AVERAGED PRESSURE COEFFICIENTS FOR RECTANGULAR BUILDINGS

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SUMMARY

Mean pressures obtained from an extensive series of wind-tunnel tests have been averaged over an entire side of a building to obtain a single mean pressure coefficient for a given side and wind direction. Coefficients based on either a local reference wind speed or a reference wind speed measured at the level of the roof of the building have been computed. An example and a comparison with existing building codes and standards are included to illustrate the use of these coefficients.

INTRODUCTION

Engineers who design structures for wind loading are faced with two distinct problems, the selection of an appropriate wind speed for design and the selection of a force or pressure coefficient which allows the design wind speed to be expressed in terms of a design load. The choice of a design wind speed is a function of the projected life of the structure and the location of the structure. In some cases a design wind speed is dictated by a local building code. The choice of a force or pressure coefficient is usually determined by data available in the technical literature or incorporated into standards or building codes. These coefficients will not necessarily correspond to the structure being designed and in some instances sufficient information about how the coefficients were obtained does not exist to adequately judge the values reported.

A considerable body of data is available describing mean pressures on structures of various shapes measured in wind tunnels with a uniform approach velocity (no variation of wind speed with height) and very low incident turbulence intensity. Such data have been incorporated into most modern building codes and standards. However, Jenson (1) has shown that a wind-tunnel model of a structure should be tested in a turbulent shear flow that simulates the natural wind if accurate assessments of the mean pressures caused by wind loading of buildings are to be obtained. The techniques of modelling wind forces on buildings in boundary-layer wind tunnels have advanced sufficiently to allow a more detailed examination of the effects of building geometry and incident flow properties on mean wind pressures than are currently available in modern building codes and standards. The history and present status of wind-tunnel modelling for wind loading of structures has recently been reviewed by Cermak (2) (3).

Despite these advances, very little organized information is available to describe the mean pressures on structures in properly simulated natural winds. In this paper, mean pressure coefficients which have been averaged over an entire side of a building are presented and discussed. These pressure coefficients are for rectangular flat-roofed buildings and were obtained with the structures immersed in thick turbulent boundary layers with properties which simulate neutrally-stable atmospheric flows.

The techniques used in the determination of these pressure coefficients are described briefly. A detailed discussion of the results including examples of applications is presented. These measurements were conducted using isolated, sharp-edged, smooth rectangular models. The results presented do not include information concerning the effects of corner geometry, surface roughness of the building, or adjacent structures. Because many of these effects, but certainly not all, result in reduced mean loads, these data provide a useful, and in most cases, slightly conservative estimate of surface pressure for rectangular buildings.

EXPERIMENTAL TECHNIQUES

Buildings and Pressure Measurements

A series of thirteen flat-roofed rectangular buildings were used in the study. The building geometry is described by two ratios--the side ratio, defined as the ratio of the width of the small side to the width of the large side, and the aspect ratio, defined as the ratio of the building height to the width of the small side. Side ratios of 0.25, 0.50 and 1.0 were examined over a range of aspect ratios from 1.0 to 8.0. The models were made of plexiglass and instrumented in most cases at 272 locations with pressure taps (60 on each vertical face and 32 on the roof). The buildings were mounted on a turntable at the downstream end of 16.7-m (55 ft) long test section of the industrial aerodynamics wind tunnel of the Fluid Dynamics and Diffusion Laboratory, Colorado State University.

Pressure measurements were made using a system consisting of a 72-channel pressure-selector switch, strain-gauge pressure transducers, and a digital data acquisition system. The pressures measured were the difference between the instantaneous local pressure at a location on a building and the static pressure in the ambient flow above the model building. A more detalied description of the buildings and the pressure measurement system is available in references 4 or 5.

The Boundary Layers

The four boundary layers used in the study were developed over the length of the test section using various-sized elements on the floor and spires at the entrance to the test section. The spires were used to artificially stimulate the growth of the boundary layer and in addition provided a constant-depth boundary layer for all of the roughness configurations. Table 1 is a summary of the properties of these boundary layers. The properties included in the table are: δ, the boundary layer thickness; p the exponent the power law representation of the mean velocity profile; z_o, the surface rougheness length; u_*/U_δ, the ratio of the friction velocity to the free-stream velocity; L_x, the longitudinal integral scale of the turbulence; and T_{ux}, the longitudinal turbulence intensity. Further details concerning the boundary layers including velocity spectra, cross-correlations, and profiles of turbulence intensity in three dimensions are available in reference 5.

