Equivalent Roof Panel Wind Loading for Full-Scale Sheathing Testing

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ABSTRACT

From observations of hurricane damage to wood-framed houses, there is an evident need for research and testing to understand the failures of wood roof panels, especially as they occur in building corners. Current testing protocols for roof sheathing apply uniform static pressure loads to the panel, while extreme variability in real wind produces wind effects that vary significantly in time and space. Therefore, there is a need to test roof panels in a more realistic manner. The determination of appropriate wind loads for different areas on a sheathing panel is essential for this testing. This paper describes a methodology for determining a set of equivalent wind loads for testing a 4 ft by 8 ft roof sheathing panel at a corner location of a residential gable roof structure. The sheathing panel is divided into six areas and an appropriate wind load for each area is determined. Using the tributary areas of the taps within each area, the equivalent wind loads are determined from wind tunnel data.

INTRODUCTION

Wind loads produce a significant variation in wind pressure on roofs. The magnitude of the loads is dependent on the wind speed, wind direction, roof pitch, and roof geometry. Several studies have determined the wind uplift capacity of 4ft by 8ft roof sheathing panels [1-5] using uniform pressure static uplift test methods. However, the question remains about whether a static uniform load on a roof sheathing panel is accurate (or conservative) for panels that experience highly non-uniform, dynamic loading. While building code changes since Hurricane Andrew have made significant improvements to extreme wind resistance of low-rise wood framed buildings, roof sheathing failure, especially at roof corners, is still common [6]. One possible culprit for this continued failure at less than design wind speeds is that all testing performed on roof panels was conducting using static pressure instead of more realistic fluctuating pressures. The need to evaluate roof components in a more realistic manner is a major thrust of the current research at the University of Florida (UF).

This paper proposes a new method to determine a more realistic pressure loading using wind-tunnel derived pressure coefficients. A newly developed test apparatus, the PLA developed at the University of Western Ontario [7], has the capability of following a realistic wind pressure loading, and so this study demonstrates the steps for deriving test pressures on a 4 by 8 corner roof panel of a wood residential roof structure.

WIND TUNNEL TESTING

Wind pressure distributions on a 4 by 8 roof panel were determined from a wind tunnel study of a rectangular gable roof structure. Figure 1 shows the tap layout and the equivalent roof panel of interest. Testing was conducted at Clemson University's wind tunnel at the Wind Load Test Facility (WLTF) on a 1:50 scale model of a 30ft by 60ft house having a mean roof height of 13.5ft and a 4 in 12 (18.4°) roof pitch. The wind terrain was suburban (z_o = 0.22m) with a turbulence intensity at mean roof height of 24%. Figure 2 provides the power spectrum of the wind speed (L_u^x = 25.4 m at full-scale) at an equivalent 10 m height as well as the von Karman spectra. The pressure coefficients of 20 roof pressure taps were used to evaluate the pressure distribution on the panel (see Figure 3).

