roof the wind pressure coefficients are 19% to 31% lower than the corresponding values on the windward spans of the sawtooth roof.

Fig. 4.10 presents the comparison of the peak negative wind pressure coefficients for all pressure taps on the monosloped roof and windward spans of the sawtooth roofs. The wind pressure coefficients corresponding to pressure taps with same locations on the different roof spans are compared in Fig 4.10. The x- and y-coordinates represent the peak wind pressure coefficients for different spans. Linear regression is used to qualify the difference and correlation of wind pressure coefficients for two windward spans, which is represented by the solid line. In the figure it can be seen that the more points that are closer to the linear regression line, the higher the correlation between the wind pressure coefficients for two spans. The correlation coefficient between different windward spans range from 0.75 ~ 0.89 indicating that wind pressure coefficient distributions on windward spans of sawtooth roofs are very similar.

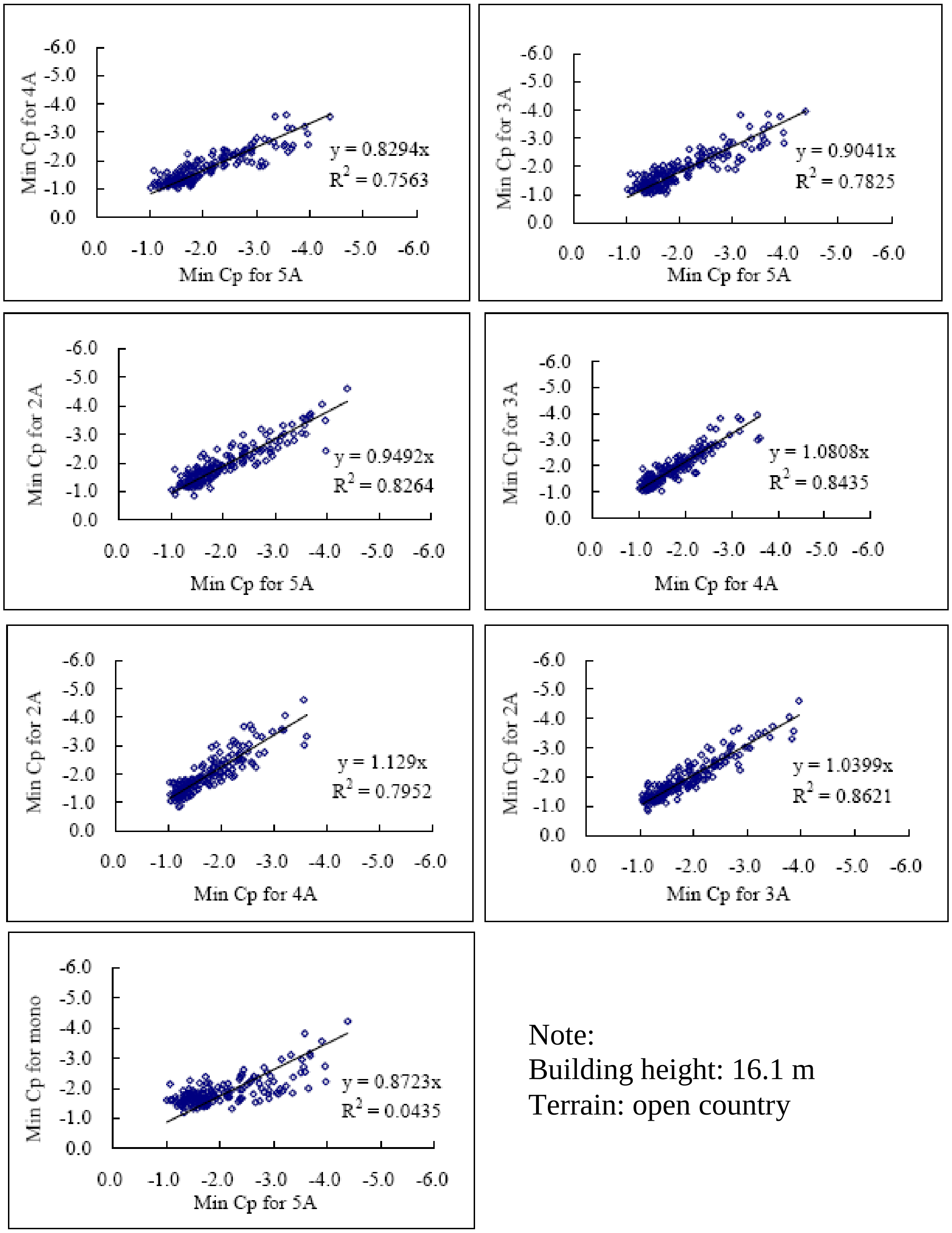


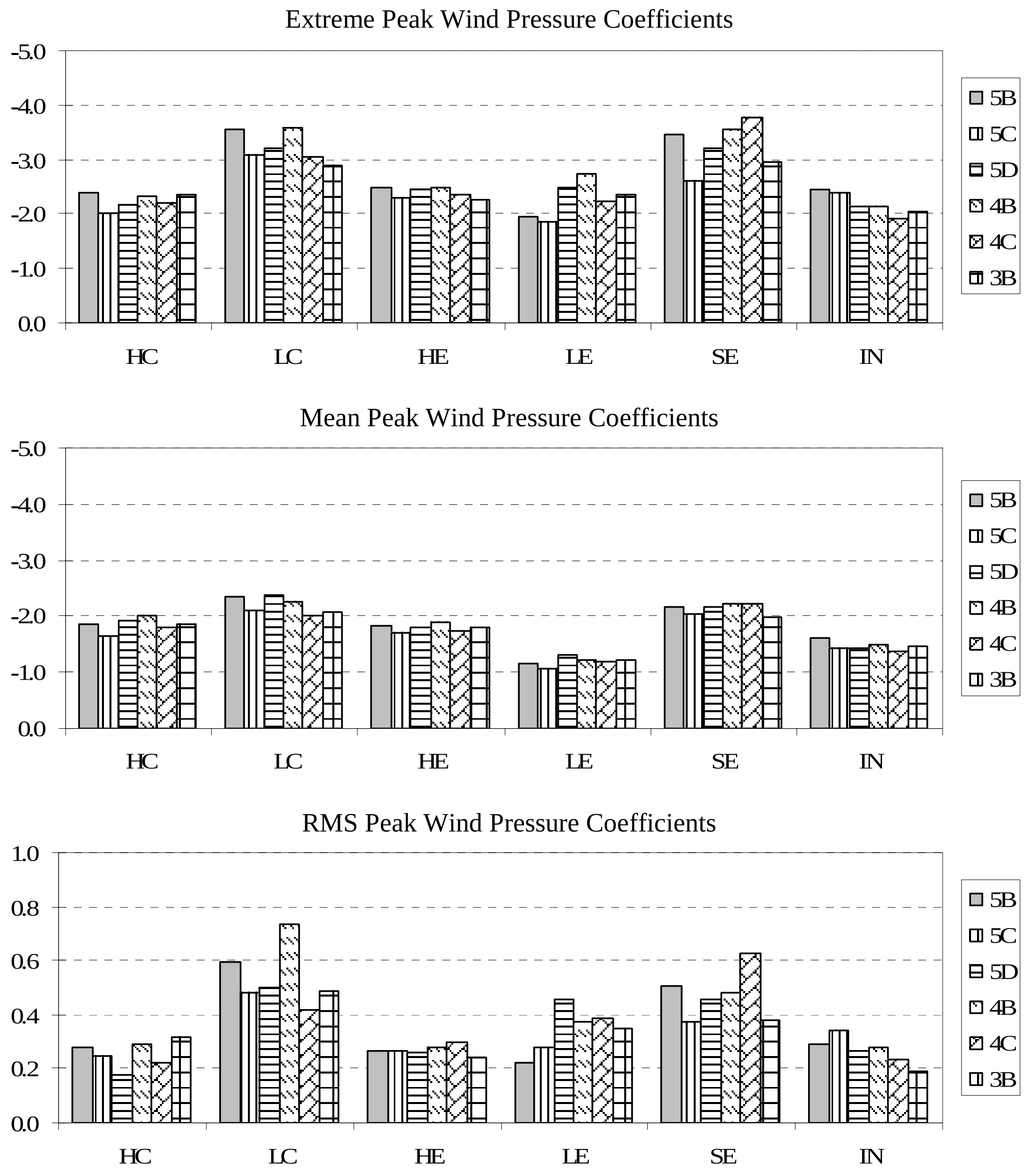
Figure 4.10 Comparisons of Peak Negative Cp for All Pressure Taps on Monosloped Roof and Windward Spans of Sawtooth Roofs

From this general comparison, it can also be concluded that the mean peak negative wind pressure coefficients on the 2-span sawtooth roof and 5-span sawtooth roofs are higher than those on the 3-span and 4-span sawtooth roofs. The highest mean peak wind pressure coefficient occurs on the windward span of the 5-span sawtooth roof. It exceeds the values for the windward spans of 2-, 3-, 4-span sawtooth roofs by 5%, 10%, and 17% respectively.

A comparison of the peak negative wind pressure coefficients indicates a weak correlation between monosloped roof and windward span of sawtooth roofs, although the wind pressure coefficients for the high edge and high corner of the monosloped roof are very similar to those for the windward span of sawtooth roofs.

4.4.1.2.2 Middle Spans of Sawtooth Roofs

Comparisons of the peak negative wind pressure coefficients for each zone of middle spans of 3-, 4-, and 5-span sawtooth roofs are presented in Fig. 4.11. The detailed statistical values are shown in Table 4.11. Wind suction occurring in both the low corner and sloped edge zones is higher than that in the other pressure zones of the middle spans of these saw tooth roofs. The peak negative wind pressure coefficients for the low corner and sloped edge zones on the middle spans range from -3.60 to -3.78. For the other pressure zones, the peak negative wind pressure coefficients range from -2.40 to -2.73.



(Building height: 16.1 m; Terrain: open country)

Figure 4.11 Comparisons of Statistical Values of Peak Negative Cp for Sawtooth Roofs

The mean peak negative wind pressure coefficients for the low corner and sloped edge zones of the middle spans range from -2.0 to -2.38 with the corresponding RMS wind pressure coefficients ranging from 0.37 to 0.73. The high RMS wind pressure coefficients indicate that the wind suction is not at the same level for all pressure taps in the pressure region. For example some pressure coefficients are lower than the peak value by over 100%.

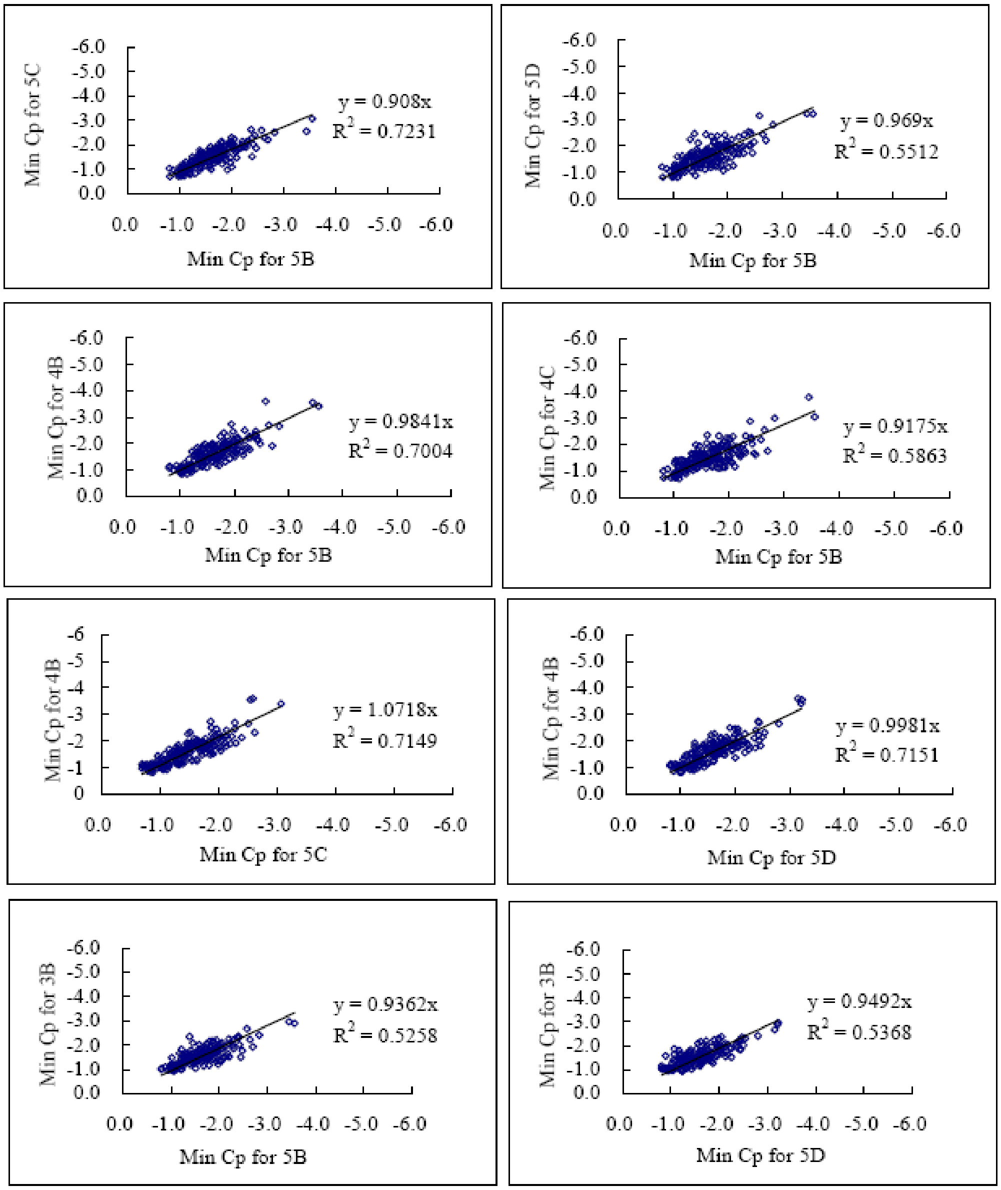
Table 4.11 Statistical Values of Peak Negative Cp for Middle Spans of Sawtooth Roofs

Zone	Statistics	5B	5C	5D	4B	4C	3B
HC	Extreme	-2.40	-2.01	-2.18	-2.32	-2.19	-2.37
	Mean	-1.87	-1.66	-1.92	-2.01	-1.81	-1.85
	RMS	0.28	0.25	0.18	0.29	0.22	0.32
LC	Extreme	-3.56	-3.07	-3.21	-3.60	-3.04	-2.89
	Mean	-2.34	-2.11	-2.38	-2.25	-2.03	-2.06
	RMS	0.59	0.48	0.50	0.73	0.42	0.49
HE	Extreme	-2.48	-2.30	-2.44	-2.50	-2.35	-2.25
	Mean	-1.82	-1.71	-1.80	-1.90	-1.73	-1.81
	RMS	0.26	0.27	0.26	0.28	0.30	0.24
LE	Extreme	-1.95	-1.87	-2.47	-2.73	-2.24	-2.35
	Mean	-1.14	-1.06	-1.32	-1.21	-1.19	-1.22
	RMS	0.22	0.28	0.46	0.37	0.38	0.35
SE	Extreme	-3.45	-2.62	-3.22	-3.55	-3.78	-2.96
	Mean	-2.18	-2.03	-2.16	-2.24	-2.22	-1.98
	RMS	0.51	0.37	0.45	0.48	0.63	0.38
IN	Extreme	-2.45	-2.40	-2.13	-2.13	-1.93	-2.05
	Mean	-1.60	-1.44	-1.44	-1.49	-1.37	-1.47
	RMS	0.29	0.34	0.26	0.28	0.23	0.19
Note: Building height: 16.1 m; Terrain: open country							

The extreme and mean peak wind pressure coefficients for the high edge are close to those for the high corner on the middle spans of sawtooth roofs. For the high edge zones on all middle spans of the sawtooth roof models, the extreme peak negative wind pressure coefficients range from -2.25 to -2.48 and the mean peak wind pressure coefficients range from -1.7 to -1.9. The extreme peak negative wind pressure coefficients for the high corners range from -2.0 to -2.4

and the mean peak wind pressure coefficients for high corners range from -1.66 to -2.0. The highest RMS value of the peak negative wind pressure coefficients for both the high corner and high edge zones is 0.32 for all middle spans of the sawtooth roofs. This indicates that on middle spans of sawtooth roofs the high corner and high edge zones can be attributed to one pressure zone with same design wind pressure coefficient.

The mean peak negative wind pressure coefficients in the low edge range from -1.0 to -1.3, which are lower than the mean values recorded on the high edge by at least 20%. However, the peak values on both the high edge and low edge zones are very close. The extreme peak negative wind pressure coefficients for the high edges on all middle spans is -2.50 as compared to the value of -2.73 for the low edge. The RMS wind pressure coefficients for low edge are up to 0.46 as compared to the highest RMS value of 0.30 for the high edge. This indicates wind pressure coefficients for pressure taps at the low edge are distributed over a significantly larger range than on the high edge of a middle span.



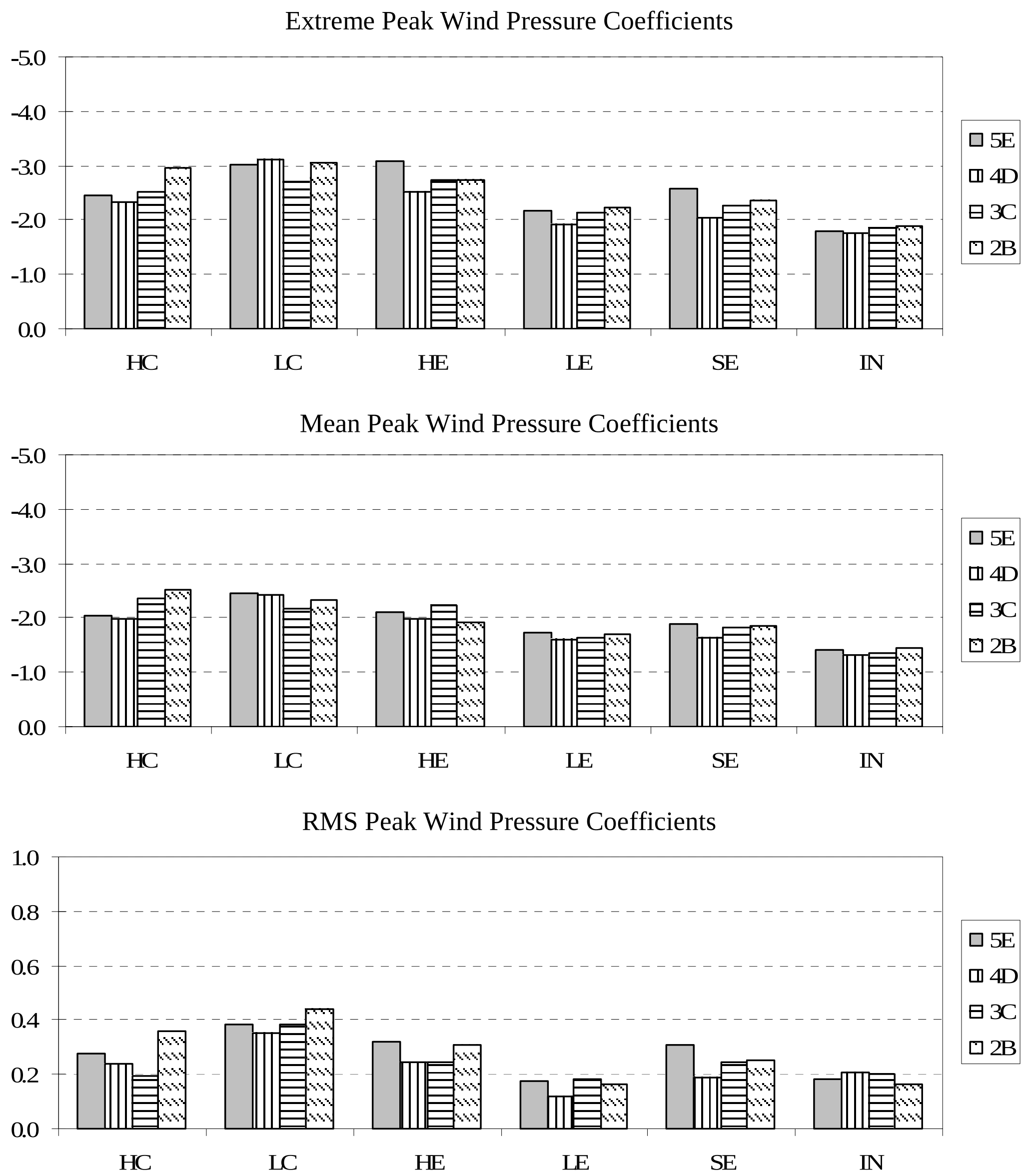
(Building height: 16.1 m; Terrain: open country)

Figure 4.12 Comparisons of Peak Negative Cp for All Pressure Taps on Middle Spans of Sawtooth Roofs

Fig. 4.12 presents the comparisons of peak negative wind pressure coefficients for all pressure taps on the middle spans of the sawtooth roofs. By using linear regression it can be concluded that the average peak negative wind pressure coefficients for the middle spans of the sawtooth roofs are similar to each other with a difference less than 10%.

4.4.1.2.3 Leeward Spans of Sawtooth Roofs

Fig.4.13 presents comparisons of peak negative wind pressure coefficients for each zone on the leeward spans of sawtooth roofs. The detailed statistical values are shown in Table 4.12. The extreme peak negative wind pressure coefficient for the leeward spans of sawtooth roofs occurs at the low corner, and the most critical negative wind pressure coefficient observed on all leeward spans is -3.11. However, the extreme peak negative wind pressure coefficients for the high corner, low corner and the high edge on leeward spans are similar to one another with a difference of less than 5%. Compared to the wind pressure coefficients for the corners and high edge, the extreme peak negative wind pressure coefficients for the sloped edge, low edge and interior are rather low with values of -2.59, -2.23 and -1.88 respectively. The variation of peak negative wind pressure coefficients for each pressure zone is less than 21% between different leeward spans, which is less than the variation of wind pressure coefficients for the other spans between different sawtooth roofs.



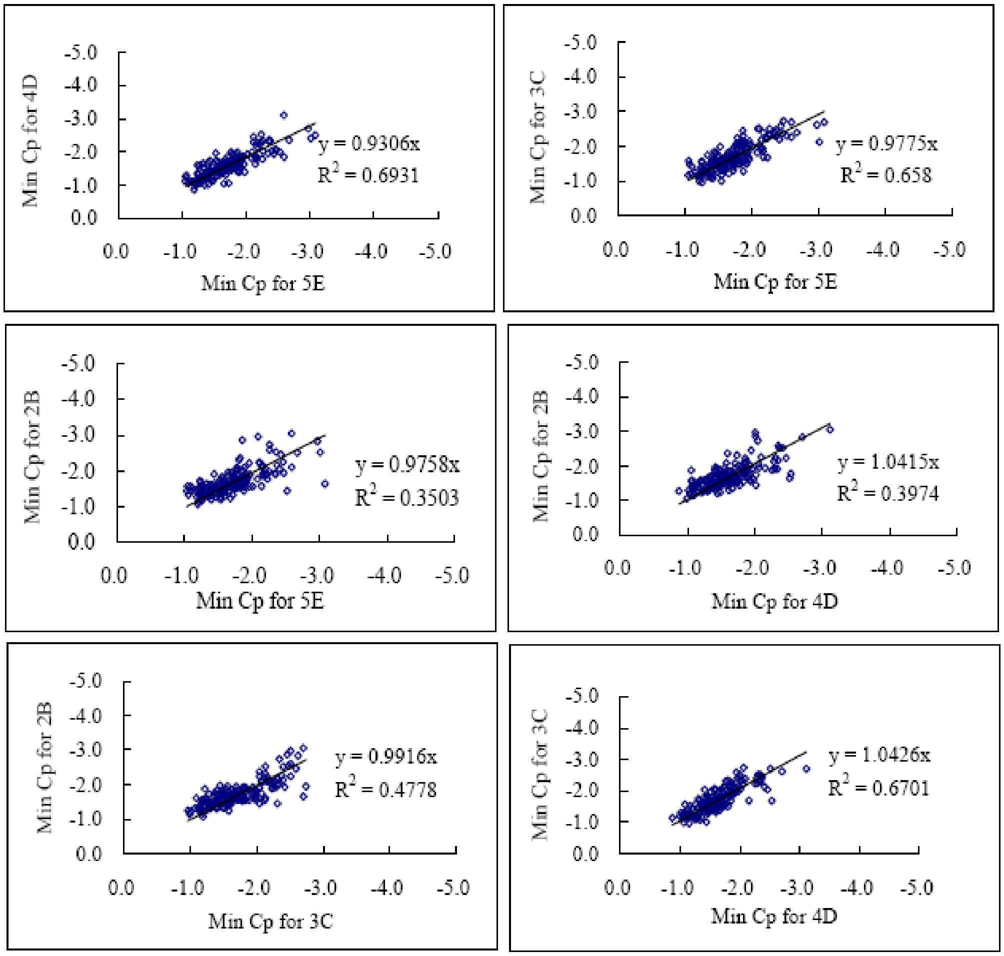
(Building height: 16.1 m; Terrain: open country)

Figure 4.13 Comparisons of Statistical Values of Peak Negative Cp for Leeward Spans of Sawtooth Roofs

Table 4.12 Statistical Values of Peak Negative Cp for Leeward Spans of Sawtooth Roofs

Zone	Statistics	5E	4D	3C	2B
HC	Extreme	-2.46	-2.34	-2.51	-2.97
	Mean	-2.04	-1.98	-2.35	-2.52
	RMS	0.28	0.24	0.19	0.36
LC	Extreme	-3.01	-3.11	-2.70	-3.06
	Mean	-2.45	-2.43	-2.15	-2.33
	RMS	0.38	0.36	0.38	0.44
HE	Extreme	-3.08	-2.51	-2.74	-2.74
	Mean	-2.10	-1.98	-2.23	-1.93
	RMS	0.32	0.25	0.24	0.31
LE	Extreme	-2.16	-1.92	-2.15	-2.23
	Mean	-1.74	-1.61	-1.64	-1.69
	RMS	0.17	0.12	0.18	0.16
SE	Extreme	-2.59	-2.05	-2.27	-2.37
	Mean	-1.88	-1.64	-1.84	-1.84
	RMS	0.31	0.19	0.25	0.25
IN	Extreme	-1.80	-1.77	-1.84	-1.88
	Mean	-1.40	-1.32	-1.37	-1.46
	RMS	0.18	0.21	0.20	0.17
Note: Building height: 16.1 m; Terrain: open country					

Fig. 4.14 presents comparisons of peak negative wind pressure coefficients for all pressure taps on the leeward spans of sawtooth roofs. Linear regression is also used to determine the average variation of the middle spans. On average, the difference of peak negative wind pressure coefficients between two leeward spans is less than 10%.



(Building height: 16.1 m; Terrain: open country)

Figure 4.14 Comparisons of Peak Negative Cp for All Pressure Taps on Leesward Spans of Sawtooth Roofs

4.4.1.3 Peak Positive Wind Pressure Coefficients

Maximum and minimum values of extreme peak and mean positive wind pressure coefficients for each pressure zones on 2- to 5-span sawtooth roofs are shown in Table 4.13. Maxima and minima of peak and mean positive wind pressure coefficients for each pressure zone on the monosloped roof are also presented below for comparison with sawtooth roofs.

Table 4.13 Statistical Values of Peak Positive Cp for Monosloped Roof and 2- to 5-Span Sawtooth roofs

	Windward Spans		Middle Spans		Leeward Spans		Monosloped Roof
Zone	Extreme Peak Local Wind Pressure Coefficients						Extreme
	Max	Min	Max	Min	Max	Min	
HC	0.77	0.52	0.75	0.54	0.51	0.39	0.47
LC	1.12	0.95	1.42	1.04	0.63	0.60	0.73
HE	0.92	0.64	0.91	0.71	0.69	0.55	0.83
LE	1.07	0.72	1.88	1.20	0.63	0.60	0.72
SE	0.91	0.72	0.94	0.70	0.53	0.43	0.62
IN	1.28	0.90	1.20	0.99	0.77	0.63	0.95
Zone	Mean Peak Local Wind Pressure Coefficients						Mean Peak
	Max	Min	Max	Min	Max	Min	
HC	0.57	0.43	0.63	0.45	0.35	0.28	0.30
LC	0.88	0.57	0.84	0.71	0.52	0.48	0.56
HE	0.57	0.47	0.61	0.51	0.41	0.36	0.34
LE	0.66	0.54	0.89	0.74	0.40	0.39	0.44
SE	0.54	0.51	0.58	0.54	0.35	0.33	0.39
IN	0.71	0.61	0.69	0.62	0.40	0.37	0.44
Building height: 16.1 m; Terrain : open country							

The low edge of the middle spans of sawtooth roofs is the critical pressure zone. The observed extreme peak positive wind pressure coefficients for the low edge on the middle spans of 3- to 5-span sawtooth roofs is 1.88, while the mean peak positive wind pressure coefficients for the low edge range from 0.74 to 0.89. Within the middle spans, high pressures are also recorded in the low corner and interior. The most critical value for the low corner and interior regions are 1.42 and 1.20 respectively.

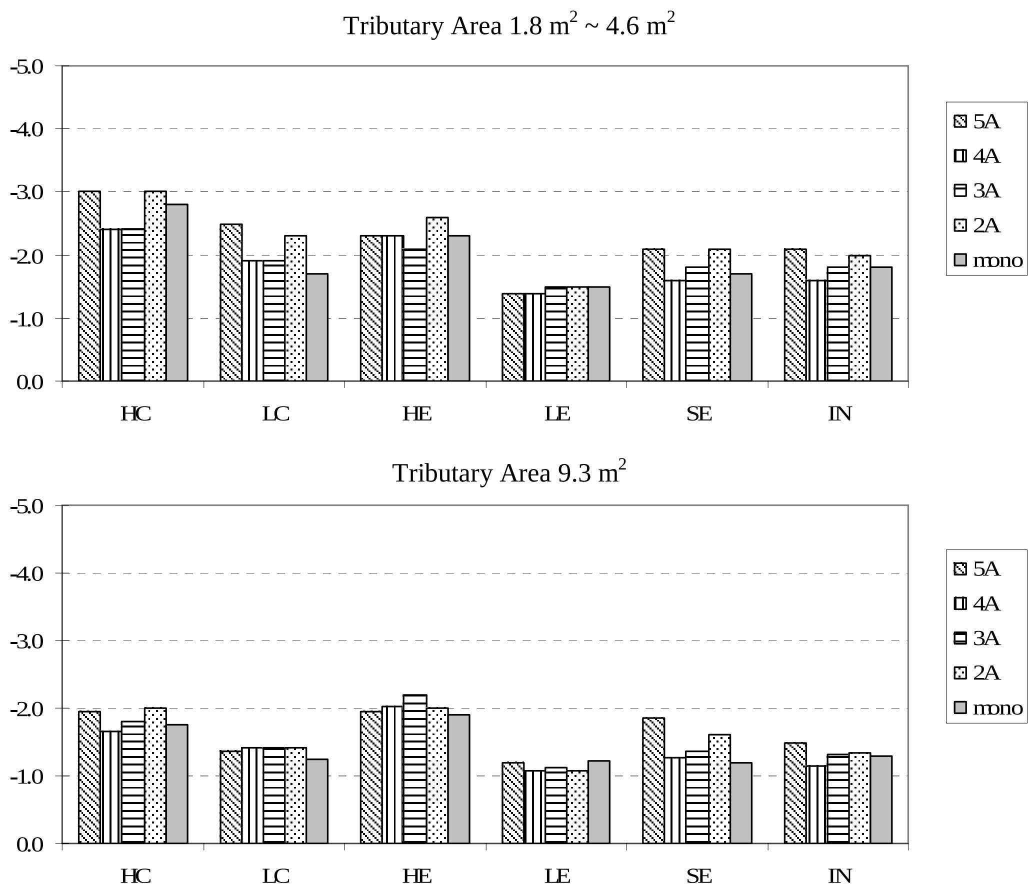
On the windward spans, the high pressures were recorded in the low corner, low edge and interior zones. The most critical positive wind pressure coefficient on the windward spans is 1.28, occurring within the interior zone. The pressures occurring on the leeward spans and on the monosloped roof are found to be lower than on the windward and middle spans of sawtooth roofs. The most critical peak positive wind pressure coefficient on the leeward spans is 0.77. The value for the monosloped roof is 0.95, which is similar to that recorded on leeward spans of the sawtooth roofs.