TABLE 1. Boundary Layer Characteristics

Boundary Layer	δ (m)	p	z_o (m)	u_*/U_δ	L_x @ z/δ=0.2 (m)	T_{ux} @ z/δ=0.2 (%)
1	1.27	0.12	1.2×10^{-5}	0.028	0.40	7.2
2	1.27	0.27	2.8×10^{-3}	0.052	0.54	12.5
3	1.27	0.34	5.0×10^{-3}	0.051	0.43	15.0
4	1.27	0.38	1.1×10^{-2}	0.062	0.34	17.3

Data Reduction

Mean pressure coefficients were averaged over an entire side of a building. Through the use of a more sophisticated integration procedure it was established that an accurate averaging was obtained if an appropriate area was assigned to each pressure-tap location and a vector summing of pressure times a representative area was used. The pressure coefficients used were defined by two equations,

$$\overline{C}_{PL} = \overline{\left(\frac{P-P_o}{0.5\rho V(z)^2}\right)} \quad (1)$$

$$\overline{C}_{PR} = \overline{\left(\frac{P-P_o}{0.5\rho V(H)^2}\right)}. \quad (2)$$

$\overline{C}_{PL}$ is a local pressure coefficient averaged over an entire side of a building. It is the nondimensional ratio of $P-P_o$, the difference between the pressure at a location on the building and the local static pressure, to $0.5\rho V^2(z)$, the dynamic pressure based on the wind speed in the approach flow at the height of the pressure measurements, $V(z)$. This value was determined at each point on the side of a building and averaged as a pressure coefficient. The overbar in both equations is used to denote spatial averaging over an entire side. $\overline{C}_{PR}$ is a pressure coefficient based upon a fixed reference wind speed measured at the level of the roof of the building. This coefficient was also averaged over an entire side of a building. $V(H)$, used in equation (2), denotes the wind speed at the height of the building, H.

Based on the results of previous work (5), the buildings used were grouped by side ratio for all aspect ratios and boundary layers tested. The values of both $\overline{C}_{PR}$ and $\overline{C}_{PL}$ for all cases of corresponding side ratio were averaged to obtain one set of values. In most cases from eight to ten separate cases were averaged to obtain a single result.

The coordinate system used to describe the averaged pressure coefficients is shown in Fig. 1. The pressure coefficients were obtained for each of four sides and the roof. Measurements were obtained at eleven wind directions from 0 to 90°. Only five of the directions are shown in the figure. The sides were numbered such that side 2 was upwind for a wind direction of 0° and side 3 was upwind for a wind direction of 90°. All of the buildings studied were placed in an isolated environment with no adjacent structures present. A 90° variation in wind direction was therefore adequate to define the pressures acting on the structure for any wind direction. No corrections for tunnel blockage were applied because the blockage was small (less than 7 percent) and the flexible roof was adjusted to remove the longitudinal pressure gradient in the tunnel.

RESULTS AND DISCUSSION

The consideration of these two types of averaged pressure coefficients was motivated by interest expressed in more complicated pressure distributions reported in reference 5. These distribtuions were reported in terms of local pressure coefficients defined using a local wind speed at the height of the pressure measurement in the approach flow. This choice of coefficient allowed the pressure distributions to be expressed as a function of side ratio only with very little dependence on aspect ratio or approach flow properties. The use of such a distribution allows an accurate estimate of the distribution of pressures on a building. Such a procedure may be too detailed or complicated for some applications. In certain instances a single pressure coefficient over the side of a structure may be adequate. If this coefficient is obtained by averaging, there will naturally be some locations which will experience pressures above the average and other locations which will experience pressures below the average. If such an approximation is appropriate in the design of a structure, then the values of averaged pressure coefficients reported in this paper should be useful.