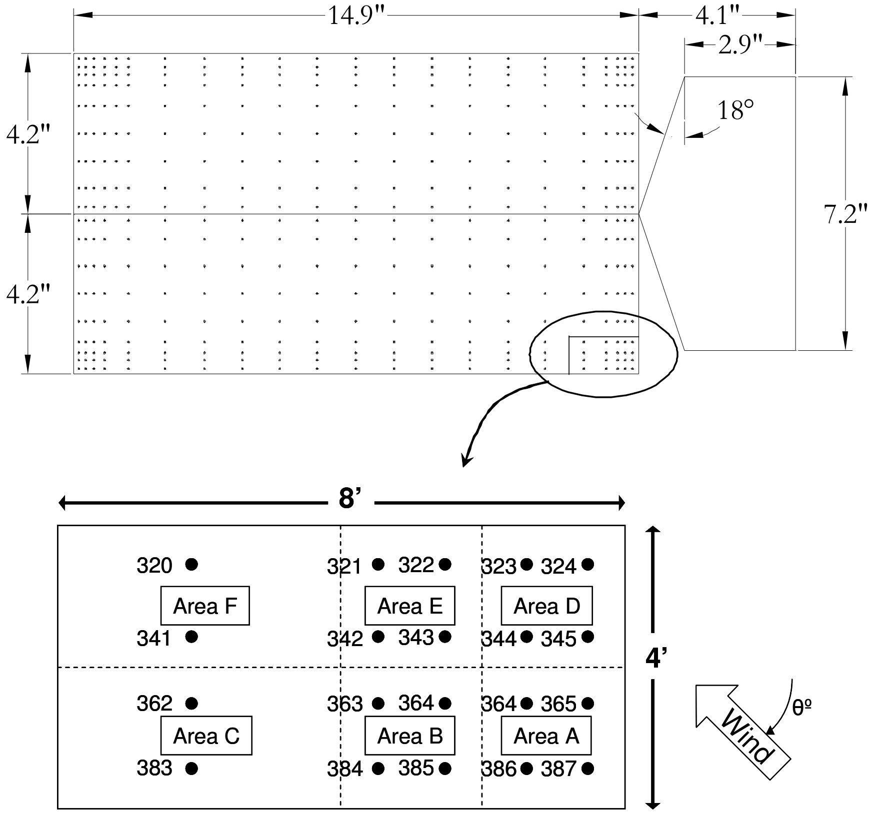


Figure 1: Pressure tap layout and current study corner roof panel pressure taps and areas

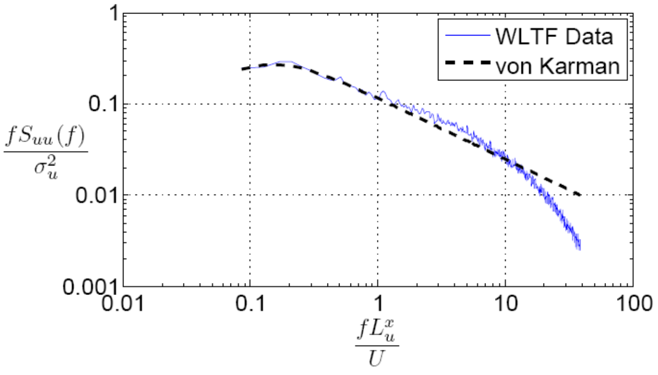
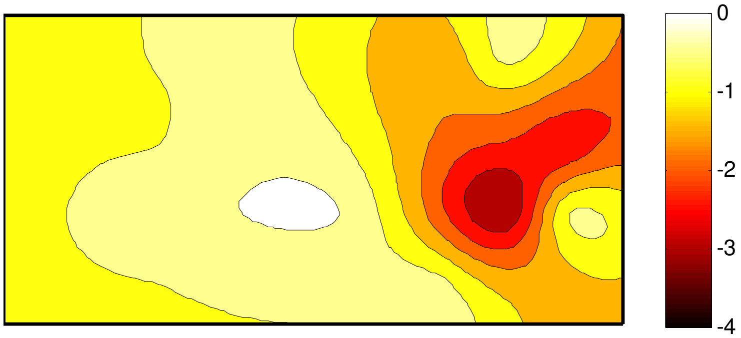


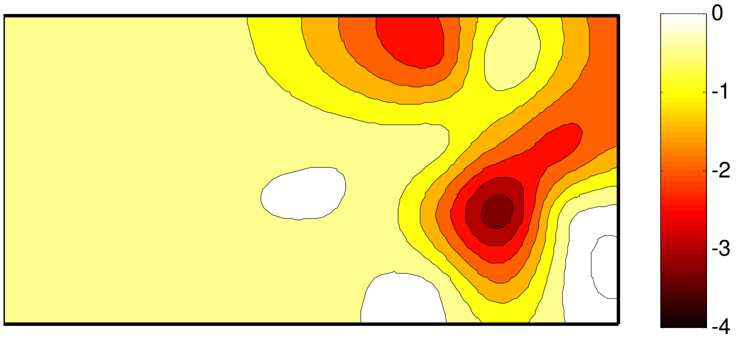
Figure 2: Power spectrum at equivalent 10m height

The mean wind speed at mean roof height was 6.54 m/s, and the mean wind speed at the reference location (1 ft below the ceiling) was 13.03 m/s. The pressure coefficients were calculated as the pressure recorded at the taps divided by the mean reference pressure (1 ft from ceiling). Using the equations from Simiu and Scanlan [8], the pressure coefficients were converted so that they were referenced to mean roof height and 3-second gusts (β = 5.25, $C(t)$ =

2.85, $z = 4.2$m, $z_0 = 0.22$m). This resulted in the pressure coefficients being multiplied by 1.1168. The pressure coefficients were then low-pass filtered (8th order Butterworth) at 150 Hz and adjusted for the tubing response of the pressure scanning system.