4.4.1.4 Area-Averaged Wind Pressure Coefficients

The area-averaged wind pressure coefficients were investigated on a 16.1 m high monosloped roof and a 16.1 m high 2- through 5-span sawtooth roof. The area-averaged wind pressure coefficients were calculated for two groups of panels as shown in Fig. 4.3.

4.4.1.4.1 Monosloped Roof and Windward Span of Sawtooth Roofs

The peak area-averaged negative wind pressure coefficients for the 16.1 m high monosloped roof and the windward spans of 16.1 m high 2- to 5-span sawtooth roofs are presented in Fig 4.15. For tributary areas in the range of 1.8 m^2 to 4.6 m^2, the peak wind pressure coefficient occurs on the high corner. The most critical peak value is -3.0, which occurs on the high corners of the windward spans of the 2-span and 5-span sawtooth roofs. However, both peak area-averaged negative wind pressure coefficients for the windward spans of 3-span and 4-span sawtooth roofs are -2.4, which are less than the peak value for the windward spans of the 2- and 5-span sawtooth roofs by 20%. On the low edge, where the peak values on all windward spans are similar to one another, the difference is less than 7%. In all other roof regions, the variation of peak values between any two models range from 19% to 24% of the extreme peak value for the corresponding pressure zones.



(Building height: 16.1 m; Terrain: open country)

Figure 4.15 Peak Negative Area-averaged Cp for Monosloped Roof and Windward Spans of Sawtooth Roofs

As the tributary area increases to 9.3 m^2, the discrepancy of peak negative wind pressure coefficients for any two windward spans of test sawtooth roofs is less than 11% for the low corner, high edge and low edge. Variations of the peak negative wind pressure coefficients for the high corner, sloped edge and interiors, range from 17% to 32% of the extreme peak value for the corresponding pressure zone. The detailed comparisons are shown in Table 4.14.

Table 4.14 Comparisons of Zonal Area-averaged Negative Cp for Monosloped Roof and Windward Spans of Sawtooth Roofs

Model		5A	4A	3A	2A	Mono
Pressure Zones	Area (m^2)	Tributary Area 1.8 m^2 ~ 4.6 m^2				
HC	2.5	-2.96	-2.4	-2.43	-2.98	-2.79
LC	2.1	-2.5	-1.89	-1.9	-2.27	-1.69
HE	3.1	-2.33	-2.29	-2.11	-2.57	-2.32
LE	2.6	-1.42	-1.22	-1.33	-1.27	-1.4
SE	3.5	-2.14	-1.63	-1.64	-1.76	-1.37
IN	4.4	-1.58	-1.57	-1.48	-1.39	-1.45
Pressure Zones	Area (m^2)	Tributary Area 7.4 m^2 ~ 11 m^2				
HC	8.7	-1.95	-1.66	-1.81	-1.99	-1.75
LC	9.6	-1.37	-1.41	-1.41	-1.42	-1.25
HE	7.7	-1.94	-2.02	-2.19	-2	-1.91
LE	8.5	-1.19	-1.06	-1.13	-1.07	-1.21
SE	10.9	-1.85	-1.26	-1.37	-1.62	-1.2
IN	9.7	-1.48	-1.15	-1.32	-1.34	-1.3
Building Height: 16.1 m; Terrain: open country						

Though the area-averaged wind pressure coefficients for most pressure zones on the monosloped roof are similar to those for the windward spans of sawtooth roofs, the values for the monosloped roof are generally lower than those for the windward span of sawtooth roofs. The area-averaged wind pressure coefficients for the high corner and high edge of the monosloped roof are slightly lower than those for the windward span of the sawtooth roofs. The difference is less than 13% of the peak value for the corresponding pressure zone of the windward span in the sawtooth roofs. The peak area-averaged negative wind pressure coefficients, for the low edge of the monosloped roof, are identical to the values for the low edge of the windward span of sawtooth roofs. Regarding the interior, the area-averaged wind pressure coefficient for the monosloped roof is 14% lower than that for the windward span of sawtooth roofs. Of particular note is the observation that the area-averaged wind pressure coefficients for the sloped edge and low corner of the monosloped roof are significantly lower than those for the windward span of sawtooth roofs by up to 30%.

The increase in area significantly reduces wind pressure coefficients. For the windward span of the sawtooth roofs, the critical negative wind pressure coefficient for the high corner is reduced by 35% with the tributary area increasing to 2.5 m^2 (-4.61 versus -2.98). For the tributary area of 8.7 m^2 the peak negative wind pressure coefficient for the high corner is -2.0. In the low corner, the peak negative value with tributary area of 2.1 m^2 is -2.5 and the value with tributary area of 9.6 m^2 is -1.42. The reduction from the peak local negative wind pressure coefficient of -3.97 is 37% and 64% for the tributary areas 2.1 m^2 and 9.6 m^2 respectively. In general, for windward span of the sawtooth roofs, the reduction of local peak negative wind pressure coefficient with an increase in the tributary area of 1.8 m^2 ~ 4.6 m^2 is in the range of 25% to 50%. When the tributary area increases to 7.4 m^2 ~ 15.8 m^2, the reduction is between 36% and 64%. The peak local and area-averaged wind pressure coefficients for both the monosloped roof and the windward span of sawtooth roofs are showed in Table 4.15. Reduction rates of peak negative wind pressure coefficients with tributary areas are also shown there.

Table 4.15 Extreme Local and Area-averaged Negative Cp for Monosloped Roof and Windward Span of Sawtooth Roof

Monosloped Roof							
Zone	Local Cp	Area averaged Cp					
		Area(m^2)	Cp	Reduction	Area (m^2)	Cp	Reduction
HC	-4.22	2.5	-2.79	34%	8.7	-1.75	59%
LC	-2.73	2.1	-1.69	38%	9.6	-1.25	54%
HE	-3.11	3.1	-2.32	25%	7.7	-1.91	39%
LE	-1.97	2.6	-1.4	29%	8.5	-1.21	39%
SE	-2.34	3.5	-1.37	41%	10.9	-1.2	49%
IN	-2.17	4.4	-1.45	33%	9.7	-1.3	40%
Windward Span of Sawtooth Roof							
Zone	Local Cp	Area averaged Cp					
		Area(m^2)	Cp	Reduction	Area (m^2)	Cp	Reduction
HC	-4.61	2.5	-2.98	35%	8.7	-1.99	57%
LC	-3.97	2.1	-2.5	37%	9.6	-1.42	64%
HE	-3.42	3.1	-2.57	25%	7.7	-2.19	36%
LE	-1.79	2.6	-1.42	21%	8.5	-1.13	37%
SE	-3.09	3.5	-2.14	31%	10.9	-1.85	40%
IN	-3.19	4.4	-1.58	50%	9.7	-1.48	54%
Building height: 16.1 m; Terrain: open country							

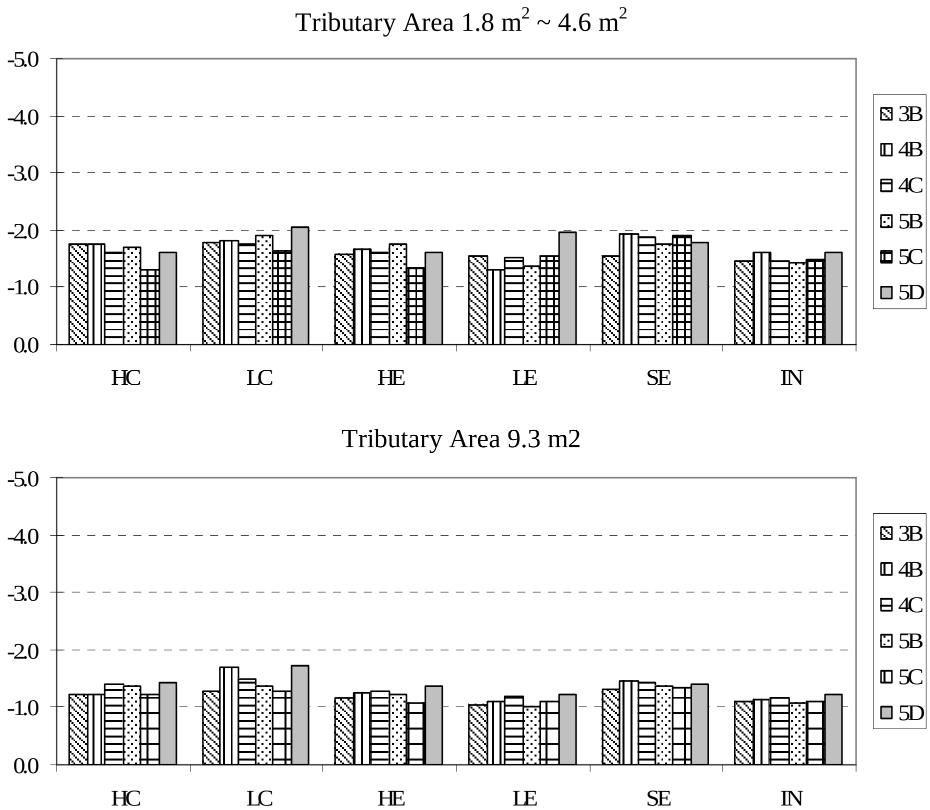
The peak local and area-averaged positive wind pressure coefficients for the monosloped roof and the windward spans of sawtooth roofs are showed in Table 4.16. For the monosloped roof, the peak positive pressure coefficients are reduced to 0.2 ~ 0.5 when the tributary area increases to the range of 1.8 m^2 ~ 4.6 m^2. The peak value, occurring in the low edge and the low corner, is 0.46. For the windward span of the sawtooth roofs, the values fall in the range of 0.37 ~ 0.83 when tributary area increases to 1.8 m^2 ~ 4.6 m^2. As the tributary area increases to 9 m^2, the peak positive area-averaged wind pressure coefficient for the monosloped roof reduces to 0.41 for both the low edge and the low corner. On the windward span of sawtooth roofs, the 9 m^2 area-averaged positive wind pressure coefficients fall in the range of 0.3 ~ 0.5 with the peak value occurring at the low edge.

Table 4.16 Comparisons of Peak Local and Area-averaged Positive Cp for Monosloped Roof and Windward Spans of Sawtooth Roofs

Model		5A	4A	3A	2A	mono
Pressure Zones		Local Value				
HC		1.05	0.76	0.71	1	0.59
LC		1.12	0.97	0.95	1.1	0.73
HE		0.92	0.8	0.91	0.92	0.83
LE		1.28	0.9	0.94	0.95	0.95
SE		1.11	0.7	0.78	0.82	0.62
IN		1.12	0.97	1.03	1.1	0.73
Zone	Area(m^2)	Tributary Area 1.8 m^2 ~ 4.6 m^2				
HC	2.5	0.41	0.46	0.54	0.48	0.27
LC	2.1	0.83	0.42	0.55	0.62	0.46
HE	3.1	0.52	0.56	0.57	0.52	0.35
LE	2.6	0.63	0.44	0.46	0.7	0.46
SE	3.5	0.37	0.41	0.36	0.46	0.26
IN	4.4	0.45	0.34	0.33	0.43	0.24
Zone	Area(m^2)	Tributary Area 7.4 m^2 ~ 11 m^2				
HC	8.7	0.27	0.27	0.31	0.31	0.14
LC	9.6	0.43	0.22	0.15	0.27	0.41
HE	7.7	0.28	0.36	0.31	0.34	0.11
LE	8.5	0.48	0.37	0.31	0.44	0.41
SE	10.9	0.28	0.24	0.25	0.18	0.16
IN	9.7	0.22	0.22	0.29	0.31	0.19
Building height: 16.1 m; Terrain: open country						

4.4.1.4.2 Middle Spans of Sawtooth Roofs

Fig. 4.16 presents the peak negative area-averaged wind pressure coefficients for pressure zones in the middle spans of 3- to 5-span sawtooth roofs. Between these two middle spans, the variation of the peak negative wind pressure coefficients for a pressure zone ranges from 10% to 34%. The most critical area-averaged wind pressure coefficient on a middle span occurs at the low corner or the sloped edge.



(Building height: 16.1 m; Terrain: open country)

Figure 4.16 Peak Negative Area-averaged Cp for Middle Spans of Sawtooth Roofs

The peak local and area-averaged negative wind pressure coefficients for all middle spans of the sawtooth roofs are presented in Table 4.17. The tributary areas of 1.8 m^2 ~ 4.6 m^2 reduce the peak local negative wind pressure coefficients by a factor of 26% to 49%. When the tributary area increases to 9.3 m^2, the reduction rate falls between 40% and 62%.

Table 4.17 Extreme Local and Area-averaged Negative Cp for Middle Spans of Sawtooth Roof

Model	Middle Spans	Area averaged Cp					
Zone	Local Cp[1]	Area(m^2)	Cp[2]	([1]-[2])/[1]	Area(m^2)	Cp[3]	([1]-[3])/[1]
HC	-2.4	2.5	-1.77	26%	8.7	-1.44	40%
LC	-3.6	2.1	-2.05	43%	9.6	-1.72	52%
HE	-2.5	3.1	-1.75	30%	7.7	-1.38	45%
LE	-2.73	2.6	-1.97	28%	8.5	-1.21	56%
SE	-3.78	3.5	-1.94	49%	10.9	-1.45	62%
IN	-2.45	4.4	-1.62	34%	9.7	-1.23	50%
Building height: 16.1 m; Terrain: open country							

Table 4.18 Extreme Local and Area-averaged Positive Cp for Middle Spans of Sawtooth Roof

Model	Middle Spans	Area averaged Cp					
Zone	Local Cp[1]	Area(m^2)	Cp[2]	([1]-[2])/[1]	Area(m^2)	Cp[3]	([1]-[3])/[1]
HC	0.94	2.5	0.6	36%	8.7	0.34	64%
LC	1.42	2.1	1.09	23%	9.6	0.6	58%
HE	1.2	3.1	0.64	47%	7.7	0.36	70%
LE	1.53	2.6	0.93	39%	8.5	0.71	54%
SE	0.92	3.5	0.5	46%	10.9	0.37	60%
IN	1.11	4.4	0.52	53%	9.7	0.37	67%
Building height: 16.1 m; Terrain: open country							

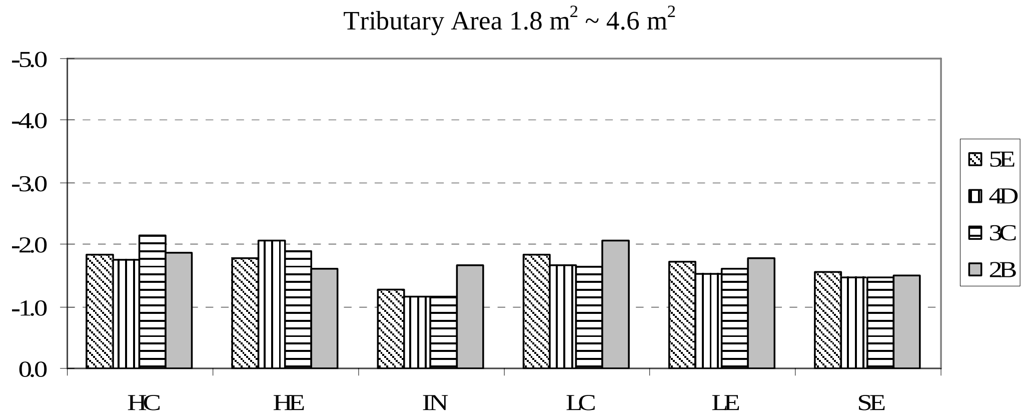
Table 4.18 shows peak local and area-averaged positive wind pressure coefficients for all middle spans of the sawtooth roofs. The most critical positive wind pressure coefficient for the middle spans occurs in the low edge or low corner. The most critical positive wind pressure coefficient with tributary area of 2.1 m^2 is 1.1. The peak value drops to 0.71 when the tributary area increases to 9 m^2.

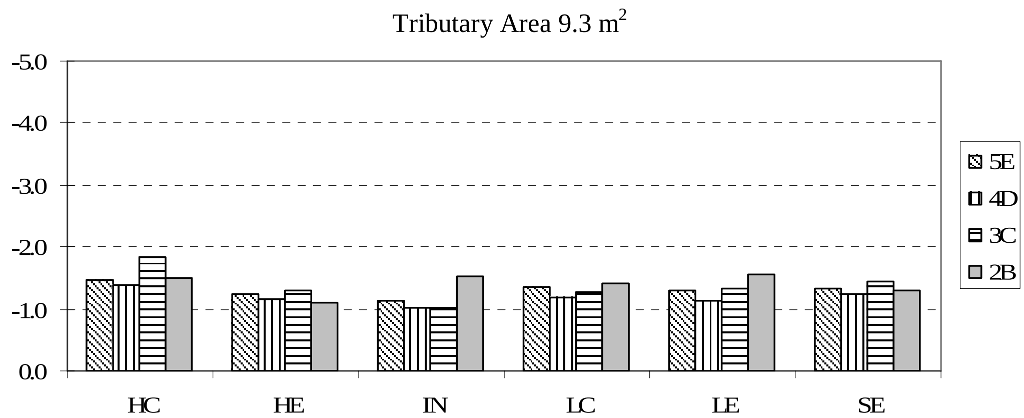
4.4.1.4.3 Leeward Spans of Sawtooth Roofs

In Fig. 4.17, the peak area-averaged wind pressure coefficients are compared between leeward spans, showing a variation of peak value for a pressure zone between two sawtooth roofs of up to 30%. For example, in the high corner the peak area-averaged negative wind pressure coefficients with 2.5 m^2 tributary area range from -1.76 to -2.15. As the tributary area increases to 8.7 m^2, the peak area-averaged negative wind pressure coefficients range from -1.39 to -1.83.

Table 4.19 shows the peak values of local and area-averaged negative wind pressure coefficients for all leeward spans. The tributary area ranging from 1.8 m^2 to 4.6 m^2 causes a reduction of 11% ~ 34% to the local peak negative wind pressure coefficient for a pressure zone. When the tributary area increases to 9.3 m^2, the peak negative wind pressure coefficients decrease by 19% ~ 58% in this pressure zone. The local and small tributary area negative wind pressure coefficients for the high corner, low corner and high edge are quite close to one another, with a maximum difference in wind pressure coefficient of less than 5% between them.

Spatially averaging can also significantly reduce peak positive wind pressure coefficients for leeward spans, as shown in Table 4.20. The most critical coefficient value with tributary area of 2.1 m^2 is 0.4, which is 37% lower than the local peak value in the same pressure zone. When the tributary area increases to 9.3 m^2, the positive wind pressure coefficient falls to 0.34.





(Building height: 16.1 m; Terrain: open country)

Figure 4. 17 Peak Area-averaged Negative Cp for Leeward Spans of Sawtooth Roofs

Table 4.19 Extreme Local and Area-averaged Negative Cp for Leeward Spans of Sawtooth Roof

Model	Leeward Spans	Area averaged Cp					
Zone	Local Cp[1]	Area(m^2)	Cp[2]	([1]-[2])/[1]	Area(m^2)	Cp[3]	([1]-[3])/[1]
HC	-2.97	2.5	-2.15	28%	8.7	-1.83	38%
LC	-3.11	2.1	-2.06	34%	9.6	-1.4	55%
HE	-3.08	3.1	-2.05	33%	7.7	-1.3	58%
LE	-2.23	2.6	-1.78	20%	8.5	-1.56	30%
SE	-2.16	3.5	-1.55	28%	10.9	-1.43	34%
IN	-1.88	4.4	-1.68	11%	9.7	-1.52	19%
Building height: 16.1 m; Terrain: open country							

Table 4.20 Extreme Local and Area-averaged Positive Cp for Leeward Spans of Sawtooth Roof

Model	Leeward Spans	Area averaged Cp					
Zone	Local Cp[1]	Area(m^2)	Cp[2]	([1]-[2])/[1]	Area(m^2)	Cp[3]	([1]-[3])/[1]
HC	0.51	2.5	0.23	55%	8.7	0.15	71%
LC	0.63	2.1	0.4	37%	9.6	0.34	46%
HE	0.68	3.1	0.36	47%	7.7	0.19	72%
LE	0.77	2.6	0.33	57%	8.5	0.26	66%
SE	0.63	3.5	0.34	46%	10.9	0.26	59%
IN	0.63	4.4	0.24	62%	9.7	0.19	70%
Building height: 16.1 m; Terrain: open country							

4.4.1.5 Summary

The experimental studies discussed in this section provide detailed results of the local and area-averaged wind pressure coefficients for a monosloped roof and 2- through 5-span sawtooth roofs under open country exposure. Typical local and area-averaged wind pressure coefficients for the monosloped and sawtooth roofs with 16.1 m mean roof height are summarized in Table 4.21 and Table 4.22 below. Zonal peak local and area-averaged wind pressure coefficients for the monosloped roof and for windward, middle, and leeward spans on sawtooth roofs are compared in Figure 4.18.

Table 4.21 Summary of Extreme Negative Cp for Monosloped and Sawtooth Roofs

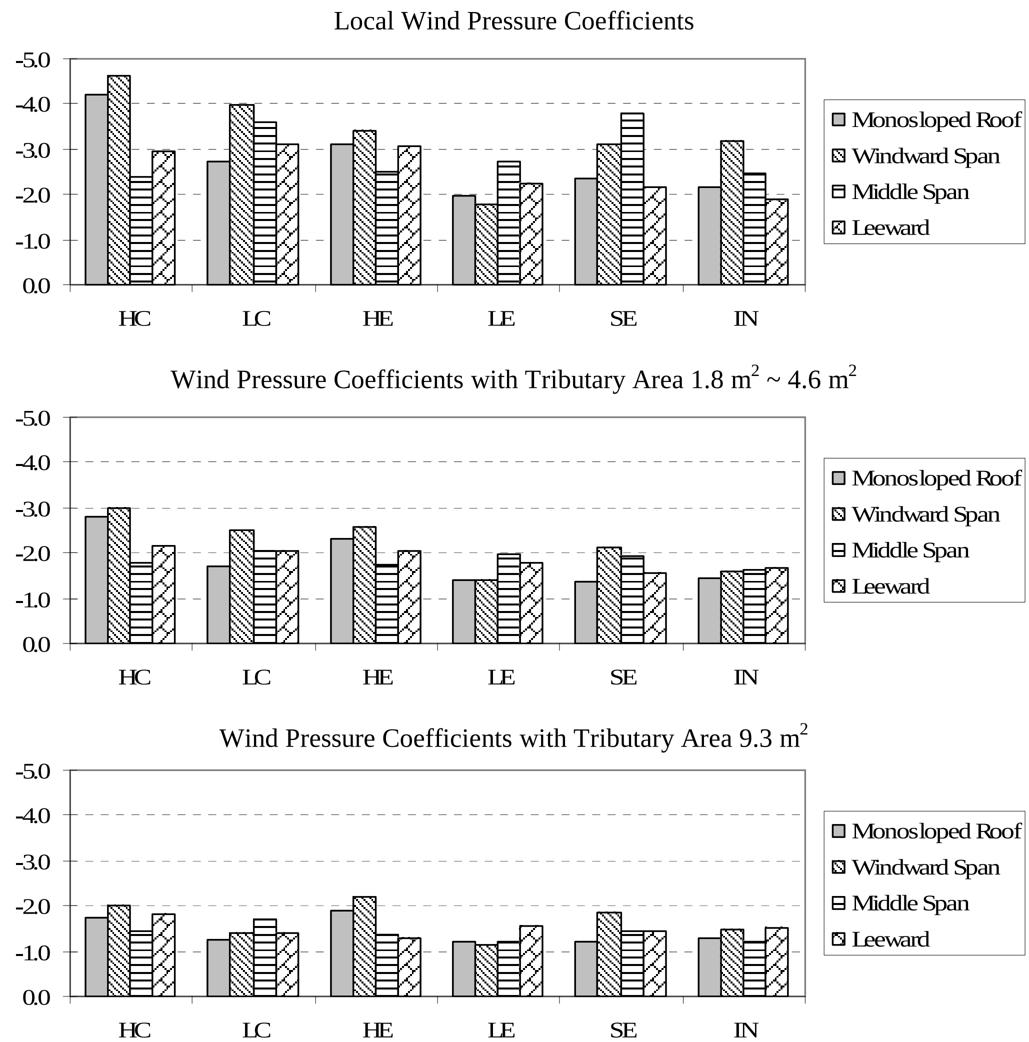
Local Wind Pressure Coefficients					
Location		Monosloped Roof	Sawtooth Roofs		
			Windward Span	Middle Span	Leeward Span
HC		-4.22	-4.61	-2.4	-2.97
LC		-2.73	-3.97	-3.6	-3.11
HE		-3.11	-3.42	-2.5	-3.08
LE		-1.97	-1.79	-2.73	-2.23
SE		-2.34	-3.09	-3.78	-2.16
IN		-2.17	-3.19	-2.45	-1.88
Area-averaged Wind Pressure Coefficients with Averaging Area of 1.8 m^2 ~ 4.6 m^2					
Zone	Area(m^2)	Monosloped Roof	Sawtooth Roofs		
			Windward Span	Middle Span	Leeward Span
HC	2.5	-2.79	-2.98	-1.77	-2.15
LC	2.1	-1.69	-2.5	-2.05	-2.06
HE	3.1	-2.32	-2.57	-1.75	-2.05
LE	2.6	-1.4	-1.42	-1.97	-1.78
SE	3.5	-1.37	-2.14	-1.94	-1.55
IN	4.4	-1.45	-1.58	-1.62	-1.68
Area-averaged Wind Pressure Coefficients with Averaging Area of 9.3 m^2					
Zone	Area(m^2)	Monosloped Roof	Sawtooth Roofs		
			Windward Span	Middle Span	Leeward Span
HC	8.7	-1.75	-1.99	-1.44	-1.83
LC	9.6	-1.25	-1.42	-1.72	-1.4
HE	7.7	-1.91	-2.19	-1.38	-1.3
LE	8.5	-1.21	-1.13	-1.21	-1.56
SE	10.9	-1.2	-1.85	-1.45	-1.43
IN	9.7	-1.3	-1.48	-1.23	-1.52
Building height: 16.1 m; Terrain: open country					

Table 4.22 Summary of Extreme Positive Cp for Monosloped and Sawtooth Roofs

Local Wind Pressure Coefficients				
Zone	Monosloped Roof	Sawtooth Roofs		
		Windward Span	Middle Span	Leeward Span
HC	0.59	1.05	0.94	0.51
LC	0.73	1.12	1.2	0.63
HE	0.83	0.92	1.11	0.68
LE	0.95	1.28	1.42	0.77
SE	0.62	1.11	1.53	0.63
IN	0.73	1.12	0.92	0.63

Area-averaged Wind Pressure Coefficients with Averaging Area of 1.8 m^2 ~ 4.6 m^2					
Zone	Area(m^2)	Monosloped Roof	Sawtooth Roofs		
			Windward Span	Middle Span	Leeward Span
HC	2.5	0.41	0.54	0.6	0.23
LC	2.1	0.83	0.83	0.64	0.4
HE	3.1	0.52	0.57	0.52	0.36
LE	2.6	0.63	0.7	1.09	0.33
SE	3.5	0.37	0.46	0.93	0.34
IN	4.4	0.45	0.45	0.5	0.24

Area-averaged Wind Pressure Coefficients with Averaging Area of 9.3 m^2					
Zone	Area(m^2)	Monosloped Roof	Sawtooth Roofs		
			Windward Span	Middle Span	Leeward Span
HC	8.7	0.27	0.31	0.34	0.15
LC	9.6	0.43	0.43	0.36	0.34
HE	7.7	0.28	0.36	0.37	0.19
LE	8.5	0.48	0.48	0.6	0.26
SE	10.9	0.28	0.28	0.71	0.26
IN	9.7	0.22	0.31	0.37	0.19
Building height: 16.1 m; Terrain: open country					



(Building height: 16.1 m; Terrain: open country)

Figure 4.18 Comparisons of Peak Local and Area-averaged Cp for Monosloped Roof and Sawtooth Roofs

1. The highest suction occurs within the high corner of the windward span. While the low corners and sloped edges of all spans are also high suction zones, the suction occurring on these pressure zones is lower than on the high corner of windward span.
2. The peak suctions on the middle spans of a sawtooth roof occur at the low corner and sloped edge. The wind pressure coefficients for these

zones are higher than those for the other pressure zones on middle spans by 30%. The wind pressure coefficient for the high corner is similar to that for the high edge on the middle spans.

3. The change of number of spans on a sawtooth roof can cause local and area-averaged wind pressure coefficients change with a maximum variation of more than 30%.
4. The extreme local negative wind pressure coefficient for a monosloped roof is identical to that for the windward span of a sawtooth roof possessing identical geometric characteristics with the monosloped roof. However, the extreme area-averaged negative wind pressure coefficient for the monosloped roof is slightly lower than that for windward span of sawtooth roofs, with the tributary area between 2 m^2 ~ 9 m^2.
5. Positive wind pressure coefficients for the windward and middle spans on a sawtooth roof are significantly higher than for the leeward span of the sawtooth roof. The extreme positive wind pressure coefficient is more than 1.5 on the windward and middle spans as compared the value of less than 1.0 for the leeward span. Positive wind pressure coefficients for the monosloped roof are similar with those on the leeward span of sawtooth roofs.
6. Spatial averaging sharply reduced wind pressure coefficients; even a small tributary area such as 2.8 m^2 causes more than a 30% reduction of the local wind pressure coefficient.

4.4.2 Effect of Building Height

The effect of building height on wind pressure coefficients for monosloped and sawtooth roofs were studied by wind tunnel tests on models with three heights of 7.0 m, 11.6 m and 16.1 m under open country exposure. A full description of the test procedures and setup is provided in Chapter 3. The building models were installed on the turntable in the wind tunnel and the wind pressure coefficients were measured for 19 wind directions ranging from 90^o to 270^o in 10^o increments.