In order to provide a summary of the current methods of using pressure coefficients, the techniques suggested in the ANSI A58.1-1972 (6), "Building Code Requirements for Minimum Design Loads in Buildings and Other Structres," will be briefly reviewed. Techniques suggested in other codes and standards for the determination of mean pressures on a building are quite similar to those used in ASNI A58.1-1972. Table 7 of the standard provides values of external pressure coefficients for walls. These are reported for windward walls, side walls, and leeward walls, corresponding to wind directions of 0° or 90° from Fig. 1 of this paper. In order to obtain a pressure, these coefficients are multiplied by a reference dynamic pressure which increases with height. This corresponds to the reference pressure used in the definition of a local pressure coeeficient, Eq. 1. While this may indicate that the pressure coefficients reported in ANSI A58.1-1972 are local pressure coefficients (based on a reference wind speed measdured at the height of the pressure measurement in the approach flow), such is not the case. The coefficients provided in the standard were obtained in a uniform flow, no variation of wind speed with height, and for this case both definitions of pressure coeffient reduce to the same value, i.e. $V(z) = V(H)$ for all z. The choice of a height dependent reference pressure (proportional to the square of the wind speed) is interpreted as an effort to make the coefficients obtained in a uniform flow useable in a boundary layer flow. It should be noted that these coefficients were obtained prior to recent advances in techniques in wind-tunnel modeling. The use of a pressure coefficient which is constant over an entire side of a building with a reference pressure which increases with height provides a design pressure which increases with height but does not vary in the horizontal across a side of a building.

The averaged local pressure coefficients, $\overline{C}_{PL}$, for side ratios of 1.0, 0.5 and 0.25 are presented graphically in Figures 2-4 respectively. The curves shown in Figure 2 for a side ratio of 1.0 are symmetrical about 45° for sides 2 and 3 and sides 4 and 1. This symmetry is to be expected. If the values for a wind direction of 0° are considered the maximum magnitudes of the coefficients are obtained. For a side ratio of 0.5, Figure 3, the values for a wind direction of 90° (normal to the wider-side) must be used to obtain the maximum magnitudes. For a side ratio of 0.25, the maximum magnitude of the pressure coefficient for side 2 occurs at an approach wind of 70°. For side ratios of both 0.5 and 0.25, the coefficients