Wind direction: 0°



Wind direction: 45°

Figure 3: Pressure coefficients on corner 4 x 8 roof sheathing panel

WIND PRESSURE COEFFICIENT DISTRIBUTIONS

Figure 1 shows the corner roof panel with the pressure taps and areas labeled. Each of the six regions have two or four pressure taps, and the process of determining a single appropriate time history trace for each panel is presented. For purposes of this paper, only data for a wind direction of 0° is presented (see Figure 1). Probability distributions as well as the statistics of the pressure coefficients for individual taps and the combined area data are presented.

PROBABILITY DISTRIBUTIONS

Probability density functions (PDF) were fit to each tap. Several probability distributions were investigated for best fit to the data: Gaussian, Lognormal (3-parameter), Reverse Lognormal (3-parameter), Weibull (3-parameter), and Extreme Value (EV) Type I (smallest). The reverse lognormal distribution is just the lognormal distribution mirrored about the vertical axis allowing the longer tail of the lognormal distribution to trail to the left. The probability density function, $p(x)$, of the lognormal distribution is given by:

$$p(x) = \frac{1}{(x-\theta)\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln(x-\theta)-\mu}{\sigma} \right)^2 \right] \qquad (1)$$

where θ is the location parameter, μ is the scale parameter, and σ is the shape parameter. To determine the parameters for the reverse lognormal PDF, the "x"-values, or data points, are multiplied by negative one (-1), i.e., compute $p(-x)$. Then to plot the reverse lognormal, the values of $p(-x)$ are plotted against $(+x)$. Figure 4 shows the lognormal and reverse lognormal distributions. The parameters of each distribution were estimated using a least squares or maximum likelihood estimator (MLE) technique.

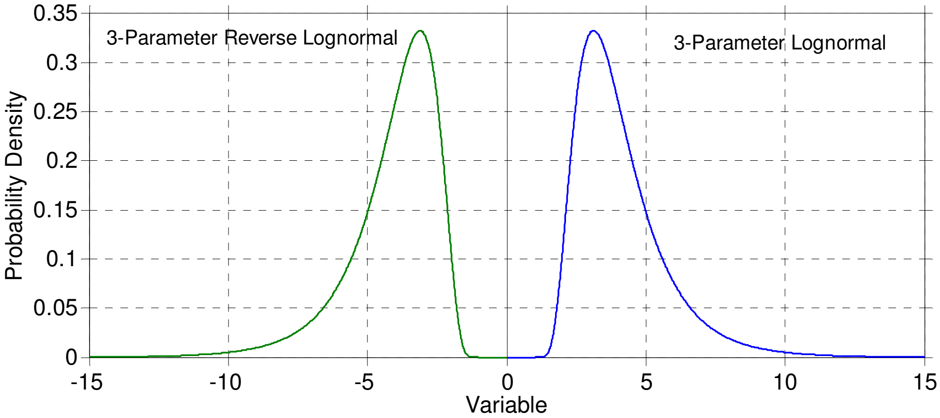


Figure 4: Lognormal and Reverse Lognormal Probability Density Functions ($\theta = 1$, $\mu = 1$, $\sigma = 0.5$)

To determine goodness of fit of the pressure coefficient data to a PDF, a method similar to that presented by [9] was utilized for this purpose. The mean square error (MSE) test was used to determine the goodness of fit of the distributions of each sample for each tap. However, the MSE test places more weight near the center of the distribution and not a lot of weight on the tails. To more accurately model the tail portions where the most extreme uplift peaks occur, a more robust method was used that only used the points in the most extreme 20% of the range for a given record. For this tail region, the MSE was calculated separately from the entire model and compared in addition to the MSE of the entire model.

