Discrepancy in Wind Pressure Coefficients on Sawtooth and Monosloped Roofs

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Abstract: Wind tunnel studies were conducted on 1:100 scale building models of monosloped and several (2- through 5-span) sawtooth roof buildings to determine appropriate peak and area-averaged wind pressure coefficients. The results showed that the peak negative pressures coefficients in the high corner regions of monosloped roof buildings are nearly equal to the high corner peak negative pressure coefficients on the windward span of the sawtooth roof building, and the low corner peak negative pressure coefficients on sawtooth roofs zones are approximately 150% greater than on monosloped roofs. The test results generally confirm peak negative pressure coefficients found by (Saathoff and Stathopoulos 1992), and they suggest that loads obtained by (Holmes 1987) may underestimate wind design loads. The data suggest that current ASCE 7 wind design provisions underestimate the high corner design wind pressures for monosloped roof buildings but more studies are continuing. In addition, area-averaged pressure coefficients were found to decrease more rapidly, producing a 40% reduction for a 2.5 m^2 area in contrast with previous studies that suggested near constant pressure coefficients out to 10 m^2.

Introduction: Current wind design provisions are based on wind tunnel testing conducted from the late 1970s through 1990s on several building shapes. However, only two wind tunnel studies were conducted on sawtooth roof buildings (Holmes 1987; Saathoff and Stathopoulos 1992), and they provide the database used to develop the Australian (Standards Australia 2002) and American (ASCE/SEI 2006) wind load provisions respectively. Predicted wind design pressures regarding the peak wind uplift loads on sawtooth roofs in those papers do not agree and those discrepancies are yet to be resolved. As a result, significant discrepancies remain between the US and Australian wind load design provisions calculated for identical buildings in accordance with ASCE 7-05 and AS/NSZ 1170. The high corner peak design pressures for components and cladding based on ASCE 7 (ASCE/SEI 2006) are approximately 74% greater than AS/NSZ 1170 (Standards Australia 2002) design wind pressures.

The objective of this study is to determine and compare the peak and area-averaged wind pressure coefficients on monosloped and sawtooth roofs in an effort to resolve existing discrepancies between previous wind tunnel studies and existing building codes. This study uses larger scale models (1:100 scale) than were used previously and a dense 290 pressure tap array providing a single pressure tap tributary area of less than 0.4 m^2, or 0.2% of total roof monitor area. Full experimental details and additional results are provided in Cui (2007).

Previous Studies: Holmes (1987) investigated the distribution of local and area-averaged wind pressure coefficients using a 1:200, scale 5-span sawtooth model with a 20° roof slope and 60 pressure taps installed in the roof. The peak local negative wind pressure coefficient in the high corner zone (windward span) was -7.6 (normalized to the mean wind speed measured at low eave height), and highest peak area-averaged pressure coefficient (on a 31.2 m^2 roof panel, 3% of roof monitor area) was -3.86. Saathoff and Stathopoulos (1992) used 1:400 scale models with 72 pressure taps to determine local and area-averaged wind pressures on a monosloped roof and on two-span and four-span sawtooth roof models. Pressure coefficients were referenced to mean wind speed at lower eave height. They obtained peak local pressure coefficients in the high corner roof zones that were larger than Holmes' results, and the peak and mean pressure coefficients on the monosloped roof matched the corresponding values on the sawtooth roof model. They also reported the area-averaged peak negative pressure coefficients remained almost constant for a tributary area range of 0 to 10 m^2 (using 2 pressure tappings) and decreased for tributary areas over 36 m^2 (using 4 pressure tappings).

Experimental Setup: Wind tunnel studies were conducted in Clemson University's boundary layer wind tunnel, using 1:100 scale building models. The wind tunnel is an open-return one with a 18 m (48 ft) long by 3 m (10 ft) wide by 2.1 m (7 ft) tall test section, powered by two 1.8 m (5 ft) diameter fans. Test models are mounted on the 2.7 m (9 ft) diameter turntable, approximately 15 m from the test section entrance. We simulated the upwind terrain at 1:100 geometric scale and modeled the velocity profile and turbulence intensity for suburban exposures and open country (z_0 = 0.036m, turbulence intensity 19% and wind velocity 8.3 m/s at 10 m).