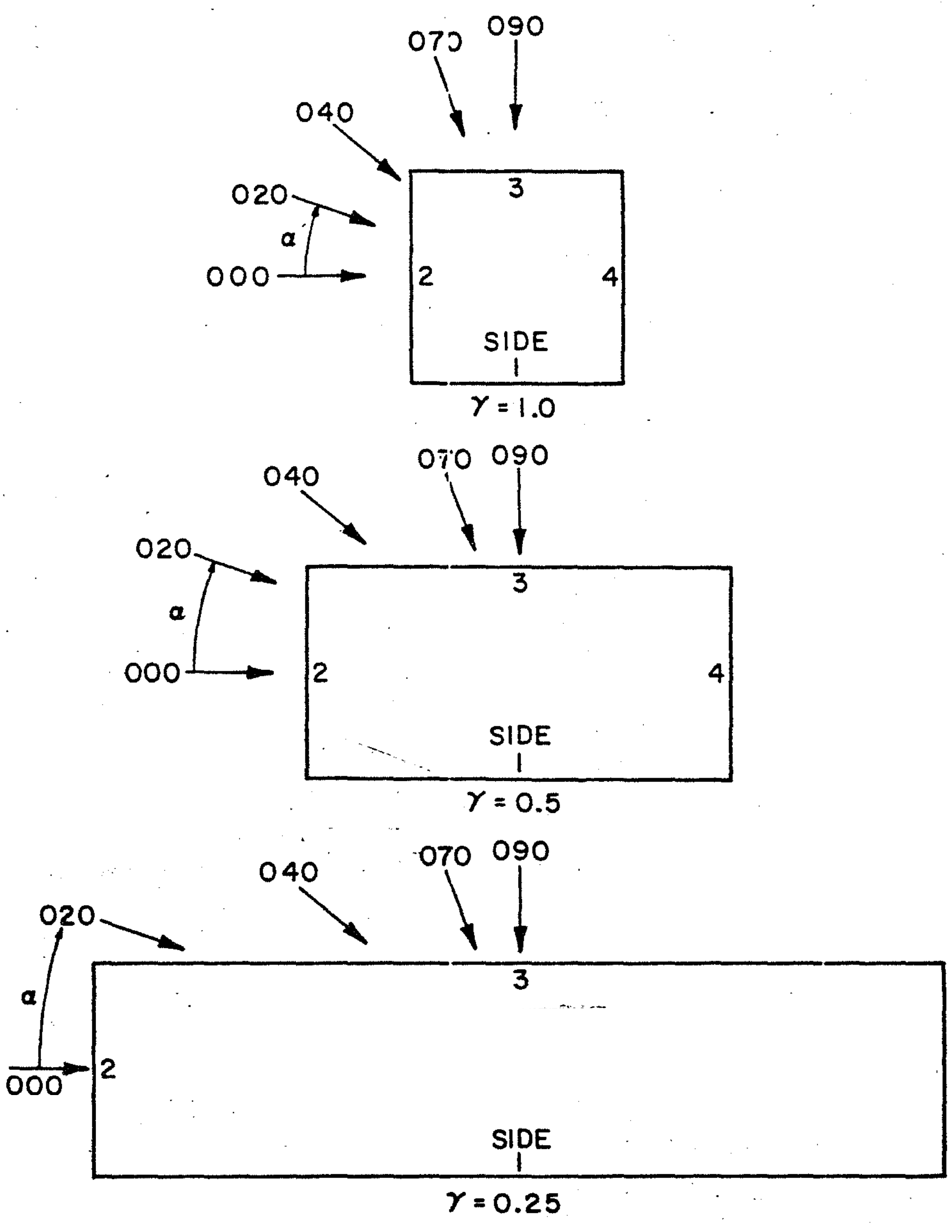

Figure 1. Wind Directions and Nomenclature for the Sides

for a 0° wind (normal to the narrow side), are of a smaller magnitude on the sides and the rear surface than for the case of 90° wind. The format of an averaged local pressure coefficient incorporates the effects of different approach boundary layers and different height buildings in the same boundary layer. The use of a variable reference pressure, $0.5\rho V(z)^2$, with a constant averaged local pressure coefficient will result in a constant design pressure at a given height and a design pressure which increases with height. While this is not an exact description of the actual physical situation, it is one compromise which allows the description of a pressure which varies over an entire surface by one coefficient.

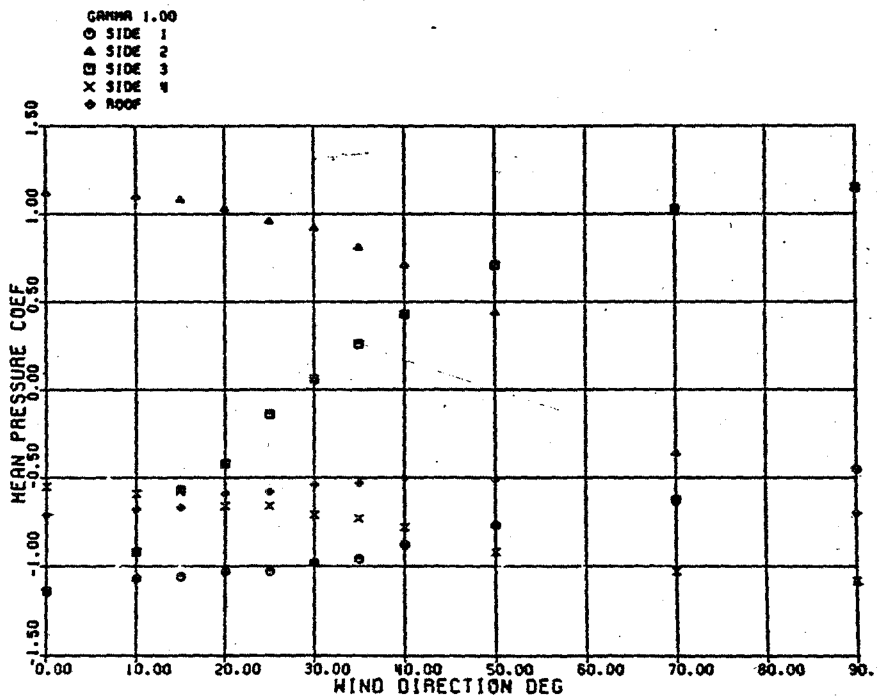

Figure 2. Averaged Local Pressure Coefficients, $\overline{C}_{PL}$, for a Side Ratio of 1.0