The reverse lognormal and Extreme Value Type I distributions were the best fit for almost all of the pressure taps located in the roof panel of interest. When the area-averaged pressure coefficient time histories were developed, the corresponding distributions were also the reverse lognormal and Extreme Value Type I distributions.

CORRELATION ANALYSIS

Table 1 provides the average correlation coefficients between taps within a single panel area. The correlation coefficient provides a measure of the correlation (i.e. trends – if one increases does the other increase, etc.) of the pressure coefficients among the pressure taps within a particular area. The tap numbers are shown on the horizontal and vertical axes. Since the matrices are symmetric, only half of each correlation coefficient matrix is shown for clarity.

Development of the area averaged pressure coefficient time history involves using the tributary areas of the individual pressure taps within each region relative to the total area (4 ft^2 or 8 ft^2 full-scale). The area time histories were calculated by multiplying the pressure coefficient time history at each tap by the respective normalized tributary area (i.e. all tributary areas within a certain panel area sum to 1.0) and then adding all the time histories within a given area (either 2 or 4) together to produce an area averaged time history. This method is based on the fact that the taps are highly correlated within each area. Table 2 provides the average correlation coefficient values between areas for the combined time histories based on area averaging. There is high correlation between the different areas, especially for adjoining areas.

Table 1: Correlation coefficients between pressure taps in the same area for wind direction 0º

Tap	320	341
320	1.000	0.839
341		1.000

Area F

Tap	321	322	342	343
321	1.000	0.944	0.458	0.850
322		1.000	0.401	0.880
342			1.000	0.598
343				1.000

Area E

Tap	323	324	344	345
323	1.000	0.666	0.518	0.458
324		1.000	0.816	0.777
344			1.000	0.968
345				1.000

Area D

Tap	362	383
362	1.000	0.386
383		1.000

Area C

Tap	363	364	384	385
363	1.000	0.530	0.853	0.782
364		1.000	0.519	0.708
384			1.000	0.872
385				1.000

Area B

Tap	365	366	386	387
365	1.000	0.949	0.867	0.853
366		1.000	0.877	0.798
386			1.000	0.846
387				1.000

Area A

Table 2: Correlation coefficients between areas

Area	A	B	C	D	E	F
A	1.000	0.868	0.456	0.969	0.976	0.587
B		1.000	0.733	0.828	0.886	0.884
C			1.000	0.467	0.562	0.910
D				1.000	0.981	0.570
E					1.000	0.665
F						1.000

DETERMINATION OF DYNAMIC PRESSURE TRACES

The current static testing method used at UF to determine roof sheathing panel failure pressures involves a step-wise increasing pressure trace, developed from a Modified ASTM E-330 test protocol [10, 11]. The pressure is increased in 15 psf increments and held for 10 seconds at each interval. This process is repeated until failure occurs. For the purpose of comparing performance with a dynamic pressure trace, an equivalent 10 second interval was selected and the peak pressure in each 10 second segment of pressure was also increased by 15 psf.

The following steps describe the process of determining the dynamic wind load trace for full-scale testing. This procedure is outlined for a wind direction of 0º on a corner roof panel.

1. Select a wind tunnel time history to use as a starting point. For this step, a trace from Area 1 was selected and is shown in Figure 5.

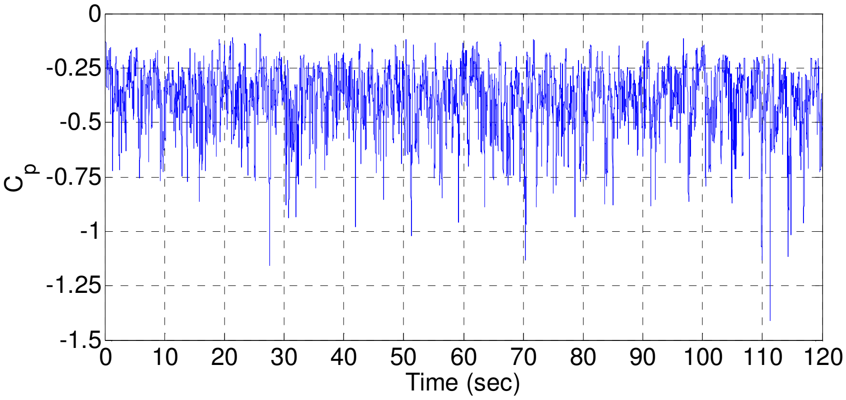


Figure 5: Pressure Coefficient Trace for Area 1 (Direction: 0º)