The study evaluates the effect of building height on wind pressure coefficient referenced in two ways, namely a) with respect to reference wind speed in the wind tunnel, and b) with respect to the 3-second gust wind speed at the mean roof height of the building. Unless, specifically noted, the wind pressure coefficients in this study are referenced to the mean dynamic wind pressure at the reference height of the wind tunnel.

4.4.2.1 Monosloped Roofs

The contours of local negative wind pressure coefficients are obtained from statistical analysis of results from the 170 pressure taps distributed on one half of the roof area (approximately 7.9m by 14.9 m at full-scale). The contours of peak values are plotted to display the distributions of the wind pressure coefficients for the three heights of monosloped roofs as shown in Fig. 4.19. It can be seen that high suction area in high corner zone increases with the building height. However, there is little difference (less than 5%) among the extreme peak negative wind pressure coefficients observed on the three roof heights.

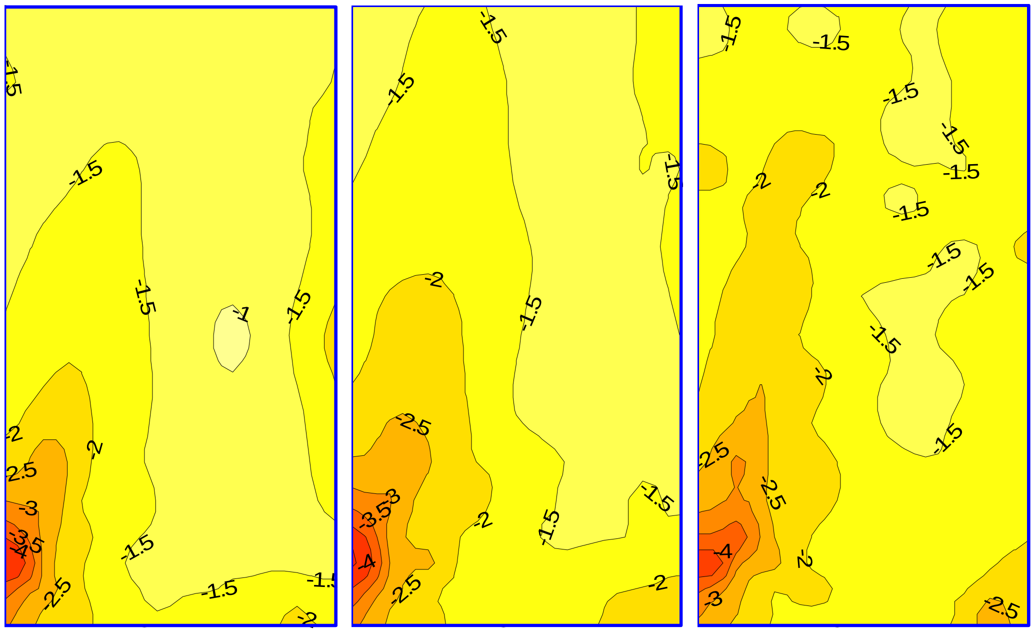


Figure 4.19 Contours of Local Negative Cp for One-half Roof of Three Monosloped Roof Heights under Open Exposure
(Note: High Edge is at Left Side).

Table 4.23 Extreme Negative Cp for Three Monosloped Roof Heights under Open Country Exposure

Zone \ Height	7.0 m	11.6 m	16.1 m
HC	-4.14	-4.07	-4.22
LC	-2.08	-2.35	-2.73
HE	-2.85	-2.87	-3.11
LE	-1.9	-2.07	-1.97
SE	-2.1	-2.12	-2.34
IN	-2.13	-2.57	-2.61

The zonal extreme peak negative wind pressure coefficients on the three monosloped roofs are shown in Table 4.23. While it is evident that the zonal peak values increase with building height increasing, the increase of peak values for the high corner, high edge, sloped edge, and the low edge is insignificant. In these pressure zones, the maximum variation between peak negative pressure coefficients for different models is less than 12%. The large increase of wind pressure coefficients occurs at the low corner and sloped edge by more than 30% as the building height increases from 7.0 m to 16.1 m.

Table 4.24 Mean and RMS Peak Negative Cp for Three Monosloped Roof Heights under Open Exposure

	Mean			RMS		
Zone \ Height	7.0 m	11.6 m	16.1 m	7.0 m	11.6 m	16.1 m
HC	-3.06	-3.11	-3.16	0.48	0.50	0.56
LC	-1.68	-2.02	-2.21	0.21	0.26	0.29
HE	-1.74	-1.93	-2.01	0.49	0.50	0.41
LE	-1.43	-1.56	-1.67	0.19	0.21	0.11
SE	-1.68	-1.78	-1.86	0.22	0.18	0.23
IN	-1.45	-1.70	-1.77	0.33	0.39	0.32

Table 4.24 shows the mean and RMS peak negative wind pressure coefficients for the six pressure zones on the three heights of monosloped roof models. The change of mean peak wind pressure coefficients reflects the general trend of wind pressure coefficient change with building height. In the highest suction zone, high corner (HC), the mean peak values are very close for these three models; the maximum difference between them is only 3.17%. However, in other zones, the increasing of mean peak negative wind pressure coefficients ranges from 11% to 32% as building height increases from 7.0 m to 16.1 m. The largest increase occurs at the low corner (LC).

The comparison of extreme wind pressure coefficients indicates that building height does not significantly affect the most critical peak negative wind pressure coefficients for monosloped roofs. However, except for high corner most zonal wind pressure coefficients will increase significantly with the increasing of building height. The largest increase of zonal wind pressure coefficient is more than 30%.

Table 4.25 Critical Peak Positive Cp for Three Monosloped Roof Heights under Open Exposure

Zone \ Height	7.0 m	11.6 m	16.1 m
HC	0.14	0.13	0.59
LC	0.33	0.38	0.73
HE	0.26	0.29	0.73
LE	0.49	0.4	0.72
SE	0.25	0.29	0.62
IN	0.32	0.39	0.8

Table 4.26 Mean and RMS Peak Positive Cp for Three Monosloped Roofs Heights under Open Exposure

	Mean			RMS		
Zone \ Height	7.0 m	11.6 m	16.1 m	7.0 m	11.6 m	16.1 m
HC	0.08	0.09	0.34	0.04	0.03	0.09
LC	0.27	0.29	0.47	0.04	0.04	0.09
HE	0.04	0.09	0.37	0.07	0.06	0.06
LE	0.31	0.27	0.40	0.06	0.06	0.11
SE	0.19	0.20	0.45	0.04	0.04	0.11
IN	0.20	0.24	0.44	0.06	0.06	0.11

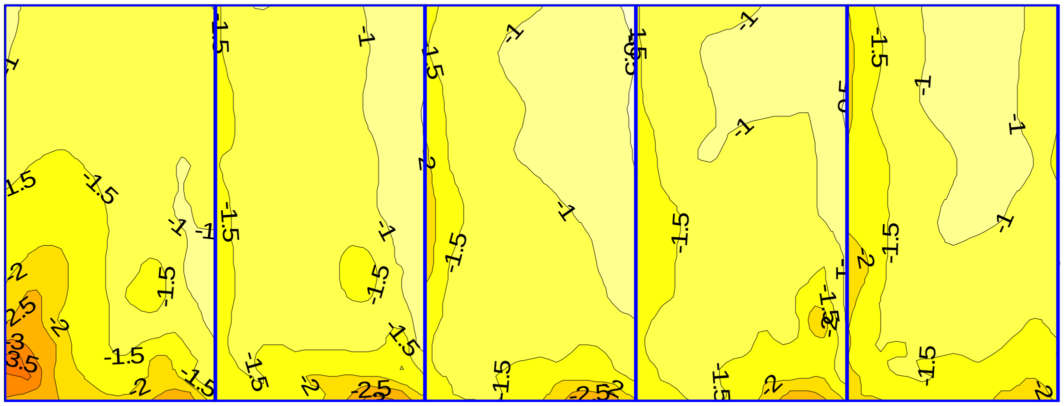
Table 4.25 and Table 4.26 show maximum and mean peak positive wind pressure coefficients for six pressure zones on the three monosloped roof heights. Both maximum and mean peak positive wind pressure coefficients increase with an increase in building height. It should be noted that the pressures on the 16.1 m high model are more than those on the 7.0 m and 11.6 m models. The maximum

peak positive wind pressure coefficients for all pressure zones range from 0.59 to 0.8 for the 11.6 m monosloped roof. However, for the 7.0 m and 11.6 m monosloped roofs, the maximum peaks only range from 0.13 to 0.49.

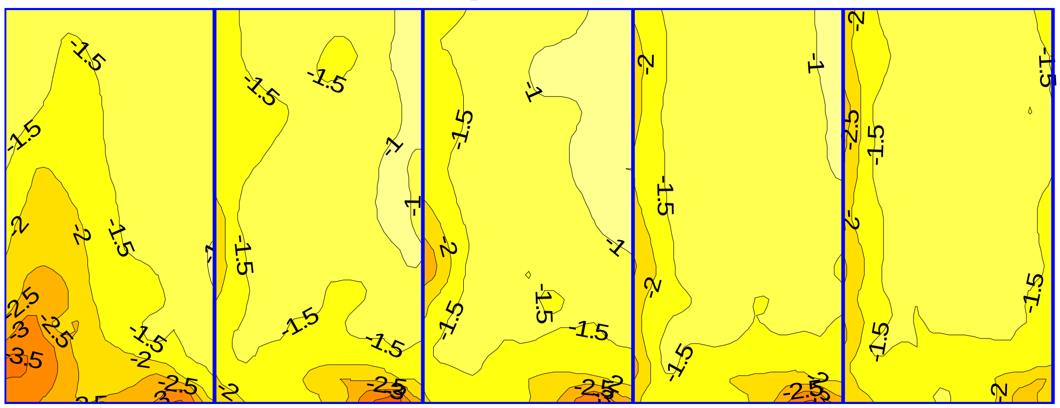
4.4.2.2 Sawtooth Roofs

Fig. 4.20 shows the contours of peak local negative wind pressure coefficients on the one half roof section of 7.0 m, 11.6 m and 16.1 m high 5-span sawtooth roofs. By comparing the contours of three sawtooth roof heights the same conclusion can be obtained with the monosloped roof; the area of high suction region on the roof increases with the increase in building height.

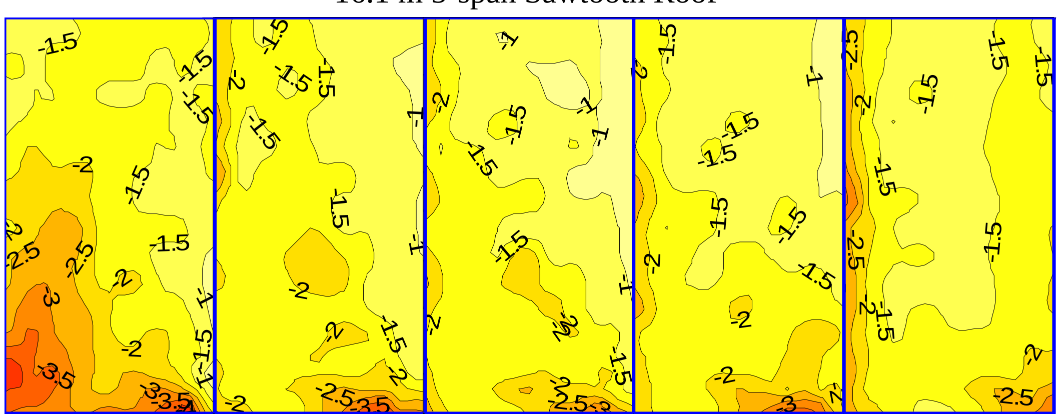
7.0 m 5-span Sawtooth Roof



11.6 m 5-span Sawtooth Roof



16.1 m 5-span Sawtooth Roof



(Note: High edge of span is at left)

Figure 4.20 Contours of Local Negative Cp for One-half Roof of Three Sawtooth Roof Heights under Open Exposure

Table 4.27 Extreme and Mean, RMS Peak Negative Cp for Sawtooth Roofs under Open Country Exposure

	Extreme			Mean			RMS		
Height	7.0 m	11.6 m	16.1 m	7.0 m	11.6 m	16.1 m	7.0 m	11.6 m	16.1 m
Zonal (Windward Span, A)									
HC	-3.79	-3.79	-4.38	-3.18	-3.35	-3.63	0.35	0.22	0.33
LC	-2.58	-3.29	-3.97	-1.88	-2.21	-2.46	0.44	0.65	0.99
HE	-2.61	-2.83	-3.32	-1.56	-1.81	-1.99	0.54	0.56	0.61
LE	-2.08	-2.43	-1.88	-1.25	-1.35	-1.44	0.30	0.33	0.19
SE	-2.55	-3.06	-3.65	-2.14	-2.61	-2.99	0.27	0.27	0.36
IN	-2.57	-3.09	-3.59	-1.64	-1.91	-1.98	0.39	0.53	0.52
Zonal (Middle Spans, B C & D)									
HC	-1.86	-2.26	-2.4	-1.67	-1.89	-2.04	0.13	0.23	0.23
LC	-2.65	-3.4	-3.56	-1.96	-2.34	-2.45	0.40	0.59	0.52
HE	-1.96	-2.53	-2.48	-1.53	-1.76	-2.1	0.21	0.23	0.27
LE	-2.39	-2.38	-2.47	-1.39	-1.36	-1.74	0.45	0.41	0.32
SE	-2.84	-3.15	-3.45	-2.01	-2.16	-1.91	0.37	0.41	0.50
IN	-1.8	-2.05	-2.45	-1.33	-1.49	-1.43	0.23	0.23	0.31
Zonal (Leeward Span, E)									
HC	-2.03	-2.09	-2.46	-1.85	-1.87	-1.92	0.16	0.23	0.25
LC	-2.43	-2.72	-3.01	-1.9	-2.28	-2.38	0.28	0.31	0.38
HE	-2.19	-2.27	-3.08	-1.73	-1.9	-1.82	0.20	0.23	0.34
LE	-2	-2.57	-2.16	-1.42	-1.66	-1.32	0.25	0.33	0.17
SE	-2.02	-2.03	-2.59	-1.69	-1.69	-2.31	0.17	0.19	0.37
IN	-1.65	-1.83	-1.94	-1.23	-1.39	-1.62	0.23	0.18	0.21

Table 4.27 shows extreme and mean values of peak negative wind pressure coefficients for pressure taps in each pressure zone on the studied sawtooth roofs. Again, as the building height increases, both extreme and mean peak negative wind pressure coefficients increase. For most pressure zones, the increase rates of both critical and mean peak values range from 20% to 40% of the extreme peak negative wind pressure coefficients for the 7.0 m model.

Table 4.28 Extreme and Mean, RMS Peak Positive Cp for Sawtooth Roofs under Open Country Exposure

	Extreme			Mean			RMS		
Height	7.0 m	11.6 m	16.1 m	7.0 m	11.6 m	16.1 m	7.0 m	11.6 m	16.1 m
Zonal (Windward Span, A)									
HC	0.66	0.63	0.60	0.36	0.46	0.45	0.14	0.09	0.10
LC	0.95	0.93	1.12	0.68	0.74	0.88	0.19	0.16	0.20
HE	0.58	0.58	0.64	0.34	0.46	0.48	0.09	0.08	0.09
LE	0.95	0.93	1.07	0.60	0.68	0.66	0.15	0.16	0.18
SE	0.5	0.63	0.54	0.41	0.45	0.46	0.06	0.10	0.06
IN	0.68	0.88	1.28	0.52	0.61	0.69	0.12	0.14	0.20
Zonal (Middle Spans, B C & D)									
HC	0.62	0.83	0.75	0.56	0.61	0.83	0.05	0.07	0.09
LC	1.08	0.78	1.13	0.70	0.59	1.13	0.22	0.13	0.23
HE	0.65	0.72	0.89	0.53	0.59	0.89	0.06	0.06	0.10
LE	1.17	0.88	1.88	0.78	0.68	1.88	0.19	0.11	0.27
SE	0.62	0.71	0.77	0.49	0.51	0.77	0.10	0.13	0.10
IN	0.81	0.94	1.11	0.53	0.58	1.11	0.12	0.14	0.14
Zonal (Leeward Span, E)									
HC	0.3	0.32	0.51	0.22	0.27	0.35	0.04	0.05	0.08
LC	0.5	0.65	0.62	0.44	0.50	0.48	0.04	0.06	0.09
HE	0.4	0.43	0.55	0.27	0.32	0.36	0.06	0.05	0.07
LE	0.46	0.65	0.63	0.39	0.41	0.40	0.06	0.08	0.09
SE	0.43	0.4	0.45	0.31	0.30	0.33	0.06	0.06	0.07
IN	0.44	0.42	0.66	0.30	0.34	0.38	0.06	0.05	0.09

The extreme and mean values of peak positive wind pressure coefficients for pressure taps in each pressure zone on the sawtooth roofs are showed in Table 4.28. The peak positive wind pressure coefficients also increase as the building height increases. The increase rate for most pressure zones falls in the range of 10% - 30%. From the comparisons shown in Table 4.28 and Table 4.29 it is evident that the effect of building height on wind pressure coefficients for sawtooth roofs is more significant than it is for the monosloped roofs. The extreme wind pressure coefficient increases by 16% for sawtooth roofs, compared to an increase of less than 5% for monosloped roofs. The mean peak wind pressure coefficient for the high corner in which the extreme wind pressure coefficient occurs, increases by 14% for the sawtooth roof when the building height increases from 7.0 m to 16.1 m. However, the increase of mean wind pressure coefficient for the high corner on the monosloped roofs is less than 5%. On other pressure zones, such as the edge region, the increase of peak wind pressure coefficient for the sawtooth roof ranges from 25% - 40% compared with an increase of less than 12% for monosloped roofs.

4.4.2.3 Effect on Wind Pressure Coefficients Referenced Different Wind Speeds

Test wind pressure coefficients mentioned in the above sections are normalized to the mean wind pressure at the reference height. The difference of test wind pressure coefficients indicates the difference of corresponding wind pressures. As mentioned in the above section the increase of building height can cause a corresponding increase in the test wind pressure coefficient for sawtooth roofs by up to 40%. This indicates the largest possible increase of wind pressure caused by the increase of building height. The ASCE 7-02 uses the 3-second gust wind speed measured at a mean roof height as the reference for the wind pressure coefficients. One of the purposes applying this reference wind speed is to decrease the building height effect on the wind pressure coefficients. In this section test wind pressure coefficients for the monosloped and 5-span sawtooth roofs with three heights are converted to the wind pressure coefficients referenced to the 3-s gust wind speed at the mean roof height. By comparing the converted wind pressure coefficients for varying building heights the building height effect on the wind pressure coefficients referenced to 3-s gust wind speed at mean roof height for both monosloped and sawtooth roofs are determined.

To convert the test wind pressure coefficients to ASCE-7 standard wind pressure coefficients, an adjustment factor is required using the following procedure that outlines the derivation of the adjustment factor. The test wind pressure coefficients obtained through wind tunnel experiments are shown in Eq. 4.6 below:

$$C_p = \frac{P}{\overline{P}_{ref.}} \tag{4.6}$$

where:

C_p = Pressure Coefficient

P = Pressure at pressure tap location

$\overline{P}_{ref.}$ = Measured mean wind pressure at the reference height in the wind tunnel

ASCE 7 standard wind pressure coefficients are defined by Eq. 4.7:

$$C_p^{'} = \frac{P}{\frac{1}{2}\rho V_{3s,rmh}^2} \tag{4.7}$$

where:

$V_{3s,rmh}$ = 3s gust wind speed at mean roof height

ρ = air density in wind tunnel

The adjustment factor can be calculated using Eq. 4.8 ~ Eq. 4.10 below:

$$C_a = \frac{C_{p'}}{C_p} = \frac{\overline{P}_{ref.}}{\frac{1}{2}\rho V_{3s,rmh}^2} \tag{4.8}$$

$$\overline{P}_{ref.} = \frac{1}{2}\rho \overline{V}_{ref.}^2 \tag{4.9}$$

$$C_a = \frac{\overline{V}_{ref.}^2}{V_{3s,rmh}^2} \tag{4.10}$$

where: $\overline{V}_{ref.}$ = mean wind speed at the reference height which was measured during the wind speed profile test; C_a denotes the adjustment factor.

Thus in order to calculate the adjustment factor C_a, the 3-second gust wind speed is needed for each building height under study, which is derived from wind speed time histories obtained in the wind tunnel. The instantaneous time history of wind speed was measured for 60 second with 2000 sampling rate by using an IFA 300 anemometer and hot-film probe test system. Data acquisition software of TSI inc. was used to collect wind speed data. This 3-second gust wind speed was determined using the following method.

1. Wind speed time series at heights for 70 mm, 115.8 mm, and 161.5 mm (corresponding to 7.0 m, 11.6 m and 16.1 m at full scale) were recorded for 60 seconds at a rate of 2000 samples per second under 1:100 open country exposure.

2. The design mean wind speed at 10 m height above ground was determined. The design wind speed is assumed to be 57.8 m/s (130 mph), defined as a 3-second gust wind speed at 10 meter height for open country terrain and

adjusting gust wind speed to mean wind speed. The Eq. 4.11 from Simiu and Scanlan (1996) was applied to determine the mean wind speed.

$$U_{3600} = U_{3s} / \left(1 + C(3) \frac{\sqrt{\beta}}{2.5 \ln\left(\frac{z}{z_0}\right)} \right) \tag{4.11}$$

3-second gust factor *C(3)* in Eq. 4.11 can be determined by the values presented in Table 4.29 (Simiu and Scanlan, 1996).

Table 4.29 Gust factors *C(t)*

T(s)	1	10	20	30	50	100	200	300	600	1000	3600
C(t)	3	2.32	2	1.73	1.35	1.02	0.7	0.54	0.36	0.16	0

$\beta = 6.0$ (Simiu and Scanlan, 1996); test roughness length $z_0 = 0.036\ m$ for open country terrain. It is assumed that the gust factors in Table 4.29 can be applied to hurricane winds.

$$U_{3600} = U_{3s} / \left(1 + 2.85 \times \frac{\sqrt{6}}{2.5 \ln\left(\frac{10}{0.036}\right)} \right) = 38.84 \quad m/s \tag{4.12}$$

3. Determine the model scale test time corresponding to 3 seconds at full scale.

Based on the measured wind speed profile for simulated open country exposure, the test wind speed at 10 m height is 8.29 m/s. The following equations are used to determine the number of samples for wind speed measurement in the wind tunnel corresponding to three seconds at full scale.

$$\frac{f_m B_m}{V_m} = \frac{f_p B_p}{V_p}$$
$$\frac{B_m}{T_m V_m} = \frac{B_p}{T_p V_p} \qquad (4.13)$$
$$T_m = \frac{T_p V_p B_m}{V_m B_p} = \frac{3 \times 38.84 \times 1}{8.29 \times 100} = 0.14$$

where:

f_m: Sampling rate for wind tunnel test

T_m: Period of model scale measurement (unit: second).

T_p: Period of prototype scale measurement (3 second)

f_p: Sampling rate for prototype model measurement

B_m/B_p: Model scale (1/100)

V_m: mean wind speed at the full scale height of 10 m in the scaled terrain.

V_p: mean wind speed at 10 m height for full scale measurement.

The sampling period of 0.14 second for the wind tunnel measurement corresponding to the full scale measurement period of 3 second is obtained based on Eq. 4.13. The sampling rate for the wind speed measurement in the wind tunnel is 2000 samples per second. The number of samples for equivalent three-second averaging time is 280 obtained by Eq. 4.14.

$$N = T_m f_m = \frac{T_p V_p B_m}{V_m B_p} \times 2000 = 0.14 \times 2000 = 280 \qquad (4.14)$$

4. Create time history of an equivalent 3-second gust wind speed by moving averaging measured instantaneous wind speed time series by every 280 samples. The peak values of an equivalent 3-second gust wind speed time series for the mean roof heights of full scale 7.0 m, 11.6 m and 16.1 m are 11.2 m/s, 11.7 m/s and 12.0 m/s. The measured reference wind speed at the height of 300 mm below the tunnel ceiling (corresponding to full scale height of 180 m) in the wind tunnel is 12.9 m/s.

5. Calculate adjustment factors by Eq. 4.10. The adjustment factors for these three heights are shown in Table 4.30.

Table 4.30 Adjustment Factors for Wind Pressure Coefficients

Height (Full Scale) m	Height (1:100 scaled) mm	Test 3-second Wind Speed at Mean Roof Height (m/s)	Reference Wind Speed (m/s)	Adjustment Factor
7.0	70	11.20	12.9	1.330
11.6	115.8	11.70	12.9	1.219
16.1	161.5	12.00	12.9	1.159

The adjusted wind pressure coefficients for the monosloped roof and 5-span sawtooth roofs are presented in Table 4.31 and Table 4.32. The comparisons of wind pressure coefficients for different building heights indicate that the adjusted wind pressure coefficients still increase with an increase in building height. Although the discrepancy of wind pressure coefficients for varying building height reduces when 3-second gust wind speed at the mean roof height is used as reference wind speed, the variation of peak wind pressure coefficients for many pressure zones between 7.0 m and 11.6 m sawtooth roofs is still over 20%, (e.g. in low corner on windward span, edges in leeward span on sawtooth roofs). Therefore, the effect of building height on wind pressure coefficients for the sawtooth roof can not be ignored.

For monosloped roofs, the highest wind pressure coefficient does not always occur on the building with the highest heights. For example, the adjusted extreme peak negative wind pressure coefficient occurs at a high corner of the 7.0 m high monosloped roof. The largest variation of peak wind pressure coefficients between two heights monosloped roofs is still less than 15%. From this lack of variation between pressure coefficients, it can be inferred that the building height effect on adjusted wind pressure coefficients for monosloped roofs is less than those for sawtooth roofs.

Table 4.31 Adjusted Peak Negative Cp for Monosloped Roofs

Height / Zone	7.0 m	11.6 m	16.1 m
HC	-5.51	-4.96	-4.89
LC	-2.77	-2.86	-3.16
HE	-3.79	-3.50	-3.60
LE	-2.53	-2.52	-2.28
SE	-2.79	-2.58	-2.71
IN	-2.83	-3.13	-3.02
Terrain: open country Reference wind speed: 3-s gust wind speed at mean roof height			

Table 4.32 Adjusted Peak Negative Cp for Sawtooth Roofs

	Extreme Peak Negative Wind Pressure Coefficients		
Building Height	7.0 m	11.6 m	16.1 m
Zonal (Windward Span, A)			
HC	-5.04	-4.62	-5.08
LC	-3.43	-4.01	-4.60
HE	-3.47	-3.45	-3.85
LE	-2.77	-2.96	-2.18
SE	-3.39	-3.73	-4.23
IN	-3.42	-3.77	-4.16
Zonal (Middle Spans, B, C & D)			
HC	-2.47	-2.75	-2.78
LC	-3.52	-4.14	-4.13
HE	-2.61	-3.08	-2.87
LE	-3.18	-2.90	-2.86
SE	-3.78	-3.84	-4.00
IN	-2.39	-2.50	-2.84
Zonal (Leeward Span, E)			
HC	-2.70	-2.55	-2.85
LC	-3.23	-3.32	-3.49
HE	-2.91	-2.77	-3.57
LE	-2.66	-3.13	-2.50
SE	-2.69	-2.47	-3.00
IN	-2.19	-2.23	-2.25
Terrain: open country Reference wind speed: 3-s gust wind speed at mean roof height			

The following conclusions can be made based on comparisons of wind pressure coefficients with different reference wind speeds:

1. The negative wind pressures on monosloped and sawtooth roofs increase with the building height increasing. When wind pressure coefficients are referenced to the mean wind pressure at the reference height in the wind tunnel, the variation of wind pressure coefficient represents the variation of corresponding wind pressure. The increase of building height from 7.0 m to 16.1 m can cause an increase of

30% in the local wind pressure coefficients for monosloped and sawtooth roofs.

2. Wind pressure coefficients normalized to 3-second gust wind speed at the mean roof height do not reflect the real wind pressures on buildings because the wind speed at mean roof height changes case by case. To some respect, normalizing to mean roof height decreases the difference of values of wind pressure coefficients. However, the effect of building height still is significant with the highest difference of wind pressure coefficients being more than 20% for both monosloped and sawtooth roofs.

4.4.3 Terrain Effect

Wind tunnel tests on the model buildings were conducted in various exposures to identify the effect of terrain on wind pressure coefficients for the monosloped and sawtooth roofs. The purpose of this series of tests is to evaluate the reasonableness of current wind design procedure in ASCE 7 that uses the identical set of wind pressure coefficients regardless of terrain exposure. The wind pressure coefficients are also referenced to the mean wind pressure at the reference height (300 mm below tunnel ceiling) in the wind tunnel except those specially noted.

4.4.3.1 Wind Pressure Coefficients for Classic Suburban Exposure

Wind tunnel tests for the 7.0 m and 11.6 m high monosloped and 5-span sawtooth roofs were conducted for the simulated classic suburban terrain (Shown in Fig. 3.2) for which the local terrain around the test model on the turntable is smooth and flat. The peak negative wind pressure coefficient contours which are shown in Fig 4.21 and Fig. 4.22 provide a direct reference for the critical wind pressure coefficient distributions.