Wind flow characteristics in the wind tunnel are measured using hot-wire probes and a Thermal System Incorporated (TSI) IFA300 constant temperature hot-film anemometer system. Wind speed data is taken at 2000 samples per second for 60 seconds at each height above ground in the location of the model (with the model removed), and the mean wind speed and turbulence intensities are determined. Pressure data was collected using eight Scanivalve ZOC33 electronic pressure scanning modules, connected to a RAD3200 digital remote analog to digital converter that interfaces the pressure scanners with a computer. A reference Pitot tube installed 300 mm below the top of the wind tunnel test section provide the reference static pressure for normalizing the surface pressures on the model and a measure of the mean wind velocity in the tunnel.

Building Model: The sawtooth building models were constructed by combining several monosloped roof models, each having a 21° roof slope to be akin to the teeth of a saw blade. In this way, tests were conducted on a monosloped roof, and on 2-, 3-, 4-, and 5-span sawtooth roof building models. The tests also included three building heights corresponding to full-scale mean roof heights of 7 m, 11.6 m and 16.1 m. The sawtooth roof spans were designated in conformance with ASCE-7 naming conventions (Figure 1).

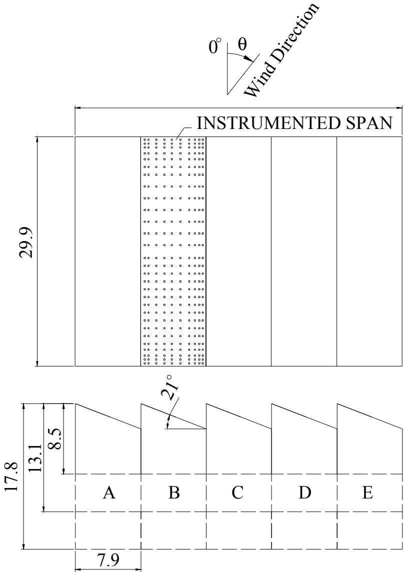
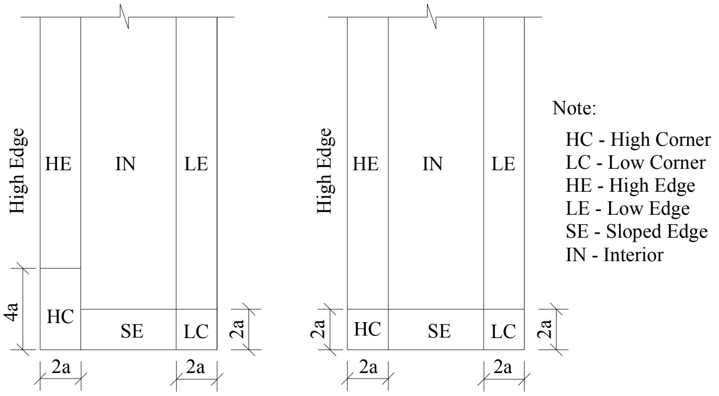


Figure 1 Plan and Elevations of Sawtooth Building Models (dimensions are in m).

The five single pitched models were constructed using Plexiglas sheet and 290 pressure taps were installed in one of the model roofs. Due to symmetry, the pressure tappings on only approximately one-half of the roof monitor have been used. Additional pressure taps were installed in the vertical wall of the roof monitor and the side walls. The monosloped building model is 79 mm wide by 299 mm long, and adjustable inserts to form three building heights with mean roof height of 70 mm, 11.6 mm and 16.1 mm. The location of the instrumented span was changed during the tests and data collected in order to collect wind pressure data for the whole sawtooth roof system.

Experimental Procedure: Wind tunnel pressure data was collected from a single 120 second test run. The tap pressures were sampled at 300 Hz, and based on the velocity scale of 1:4 and the 1:100 geometric length scale, the sample time corresponds to a full-scale record of approximately 50 minutes. At the critical wind (cornering) directions, 8 or 16 repeats were performed. An extrapolation method was used for determining peak pressure coefficients from the single wind tunnel runs.