2. Select a *peak pressure coefficient* value and *location* within the wind tunnel trace to begin equivalent full-scale trace. The starting point was arbitrarily selected to use a segment that would have approximately the same peak pressure occurring twice within a short period. This enables the full-scale trace to have two or more peak pressures applied to the panel area within the 10 second full-scale time duration. Figure 6 shows where this was chosen.

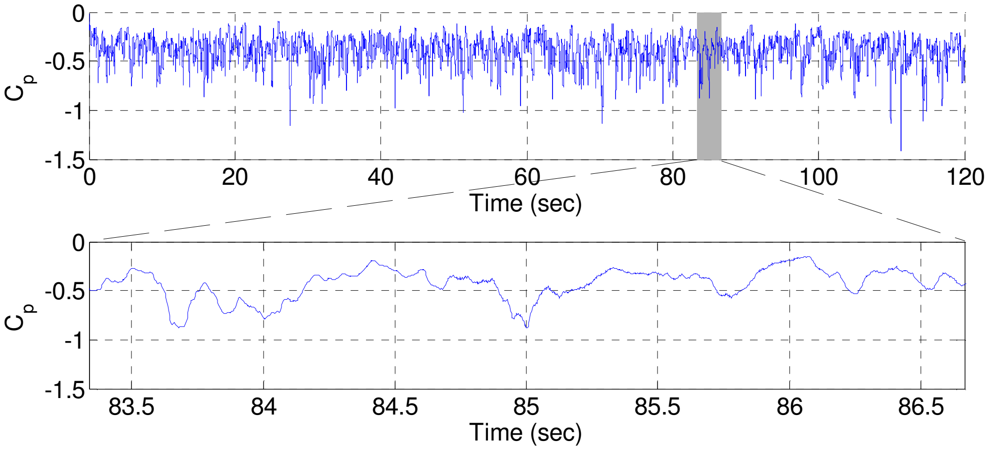


Figure 6: Segment of Pressure Coefficient Trace Selected for Developing the Dynamic Pressure Trace

3. Based on the selected peak pressure coefficient, the equivalent full-scale wind speed needed to produce a desired pressure is calculated from

$$p = 0.00256V^2C_p \tag{2}$$

where p is pressure, V is wind speed in mph, and C_p is the peak pressure coefficient of interest. The pressure is selected as 15 psf, 30 psf, 45 psf, etc. corresponding to the 15 psf increment desired for the trace, and the wind velocity is calculated.

4. To determine the equivalent full-scale sampling frequency for each pressure step, reduced frequency scaling was used [12]. The reduced frequency scaling is related by:

$$\left(\frac{fL_b}{V}\right)_m = \left(\frac{fL_b}{V}\right)_p \qquad (3)$$

where: f is frequency or 1/time ($1/t$); L_b is a characteristic dimension; V is wind velocity; and m and p subscripts are model and prototype, respectively. Rearranging Equation 3 yields:

$$\frac{f_p}{f_m} = \frac{L_{b_m}}{L_{b_p}}\frac{V_p}{V_m} \qquad (4)$$

5. Using the new full-scale sampling frequency, the desired 10 seconds of data are taken from the wind tunnel pressure coefficient trace.

6. Calculate the pressure time history from the new, shorter pressure coefficient trace by multiplying the pressure coefficients by $0.00256V^2$.