The values of $\overline{C}_{PR}$, the pressure coefficients based upon a reference dynamic pressure measured at the height of the building in the approach flow, are shown in Figures 5, 6 and 7 for side ratios of 1.0, 0.5, and 0.25 respectively. These coefficients were obtained from the same data as were used in determining $\overline{C}_{PL}$. The properties of the boundary layers used in the study were utilized to obtain both types of coefficients. In comparing the data in Figures 2 and 4, both for a side ratio of 1.0, the values of $\overline{C}_{PR}$ are approximately half of those of $\overline{C}_{PL}$. This is because the pressures were divided by a larger reference pressure to create a nondimensional coefficient. With this difference in magnitude, the trends for $\overline{C}_{PR}$ are the same as those noted for $\overline{C}_{PL}$. The largest magnitudes of the coefficients occur at 0° or 90° for a side ratio of 1.0 and at 90° for side ratios of 0.5 and 0.25. Again the maximum magnitude of the coefficients for a side ratio of 0.25 occurs at 70° for side 2. The coefficients based upon a

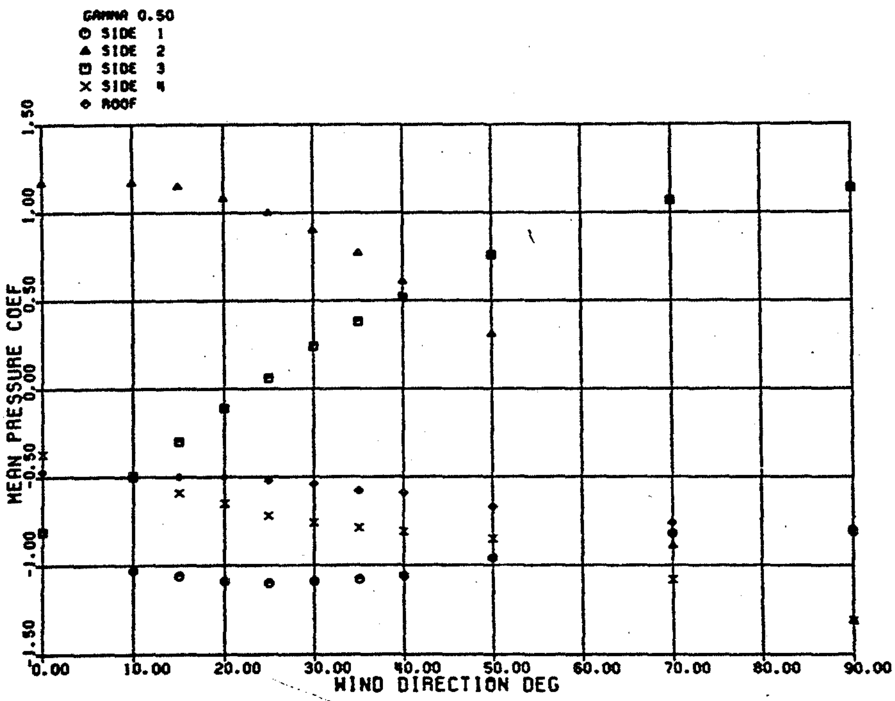

Figure 3. Averaged Local Pressure Coefficients, $\overline{C}_{PL}$, for a Side Ratio of 0.5

reference pressure of $0.5\rho V(H)^2$ will only require a single value of reference wind speed, V(H). The use of these coefficients will result in a constant design pressure over an entire side of a building.

At this point it should be noted that no matter how one chooses to define a pressure coefficient the decision to average the coefficients over an entire side of a building will result in some differencies between the actual pressure a building experiences and the pressure predicted using an average coefficient. To obtain a feel for the magnitude of the differences which could be expected, the averaged local pressure coefficients, $\overline{C}_{PL}$ may be compared with the distributions of local pressure coefficients over a surface reported in reference 5. Table 2 is a comparison for the case of a wind direction of 0° and a side ratio of 1.0. The three columns of data show the averaged local pressure coefficient for each side (corresponding to Fig. 2) and the maximum and minimum mean local pressure coefficient on a side. These data show that the use of an averaged pressure coefficient can result in both over and under prediction of pressures by up to 100%. Some design situations such as cladding design for large buildings may not be appropriate application of a spatially averaged pressure coefficient. In other instances such as low rise buildings or overall loadings, the concept should be useful.