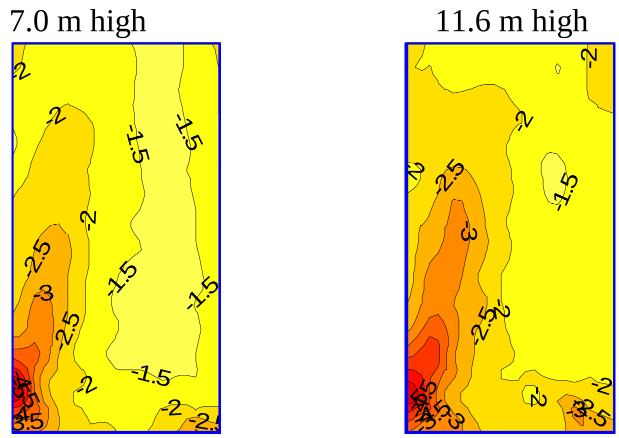


Figure 4.21 Contours of Peak Negative Cp for One-half Roof of Monosloped Roofs under Classic Suburban Exposure
(High Edge is at Left Side)

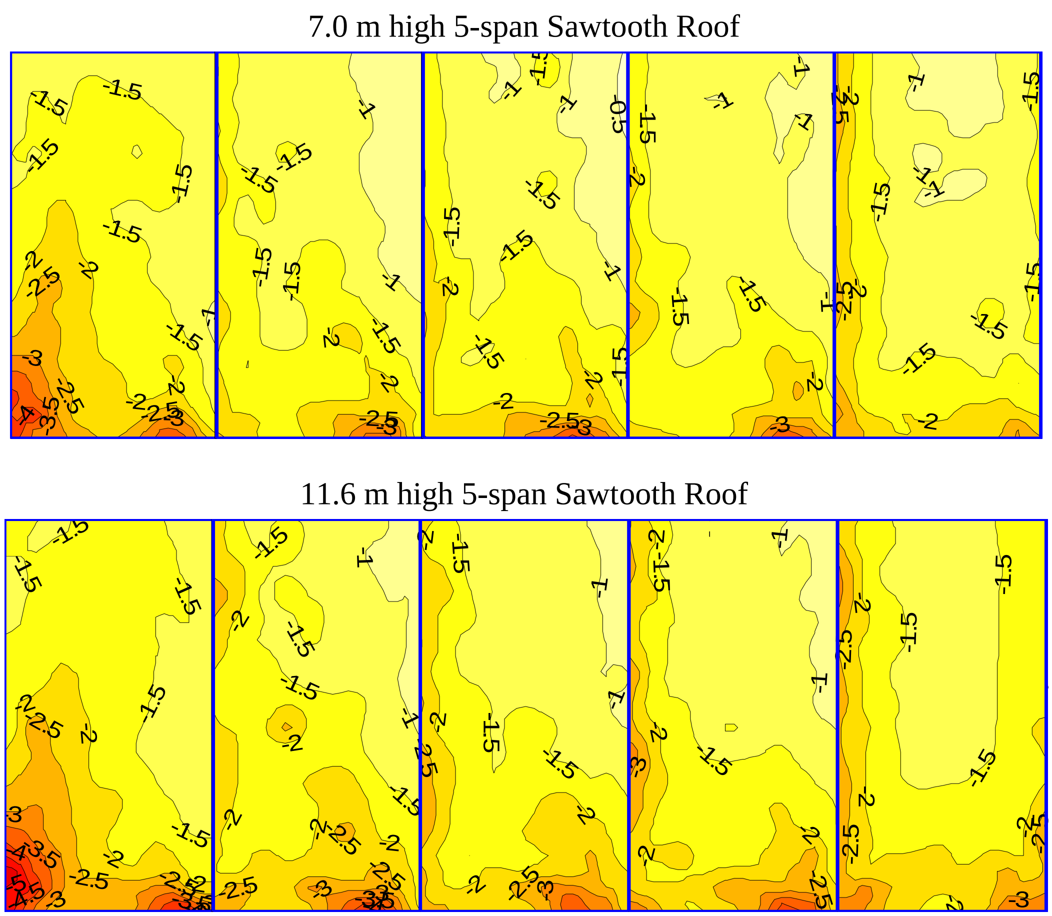


Figure 4.22 Contours of Peak Negative Cp for One-half Roof of Sawtooth Roofs under Classic Suburban Exposure
(Left side is high edge)

A comparison of the zonal peak wind pressure coefficients between the 7.0 m and 11.6 m high models in Table 4.33 and Table 4.34 reveals that for the monosloped roofs and the windward spans of the sawtooth roofs the negative wind pressure coefficients increase with the increasing building height. For the monosloped roof, the increase in the zonal peak negative wind pressure coefficients in all pressure zones except in the high corner zone ranges from 10% to 32%. In the high corner areas, the extreme wind pressure coefficients for two monosloped roofs are quite similar to each other with only 2% difference between them.

Table 4.33 Zonal Peak Negative Cp for Monosloped Roofs under Classic Suburban Exposure

Zone	HC	LC	HE	LE	SE	IN
7.0 m high	-4.98	-2.9	-3.4	-2	-2.41	-2.79
11.6 m high	-5.1	-3.18	-3.9	-2.38	-3.17	-3.19
Increasing rate by height	2%	10%	15%	19%	32%	14%

Table 4.34 Zonal Peak Negative Cp for Sawtooth Roofs under Classic Suburban Exposure

Span	Zone	HC	LC	HE	LE	SE	IN
Windward Span	7.0 m high	-4.41	-3.44	-2.85	-2.04	-3.46	-2.8
	11.6 m high	-5.2	-4.11	-3.03	-2	-3.63	-3.38
	Increase	18%	19%	6%	-2%	5%	21%
Middle Spans	7.0 m high	-2.35	-3.28	-2.47	-2.53	-3.66	-2.41
	11.6 m high	-2.89	-3.83	-2.89	-2.78	-3.95	-2.64
	Increase	23%	17%	17%	10%	8%	10%
Leeward span	7.0 m high	-2.87	-3.01	-2.37	-2	-2.3	-1.97
	11.6 m high	-3.19	-3.35	-2.65	-2.5	-2.56	-2.37
	Increase	11%	11%	12%	25%	11%	20%

For the sawtooth roofs, the variation of the peak negative wind pressure coefficients for the edge zones of the windward spans is less than 6% between the 7.0 m high and 11.6 m high 5-span sawtooth roofs. For the other pressure zones on these two 5-span sawtooth roofs, the increase in peak negative wind pressure coefficients ranges from 8% to 27%.

4.4.3.2 Effect of Modified Suburban Exposure

The mean wind speed profiles between generally simulated suburban (Fig. 3.2) and modified suburban terrains (Fig. 3.5) are closely analogous to one another; only the turbulence intensity profile below 20 m is subject to change. Test wind speed and turbulence intensity values for 7.0 m and 11.6 m heights under classic and modified suburban exposures are presented in Table 4.35. The difference in wind speed between the two terrains is less than 2%. The turbulence intensities under modified suburban terrain are more than those under classic suburban by 1.8% and 1.7% for 7.0 m and 11.6 m respectively.

Table 4.35 Wind Speed and Turbulence Intensity for Heights of 7.0 m and 11.6 m under Classic and Modified Suburban Exposure

	Classic Suburban		Modified Suburban	
Height (m)	U (m/s)	Turbulence Intensity	U (m/s)	Turbulence Intensity
7	6.35	27.6%	6.25	29.3%
11.6	6.92	26.7%	6.97	28.3%

Wind pressure distributions on the 11.6 m high monosloped roof and the windward span of the 11.6 m high 5-span sawtooth roof under the modified suburban exposure are presented in Fig. 4.23. The zonal peak negative pressure coefficients for these two models are presented in Table 4.36.

11.6 m High Monosloped Roof

Windward Span of 11.6 m High
5-span Sawtooth Roof

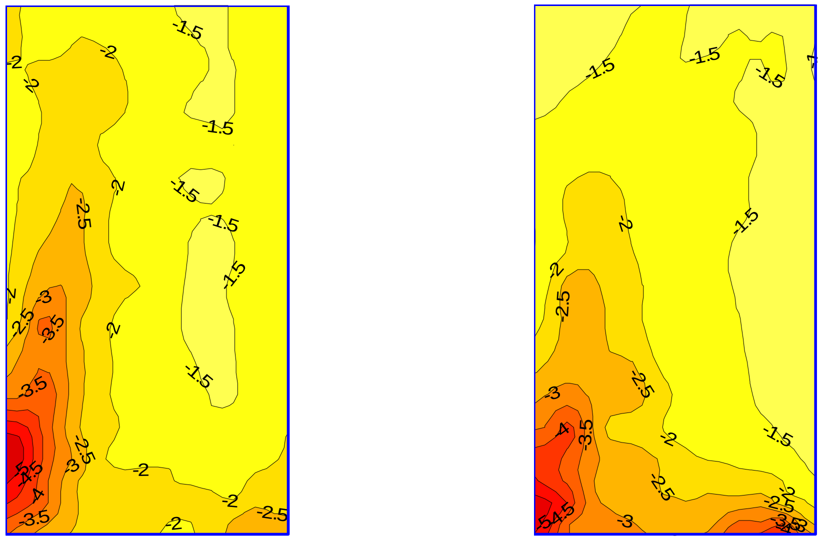


Figure 4.23 Contours of Peak Negative Cp for One-half Roof of Monosloped Roof and Windward Span of 5-span Sawtooth Roof under Modified Suburban Exposure (High edge is at Left Side)

Table 4.36 Zonal Peak Negative and RMS Cp for Monosloped Roof and Windward Span of Sawtooth Roof under Modified Suburban Exposure

Zone \ Model	Monosloped Roof (11.6 m high)		Windward Span of 5-span Sawtooth Roof (11.6 m high)	
HC	Peak	RMS	Peak	RMS
HC	-5.09	0.5	-5.09	0.46
LC	-2.78	0.27	-3.96	0.3
HE	-3.94	0.4	-3.23	0.33
LE	-2.01	0.18	-1.82	0.16
SE	-2.6	0.24	-3.57	0.31
IN	-2.96	0.29	-2.96	0.3

The effect of the modified suburban terrain on the peak negative wind pressure coefficients in a more global sense is presented in Fig. 4.24 and Fig. 4.25 for the 11.6 m high monosloped roof and the windward span of the 11.6 m high 5-span sawtooth roof respectively. Results obtained under classic suburban and modified suburban terrains are compared. The application of linear regression shows the average effect of modified suburban terrain results in a 5% decrease in wind pressure coefficients for the windward span of the sawtooth roof and only 1% decrease for the monosloped roof. The linear regressions also show high correlation coefficients of 0.87 and 0.93 for the trend lines of the monosloped roof and windward span of the sawtooth roof. Therefore, little change (within 2%) in the turbulence intensity below 20 m have little or no impact on the average wind pressure coefficient for monosloped and sawtooth roofs.

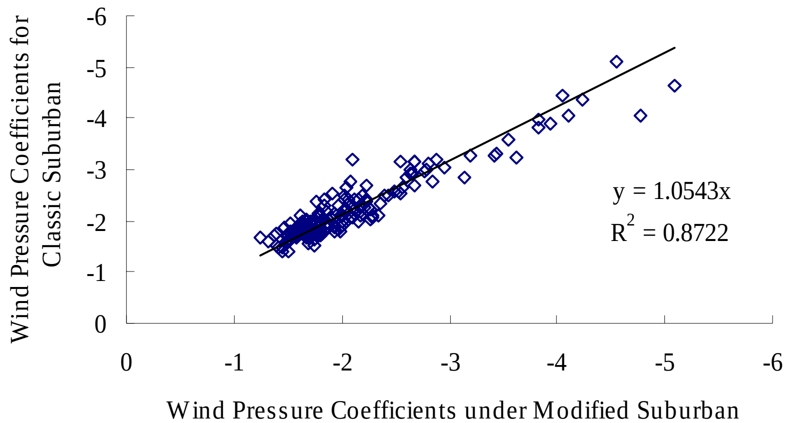


Figure 4.24 Comparisons of Cp for Windward Span of 5-span Sawtooth Roof under Classic and Modified Suburban Terrains

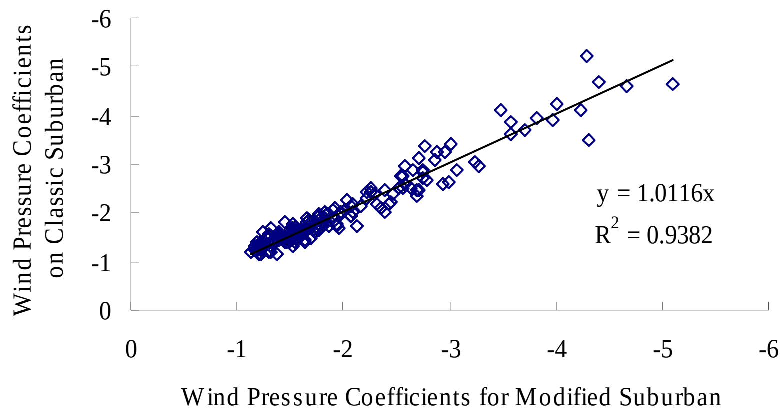


Figure 4.25 Comparisons of Cp for Monosloped Roof under Classic and Modified Suburban Terrains

4.4.3.3 Effect of Surrounding Houses

The wind tunnel tests were conducted for an 1:100 scaled 5-span sawtooth roof model with a full scale height of 11.6 m surrounded by residential houses with similar sizes to the test building (as shown in Fig. 3.7). Wind pressures on windward span and one middle span B of the 5-span sawtooth roof were recorded. The zonal peak negative wind pressure coefficients for these two spans are presented in Table 4.37.

Table 4.37 Zonal Peak Negative Cp for Sawtooth Roof with Surrounding Houses under Suburban Exposure

Span / Zone	Windward Span	Span B
HC	-4.37	-2.82
LC	-3.29	-3.49
HE	-2.59	-2.22
LE	-1.72	-1.69
SE	-3.18	-3.7
IN	-3.16	-2.16

Wind pressure coefficients on the sawtooth roof with surrounding houses are found to be less than the pressure coefficients for the sawtooth roof of the isolated building. The comparisons of wind pressure coefficients for the two cases (isolated model and surrounding model) are presented in Fig. 4.26 and Fig. 4.27. Fig. 4.26 shows the comparisons for the windward span of the 11.6 m high 5-span sawtooth roof and Fig. 4.27 shows the comparisons for the first middle span (Span B) of the 5-span sawtooth roof. On average, the results indicate that the surrounding houses cause a reduction in the wind pressure coefficients of 14% for the windward span and about 19% for the first middle span of the sawtooth roof.

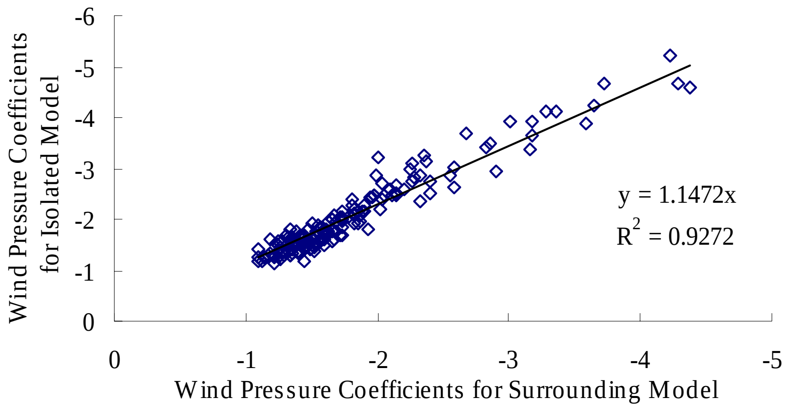


Figure 4.26 Comparisons of Cp for Windward Span of Isolated and Surrounding Sawtooth Roof Models under Suburban Exposure

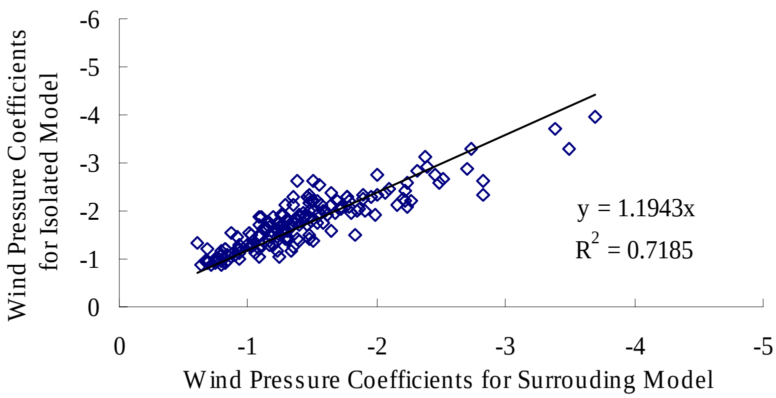


Figure 4.27 Comparisons of Cp for Span B of Isolated and Surrounding Sawtooth Roof Models under Suburban Exposure

The zonal peak wind pressure coefficients for the windward span and span B of the sawtooth roof between with and without surrounding houses are compared in Fig. 4.28 and Fig. 4.29 respectively. For the windward span the reduction of zonal peak wind pressure coefficients caused by these surrounding houses resulted in a corresponding wind pressure coefficient decrease of 10% ~ 20%, particularly for the corner and edge zones, the decrease is more than 15%. For the Span B, the reduction caused by these surrounding houses for the corner and sloped edge zones is less than 10%, however the reduction in the zonal wind pressure coefficients for the high edge, low edge and interior zones ranges from 13% ~ 27%.

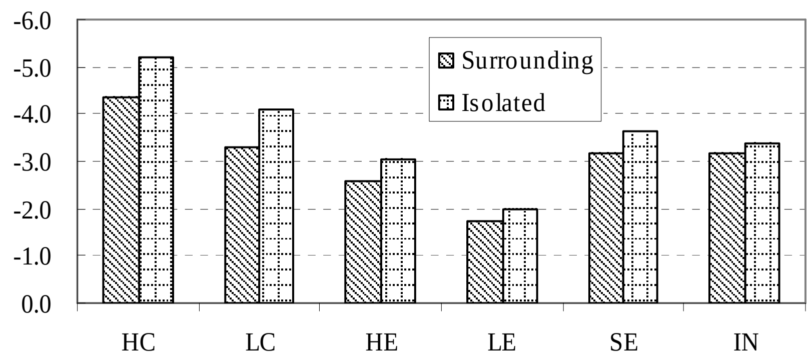


Figure 4.28 Comparisons of Zonal Cp for Windward Span of Sawtooth Roof between Isolated and Surrounding Sawtooth Roof Models

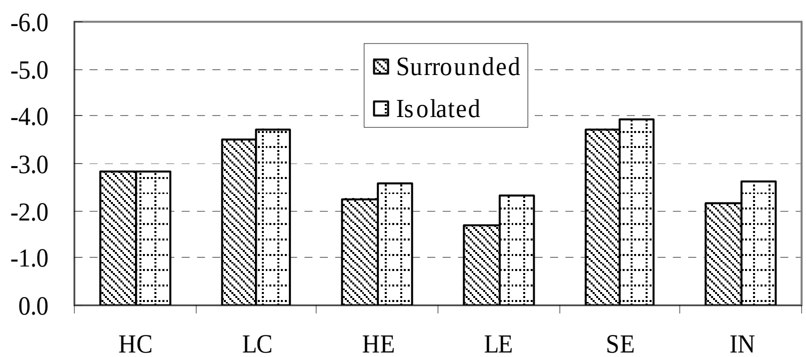


Figure 4.29 Comparisons of Zonal Cp for Span B of Sawtooth Roof between Isolated and Surrounding 5-span Sawtooth Roof Models

4.4.3.4 Comparisons between Open and Suburban Terrains

To evaluate terrain effect on wind pressures on monosloped and sawtooth roofs, wind tunnel tests were conducted on 1:100 scaled monosloped roof and 5-span sawtooth roof buildings with full scale heights of 7.0 m and 11.6 m. The test wind pressure coefficients are referenced to the mean wind pressure at the reference height in the wind tunnel. However the wind speeds at that height are not the gradient wind speed for the simulated terrains. To determine terrain exposure effect on wind pressures, wind pressure coefficients for the buildings in two terrains are converted to those referenced to the gradient wind speed.

In this study the roughness lengths for suburban and open country terrains are 0.42 m and 0.036 m respectively, as discussed previously in Section 3.3. The wind speeds at the full scale height of 10 m are 8.29 m/s and 6.73 m/s for the open country terrain and suburban terrain respectively. Gradient wind speed can be obtained based on the following equations (ESDU, 1982).

$$f = 2\Omega \sin\phi \tag{4.15}$$

where $\Omega = 72.9\times10^{-6}\, rad/s$ is the angular velocity of the Earth. ϕ is the local angle of latitude.

$$\text{Friction velocity: } U_* = \frac{U_{10}}{2.5\ln(10/z_0)} \tag{4.16}$$

where U_{10} denotes the mean wind speed at the height of 10 m. z_0 denotes the roughness length of the terrain.

$$U_{grad.} = U_* \times 2.5\left[\ln\left(\frac{U_*}{fz_0}\right) - A\right] \tag{4.17}$$

$U_{grad.}$ denotes the gradient wind speed. The universal constant A was established empirically by calibrating against measured wind profile data from which A = -1.

Based on Eq. 4.15 ~ Eq. 4.17 the gradient wind speeds for the open country and suburban terrains can be calculated. Table 1 shows calculated gradient wind speeds for the two terrains with a variety of latitude angles.

Table 4.38 Theoretical Gradient Wind Speed for Open Country and Suburban

	Open Country	Suburban	Open Country	Suburban
Roughness Length (m)	0.036	0.42	0.036	0.42
U10 (m/s)	8.29	6.73	8.29	6.73
Fricition Velocity	0.589	0.849	0.589	0.849
Latitude Angle (degree)	45	45	90	90
f	0.000103	0.000103	0.000146	0.000146
Ugrad. (m/s)	17.64	20.98	17.13	20.25

Table 4.38 shows the change of local latitude angle from 45 degree to 90 degree has little effect on the gradient wind speed magnitude. In this case the local latitude angle is assumed to be 45 degree. Thus the gradient wind speed for the open country and suburban terrains are 17.64 m/s and 20.98 m/s respectively. The measured wind speed at the reference height in the wind tunnel is 13 m/s for both the open country and suburban terrains. The adjustment factors for converting the test wind pressure coefficients to those referenced to the gradient wind speed are calculated based on the following Equations.

Adjustment factor for open country:

$$C_{a,open} = \frac{C'_{p,open}}{C_{p,open}} = \frac{\dfrac{p_{open}}{\frac{1}{2}\rho V^2_{grad,open}}}{\dfrac{p_{open}}{\frac{1}{2}\rho V^2_{ref.,open}}} = \frac{V^2_{ref.,open}}{V^2_{grad,open.}} = \frac{13^2}{17.64^2} = 0.54 \qquad (4.18)$$

Adjustment factor for suburban:

$$C_{a,sub} = \frac{C'_{p,sub}}{C_{p,sub}} = \frac{\dfrac{p_{sub}}{\frac{1}{2}\rho V^2_{grad,sub}}}{\dfrac{p_{sub}}{\frac{1}{2}\rho V^2_{ref.,sub}}} = \frac{V^2_{ref.,sub}}{V^2_{grad,sub.}} = \frac{13^2}{20.98^2} = 0.38 \tag{4.19}$$

Thus the adjustment factors for the open country and suburban terrains are 0.54 and 0.38 respectively. By multiplying the test wind pressure coefficients by these adjustment factors, the test wind pressure coefficients are converted to those referenced to the gradient wind speed.

In evaluating the terrain effect on wind pressures, the pressure tap locations have been grouped into categories which corresponding to the pressure zones as shown in Fig. 4.3.2. Data in Table 4.39 and Table 4.40 show the comparisons of converted wind pressure coefficients for the monosloped and 5-span sawtooth roofs between the two terrains. Since the converted wind pressure coefficients are referenced to the gradient wind speed, the ratio of wind pressure coefficients between two terrains is same as the ratio of corresponding wind pressures.

The reductions of peak wind suction on the local taps due to terrain conditions are variable between each identified region, usually ranging from 0.69 to 1.0 for the sawtooth roofs and ranging from 0.69 to 0.95 for the monosloped roofs. Generally, the reduction of wind suction on the low edge and interior zones are higher than the other pressure zones. The wind suctions for the taps in the high suction zones in the suburban terrain can be close to those in the open country with a reduction of less than 10% such as in the corners and sloped edge regions.

Table 4.39 Comparisons of Cp for Monosloped Roofs in Two Terrains

Model	7.0 m high monosloped roof			11.6 m high monosloped roof		
Zone	Open [1]	Suburban [2]	[2]/[1]	Open [1]	Suburban [2]	[2]/[1]
HC	-2.24	-1.89	0.85	-2.20	-1.94	0.88
LC	-1.12	-0.98	0.88	-1.27	-1.21	0.95
HE	-1.54	-1.29	0.84	-1.55	-1.48	0.96
LE	-1.03	-0.76	0.74	-1.12	-0.90	0.81
SE	-1.13	-0.92	0.81	-1.14	-1.08	0.94
IN	-1.15	-0.80	0.69	-1.39	-1.18	0.85
Note: wind pressure coefficients are referenced to the gradient wind speed						

Table 4.40 Comparisons of Cp for 5-span Sawtooth Roofs in Two Terrains

7.0 m high 5-span Sawtooth Roof									
Span	Windward Span			Middle Spans			Leeward span		
Zone	Open [1]	Suburban [2]	[2]/[1]	Open [1]	Suburban [2]	[2]/[1]	Open [1]	Suburban [2]	[2]/[1]
HC	-2.0	-1.7	0.82	-1.0	-0.9	0.89	-1.1	-1.1	0.99
LC	-1.4	-1.3	0.94	-1.4	-1.2	0.87	-1.3	-1.1	0.87
HE	-1.4	-1.1	0.77	-1.1	-0.9	0.89	-1.2	-0.9	0.76
LE	-1.1	-0.8	0.69	-1.3	-1.0	0.74	-1.1	-0.8	0.70
SE	-1.4	-1.3	0.95	-1.5	-1.4	0.91	-1.1	-0.9	0.80
IN	-1.4	-1.1	0.77	-1.0	-0.9	0.94	-0.9	-0.7	0.84
11.6 m high 5-span Sawtooth Roof									
Span	Windward Span			Middle Spans			Leeward span		
Zone	Open [1]	Suburban [2]	[2]/[1]	Open [1]	Suburban [2]	[2]/[1]	Open [1]	Suburban [2]	[2]/[1]
HC	-2.0	-2.0	0.97	-1.2	-1.1	0.90	-1.2	-1.2	1.02
LC	-1.8	-1.6	0.88	-1.8	-1.5	0.79	-1.5	-1.3	0.87
HE	-1.5	-1.2	0.75	-1.4	-1.1	0.80	-1.2	-1.0	0.82
LE	-1.3	-0.8	0.58	-1.3	-1.1	0.82	-1.4	-1.0	0.68
SE	-1.7	-1.4	0.83	-1.7	-1.5	0.88	-1.1	-1.0	0.89
IN	-1.7	-1.3	0.77	-1.1	-1.0	0.91	-1.0	-0.9	0.91
Note: wind pressure coefficients are referenced to the gradient wind speed									

The terrain effect on the peak negative wind pressure coefficients in a more global sense is presented in Fig. 4.30 and Fig. 4.31 for the monosloped and 5-span sawtooth roofs with the heights of 7.0 m and 11.6 m. Results from the open country terrain and suburban terrain are compared. The x-coordinate denotes the wind pressure coefficients for the open country and the y-coordinate denotes the values for the suburban terrain. Clearly the pressure coefficients for the suburban are lower than those for the open country. It has been found that, on average, the peak negative wind pressure coefficients for the suburban terrain are lower than those for the open country by 10% ~ 25%.

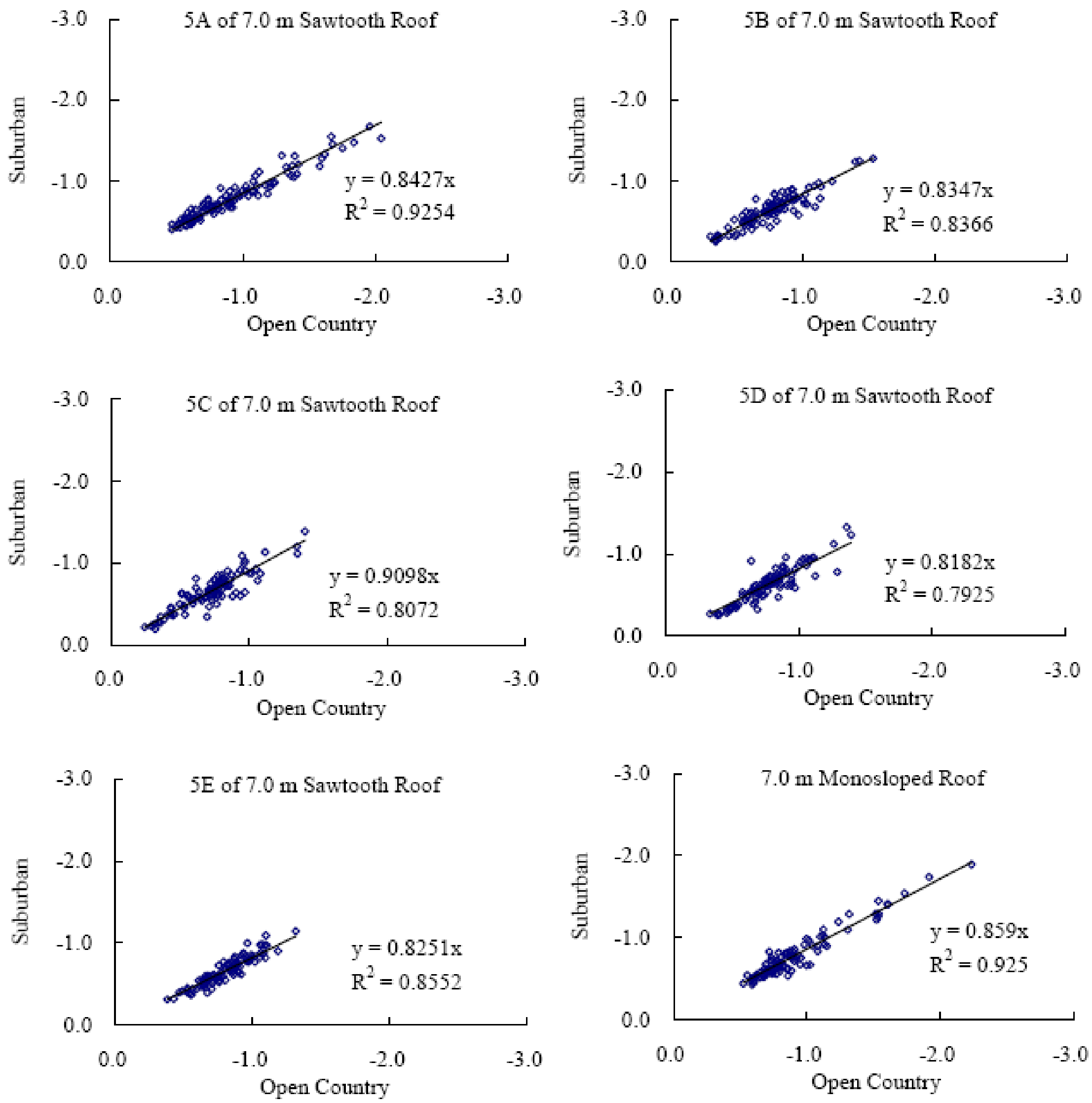


Figure 4.30 Comparisons of Cp for Pressure Taps on 7.0 m High Monosloped and Sawtooth Roofs in Two Terrains

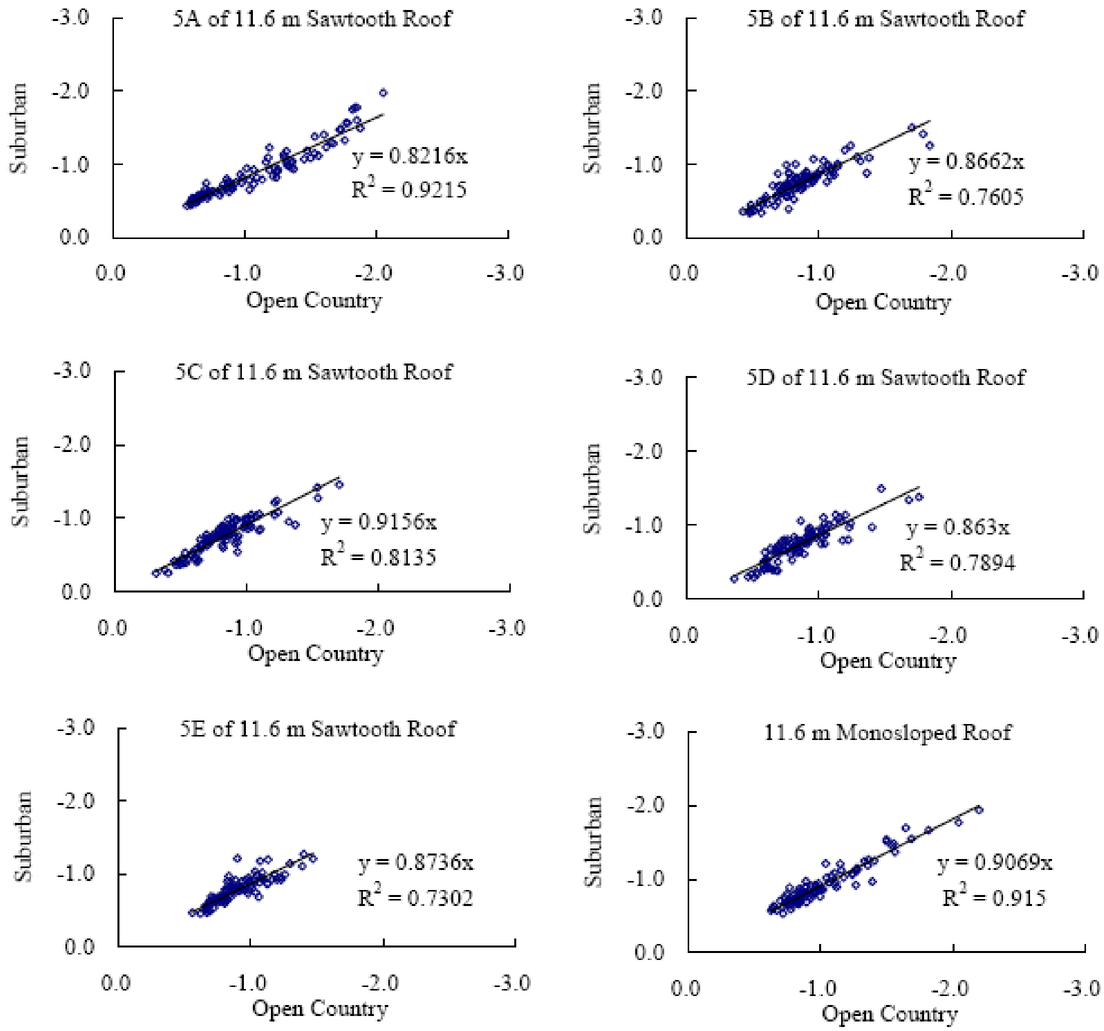


Figure 4.31 Comparisons of Cp for Pressure Taps on 11.6 m High Monosloped and Sawtooth Roofs in Two Terrains

In ASCE 7-02 the velocity pressure exposure coefficient, K_z given in Table 6-3 of ASCE 7-02, is used to adjust the velocity pressure for the buildings in varying terrain, but no adjustments are made to the pressure coefficients. In Table 4.41 the ratios of K_z values for Exposure B (suburban terrain) and Exposure C (open terrain) are presented for components and cladding loads. These ratios indicate the ASCE 7-02 design wind pressures for low rise buildings in suburban terrain should be 18% to 25% lower than the design wind pressures on the same building located in open country terrain given the other conditions are the same in two terrains, such as wind direction and topography.