The peak estimate extrapolation method was validated by comparing its results with peak pressure coefficient estimates s obtained using the Lieblien BLUE Method (Lieblein 1974) and direct peak averaging techniques from multiple (8 and 16) runs for each wind direction. The extrapolated peak estimates were found to have excellent agreement with results from the latter two approaches. The dimensions for the six roof zones were established using ASCE 7 provisions and the same dimensions were used with all building walls. The edge zones were 1.8 m wide, resulting in a low corner zone having a square plan 1.8 m on side. The high corner zone was 3.6 m long for the windward span and 1.8 m for all other spans (Figure 2).



Monosloped Roof and Windward Span of Sawtooth Roofs

Middle and Leeward Spans of Sawtooth Roofs

Figure 2 Pressure Zones for Monosloped and Sawtooth Roofs (per ASCE 7)

Results: In all cases the highest negative pressure coefficient was observed in the high corner of the windward spans, and these values ranged from -11.43 on the 2-span roof, -10.86 on the 5-span,-9.82 on the 3-span roof, and -8.95 on the windward span of the 4-span sawtooth roof building. The comparable high corner peak pressure coefficient for the monosloped roof building was -10.47. Contour plots of peak negative wind pressure coefficients for all wind directions are illustrated in Figure 3 for approximately half of the roof surface. It can be seen that the magnitudes and pressure distribution on the sawtooth building models are similar to that on the monosloped roof, except that higher peak pressures occur near the low corner zones of the sawtooth buildings. Peak pressures extend well beyond the ASCE 7-defined high corner region for the monosloped roof.

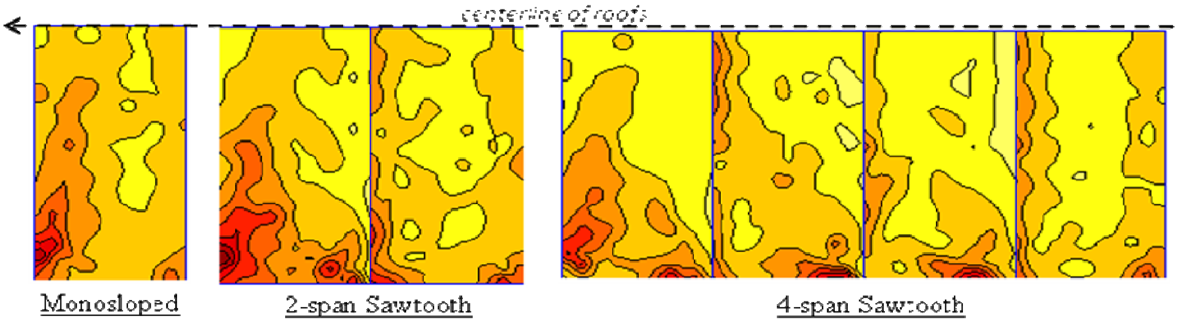


Figure 3 Contour plots showing the peak negative pressure coefficients for the 16.1 m set of buildings, normalized to mean-hourly wind speeds at mean roof height.

Figure 4 presents the peak negative pressure coefficients for various roof zones on all building models tested. The data was found to collapse very well throughout the various roof spans, consistently indicating the highest pressures in the high corner regions of the windward spans. The peak values are observed to extend well beyond the ASCE 7-defined high corner regions for the monosloped roof. At the high corner and high edge zones, the data suggests an aspect ratio effect where the middle spans experience lower peak pressures than either the windward or leeward spans. Generally, except for the low corner, the peak pressures on the monosloped roof structures were observed to be consistent with pressures on the sawtooth roof structures.