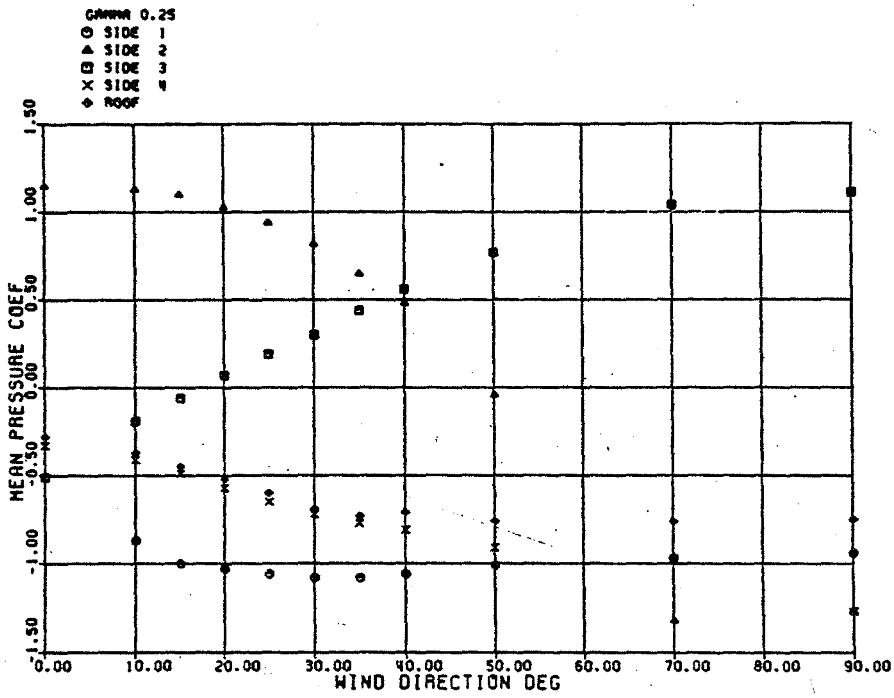

Figure 4. Averaged Local Pressure Coefficients, $\overline{C}_{PL}$, for a Side Ratio of 0.25

TABLE 2. Variation of local pressure coefficient side ratio 1.0, wind direction 0°

Side	$\overline{C}_{PL}$	Maximum C_{PL}	Minimum C_{PL}
1	-1.1	-0.5	-2.6
2	1.1	1.6	0.6
3	-1.1	-0.5	-2.6
4	-0.6	-0.4	-0.9
Roof	-0.7	-0.5	-1.0

In order to obtain a more qualitative idea of the differences between the two types of coefficients presented in this paper, an example of the calculation of the mean pressures on a 70 m (200 ft) building will be examined. This comparison will only consider the determination of mean pressures. Design techniques for