Table 4.41 Velocity Pressure Exposure Coefficients for Components and Cladding in Exposure B and C (ASCE 7-02)

Height above ground level (m)	Exposure		Ratio (B/C)
	B (Suburban)	C (Open Country)	
0 ~ 4.6	0.7	0.85	82%
6.1	0.7	0.9	78%
7.6	0.7	0.94	74%
9.1	0.7	0.98	71%
12.2	0.76	1.04	73%
15.2	0.81	1.09	74%
18	0.85	1.13	75%

The codes that have adopted the velocity exposure factor to reduce the wind pressure in suburban terrain, not only on the basis of the velocity exposure conditions alone, but consider that most buildings with an upstream suburban exposure are embedded in a similar terrain, or at least surrounded to some degree by other obstructions (Case and Isyumov, 1998). The previous section 4.4.3.3 has shown that the surrounding residential houses will add a reduction of 10% ~ 25%

to the loads that are experienced by an isolated building. Ho (1992) and Case and Isyumov (1998) have also shown that a building experiences lower loads as it becomes embedded in its surroundings and the reductions in local peak suctions may be as high as 30%.

On average, an isolated building in a suburban exposure experiences 10% ~ 25% lower loads than if located in an open country exposure. The effect of the near field terrains (surrounding houses) also can add a reduction of 10% ~ 25% to the wind suctions experienced by an isolated building. When considered together, the reduction rate is more than 20%. Comparing with this analysis results the reduction rate (18% ~ 25%) adopted by ASCE 7-02 for the low rise buildings appears appropriate.

4.5 Wind Pressure Distributions on Separated Sawtooth Roofs

The separated sawtooth roof is a specific type of sawtooth roof building, in which the individual spans of the sawtooth roof are separated by flat roof sections. To date, the effect of a separation distance on wind pressure coefficients for sawtooth roofs has never been studied. Thus, engineers have customarily used existing wind design pressure coefficients for regular sawtooth roofs to design separated sawtooth buildings or they have extrapolated the sawtooth building shape from the high edge of one sawtooth to the foot of the wall of the next leeward sawtooth span.

An experimental investigation was conducted to determine the effect of roof monitor separation distance on wind pressure distributions of sawtooth roofs. Three 1:100 scale model buildings were tested, which consisted of 4-span sawtooth roofs having mean full-scale roof height of 11.6 m, and three flat roof separation distances of 5.5 m, 7.9 m and 10.1 m (Fig. 4.32). Terrain exposure for these models is suburban. The flat roof sections are 0.9 m below the low edge of the sawtooth spans, this dimension was selected to represent actual dimensions observed on an existing separated sawtooth roof structure.

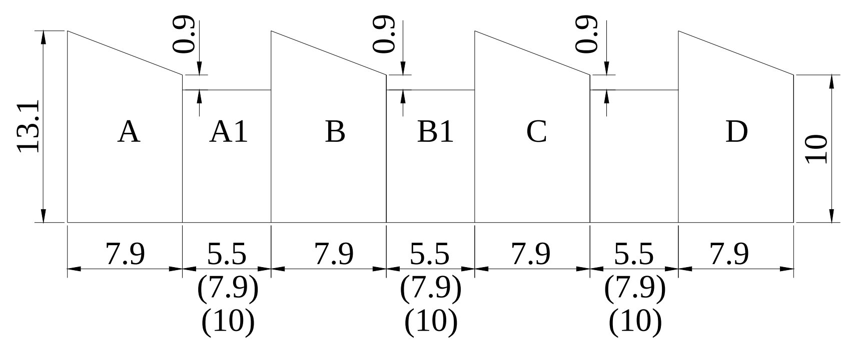
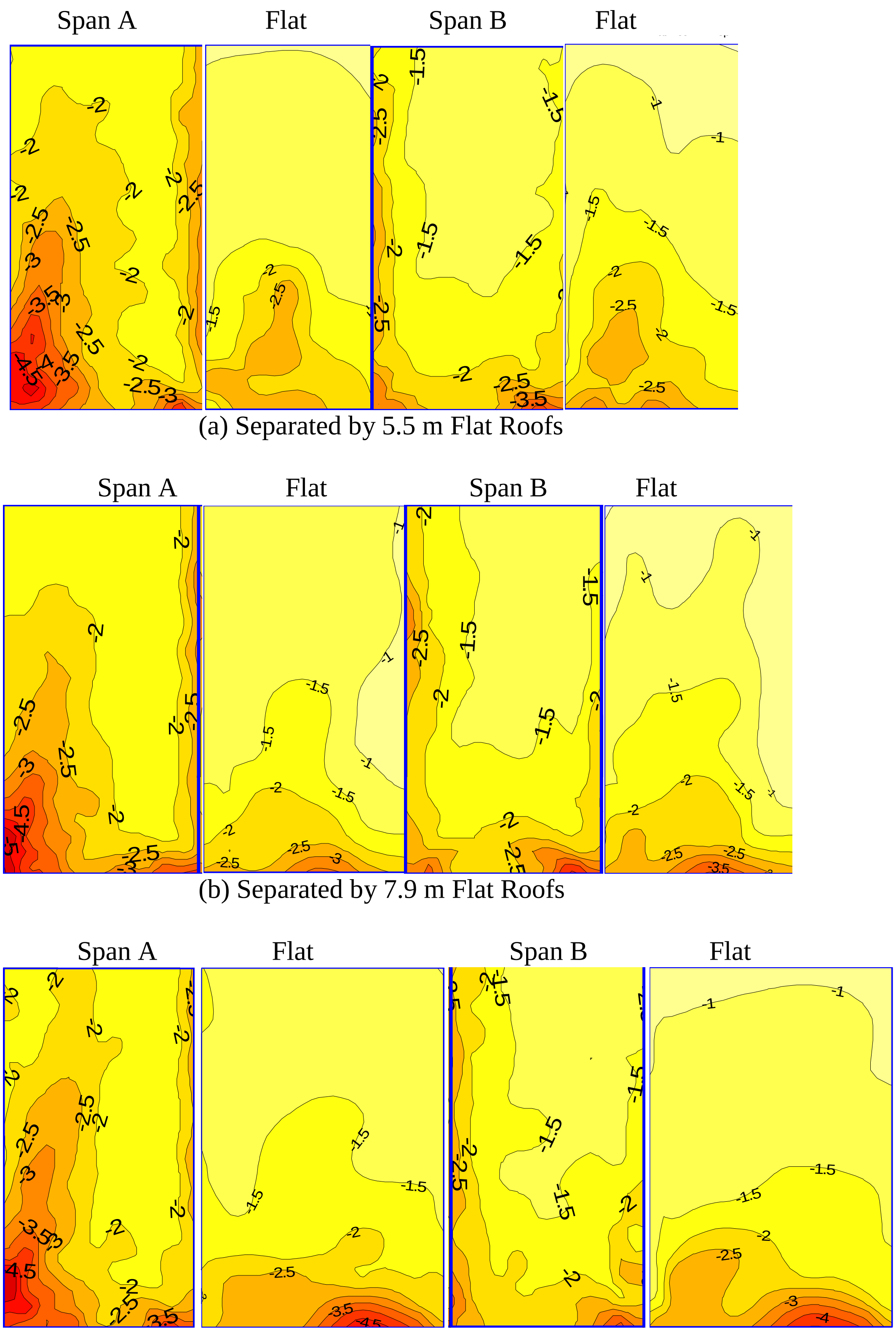


Figure 4.32 Elevation of Prototype 4-span Separated Sawtooth Roof Building (Unit: m)

Wind Pressures on Span A, Span B and flat roof Span A1 and Span B1 were measured for the three separated sawtooth roofs under suburban exposure for 120 seconds at a rate of 300 samples per seconds as discribed in Chapter 3. The extrapolation peak method is applied to obtain wind pressure coefficients for these models. Wind pressure coefficients are also normalized to wind pressure at the reference height in the wind tunnel. Contours of peak wind pressure coefficients for all test wind directions (90^o to 270^o at 10^o increments) for half roof area section of the separated sawtooth roofs are presented in Fig. 4.33.



(a) Separated by 5.5 m Flat Roofs

(b) Separated by 7.9 m Flat Roofs

(c) Separated by 10 m Flat Roofs

Figure 4.33 Contours of Peak Negative Cp for Separated Sawtooth Roofs

On the windward span of separated sawtooth roofs, the wind pressure distributions are very similar to those on the windward span of common sawtooth roofs, except in the low edge zone where higher suction occurs than on the common sawtooth roofs. On the middle spans of the separated sawtooth roof, the wind pressure distributions differ from the wind pressure distribution on the middle spans of common sawtooth roofs but the distributions are more similar to the pressure distribution observed on the leeward span of the common sawtooth roofs in that the suction occurring on the sloped edge significantly decreased.

On the flat roof sections of the separated sawtooth roofs, the peak wind pressure coefficients occur along the roof edge nearest to the vertical wall below the low edge of the roof monitor.

The pressure zones on the separated sawtooth roofs applied to this analysis is defined in Fig. 4.34. Because the characteristic length of pressure zone is determined by the dimensions of a single span single pitched roof as mentioned previously, the value of the characteristic length remains 0.9 m. The pressure zones in flat roof areas include the edge zone and interior zone based upon their respective wind pressure distributions.

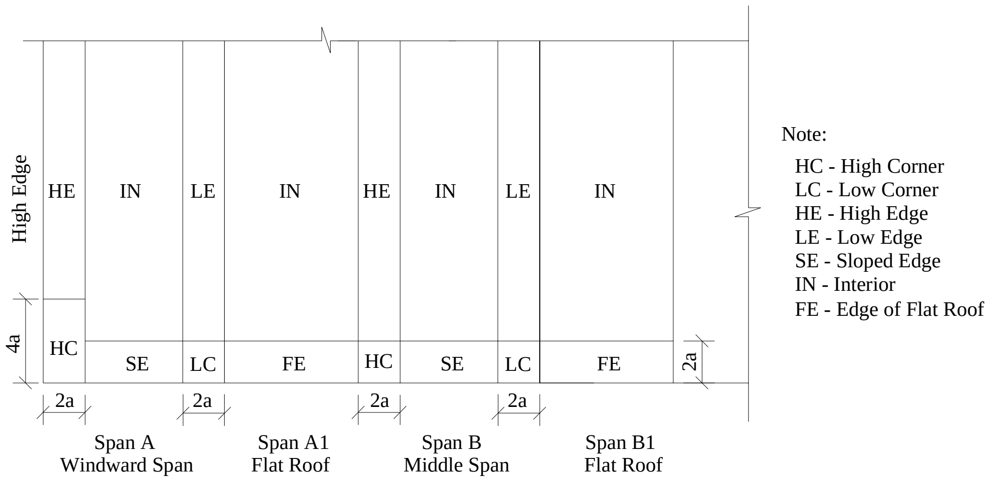


Figure 4.34 Pressure Zones on Separated Sawtooth Roofs

Typical comparisons of zonal wind pressure coefficients between separated sawtooth roofs and common sawtooth roofs are presented in Table 4.42. Both the peak and mean values of wind pressure coefficients for all pressure taps in each zone are presented. The number and letter in ‘F5.5’, ‘F7.9’ and ‘F10’ indicate the flat roof and flat roof width respectively. For example, ‘F5.5’ indicates that the separated model is separated by flat roof with width of 5.5 m. The letters ‘windward’ and ‘middle’ in table indicate the span location within sawtooth roofs. The ‘windward’ indicates the windward span of a sawtooth roofs and the ‘middle’ indicate a middle span of a sawtooth roof.

Table 4.42 Extreme and Mean Peak Cp for Common and Separated Sawtooth Roofs

Zone \ Model	[1]Common	[2]F5.5	[3]F7.9	[4]F10
Extreme Peak Wind Pressure Coefficients for Windward Span				
HC	-5.20	-5.35	-5.25	-5.17
LC	-4.11	-4.00	-3.59	-3.88
HE	-3.03	-4.03	-3.49	-3.60
LE	-2.00	-2.82	-2.66	-2.41
SE	-3.63	-4.08	-3.94	-3.84
IN	-3.38	-3.81	-3.45	-3.70
Mean Peak Wind Pressure Coefficients for Windward Span				
HC	-4.25	-4.62	-4.42	-4.49
LC	-2.81	-2.67	-2.68	-2.84
HE	-1.93	-2.34	-2.20	-2.31
LE	-1.40	-2.18	-1.95	-1.84
SE	-2.95	-3.01	-2.89	-2.99
IN	-1.91	-2.19	-2.07	-2.17
Extreme Peak Wind Pressure Coefficients for Span B				
HC	-2.82	-3.26	-3.58	-3.29
LC	-3.72	-3.80	-4.16	-3.88
HE	-2.56	-2.68	-2.86	-2.73
LE	-2.33	-2.28	-2.27	-2.95
SE	-3.95	-3.03	-3.34	-2.81
IN	-2.64	-2.30	-2.55	-2.41
Mean Peak Wind Pressure Coefficients for Sapn B				
HC	-2.43	-2.85	-2.82	-2.82
LC	-2.70	-2.77	-2.87	-2.69
HE	-1.99	-2.13	-2.18	-2.28
LE	-1.25	-1.56	-1.50	-1.56
SE	-2.74	-2.47	-2.58	-2.33
IN	-1.67	-1.47	-1.56	-1.55
Note: Mean roof height: 11.6 m; Terrain: suburban [1]common sawtooth roof; [2]5.5 m, [3]7.9 m, [4]10 m separated sawtooth roof				

The extreme and mean peak wind pressure coefficients for the windward spans of the separated sawtooth roofs are higher than the corresponding pressure coefficients observed on the common sawtooth roof. For example, in both the low edge and high edge zones of the windward span on a separated sawtooth roof with a 5.5 m separation distance, the extreme wind pressure coefficients are -2.82 and -4.03 as compared with the values of -2.0 and -3.03 for the common sawtooth roof respectively. For the separated sawtooth roof with a separation distance of 10 m, the extreme wind pressure coefficients of -2.41 and -3.60 for the low edge and high edge zones also exceed the corresponding values of -2.0 and -3.03 for common sawtooth roofs by 21% and 19% respectively. All of these discrepancies support the conclusion that the flat roof separations with heights lower than those in the low edge of the single-pitched roofs result in a significant increase in wind suction on both the high and low edge zones of the windward spans of these roof types.

The effect of the separations on the wind pressure coefficients for the other pressure zones on the windward span of the separated sawtooth roofs is not as significant as observed in either the high edge or the low edge zones. The horizontal separations only increased the wind suctions by less than 15% in the high corner, sloped edge and interior roof areas. In addition, the wind suctions within the low corner zone actually decreased slightly on the separated sawtooth roofs.

The separations between sawtooth roofs also cause the wind pressure coefficients for some pressure zones on the middle spans of sawtooth roofs increased. The extreme peak wind pressure coefficients for the high corner of the separated sawtooth roofs are 15% higher than those recorded for the classic sawtooth roof. For the high edge and low corner zones of the span B of these separated sawtooth roofs, the separations result in an increase in wind pressure coefficients of up to 15%. However for the sloped edge zone of the separated sawtooth roof there is a marked decrease ranging from 15% to 30% in wind pressure coefficients.

The above results support the hypothesis that sawtooth roof structures with flat roof separations will experience higher negative wind pressures than those occurring on common sawtooth roofs. As a result, there should be additional design guidelines for determining the design wind loads for the separated sawtooth roofs. While the loads are increased, they generally increase in proportion to each other and so a conservative design provision may be to calculate the wind load for a common sawtooth roof structure and increase the design load by 20% for the high edge and low edge zones of the windward span and increase the design load by 10% for the sloped edge of the windward span within a separated sawtooth roof. For the middle spans, the design wind loads for the high corner, high edge and low corner zones can be increased by 15%.

The extreme and mean peak wind pressure coefficients for all pressure taps in the edge and interior zones of the flat roof spans in the separated sawtooth roofs are presented in Table 4.43 and Fig. 4.35. The peak wind pressure distributions on the flat roof A1 and B1 are similar to each other and the peak value for the edge of the flat roof is close to that for the high corner of the near sloped roof. The extreme peak negative wind pressure coefficient recorded near the edge of flat roof is -4.4 which occurs on the separated sawtooth roof with 10 m wide separations. The peak wind pressure coefficients for the flat roof edge zones on the 5.5 m and 7.9 m wide flat roofs range from -3.1 to -3.5 which are lower than the pressure coefficient observed on the 10 m wide flat roof by 20%. However, the mean peak negative wind pressure coefficients for the edge zones on the flat roofs of the three separated sawtooth roofs are almost the same and in the range of -2.3 to -2.5.

Table 4.43 Extreme and Mean Peak Cp for Flat Roofs of Separated Sawtooth Roofs

	Extreme Peak Wind Pressure Coefficient		Mean Peak Wind Pressure Coefficient	
Model-Span	Edge	Interior	Edge	Interior
5.5 m - A1	-3.3	-2.8	-2.5	-1.6
7.9 m - A1	-3.2	-2.1	-2.3	-1.3
10 m - A1	-4.4	-2.1	-2.5	-1.5
5.5 m -B1	-3.1	-3.0	-2.5	-1.5
7.9 m -B1	-3.5	-2.3	-2.4	-1.3
10 m -B1	-4.1	-2.5	-2.5	-1.4
Note: Mean roof height: 11.6 m; Terrain: suburban 5.5 m, 7.9 m and 10 m are the separation distances of the separated sawtooth roofs				

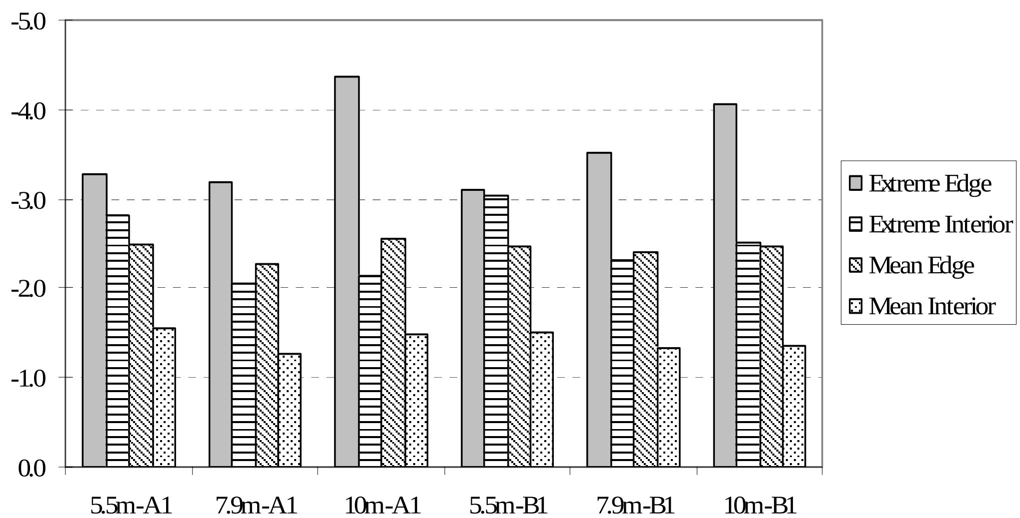


Figure 4.35 Comparisons of Extreme and Mean Cp for Flat Roofs of Separated Sawtooth Roofs

The extreme negative wind pressure coefficient for interior of flat roof is -3.0 which occurs on the flat roofs within the 5.5 m separated sawtooth roof. For 7.9 m and 10 m separated sawtooth roofs, the extreme wind pressure coefficients for the interior of flat roofs are -2.3 and -2.5 respectively.

In summary, separation distance between roof monitors increase the wind suctions occurring in the corner zones of the middle spans and in the high and low edge zones of the windward span within sawtooth roofs. For the design wind loads on the above mentioned zones on separated sawtooth roofs, an increase of 15% ~ 20% of wind loads corresponding zones on classic sawtooth roofs should be taken.

4.6 Critical Wind Directions for Monosloped and Sawtooth Roofs

Critical wind direction is defined as the direction at which the highest suction occurs. The critical wind directions for monosloped and sawtooth roofs were investigated in this study. Extreme wind pressure coefficients were also compared with the peak wind pressure coefficients for the wind directions other than the critical wind directions. For the monosloped roofs, the highest suction always occurs within the high corner zone. However, for the sawtooth roofs, except the high corners of the windward span, high suction also occurs within both the low corner and sloped edge zones in the windward span and middle spans.

Tables 4.44 through Table 4.47 present the relationship between peak pressure coefficient and critical wind direction for each pressure zone in the monosloped and sawtooth roofs. Results are presented for both the open country and suburban exposures. For convenience, the results of the critical wind directions for the monosloped roofs, windward spans, middle spans and leeward spans of the sawtooth roofs are grouped together. The wind directions and models referred in this study are plotted in Fig. 4.36

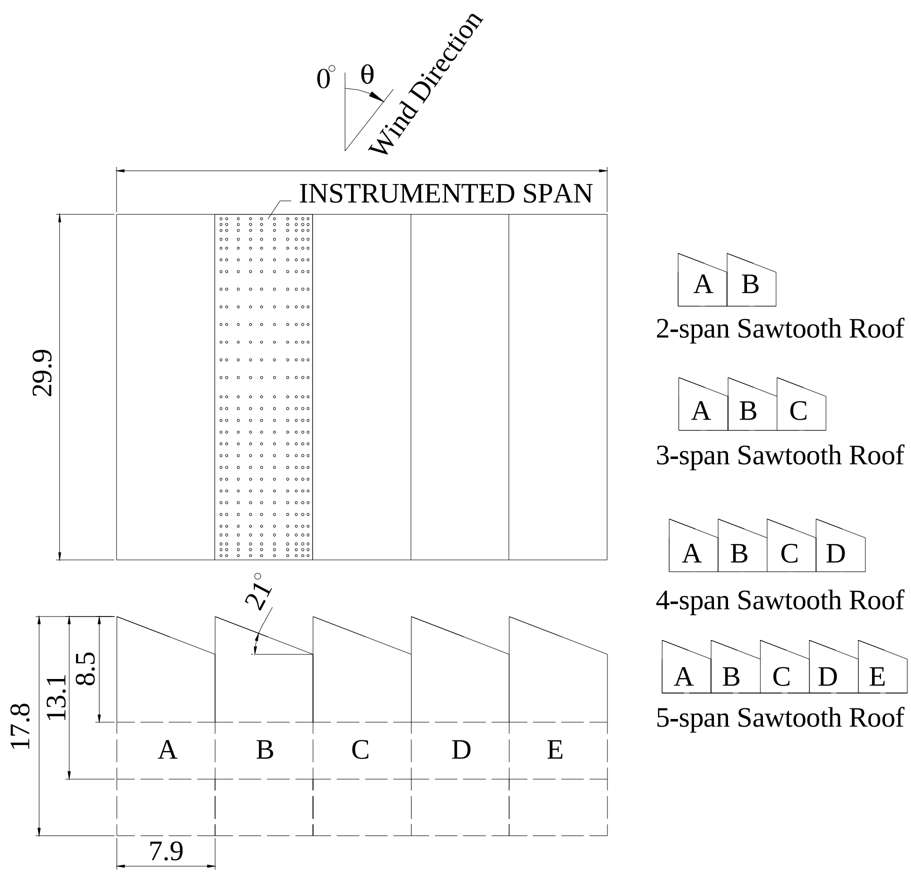


Figure 4.36 Wind Directions versus Sawtooth Models with Full Scale Dimensions (Unit: m)

Table 4.44 Critical Wind Directions for Each Pressure Zone on Monosloped Roof

Pressure Zone	High Corner	Low Corner	High Edge	Low Edge	Sloped Edge	Interior
Building Height	Open Country Exposure					
7.0 m	220°	160°	220°	270°	230°	210°
11.6 m	220°	170°	220°	270°	220°	210°
16.1 m	220°	160°	220°	270o	220°	210°
Building Height	Suburban Exposure					
7.0 m	220°	180°	220°	270°	230°	220°
11.6 m	220°	220°	230°	270°	230°	230°

Table 4.45 Critical Wind Directions for Each Pressure Zone on Windward Span of Sawtooth Roofs

Pressure Zone	High Corner	Low Corner	High Edge	Low Edge	Sloped Edge	Interior
Height - Span	Open Country Exposure					
16.1 - 2A	230°	230°	230°	120°	230°	230°
16.1 - 3A	225°	225°	225°	180°	160°	225°
16.1 - 4A	225°	225°	220°	180°	180°	225°
16.1 - 5A	240°	240°	220°	200°	240°	240°
7.0 - 5A	230°	240°	220°	170°	240°	230°
11.6 - 5A	230°	240°	220°	180°	230°	220°
Height - Span	Suburban Exposure					
7.0 - 5A	230°	170°	240°	180°	170°	240°
11.6 -5A	250°	190°	240°	230°	180°	240°

Table 4.46 Critical Wind Directions for Each Pressure Zone on Middle Spans of Sawtooth Roofs

Pressure Zone	High Corner	Low Corner	High Edge	Low Edge	Sloped Edge	Interior
Height - Span	Open Country Exposure					
16.1 - 3B	270°	170°	210°	120°	170°	180°
16.1 - 4B	260°	215°	210°	180°	180°	180°
16.1 - 4C	260°	230°	230°	120°	160°	110°
16.1 - 5B	260°	190°	210°	170°	180°	180°
16.1 - 5C	270°	170°	240°	170°	170°	180°
16.1 - 5D	270°	160°	270°	110°	160°	130°
7.0 - 5B	250°	180°	230°	190°	180°	180°
7.0 - 5C	170°	160°	250°	190°	170°	210°
7.0 - 5D	270°	160°	230°	120°	150°	200°
11.6 - 5B	160°	160°	220°	200°	160°	160°
11.6 - 5C	160°	160°	210°	190°	160°	210°
11.6 - 5D	270°	150°	210°	180°	160°	200°
Height - Span	Suburban Exposure					
7.0 - 5B	160°	170°	240°	180°	180°	200°
7.0 - 5C	180°	190°	230°	170°	190°	170°
7.0 - 5D	190°	170°	210°	130°	180°	180°
11.6 - 5B	170°	180°	210°	220°	170°	170°
11.6 - 5C	170°	190°	270°	190°	180°	200°
11.6 - 5D	170°	180°	210°	120°	170°	210°

Table 4.47 Critical Wind Directions for Each Pressure Zone on Leeward Spans of Sawtooth Roofs

Pressure Zone	High Corner	Low Corner	High Edge	Low Edge	Sloped Edge	Interior
Height - Span	Open Country Exposure					
16.1 -2B	250°	170°	250°	90°	250°	270°
16.1 -3C	260°	170°	260°	90°	160°	250°
16.1 -4D	270°	250°	260°	130°	160°	240°
16.1 -5E	270°	160°	270°	110°	160°	130°
7.0 - 5E	240°	190°	210°	190°	200°	200°
11.6 - 5E	250°	150°	260°	90°	130°	190°
Height - Span	Suburban Exposure					
7.0 - 5E	210°	170°	260°	190°	170°	170°
11.6 - 5E	170°	170°	260°	180°	170°	180°

The critical wind direction for the high corner of the monosloped roof is 220^o, as compared with the critical wind direction for high corner of sawtooth roofs, which occurs in the range of 220^o to 250^o, and is dependent upon the number of spans in the sawtooth roof studied.

The critical wind direction for the high edge zone is same with that for high corner zone within the monosloped roofs, as well as the windward span of sawtooth roofs. Critical wind directions recorded for the low corner zone on the monosloped roofs are between 160^o to 180^o whereas critical wind directions recorded for the low corner zone on the windward span of sawtooth roofs are between 220^o to 240^o.

Critical wind directions recorded for the low corner and sloped edge zones on the middle spans of sawtooth roofs occurs over a large wind angle range of 150^o to 230^o. This indicates that the cornering wind, recorded at 220^o and the wind normal to sloped edge similarly affect the wind suction occurring in this zone. Excluding the high edge zone, critical wind directions for other pressure zones on middle spans also occurred over a large range of wind directions of 210^o to 240^o. On the leeward spans, the critical wind directions for both high edge and high corner zones range from 240^o to 270^o. The critical wind directions for the other zones of the leeward spans are also equally distributed over a similar range.