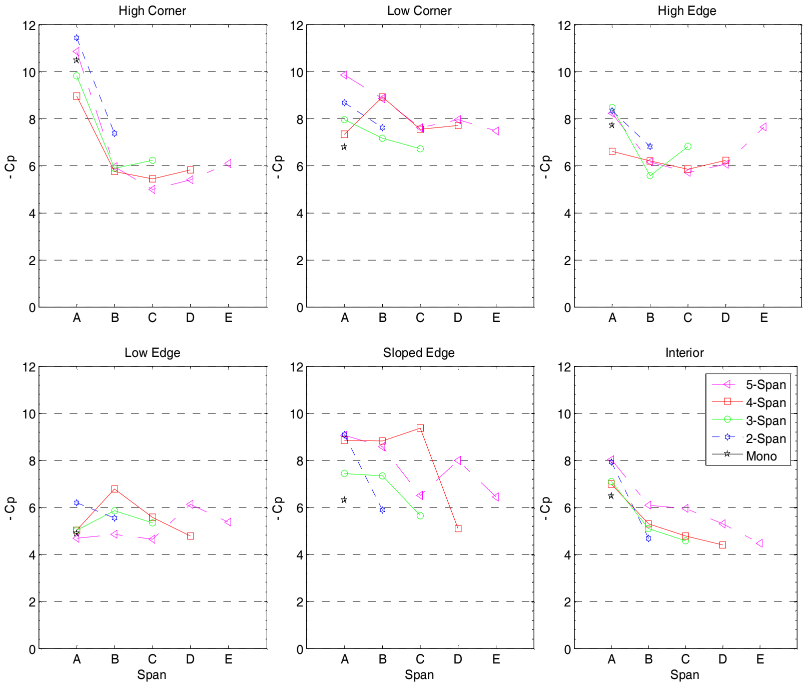


Figure 4 Comparing peak negative pressure coefficients for the five building models tested (normalized to mean wind velocity at mean roof height).

Pressure coefficients measured in the high corner zones are significantly reduced for the middle and leeward spans of all sawtooth buildings. The low edge and interior regions of all roofs experienced the smallest peak pressure coefficients in all cases tested. The highest peak pressure coefficients observed on the leeward and middle spans occurred at the low corners and sloping edge regions. These results are in general agreement with previous findings discussed earlier. The magnitudes and pressure distribution on the sawtooth building models are similar to that on the monosloped roof, except that additional peak pressures occur near the low corner zones of the sawtooth buildings. In contrast to the local peak pressure coefficients presented in the previous section, area-averaged pressure coefficients are determined using data from several pressure taps within a region; they provide the average pressure acting on the region represented by the tributary areas of the taps.

The area-averaged wind pressure coefficients are significantly reduced from the peak local pressure coefficients in all roof regions. The larger the tributary area, the greater is the reduction observed. For the Panel Group I, up to 2.5 m^2 (equivalent to individual fastener tributary areas), a 32% to 39% reduction was observed in the high corner regions on the windward span, and nearly 50 to 60% reduction on the larger Panel Group II areas (8 to 9 m^2) (equivalent to single girt or secondary member tributary area).

Figure 5 presents a comparison of the peak area-averaged negative wind pressure coefficients for the 16.1 m high monosloped roof and the windward spans of the sawtooth roofs. Numerical averaging was carried out using the pressure coefficient time histories for pressure taps, factored by their respective tap tributary areas. Area-averaged wind pressure coefficients were determined for tributary areas within the high and low corner regions, ranging from 0.9 m^2 (for two pressure taps) to 37.1 m^2 (for 49 pressure taps). The area-averaged pressure coefficients are significantly reduced from the peak local pressure coefficients in all roof regions. The larger the tributary area, the greater is the reduction observed. A 32% to 39% reduction was observed in the high corner regions up to 2.5 m^2 on the windward span, and nearly 50 to 60% reduction for the larger areas (8 to 9 m^2) (equivalent to single girt or secondary member tributary area).