7. Resample the new pressure trace with a sampling frequency of f_p to provide a 10Hz signal input for the PLA.

8. Repeat steps 3-7 for each subsequent pressure step increase (i.e. 30 psf, 45 psf, 60 psf etc.).

9. Create the complete dynamic trace by concatenating the 10 second traces as shown in Figure 7.

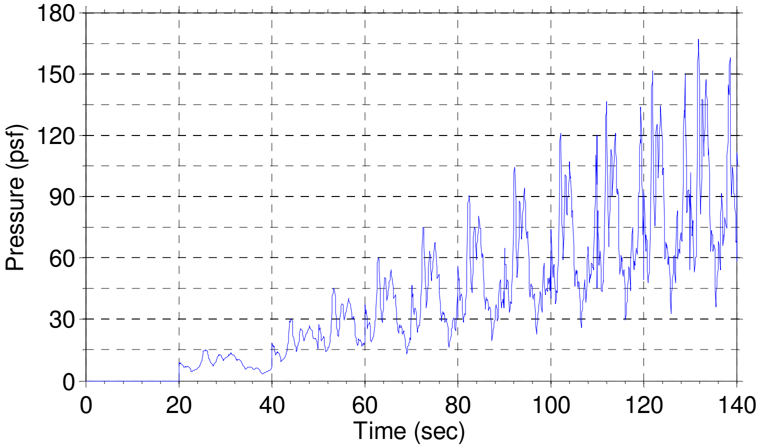
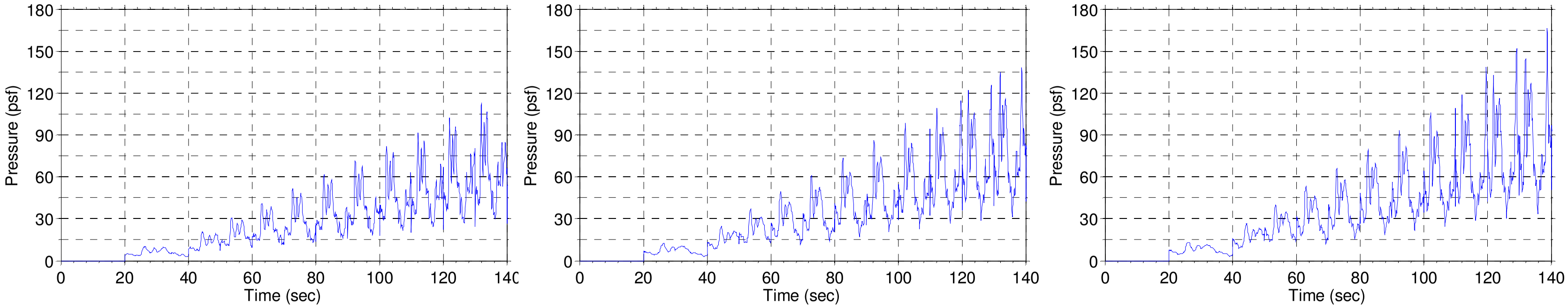
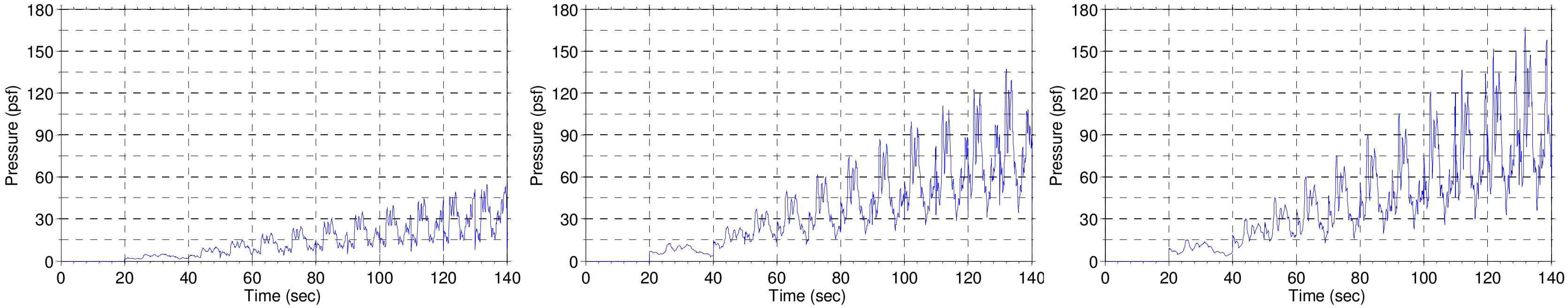


Figure 7: Dynamic Pressure Loading Trace for Area 1 (Direction: 0°)

Figure 8 shows the developed dynamic pressure trace for the entire 4 ft by 8 ft sheathing panel. To create true spatial variation of wind pressure effects on the 4 ft by 8 ft panel, the chamber would be divided into six regions and the six traces created on each respective area by six different PLAs for testing of the entire sheathing panel. Figure 9 provides the mean and peak



Area F Area E Area D



Area C Area B Area A

Figure 8: Dynamic pressure traces for loading 4ft by 8ft sheathing panel (Direction: 0º)

pressures and the coefficient of variation of each pressure step for all six areas in the sheathing panel. The mean values tend to be about half of the peak values. Also, the coefficient of variation tends to be fairly constant between 0.3 and 0.4.