To visualize the change of wind pressure coefficient distribution with wind directions, a set of wind pressure coefficient contours were created. Fig. 4.39 presents a typical set of wind pressure coefficient distributions on the one-half roof area of a monosloped roof. Based on these wind pressure coefficient contours the critical wind direction can be determined to be 220°. It is also quite evident that the wind suction is rather low for the wind directions within the range of 90° to 180°. When the wind blows from corner directions (210° to 220°), the high suction occurs over a substantially larger area in the high corners.

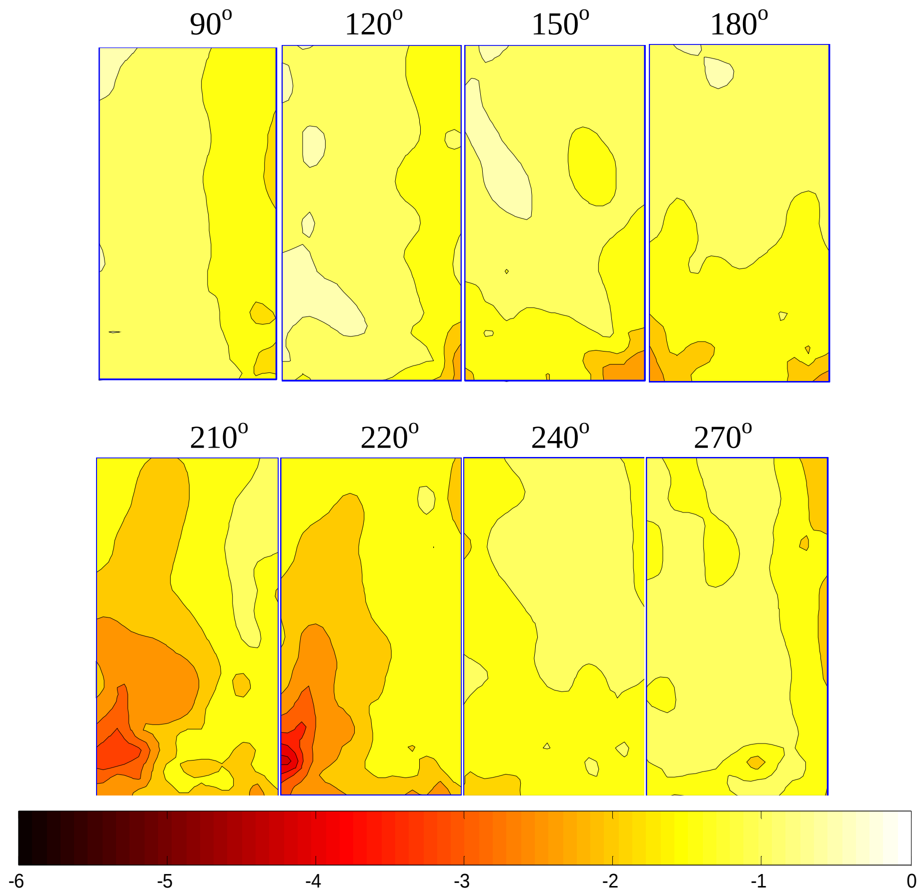


Figure 4.37 Contours of Local Negative Wind Pressure Coefficients for Monosloped Roof (11.6 m High, Open Country)

Fig. 4.37 and Fig. 4.39 present a typical set of wind pressure coefficient distributions on one half of roof area for wind directions between 90° ~ 270° at 30° increment on a 11.6 m high 5-span sawtooth roof under open exposure. High suction first occurs in the low corners of leeward and middle spans for wind direction 150^o. When the wind direction increases to 180^o, the high suction area shifts, mainly occurring on the sloped edges and low corners of the sawtooth roof. It is evident that the most critical high suction occurs in the windward span of the sawtooth roof for the wind direction of 240^o, encompassing a large suction zone area.

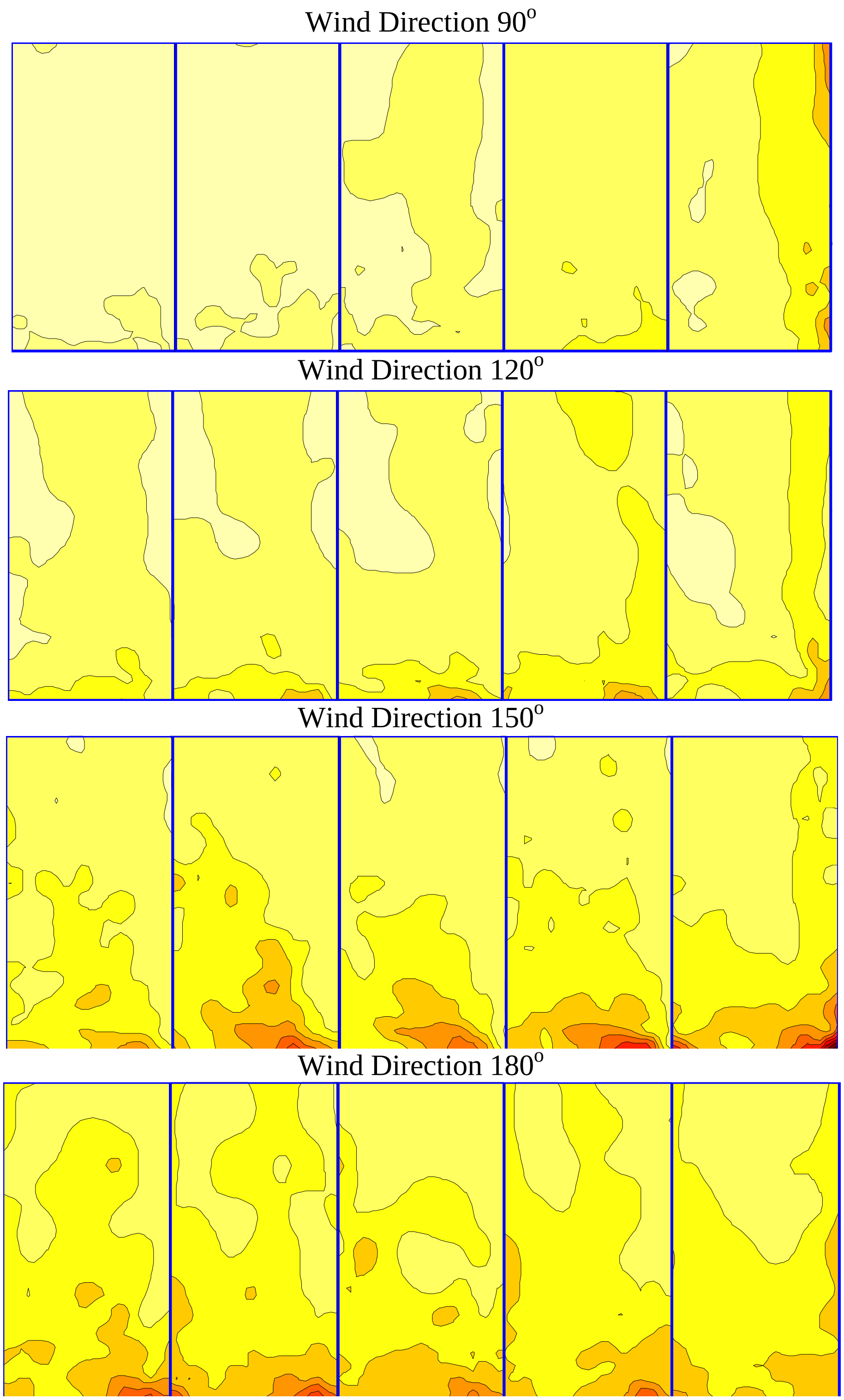


Figure 4.38 Contours of Local Negative Wind Pressure Coefficients for Sawtooth Roof for Wind Directions of 90° ~ 180° (11.6 m High; Open Country)

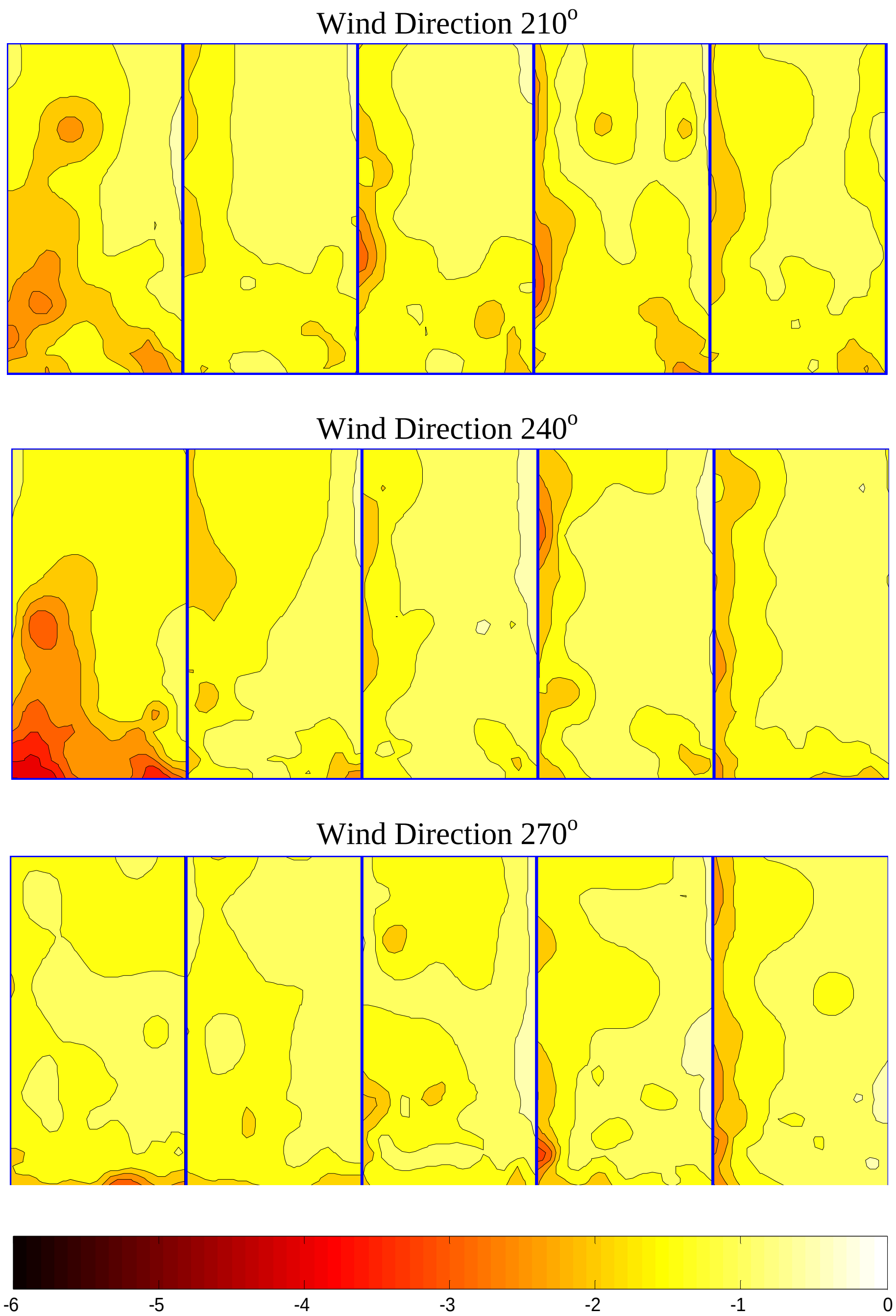


Figure 4.39 Contours of Local Negative Wind Pressure Coefficients for Sawtooth Roof for Wind Directions of 210° ~ 270° (11.6 m High; Open Country)

The contours shown in Fig. 4.37 ~ Fig. 4.39 also show that extremely high suction values on the high corner of the monosloped roof and on the windward span of the sawtooth roof occur for incident wind directions within a narrow range of 30^{o}. However, the high suction on the low corner and sloped edge occurs over a relatively large range of wind directions. To further investigate the wind effect on wind pressure coefficients for these zones, the wind pressure coefficients for wind directions from 90^{o} to 270^{o} were studied. The pressure taps in the high corner, low corner and sloped edge zones are shown in Table 4.48 and the tap locations are shown in Fig. 4.40.

Table 4.48 Pressure Taps in Selected Pressure Zones on Monosloped and Sawtooth Roofs

Pressure Zone	Monosloped Roofs and Windward Span on Sawtooth Roofs	Middle and Leeward Spans on Sawtooth Roofs
HC	1,2,11,12,21,22, 31,32,41,42	1,2,11,12,21,22
LC	8,9,10,18,19,20	8,9,10,18,19,20
SE	3,4,5,6,7,13,14,15,16,17, 23,24,25,26,27	3,4,5,6,7,13,14,15,16,17, 23,24,25,26,27

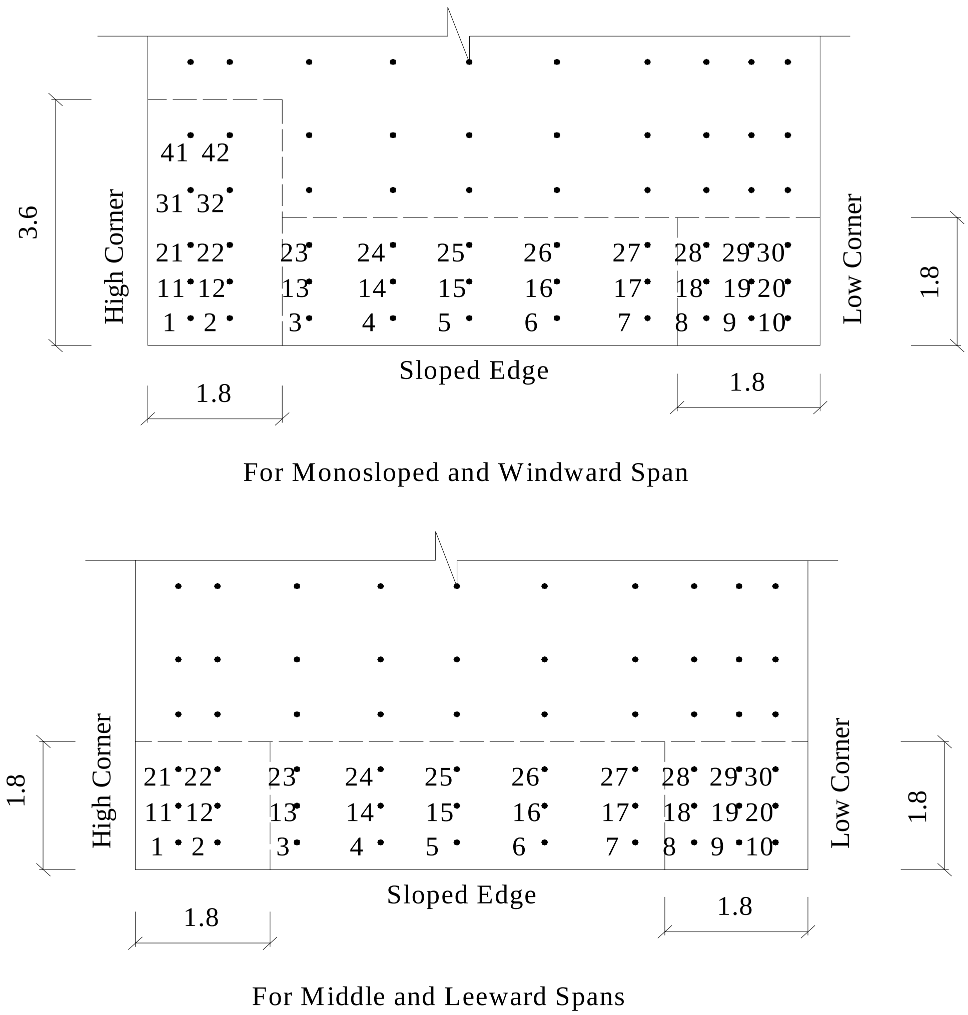


Figure 4.40 Pressure Taps in High Corner, Low Corner and Sloped Edge of Monosloped and Sawtooth Roofs

The critical wind directions for both monosloped roof and windward span of sawtooth roof occur for the wind directions with a small range of 30^{o} and 40^{o}. Fig. 4.41 and Fig. 4.42 show the variations of wind pressure coefficients with wind directions recorded on ten pressure taps located in the high corner of the 16.1 m high monosloped roof and windward span of the 16.1 m 5-span sawtooth roof under open exposure. High suction for the monosloped roof occurred over the range from 210^{o} to 230^{o}, and the suctions for the other wind directions between 90° ~ 270° were significantly lower than those for the wind directions of 210° to 230°. For example, the extreme wind pressure coefficient for the 16.1 m monosloped roof under open exposure is -4.33 and the peak value for all wind directions except the critical wind directions is -2.53.

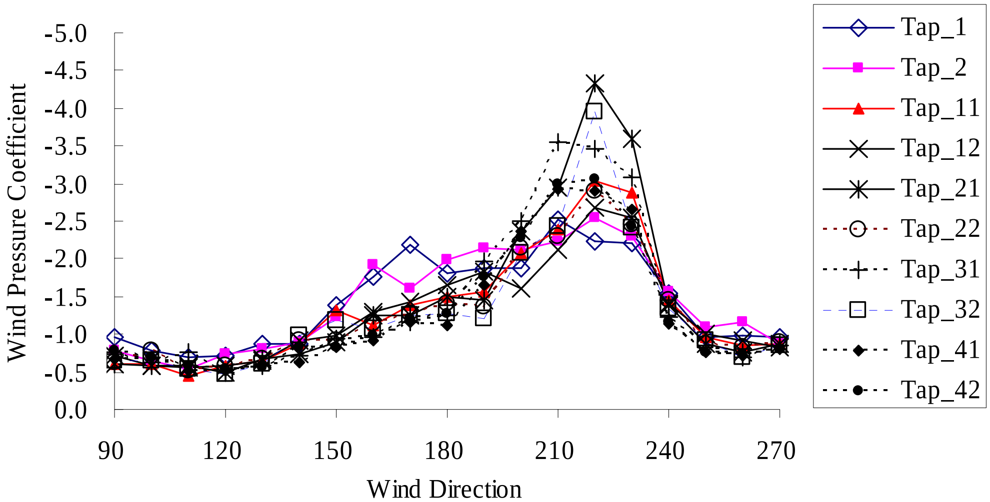


Figure 4.41 Peak Negative Cp versus Wind Directions for High Corner of Monosloped Roof (11.6 m High; Open Country)

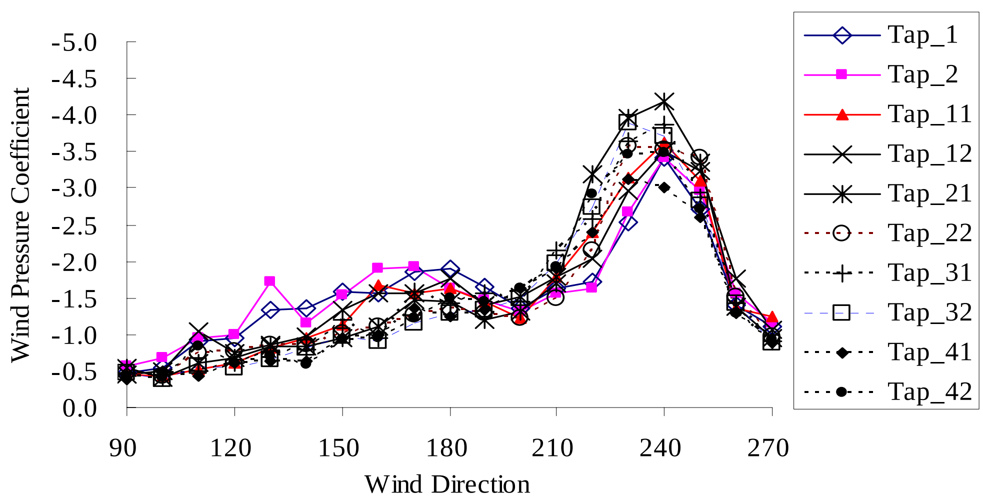


Figure 4.42 Peak Negative Cp versus Wind Directions for High Corner of Windward Span in Sawtooth Roof (11.6 m High; Open Country)

For windward spans of the sawtooth roofs, the high wind suction occurred at the wind directions in the range of 220^o to 250^o. The peak wind pressure coefficient for all other wind directions was -2.14, which is lower than the extreme value -4.18 by 48% reduction in wind pressure.

The critical wind directions for the low corner and sloped edge zones of the middle and leeward spans of sawtooth roofs occur over a large range of wind directions as shown in Fig. 4.43 ~ Fig. 4.49. High suction in these pressure zones will occur at the wind directions in the range of 160^o to 190^o and. 230^o to 260^o.

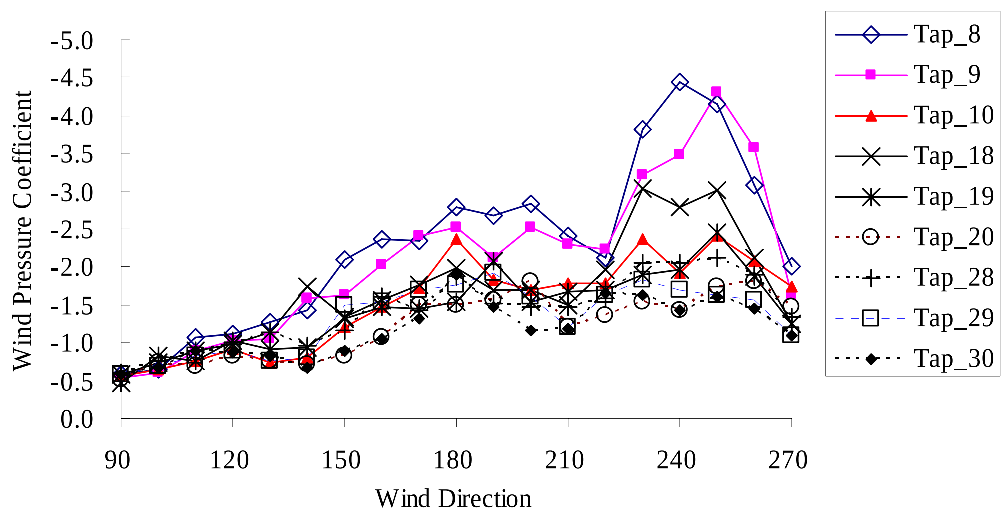


Figure 4.43 Peak Negative Cp versus Wind Directions for Low Corner of Windward Span in Sawtooth Roof (11.6 m High; Open Country)

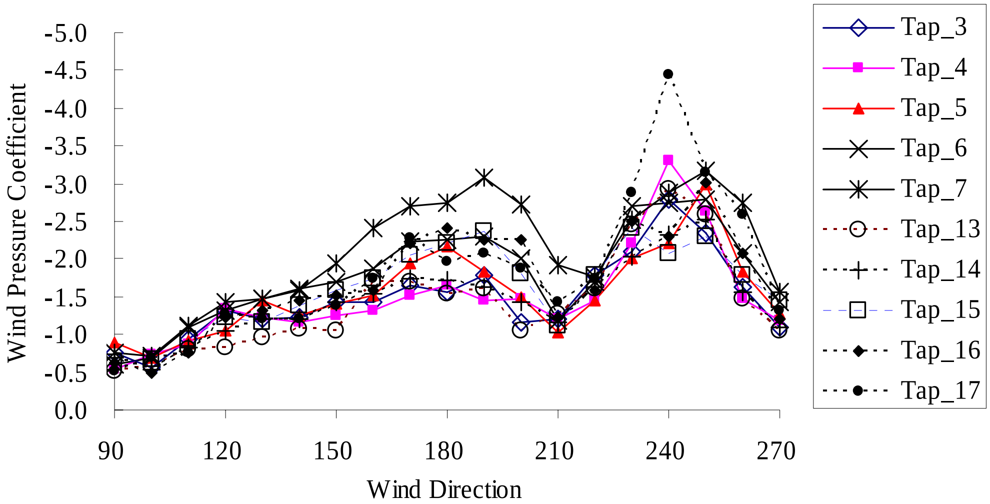


Figure 4.44 Peak Negative Cp versus Wind Directions for Sloped Edge of Windward Span in Sawtooth Roof (11.6 m High; Open Country)

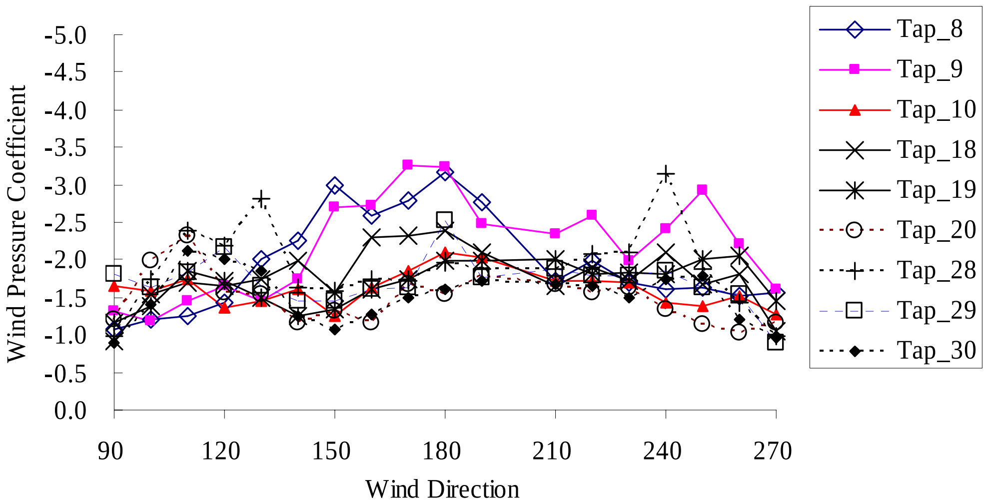


Figure 4.45 Peak Negative Cp versus Wind Directions for Low Corner of Span D in Sawtooth Roof (11.6 m High; Open Country)

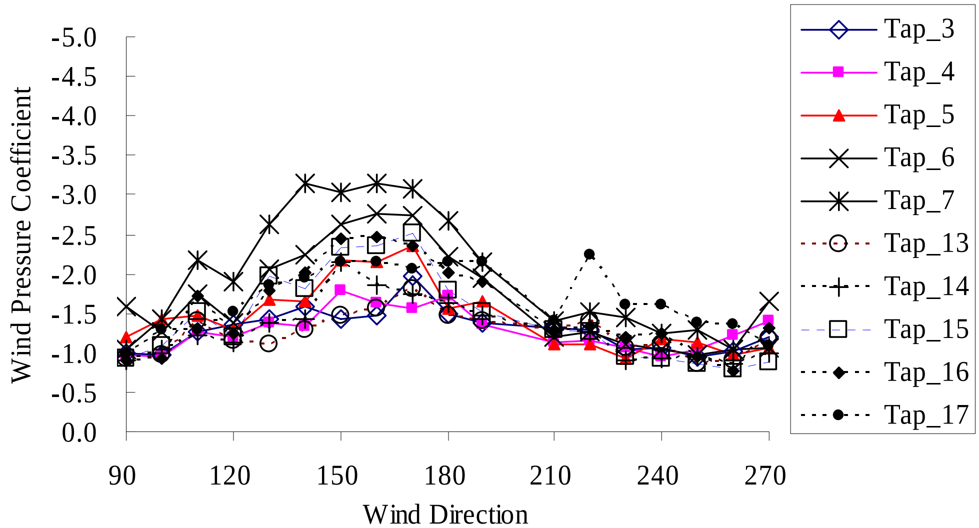


Figure 4.46 Peak Negative Cp versus Wind Directions for Sloped Edge of Span D in Sawtooth Roof (11.6 m High; Open Country)

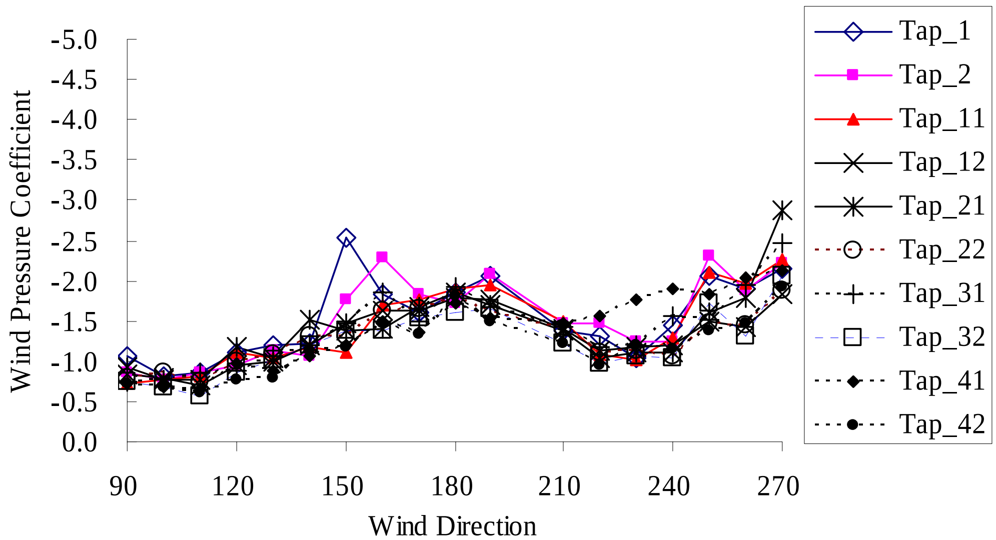


Figure 4.47 Peak Negative Cp versus Wind Directions for High Corner of Leeward Span in Sawtooth Roof (11.6 m High; Open Country)

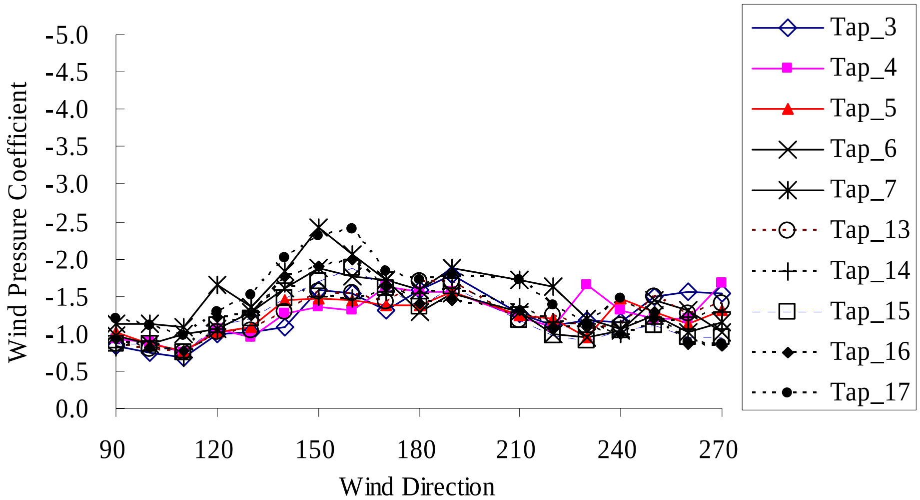


Figure 4.48 Peak Negative Cp versus Wind Directions for Sloped Edge of Leeward Span in Sawtooth Roof (11.6 m High; Open Country)

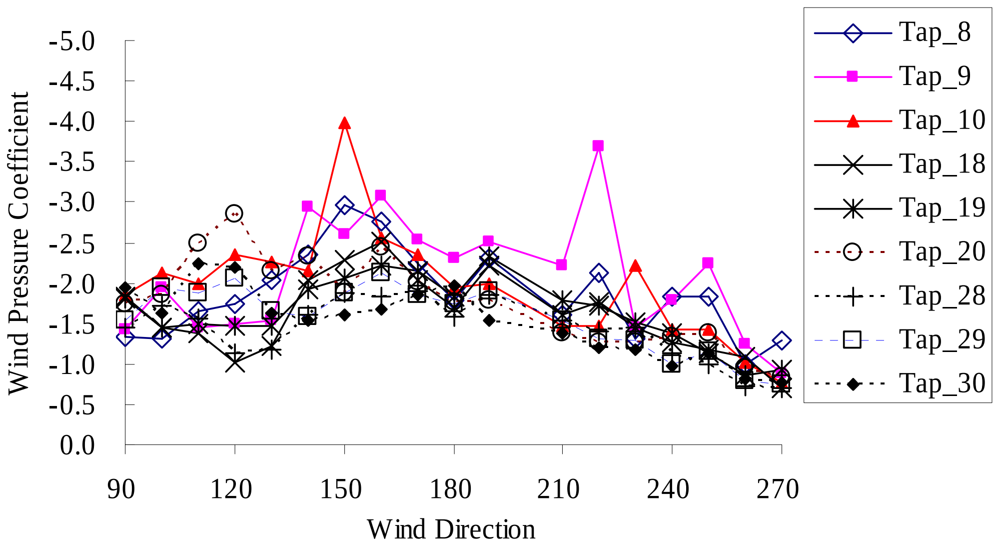


Figure 4.49 Peak Negative Cp versus Wind Directions for Low Corner of Leeward Span in Sawtooth Roof (11.6 m High; Open Country)

4.7 Root Mean Square Wind Pressure Coefficients on Monosloped and Sawtooth Roofs

Standard deviation or root mean square (RMS) of wind pressure coefficient is an important factor to evaluate wind pressure distribution on buildings besides the peak wind pressure coefficients. In this section, RMS wind pressure coefficients on the monosloped and sawtooth roofs are investigated to determine the correlation between peak and RMS wind pressure coefficients. The high suction distributions on these two types of roofs are determined based on the correlation results. Table 4.49 lists the test cases for which RMS wind pressure coefficients are analyzed. The RMS wind pressure coefficients described in this section correspond to the extreme wind pressure coefficients for all wind directions. Since RMS wind pressure coefficients are estimated based on the entire wind pressure time history, they are more stable than the peak estimates of wind pressure coefficients.