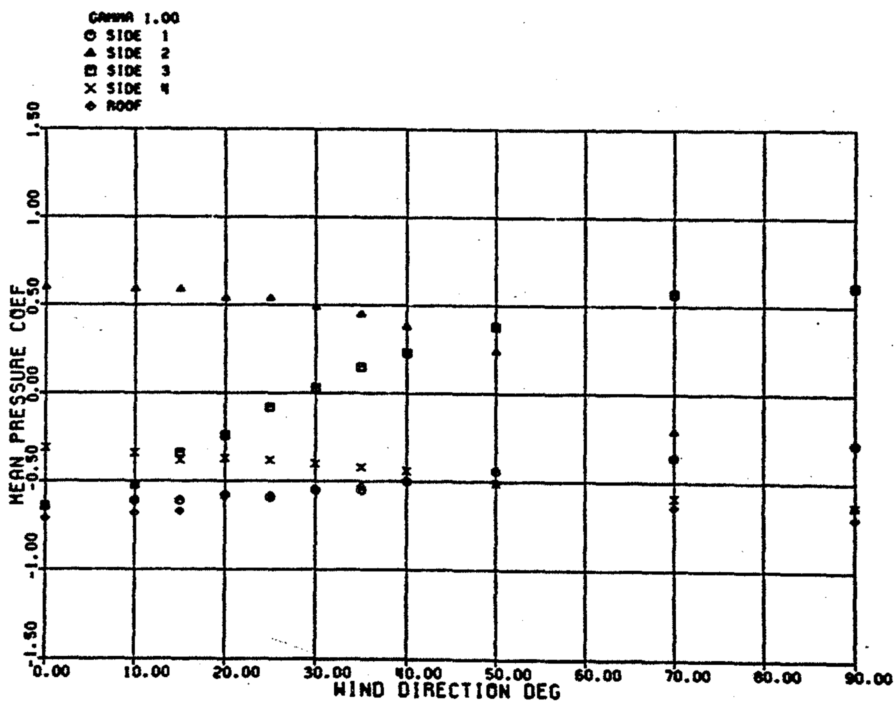

Figure 5. Averaged Presure Coefficients Based on a Reference Velocity Measured at the Roof, $\bar{C}_{PR}$, for a Side Ratio of 1.0

peak pressures are beyond the scope of this paper. The example structure is assumed to be located in an exposure with a power-law exponent of 0.22 (exposure B of Reference 6) and to experience a wind of 40 m/s (90 mph) at an elevation of 9 m (30 ft). Four separate pressures were computed for each side for a building with a side ratio of 1.0 and an incident wind normal to side 2. These four cases are: (1) using pressure coefficients from Ref. 6, (2) using $\bar{C}_{PL}$, (3) using $\bar{C}_{PR}$ and (4) using data from Ref. 5. For the purpose of this comparison, the data from Ref. 5 will be assumed to be the actual pressure at a selected location. The comparison was conducted at eight locations, in the middle of each side horizontally and at elevations representing 20% and 80% of the height of the building. The results as shown in Tables 3 and 4. At the 80% of building height level, the ANSI values have the best agreement, the $\bar{C}_{PR}$ values are low and the $\bar{C}_{PL}$ are high when compared with the actual values. At the 20% of building height level all predicted values are less than the actual values. The values predicted using $\bar{C}_{PL}$ and $\bar{C}_{PR}$ are closer to the actual values than those predicted using the coefficients from the ANSI standard.

TABLE 3. Comparison of predicted mean pressures, side ratio 1.0, elevation equal to 80% of building height

SIDE	ANSI A58.1[6]	$\overline{C}_{PL}$	$\overline{C}_{PR}$	ACTUAL VALUE[5]
1	-1.44 kPa (-30 PSF)	-2.25 kPa (-47 PSF)	-1.39 kPa (-29 PSF)	-1.58 kPa (-33 PSF)
2	1.67 kPa (35 PSF)	2.11 kPa (44 PSF)	1.34 kPa (28 PSF)	2.01 kPa (42 PSF)
3	-1.44 Pa (-30 PSF)	-2.25 kPa (-47 PSF)	-1.39 kPa (-29 PSF)	-1.58 kPa (-33 PSF)
4	-1.06 kPa (-22 PSF)	-1.25 kPa (-26 PSF)	-.72 kPa (-15 PSF)	-.77 kPa (-16 PSF)