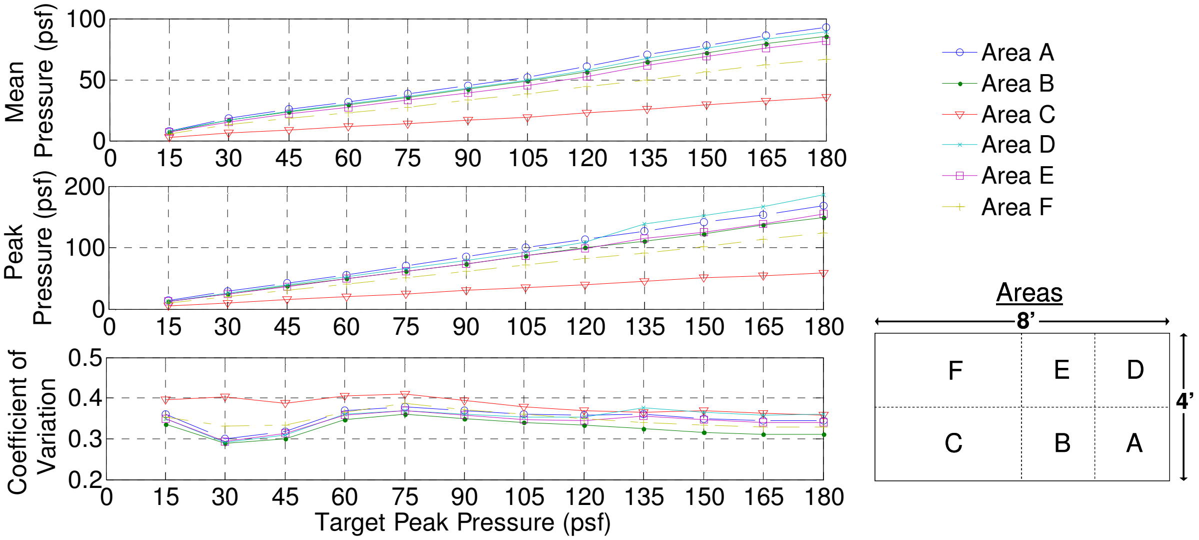


Figure 9: Comparison of mean and peak pressures and coefficient of variation for each of the 10 second intervals in the developed dynamic traces (Direction: 0°)

The correlation coefficients of the six areas are presented in Table 3. The six areas are highly correlated with one another. These correlations are much higher than the correlation of the entire pressure coefficient time histories given in Table 2. The reason for this is the trace used to develop the dynamic trace is only 10 seconds long in full scale so there are fewer points used in the correlation analysis than when the entire wind tunnel run is used.

Table 3: Correlation coefficients of dynamic pressure traces for roof panel

Area	A	B	C	D	E	F
A	1.000	0.970	0.895	0.965	0.966	0.946
B		1.000	0.950	0.982	0.989	0.988
C			1.000	0.917	0.937	0.971
D				1.000	0.997	0.952
E					1.000	0.967
F						1.000

SUMMARY AND CONCLUSION

This paper describes the methodology for determining an equivalent full-scale pressure loading regime for a 4 ft by 8 ft roof sheathing panel that accounts for the spatial variation of the wind loads as well as the temporal variation. The use of the pressure traces developed will provide useful information as roof sheathing panels are tested with this dynamic loading and compared to statically loaded panels. A similar pressure trace developed using this approach was used for dynamic testing of roof panels and the results are presented in another paper in this conference [11]. The insight gained will provide valuable information as to why roof sheathing continues to fail at below design level wind speeds.

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