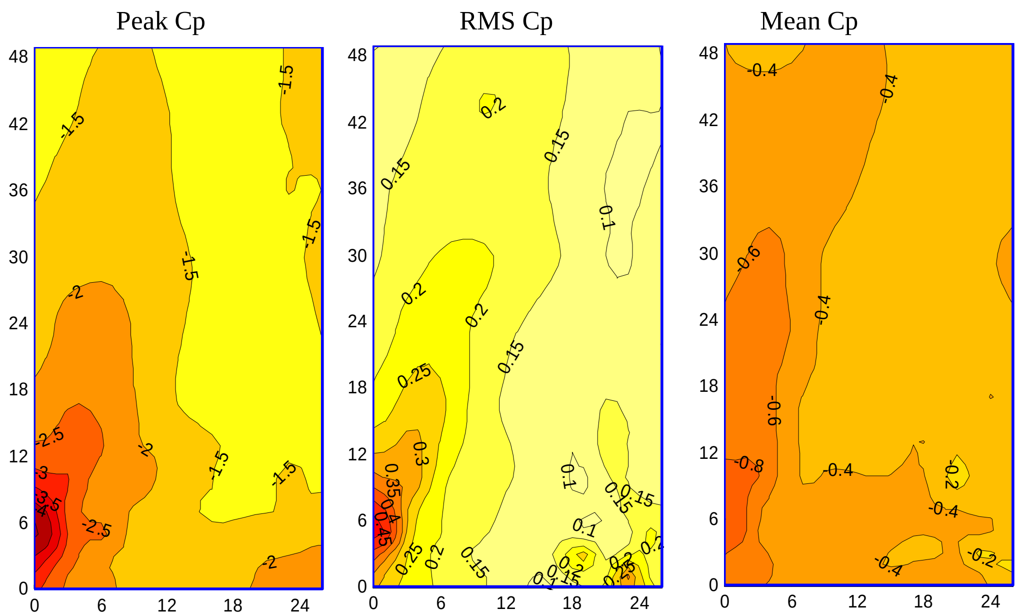
Table 4.49 Test Cases for RMS Wind Pressure Coefficient Statistics Analysis

Terrain	Model
Open Country	7.0 m, 11.6 m and 16.1 m high monosloped roof models
	2- to 5-span 16.1 m high sawtooth roofs
	7.0 m, 11.6 m high 5-span sawtooth roofs
Suburban	7.0 m, 11.6 m high monosloped roof models
	7.0 m, 11.6 m high 5-span sawtooth roof models

Fig. 4.50 ~ Fig. 4.53 provide the plots of contours of peak, RMS and mean wind pressure coefficient for one-half roof area of a monosloped roof and a 5-span sawtooth roof with mean roof height of 11.6 m under open country and suburban exposures. The distribution patterns of RMS, mean and extreme

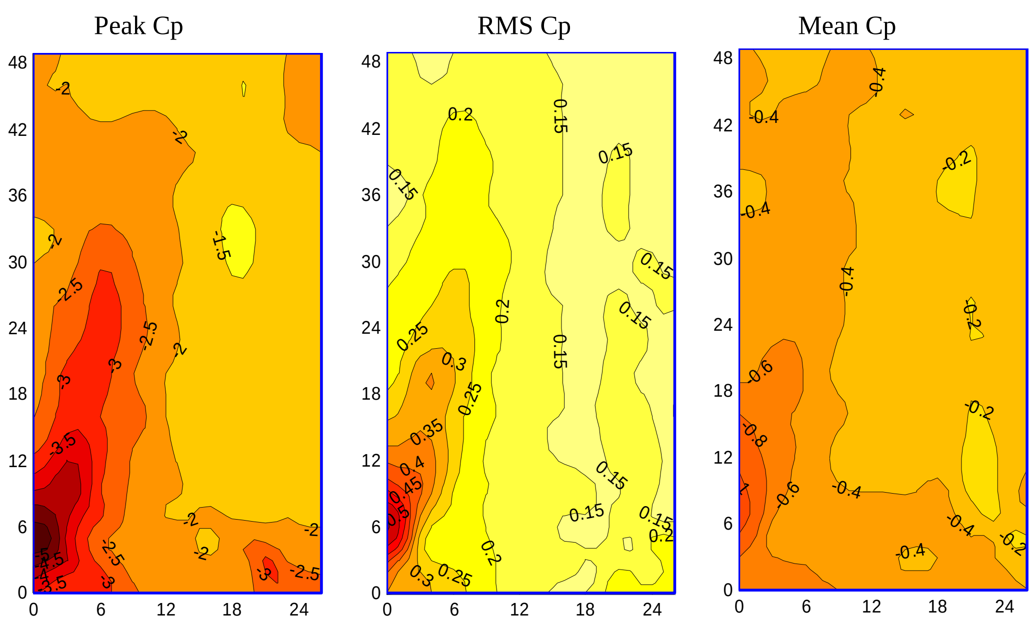
negative pressure coefficient are similar to one another. The pressure zones with high wind suction coefficients are also the zones containing the highest standard deviation and mean wind pressure coefficients, which indicates peak wind pressure distribution is highly correlated to the RMS distribution.

For the monosloped roofs, the high suction mainly concentrates on the high corner where both the peak and RMS wind pressure coefficients are significantly higher than those for the other zones by a factor of over 2.0. For the sawtooth roofs, high RMS wind pressure coefficients are also observed within the high suction zones, specifically in the corners of the windward span, the sloped edge and the low corner zones of middle spans.



11.6 m High Monosloped Roof in Open Country

Figure 4.50 Contours of Extreme, RMS and Mean Negative Cp for Monosloped Roof (Left is High Edge)



11.6 m High Monosloped Roof in Suburban

Figure 4.51 Contours of Extreme, RMS and Mean Negative Cp for Monosloped Roof (Left is High Edge)

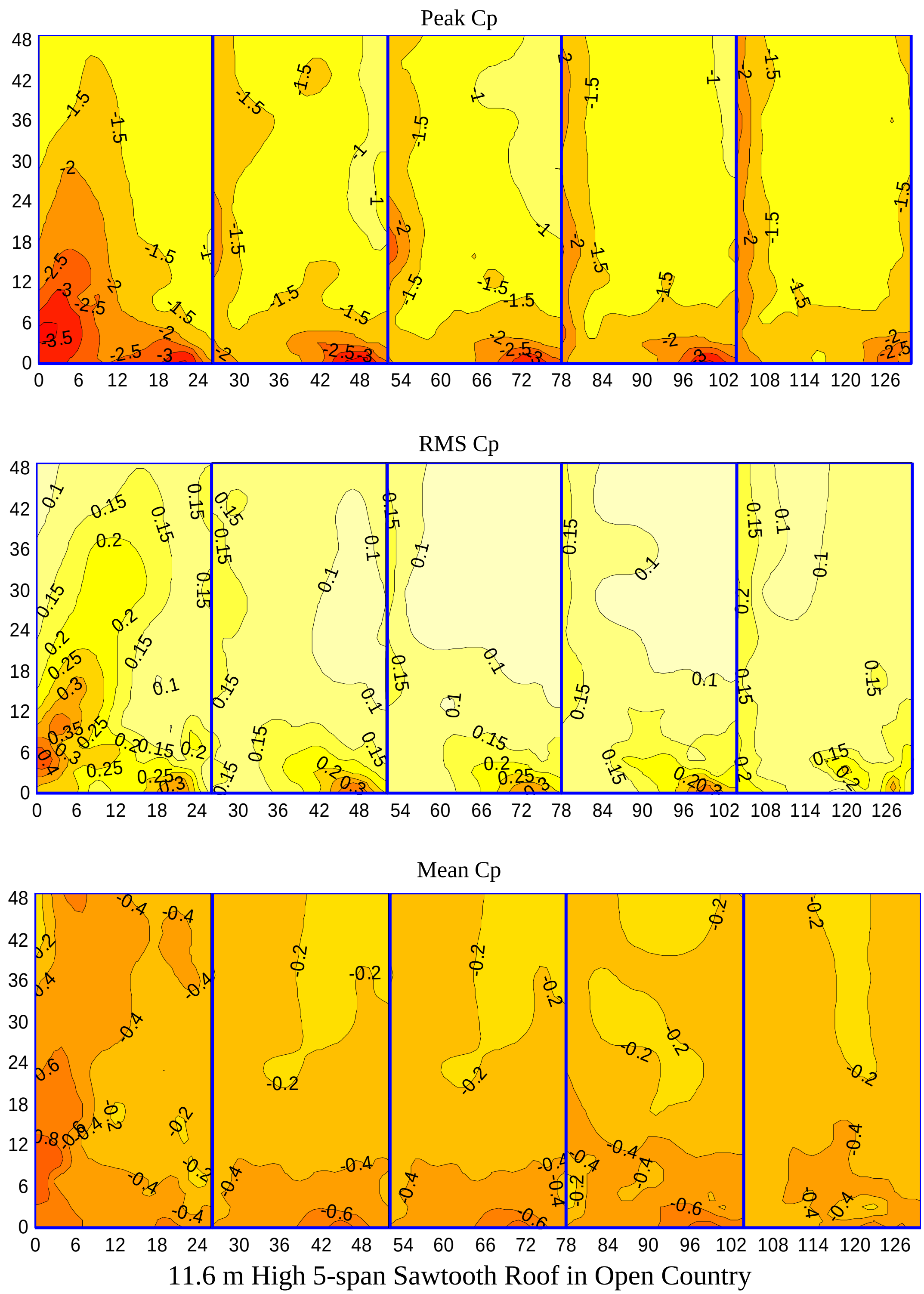


Figure 4.52 Contours of Extreme, RMS and Mean Negative Cp for Sawtooth Roof (Left is High Edge)

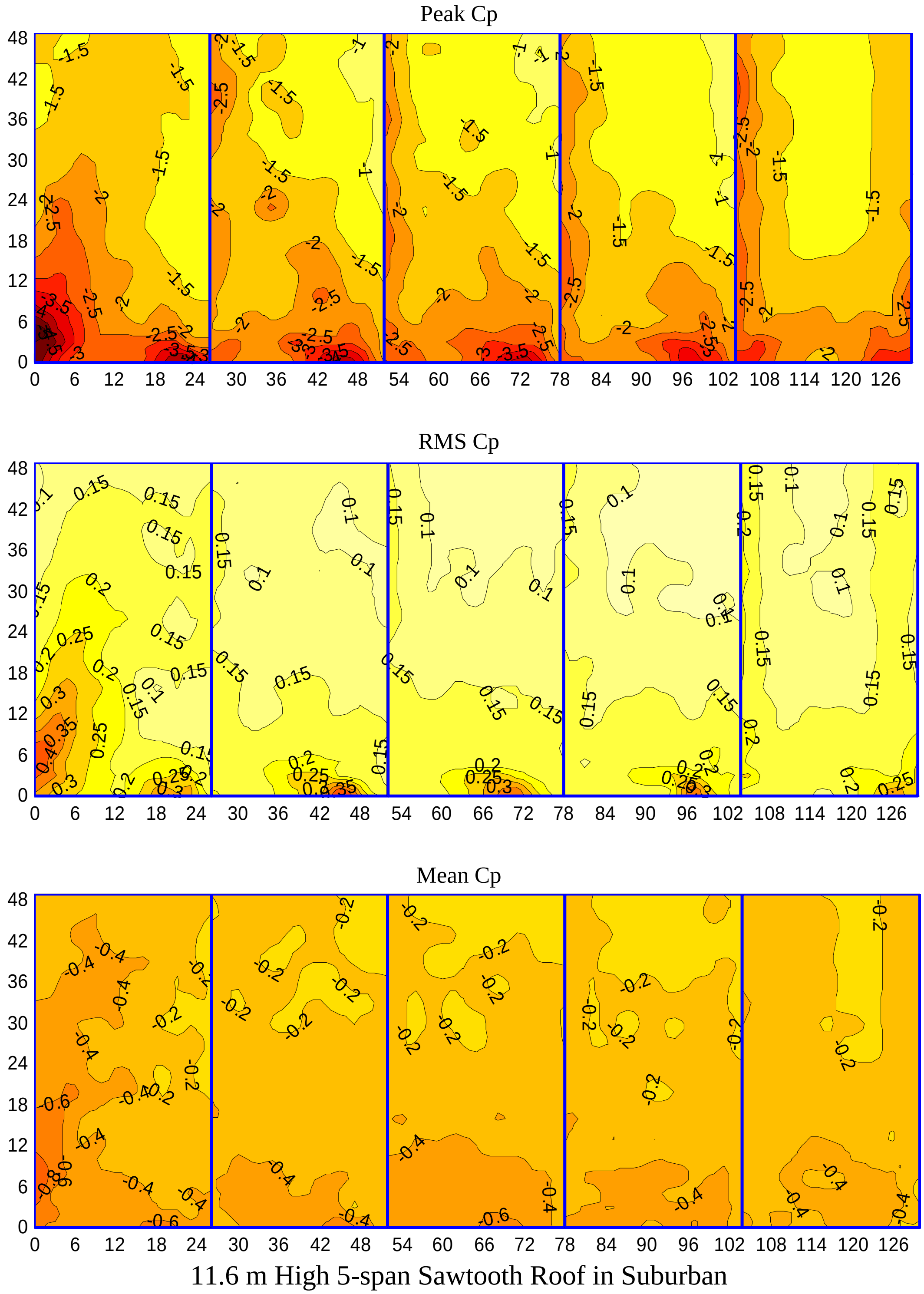


Figure 4.53 Contours of Extreme, RMS and Mean Negative Cp for Sawtooth Roof (Left is High Edge)

The extreme wind pressure coefficient for a pressure zone plays a dominant role to estimate the design wind loads. As a factor highly correlated to peak wind pressure coefficients, the corresponding zonal RMS wind pressure coefficients are studied. The extreme and RMS wind pressure coefficients for a series of monosloped and sawtooth roof models with varying building heights and under different terrain exposures are presented in Table 4.50.

Table 4.50 Extreme, RMS and Mean Cp for High Corner of Monosloped Roof and Windward Span of Sawtooth Roofs

Exposure: open country			
Model	Extreme	RMS	Mean
16.1 m -mono	-4.22	0.37	-1.00
11.6 m - mono	-4.07	0.46	-0.87
7.0 - mono	-4.14	0.48	-0.67
16.1 m - 5A	-4.38	0.44	-0.94
11.6 m - 5A	-3.79	0.43	-0.87
7.0 m - 5A	-3.79	0.40	-0.87
Exposure: Suburban			
Model	Extreme	RMS	Mean
11.6 m - mono	-5.1	0.43	-0.95
7.0 m - mono	-4.98	0.47	-0.73
11.6 m - 5A	-5.2	0.43	-0.76
7.0 m - 5A	-4.41	0.37	-0.47

The results for critical RMS wind pressure coefficients are in the range of 0.37 to 0.48 for the monosloped and sawtooth roof models. The effects of building height and building exposure on critical RMS wind pressure coefficients are not evident. For the sawtooth roofs with three heights the critical RMS values are very close to one another within range of 0.40 ~ 0.44 under open country exposure. However, under suburban exposure the RMS value (0.37) for the 7.0 m high sawtooth roof is significantly lower than the value of 0.43 for 11.6 m high sawtooth roof. For the monosloped roofs, it can be seen that the RMS values for the lower models are higher than those for the higher models under both open country and suburban exposures from Table 4.50.

Zonal statistical values for the RMS wind pressure coefficients are used to highlight the variation of RMS values gathered from different pressure zones on the roofs under study. These roof zone definitions, discussed earlier in Section 4.3, were used to maintain consistency with the pressure zones used in zonal extreme wind pressure coefficients. The comparisons of zonal extreme, RMS and mean wind pressure coefficients under open country and suburban exposures are shown in Table 4.51.

Table 4.51 Comparisons of Extreme Negative, RMS and Mean Cp for Monosloped Roofs and Sawtooth Roofs under Open and Suburban Exposures

Terrain	Open Country			Suburban		
Pressure Zone	Monosloped Roof					
	Extreme	RMS	Mean	Extreme	RMS	Mean
HC	-4.14	0.46	-0.87	-5.10	0.43	-0.95
LC	-2.35	0.36	-0.42	-3.18	0.26	-0.60
HE	-2.87	0.32	-0.78	-3.90	0.36	-1.02
LE	-1.71	0.10	-0.29	-2.38	0.22	-0.70
SE	-2.57	0.20	-0.53	-3.17	0.22	-0.57
IN	-2.51	0.24	-0.42	-3.19	0.28	-0.59
Pressure Zone	Windward Span of Sawtooth Roof					
	Extreme	RMS	Mean	Extreme	RMS	Mean
HC	-3.79	0.43	-0.87	-5.2	0.43	-0.76
LC	-3.29	0.34	-0.53	-4.11	0.43	-0.76
HE	-2.83	0.32	-0.77	-3.03	0.28	-0.50
LE	-1.62	0.14	-0.38	-2	0.34	-0.72
SE	-3.09	0.27	-0.55	-3.63	0.32	-0.60
IN	-2.99	0.25	-0.49	-3.38	0.28	-0.46
Pressure Zone	Middle and Leeward Spans of Sawtooth Roof					
	Extreme	RMS	Mean	Extreme	RMS	Mean
HC	-2.97	0.18	-0.41	-2.89	0.17	-0.39
LC	-3.60	0.27	-0.57	-3.83	0.26	-0.42
HE	-3.08	0.17	-0.39	-2.89	0.16	-0.31
LE	-2.73	0.16	-0.46	-2.78	0.18	-0.36
SE	-3.78	0.30	-0.67	-3.95	0.29	-0.49
IN	-2.45	0.14	-0.42	-2.64	0.16	-0.35

The most critical suction occurs within the high corner of the monosloped roofs and windward span of the sawtooth roofs. The RMS values for this zone of the monosloped and windward spans of sawtooth roofs range from 0.21 to 0.48, with a mean value of 0.41 under both the open country and suburban exposures. No substantial discrepancies were found between the RMS wind pressure coefficients within this zone for either open or suburban exposures.

On the high edge and low corner pressure zones of the monosloped roofs and windward spans of the sawtooth roofs, the RMS wind pressure coefficients are similar, with RMS values ranging from 0.22 to 0.37. The low edge zone for these monosloped and sawtooth roofs is a low suction zone. Compared with the high corner and high edge zones, the RMS values for this low edge zone are also lower. Indeed, the RMS wind pressure coefficients recorded on the pressure taps in this zone are less than 0.15 under open exposure. The RMS wind pressure coefficients for the interior are usually less than 0.2 for the monosloped roofs and middle and leeward spans of the sawtooth roofs under both open and suburban exposure. On the windward spans of the sawtooth roofs, RMS wind pressure coefficients are higher than those on the other spans; most observed RMS values range from 0.25 ~ 0.35.

The above discussions and comparisons indicate that RMS wind pressure coefficients are highly correlated to the high suction zones. The patterns of RMS wind pressure coefficient distribution are very similar with those of peak wind pressure coefficient distribution. In addition, the RMS values are more stable than the peak values, particularly for the peak estimates only obtained from one wind tunnel run. In general, using the RMS wind pressure coefficient distributions to determine the critical suction zone on buildings will yield more stable and accurate results than using peak wind pressure distribution.

CHAPTER 5

COMPARISIONS BETWEEN TEST RESULTS AND ASCE 7-02 PROVISIONS

The ASCE 7-02 provides the recommended wind pressure zones and pressure coefficients for the construction of monosloped and sawtooth roofs. In this chapter local and area-averaged wind pressure coefficients obtained from test results are compared with ASCE provisions.

5.1 Local Wind Pressure Coefficients

Since test wind pressure coefficients are referenced to the mean wind speed at the reference height and ASCE 7-02 pressure coefficients are referenced to 3-s gust wind speed at mean roof height, adjustment factors between different reference wind speeds are applied to adjust test wind pressure coefficients. The determination of adjustment factors for the heights of 7.0 m, 11.6 m and 16.1 m were discussed in section 4.4.2. These adjustment factors are shown in Table 5.1.

Table 5.1 Cp Adjustment Factors for Three Building Heights

Height (Full Scale)	Adjustment Factors
7.0 m	1.330
11.6 m	1.219
16.1 m	1.159

Table 5.2 Comparisons of Test Cp and ASCE 7-02 Values for Monosloped Roofs

Extreme Wind Pressure Coefficients for Three Height Monosloped Roofs			
Pressure Zone	Test	ASCE 7-02	Diff./ASCE
HC	-5.5	-2.9	90%
LC	-3.2	-1.6	98%
HE	-3.8	-1.6	137%
LE	-2.3	-1.6	43%
SE	-3.1	-1.6	96%
IN	-3.1	-1.3	136%
Note: wind pressure coefficients are referenced to 3-s gust wind speed at mean roof height.			

Diff./ASCE denotes the ratio of the difference between test wind pressure coefficients and ASCE 7-02 value divided by ASCE 7-02 value. It is clearly evident that the test wind pressure coefficients are significantly higher than ASCE 7-02 values on all wind pressure zones.

Table 5.3 Comparisons of Test Cp and ASCE 7-02 Values for Windward Span of Sawtooth Roofs

Extreme Wind Pressure Coefficients for Windward Span of Sawtooth Roofs			
Pressure Zone	Test	ASCE Cp	Diff./ASCE
HC	-5.4	-4.1	31%
LC	-4.6	-4.1	13%
HE	-4.0	-3.2	25%
LE	-2.9	-3.2	-10%
SE	-4.3	-3.2	33%
IN	-4.1	-2.2	87%
Note: wind pressure coefficients are referenced to 3-s gust wind speed at mean roof height			

Table 5.3 shows the comparisons of the test wind pressure coefficients and the ASCE values for each ASCE 7-02 recommended pressure zones on the

windward span of sawtooth roofs. The test wind pressure coefficients for the high corner, high edge and sloped edge exceed ASCE 7-02 values by 25% ~ 35%. For the interior zone test local wind pressure coefficient exceeds ASCE 7-02 value by 87%. The test wind pressure coefficient for the low corner zone is higher than the ASCE 7-02 value by 13%. However, the test wind pressure coefficient for the low edge zone is lower than the ASCE 7-02 value by 10%. To conclude, if the ASCE 7-02 pressure zones are applied to the windward spans of test models, there is a substantial discrepancy between the test results from this dissertation and the ASCE 7-02 recommended wind pressure coefficients for most pressure zones.

Table 5.4 Comparisons of Test Cp and ASCE 7-02 Values for Middle Spans of Sawtooth Roofs

Extreme Wind Pressure Coefficients for Middle Spans of Sawtooth Roofs			
Pressure Zone	Test	ASCE 7-02 Cp	Diff./ASCE
HC	-2.8	-2.6	6%
LC	-4.1	-2.6	59%
HE	-3.1	-3.2	-2%
LE	-3.1	-3.2	-2%
SE	-4.4	-3.2	37%
IN	-2.9	-2.2	31%
Note: wind pressure coefficients are referenced to 3-s gust wind speed at mean roof height			

Table 5.4 shows comparisons of test wind pressure coefficients and the ASCE 7-02 values for each pressure zone for the middle spans of sawtooth roofs. Research results clearly indicate that the higher suction occurs both on the low corner and on the sloped edge of the middle spans of sawtooth roofs. However, ASCE 7-02 provides a higher wind pressure coefficient for the edge zones (high edge, low edge and sloped edge) than the value for the corners (high corner and

low corner) on the middle spans of the sawtooth roofs. The extreme test wind pressure coefficient for the low corner is -4.1, which is 59% higher than the ASCE 7-02 value of -2.6. The extreme wind pressure coefficient of -4.4 occurs in the sloped edge, which is 37% higher than the ASCE 7-02 recommended value of -3.2. The observed extreme wind pressure coefficient for the high edge and low edge zones is -3.1, which is almost same with the ASCE 7-02 value of -3.2.

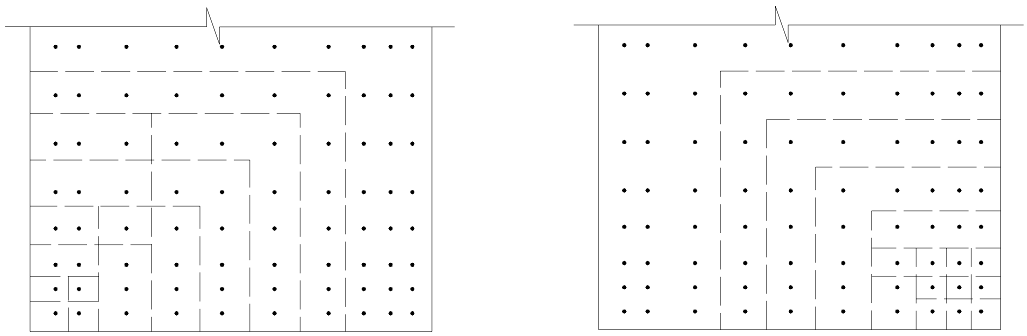
ASCE 7-02 provides the same wind pressure coefficients for the leeward span with those for the middles spans in a sawtooth roof. However, the extreme wind suction on the leeward span of sawtooth roofs is lower than those for the other spans. The observed extreme negative wind pressure coefficient for the leeward span is -3.6, which is 21% lower than the extreme value of -4.1 that occurs within the middle roof span areas. The statistical results of these zonal wind pressure coefficients for the leeward spans of sawtooth roofs show no discernable difference of wind pressure coefficients between the corners and the high and sloped edges. Test wind pressure coefficients for these pressure zones range from -3.5 to -3.6. In particular ASCE 7-02 recommends wind pressure coefficient of -3.2 for the low edge which is higher than test result of -2.6 by 18%. The extreme wind pressure coefficient for the low edge zone is also lower than the wind pressure coefficient of -3.6 on the high edge by 20%. The test wind pressure coefficient for the interior zone is very close to the ASCE 7-02 recommended value. The detailed comparisons of wind pressure coefficient between ASCE 7-02 values and test results for the leeward spans are shown in Table 5.5.

Table 5.5 Comparisons of Test Cp and ASCE 7-02 Values for Leeward Span of Sawtooth Roofs

Extreme Wind Pressure Coefficients for Span A of Sawtooth Roofs			
Pressure Zone	Test	ASCE 7-02 Cp	Diff./ASCE
HC	-3.5	-2.6	35%
LC	-3.6	-2.6	39%
HE	-3.6	-3.2	13%
LE	-2.6	-3.2	-18%
SE	-3.0	-3.2	-6%
IN	-2.1	-2.2	-3%
Note: wind pressure coefficients are referenced to 3-s gust wind speed at mean roof height			

5.2 Area-averaged Wind Pressure Coefficients

The area-averaged wind pressure coefficients for the high corner and low corner zones of the monosloped and sawtooth roofs in this study are compared with ASCE 7-02 provisions to further understand the tributary area effect on wind pressure coefficient. The tributary areas in the high and low corners of the roofs under study are defined in Fig. 5.1. The dashed line indicates various tributary areas. The minimum area in the high and low roof corners includes two pressure taps with full scale tributary area of less than 0.4 m^2. The largest full scale tributary area developed in this high corner is 35 m^2 and includes 49 pressure taps. The largest area in low corner is 32 m^2 which also includes 49 taps.



Area in High Corner

Area in Low Corner

Figure 5.1 Boundaries of Averaging Area in High Corner and in Low Corner (Left Side is High Edge)

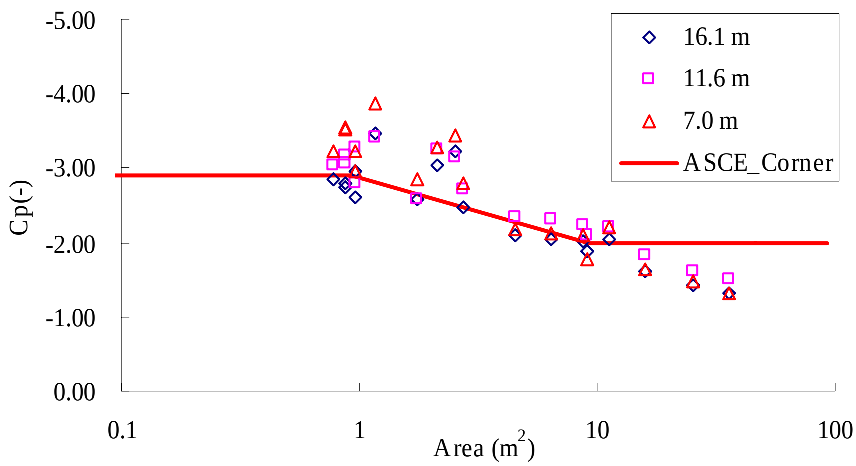


Figure 5.2 Comparisons of Test Cp and ASCE 7-02 Provisions for High Corner of Monosloped Roof

Fig. 5.2 details area-averaged wind pressure coefficients for the high corner of sawtooth roofs with heights of 7.0 m, 11.6 m and 16.1 m. The ASCE 7-02 provisions for the corner zone are also shown in Fig. 5.2. Although the test local wind pressure coefficient for the high corner of the monosloped roofs exceeds the ASCE 7-02 value by more than 30%, the test area-averaged wind pressure coefficient on this zone is very similar with ASCE 7-02 values.