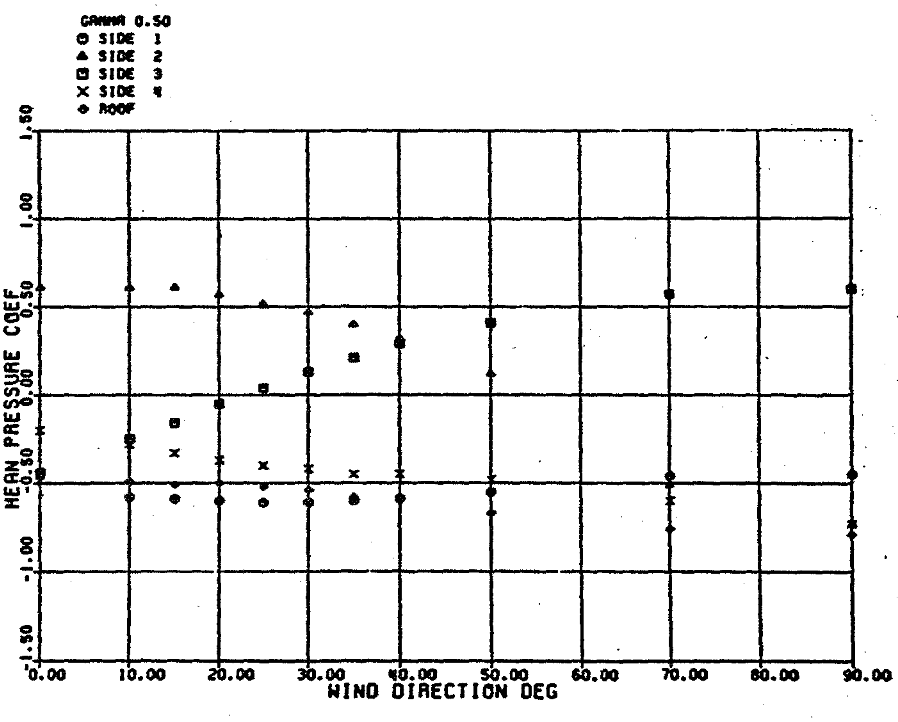

Figure 6. Averaged Pressure Coefficients Based on a Reference Velocity Measured at the Roof, $\overline{C}_{PR}$, for a Side Ratio of 0.5

TABLE 4. Comparison of predicted mean pressures, side ratio 1.0, elevation equal to 20% of building height

SIDE	ANSI A58.1[6]	$\overline{C}_{PL}$	$\overline{C}_{PR}$	ACTUAL VALUE[5]
1	-.77 kPa (-16 PSF)	-1.24 kPa (-26 PSF)	-1.39 kPa (-29 PSF)	-1.58 kPa (-33 PSF)
2	.91 kPa (19 PSF)	1.19 kPa (25 PSF)	1.34 kPa (28 PSF)	1.53 kPa (32 PSF)
3	-.77 kPa (-16 PSF)	-1.24 kPa (-26 PSF)	-1.39 kPa (-29 PSF)	-1.58 kPa (-33 PSF)
4	-.53 kPa (-11 PSF)	-.67 kPa (-14 PSF)	-.72 kPa (-15 PSF)	-.81 kPa (-17 PSF)

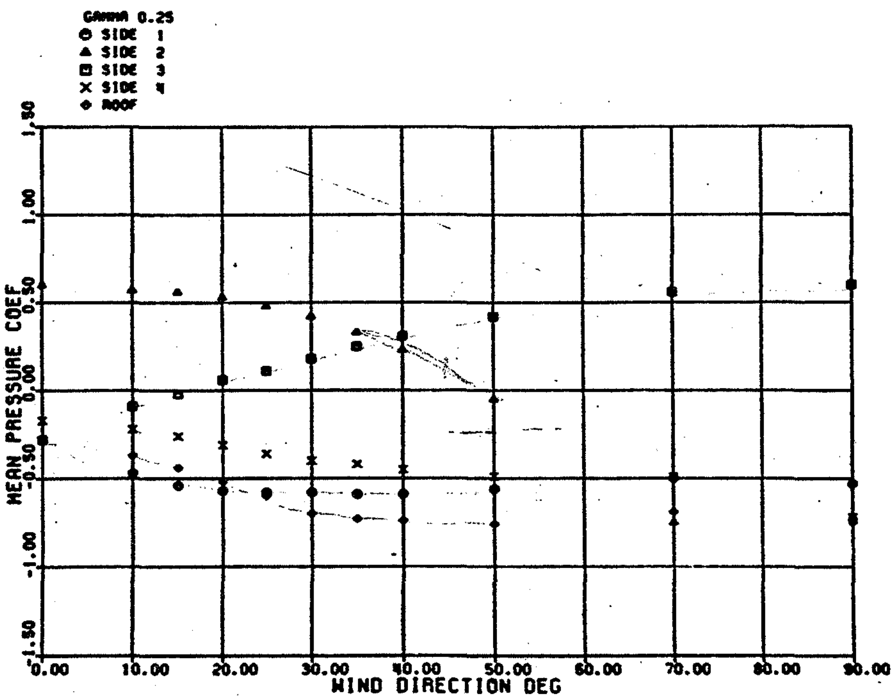

Figure 7. Averaged Pressure Coefficients Based on a Reference Velocity Measured at the Roof, $\overline{C}_{PR}$, for a Side Ratio of 0.25