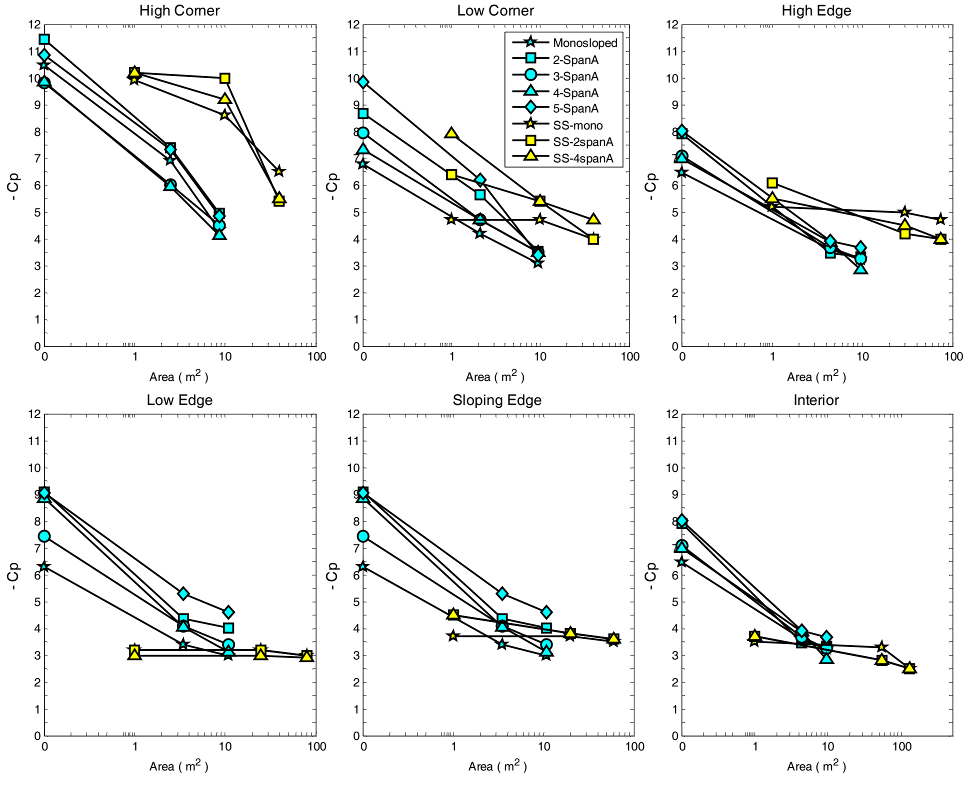


Figure 5 Area-averaged pressure coefficients (cyan) compared with results from Saathoff & Stathopoulos (1992) (yellow) for windward spans of sawtooth roof and monosloped roof.

Discussion: The results presented in this paper have shown the benefits of using larger scale wind tunnel models and with denser pressure tap arrangements. The results are directly comparable to previous results as the pressure coefficients are normalized to the mean wind velocity at mean roof height. It is observed that peak negative pressure coefficients in the high corner regions of the windward spans are nearly equal to previous data and that the trends in the data for all roof zones are also similar. The results appear to be consistent with previous findings by Saathoff and Stathopoulos (1992) and that peak pressure coefficients obtained by Holmes (1987) may underestimate the high corner wind pressures on sawtooth roofs. That Holmes obtained a lower value may be explained because the pressure tappings were located relatively far away (2 m at full scale) from the roof boundaries and would be unlikely to experience the vortex-induced peak suctions. Based on the results, it appears that ASCE 7 peak pressure coefficients for monosloped roofs may underestimate its effects.

The results for the area-averaged pressure coefficients differ significantly from those in previous studies. The results revealed faster fall-off rate of peak pressure coefficients with increasing tributary area than was previously observed. The higher pressure tap resolution and flexibility of the numerical averaging techniques used in these studies enabled a more detailed (higher resolution) investigation of small area effects. It was found that a tributary area of 2.5 m^2 or less is sufficient to produce more than 50% drop in the local peak pressure coefficient, as compared with the relatively flat relationship between pressure coefficient and area up to 10 m^2 predicted by previous studies. These results are likely to have significant impact on the wind code values for sawtooth and monosloped roof systems.

Conclusions: This paper described a wind tunnel investigation that was conducted using 1:100 scale models of monosloped and sawtooth roof structures with a dense pressure tap array in the root and results recorded to determine the peak local pressure coefficients in several roof zones. Further numerical area averaging was performed and it showed that the area-averaged pressure coefficients exhibit more rapid fall-off with increasing tributary areas than was found in the previous studies. A 40% reduction in pressure coefficients is likely for a tributary area of 2.5 m^2 at full scale. The peak negative pressure coefficients measured at the high corner of the monosloped roof are nearly the same as on the windward span sawtooth roof.

This preliminary data did not support the lower design peak pressure coefficients on monosloped roofs as compared to the sawtooth structure. The peak local pressure coefficient results generally agree with findings by Saathoff and Stathopoulos (1992) and suggest that the results obtained by Holmes (1987) may underestimate the peak local pressures on the windward spans of sawtooth roofs. A paper in preparation will address terrain effects on wind pressures.

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