Within the tributary area of 1.0 m^2, the extreme value of test results exceeds ASCE 7-02 value by 30%. When the tributary area increases to 9 m^2, the extreme test wind pressure coefficient is only higher than ASCE 7-02 value by 10%. The test area-averaged wind pressure coefficient with tributary area of 35 m^2 for the high corner is -1.5 as compared with the ASCE 7-02 value of -2.0. This phenomenon could be possibly due to the large tributary area covering not only the high corner of the roof but also part of the roof interior; and the wind pressure coefficient for interior is less than that for the higher corner.

Since the ASCE 7-02 assigns the low corner and edge of a monosloped roof to one pressure zone, test wind pressure coefficients for the low corner are compared with ASCE 7-02 values for the edge zone. Fig. 5.3 shows the test area-averaged wind pressure coefficients for the low corner of 7.0 m, 11.6 m and 16.1 m high sawtooth roofs and the ASCE 7-02 values. The local test wind pressure coefficient for the low corner of the monosloped roofs is -3.2 which is higher than the ASCE 7-02 value of -1.6 by 100%. The test area-averaged wind pressure coefficients with a small tributary area (less than 1.8 m^2) in this zone exceeds current ASCE 7-02 values by a range of 20% - 50%. For tributary area larger than 9 m^2, the test area-averaged wind pressure coefficient is still higher than ASCE 7-02 value by more than 10%. It can be concluded that ASCE 7-02 underestimates the wind suction occurring at the low corner of monosloped roofs.

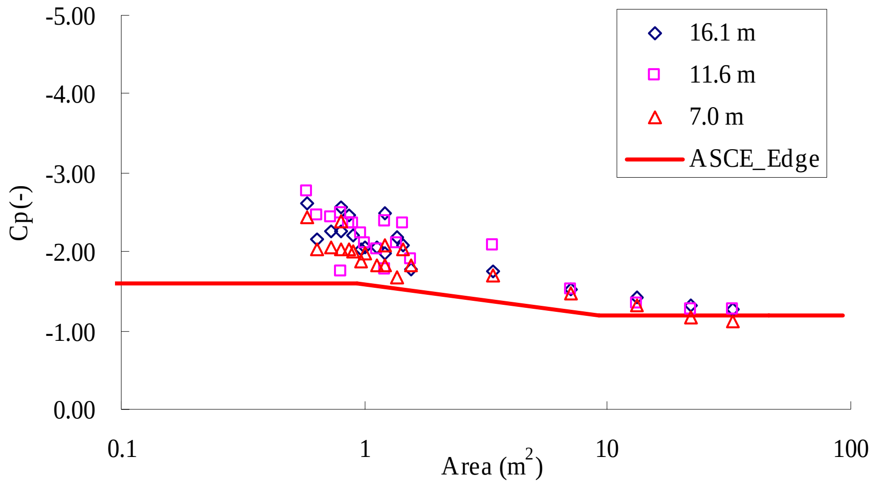


Figure 5.3 Comparisons of Test Cp and ASCE 7-02 Provisions for Low Corner of Monosloped Roof

ASCE 7-02 recommends significantly higher wind pressure coefficients for the windward span of sawtooth roofs than for the other spans of sawtooth roofs and monosloped roofs. In particular for the corner zones, the ASCE 7-02 local wind pressure coefficient for the high corner on a windward span of sawtooth roofs is -4.1 which is 41% higher than the value -2.9 for monosloped roofs and is 57% higher than the value -2.6 for the other spans of sawtooth roofs. The test local wind pressure coefficient for the high corner on a windward span of sawtooth roofs is very close to the ASCE 7-02 value with a difference of less than 5%. By the comparison of the area-averaged wind pressure coefficients for the high corner of a windward span of sawtooth roofs between test results and ASCE 7-02 provisions, it can be seen that ASCE 7-02 provides a lower reduction ratio of wind pressure coefficient caused by averaging area. With a tributary area of 0.9 m^2, the test wind pressure coefficient is -4.8, which is 17% higher than the ASCE 7-02 value -4.1. When averaging area increases to 9 m^2, the extreme test wind pressure coefficient is -2.49 which is lower than ASCE 7-02 value of -3.7 by 32%.

ASCE 7-02 gives the same wind pressure coefficient for the high and low corners on the windward span of sawtooth roofs. However, it was found that the wind suction levels on the high and low corners are not the same. The observed local wind pressure coefficients for the high corner is -5.4, or approximately 17% higher than the corresponding peak local pressure coefficient of -4.6 for the low corner. The observed area-averaged wind pressure coefficients for the high corner are also higher than the corresponding values for the low corner. With the tributary area of 0.9 m^2, the test extreme wind pressure coefficients are -4.8 and -3.65 for the high corner and low corner respectively. When the tributary area is increased to 9 m^2 the test value for the high corner is -2.4, still about 50% higher than the value of -1.6 for the low corner value. Fig. 5.4 and Fig. 5.5 show the comparisons of wind pressure coefficients for the high corner and low corner of a windward span of sawtooth roofs between test results and ASCE 7-02 provisions.

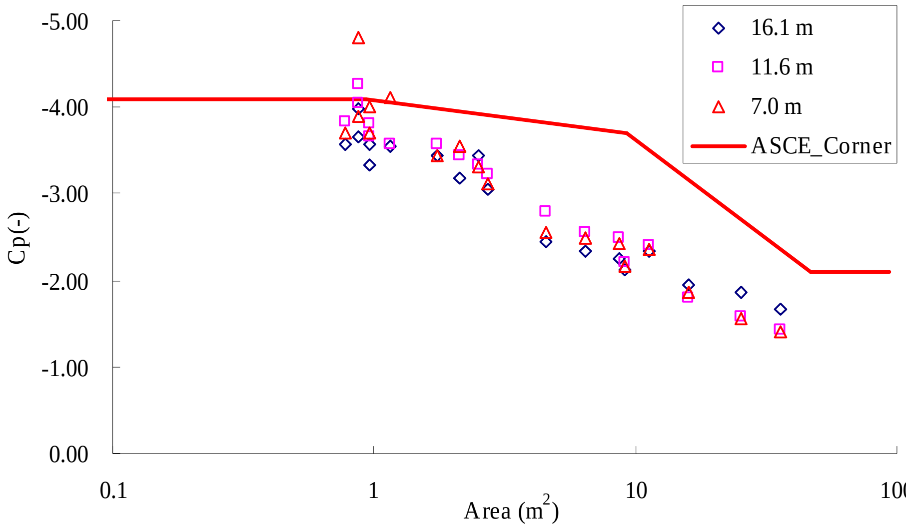


Figure 5.4 Comparisons of Test Cp and ASCE 7-02 Provisions for High Corner of Windward Span of Sawtooth Roofs

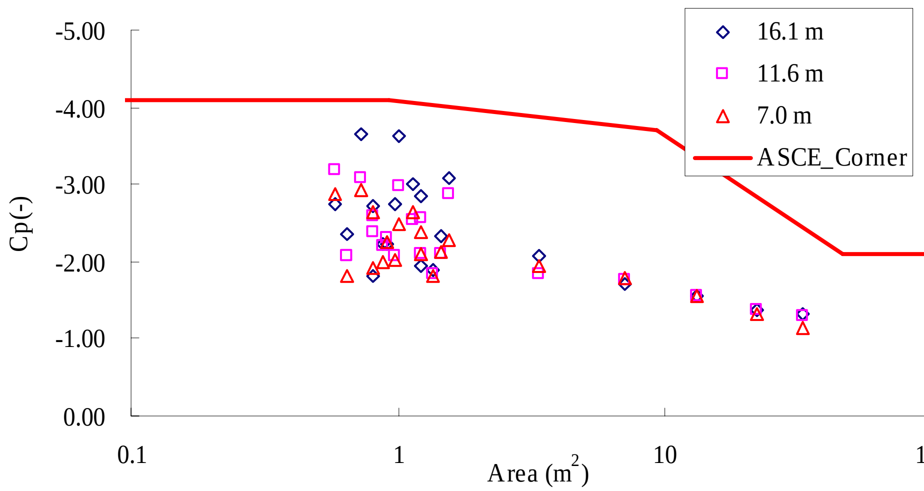


Figure 5.5 Comparisons of Test Cp and ASCE 7-02 Provisions for Low Corner of Windward Span of Sawtooth Roofs

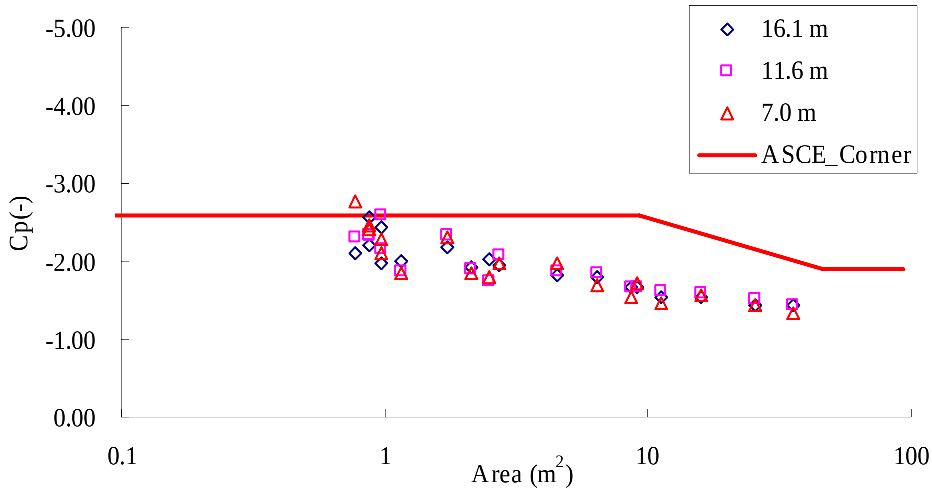


Figure 5.6 Comparisons of Test Cp and ASCE 7-02 Provisions for High Corner of Middle Span of Sawtooth Roofs

The test wind pressure coefficients for the high corner on the middle spans of sawtooth roofs are less than those for the low corner on the middle spans of sawtooth roofs. The test extreme local wind pressure coefficient for the low corner of middle spans is -4.1 which is more negative than the value -2.8 for the high corner by 46%. The test area-averaged wind pressure coefficients with tributary areas in the range of 0.9 m^2 to 9 m^2 for the low corner of middle spans are also more negative than the values for the high corner by over 20%. ASCE 7-02 suggests the same wind pressure coefficient should be used for the high and low corners. This will overestimate the wind suction occurring on the high corner of middle spans. Fig. 5.6 and Fig. 5.7 present the comparisons of wind pressure coefficients between test results and ASCE 7-02 values. It can be seen that for the low corner ASCE 7-02 wind pressure coefficients are significantly lower than the test extreme value for a small tributary area of 0.9 m^2. However, when the tributary area is increased to 9 m^2, the wind pressure coefficient for the low corner decreases by more than 30% and the value is lower than the ASCE 7-02 provision. The same situation occurs on the high corner of the middle spans, where with a 0.9 m^2 tributary area, the test wind pressure coefficient (-2.76) is very close to ASCE 7-02 value (-2.6). When the tributary area increases to 9 m^2, the test wind pressure coefficient is lower than ASCE 7-02 value by 34%.

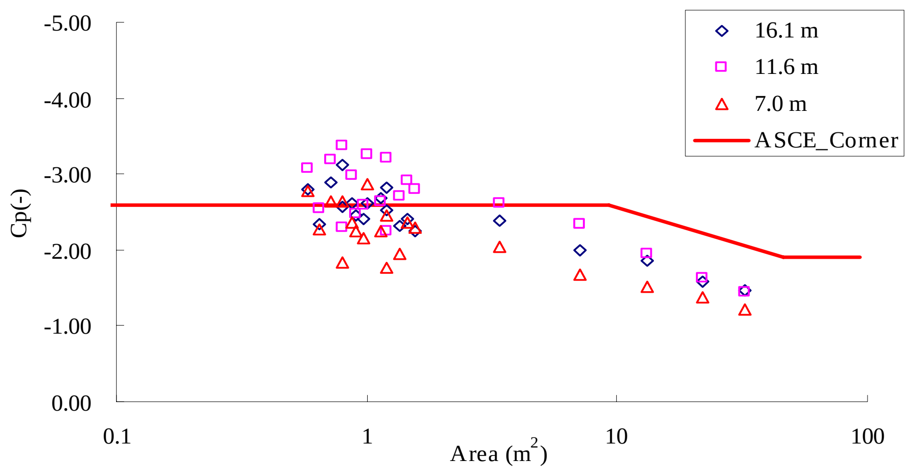


Figure 5.7 Comparisons of Test Cp and ASCE 7-02 Provisions for Low Corner of Middle Spans of Sawtooth Roof

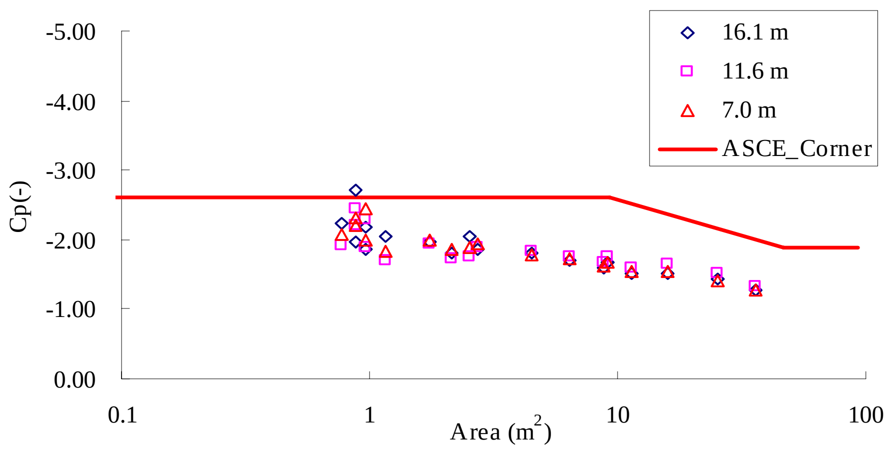


Figure 5.8 Comparisons of Test Cp and ASCE 7-02 Provisions for High Corner of Leeward Span of Sawtooth Roof

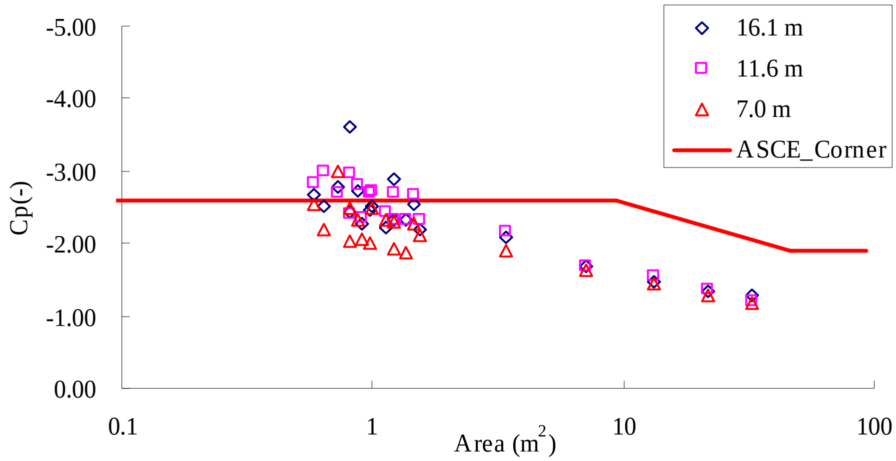


Figure 5.9 Comparisons of Test Cp and ASCE 7-02 Provisions for Low Corner of Leeward Span of Sawtooth Roof

The test area-averaged wind pressure coefficients for the corners of leeward spans are similar with the values for the corresponding location of middles spans. Although the extreme local wind pressure coefficient occurring on the middle spans of sawtooth roofs is higher than the value for the leeward spans by over 22% (-4.4 and -3.6 respectively), the area-averaged wind pressure coefficients for a 0.9 m^2 tributary area for the low corner of middle spans is very similar with that for the leeward spans (-3.4 and -3.6). In the high corner the reduction ratio for the area-averaged wind pressure coefficient with a tributary area of 9 m^2 is 35% for the leeward spans. This ratio is very close to the ratio of 37% for the middle spans. For the low corner, the reduction ratio of area-averaged wind pressure coefficient with a tributary area of 9 m^2 for the leeward span is a little lower than for the middle spans (38% and 53%). Fig. 5.8 and Fig. 5.9 present the comparisons of wind pressure coefficient for the high and low corners of the leeward spans. ASCE 7-02 typically overestimates the wind suction on the high corner zones. ASCE 7-02 also gives higher area-averaged wind pressure coefficients for high corner and low corner with tributary areas larger than 0.9 m^2.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Over the last two decades interest in wind engineering research has increasingly focused on understanding wind loads and structural capacities of the low rise structure, since much of the damage and financial losses associated with extreme wind events occur to these buildings. The atmospheric boundary layer wind tunnel has proved to be an invaluable resource in the estimation of design wind loads. In this research work, wind tunnel tests were conducted to investigate and compare the distribution of wind pressure coefficients for monosloped roofs and sawtooth roof buildings of similar geometries. The results presented herein evaluated roof wind pressures as a function of wind direction, building height, exposure terrain, and, for the sawtooth roof building, number of spans (or roof monitors) and distance between roof monitors.

6.1 Wind Pressures on Monosloped Roofs versus Sawtooth Roofs

The research set out to answer the fundamental question regarding the validity of current design wind pressures for monosloped and sawtooth roof structures. The results show there is no significant difference between the extreme wind load distribution for monosloped roofs and wind load on the windward span of sawtooth roofs of similar geometric characteristics. These research results have shown that the ASCE 7-02 design wind pressure coefficients for monosloped roofs are nearly 40% lower than the measured results. It was also shown that the pattern of wind pressure distributions on the high corner and high edge zones are the same for the monosloped roof as for the windward span of the sawtooth roof.

The results call into question the ASCE 7-02 wind design values for monosloped roofs which are more than 30% lower than comparable values on the sawtooth roof, and do not provide adequate wind uplift loads for design. It is recommended that the local wind pressure coefficients for the monosloped roof be increased to match the wind pressure coefficients for the windward span of the sawtooth roof structure.

6.2 Parameter Effects on Wind Pressure Coefficients

The major conclusions from the parametric study on wind pressure coefficients identified other characteristics of the wind load distribution on sawtooth roof structures. Firstly, although the pattern of wind pressure distribution was essentially the same on all configurations, the highest peak wind pressure coefficients occurred on the two- and five-span sawtooth roofs (-4.61 and -4.38 respectively) while the three- and four-span sawtooth roofs experienced lower peak pressure coefficients of -3.96 and -3.61 respectively. It is believed that this phenomenon occurred due to the effect of the smaller horizontal aspect ratios of the three- and four-span sawtooth roofs. For example, the aspect ratio for the 4-span roof is 1.06, as compared to aspect ratios of 1.88 and 1.33 for the two-span and five-span models respectively. The results were not sufficient to establish a definitive relationship and more work will be required.

It was observed that building height has a significant effect on extreme peak wind pressure coefficients for the sawtooth roof structures, but the effect on the monosloped roof was insignificant. The results showed an increase in extreme wind pressure coefficients (referenced to the reference height in the wind tunnel) with increasing building height of approximately 30% between the 7.0 m and 16.1 m high sawtooth roofs. However, the change in extreme wind pressure coefficients between the monosloped roof models was less than 10%.

When wind pressure coefficients are referenced to 3-second gust wind speed at mean roof height, the change of wind pressure coefficients with the increase of building height decreases. But a large difference still exists between high and low buildings. The observed difference of Cp referenced to 3-s gust wind speed at mean roof heights for monosloped roof and sawtooth roof can be more than 20%.

The effect of surrounding houses on the wind pressures is significant. The comparisons of wind pressure coefficients for the isolated building and surrounding building in suburban terrain shows that the isolated buildings experienced 15% ~ 20% higher wind suctions than on the building with surrounding houses.

By comparing wind pressure coefficients (referenced to gradient wind speed) on monosloped and sawtooth roofs it was shown that on average the isolated building in suburban terrain experience lower wind suctions than that in open country terrain by 10% ~ 25%. Considering the building in suburban terrain is usually surrounded to some degree by other obstructions, The effect of the near field terrains (surrounding houses) can add a reduction of 10% ~ 25% to the wind suctions experienced by an isolated building. The reduction rate of 18% ~ 25% (K_z coefficients) adopted by ASCE 7-02 for the low rise buildings appears appropriate.

6.3 Area-Averaged Loads on Monosloped and Sawtooth Roofs

It was observed that while extreme local wind pressure coefficients for the monosloped roofs were identical to those measured for the sawtooth roofs, the area-averaged wind pressure coefficients for the monosloped roofs fall off faster than for the windward span of sawtooth roofs and this should be taken into consideration in modifying the design wind load provisions for the monosloped roof structure. In addition, the analysis also compared local wind pressure coefficients with area-averaged wind pressure coefficients at various locations of the monosloped and sawtooth roofs. When these results were compared with wind design provisions contained in ASCE 7-02, it was found that the reduction rate in wind pressure coefficient values with a tributary area of 0.9 m^2 (33%) is higher than the rate (10%) for high corner of windward span of sawtooth roofs; for other pressure zones the reduction rates of test results are similar with ASCE 7-02 recommendations. For monosloped roofs, ASCE 7-02 recommended similar reduction rates (30%) in wind pressure coefficients with those found in test results. As a result of these findings, a modification to Fig. 6.6 and Fig. 6.11 of ASCE 7-02 may be wanted for the monosloped and sawtooth roof building.

6.4 Extrapolation Method for Estimating Peak Wind Pressure Coefficient Values

This dissertation relied upon the extrapolation method for estimating the peak wind pressure coefficients from a single wind tunnel run. The extrapolation method was used because it provided a more efficient numerical analysis method of predicting peak values. The comparison of results from the extrapolation method with the more established averaging direct peak and Lieblein BULE statistical mean peak value estimation methods showed differences of less than 5% between the methods and there was no bias in the results.

6.5 Application of RMS Contours to Predict Wind Pressure Distributions

The research also investigated the relationship between the root mean square (or standard deviation) of wind pressure coefficients and the peak negative wind pressure coefficients. It was found that, for the monosloped and sawtooth roof buildings, distributions of RMS and the peak negative pressures are strongly correlated to each other. Generally, the ratio of the peak negative wind pressure to RMS value in the highly loaded corner and edge zones ranged from 8 to 12. This stability of the relationship suggests that RMS values of wind pressure coefficient, a relatively stable statistical measure, may be used as an initial predictor of peak pressure distributions on roofs. This result is promising in that with further work it may be possible to use RMS contours to establish the pressure zones on complex roof shapes such as in typical single residential construction.

6.6 Wind Pressures Distributions on Separated Sawtooth Roofs

One of the interesting results obtained was the comparison of wind pressure distributions of the “separated” sawtooth roof structure (sloping roof monitors with flat roof sections between them) with the “classic” sawtooth roof structure. The results showed that the roof monitor separation distances caused an increase in the peak negative wind pressures occurring on the roof. This wind pressure increase was most pronounced in the high edge, sloped edge and low edge zones of the windward span on a separated sawtooth roof, resulting in wind load increases in the range of 15% to 30%. In addition, the wind pressure coefficients in the high corner and low corner zones of the middle spans also showed an increase by up to 15% over the classic sawtooth roofs.

The research investigated the effect of three flat roof widths on wind pressure coefficients of the roof monitors and it was found that the wind pressure coefficients in the high edge, low edge and sloped edge zones on the windward span of the separated sawtooth roof decreased with increasing separation distance between roof monitors. However, there was no such trend in the middle spans, as wind pressure coefficients actually increased for the high corner, low corner and sloped edge zones, for a separation distance of 7.9 m.

While it was observed that pattern of wind pressure distributions on the three flat roof sections were essentially the same, the peak wind pressure coefficients actually increased with increasing separation distance, i.e. peak pressure coefficients on the 5.5 m flat roof was –3.3, and it increased to -3.5 on the 7.9 m roof and -4.4 on the 10 m wide flat roof. The impact of these findings is significant as the wind design standards provide no guidelines for the design of the separated roof structure and structural designers have typically used design values for the classic structure, which the results show is likely to underestimate wind loading on the separated sawtooth roof.

6.7 Recommended Wind Pressure Coefficients for Monosloped and Sawtooth Roofs

A major focus of this research was to rationalize the wind pressure contour maps that are used for design purposes. The results showed that peak pressures can occur over larger corner and edge zone areas than are used in ASCE 7-02. The use of the RMS contour maps helped to identify new peak zones that provide reasonable use in design. The pressure zones presented below differ from the pressure zones contained in ASCE 7-02 because pressure zone definition in current study is not based on the traditional pressure zone definition method, but completely follows the real wind pressure distribution patterns on roofs.

It was found that on the monosloped roof and windward span of sawtooth roofs, the wind pressure coefficient for the high corner is higher than that for the low corner; the low edge zone is a low suction zone with wind pressure coefficient significantly lower than that for the high edge; on a middle span, the wind pressure coefficients for the low corner and sloped edge zones are significantly higher than for other pressure zones; on the leeward span, wind pressure coefficients for the high corner, low corner and high edge zones are significantly higher than those for other pressure zones.

In addition, the wind pressure coefficients for sawtooth roofs on the windward, middle and leeward spans cannot all be categorized with the same corner, edge and interior zones as is the case with gable roofs because the wind pressure distributions on the high corner and low corner zones are different for each span location.. Therefore, the following author-defined pressure zones (shown below in Figures 6.1 and 6.2) for monosloped and sawtooth roofs are proposed based on results from this study.

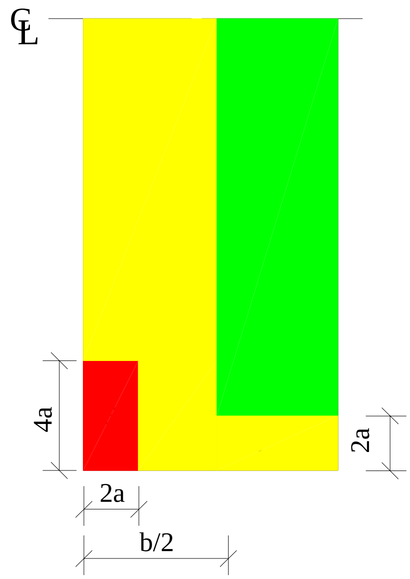


Figure 6.1 Recommended Pressure Zones on Monosloped Roofs
(Left side is high edge)

Table 6.1 Wind Pressure Coefficients for Monosloped Roof (Referenced to 3-second gust wind speed at mean roof height)

Zone	$0.1 m^2$	$0.9 m^2$	$9 m^2$
1	-2.3	-1.7	-1.5
2	-3.4	-2.5	-2
3	-5.1	-3.3	-2.2

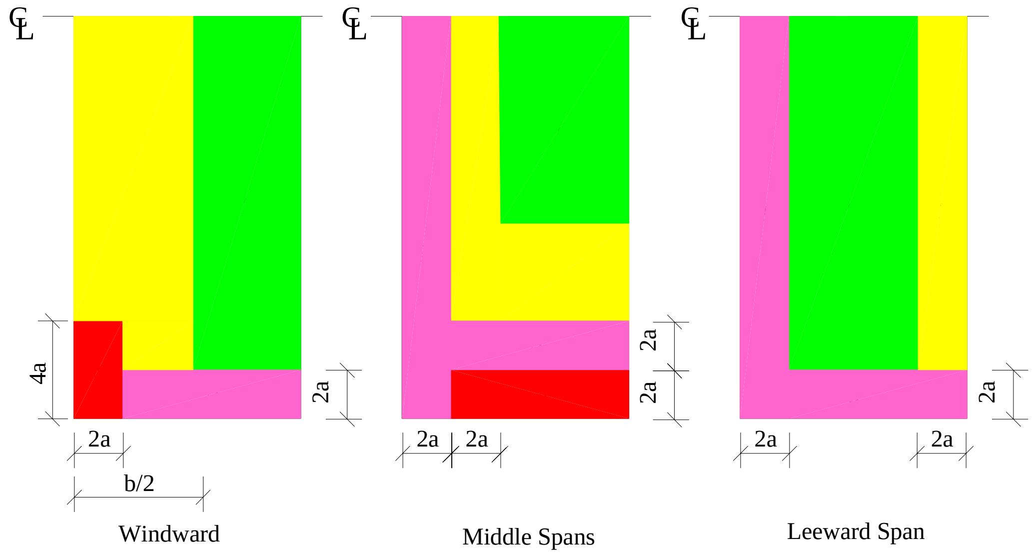


Figure 6.2 Recommended Pressure Zones on Sawtooth Roofs
(Left side is high edge)

Table 6.2 Wind Pressure Coefficients for Sawtooth Roofs (Referenced to 3-second gust wind speed at mean roof height)

Zone	Windward Span			Middle Span			Leeward Span		
	$0.1 m^2$	$0.9 m^2$	$9 m^2$	$0.1 m^2$	$0.9 m^2$	$9 m^2$	$0.1 m^2$	$0.9 m^2$	$9 m^2$
1	-2.5	-2	-1.4	-2	-1.4	-1	-2.1	-2	-1.7
2	-3.9	-3	-2.2	-2.4	-1.8	-1.4	-2.5	-2.1	-1.8
3	-4.6	-3	-2.2	-3	-2.5	-1.5	-3.5	-2.5	-2.1
4	-5.1	-3.7	-2.5	-4.6	-3	-1.7			

The dimension ‘a’ in the figures is calculated from the single span dimension and is the minimum of either 1/10 the least horizontal dimension or 0.4 times the building height, where a, should not be less than 1 m and has at least a 0.04 horizontal dimension. The width of a single span roof is denoted by ‘b’. The wind pressure coefficients provided in the tables are referenced to 3-second gust wind speed at mean roof height to decrease the building height effect and to be consistent with current ASCE 7-02 building design standard. The recommended wind pressure zones and corresponding wind pressure coefficients for monosloped and sawtooth roofs provide guidelines for wind load designs and provide possible improvements to current ASCE 7-02 building design standard.

6.8 Concluding Remarks

The above work focusing on the wind effects on monosloped and sawtooth roofs has led to new insights into wind pressure coefficient distributions on these two structures and illustrated new findings regarding the separated sawtooth structure. This work was made possible by using a larger model scale with higher pressure tap resolution than in previous studies and through the use of high-frequency pressure scanning technologies.

New analysis techniques were demonstrated and compared with established methods and it was found to yield reasonable peak values estimates. The RMS contours may one day be a useful tool in the development of pressure zones on complex roof structures.

In a series of studies it has been discovered that similar extreme wind pressure coefficients occur on the monosloped roof and windward span of the sawtooth roof from which higher wind pressure coefficients are recommended for monosloped roofs than are provided in ASCE 7-02. Further research is needed to establish the comparisons and validation of these wind tunnel test results with actual full scale pressure distributions on monosloped and sawtooth roofs. With the development of wireless pressure sensors this prospect may one day become a reality.

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