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Low Building Wind Load Variability With Application to Codes

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Abstract

Current wind code specifications are based on data from wind tunnel tests on isolated buildings in idealized homogenous upstream terrains. This paper reports on the preliminary results of a systematic wind tunnel testing program specifically designed to determine the effects of realistic surroundings on wind loads on a variety of building shapes. Wind load data obtained from the wind tunnel tests are used to determine suitable wind code specifications using a reliability approach.

1. INTRODUCTION

Significant progress in the determination of wind loads on low buildings over the past two decades has led to the development of the current format of wind load specifications for low buildings adopted by the National Building Code of Canada (NBCC) [1, 2], as well as in similar formats by various codes and standards in other countries.

A key component in this development was the extensive experimental program carried out by Stathopoulos [3] in which a variety of low buildings with different sizes, heights, roof slopes and upstream exposures was examined. However, one of the most significant parameters, namely, the effects of the immediate surroundings on wind loads was not considered in any detail. Also, the program dealt only with simple rectangular buildings which led to some uncertainties as to the applicability of the code values derived from these data to more complicated geometries. Reduction of the wind tunnel data to code specifications was empirically-based.

Probabilistic approaches have been suggested by Davenport [4] and others such as Cook and Mayne [5, 6] and Holmes et. al. [7] but the key ingredient, the representative load coefficients applicable for a wide variety of buildings in a wide variety of surroundings, is yet to be defined. The current research program uses a similar probabilistic approach and has the objectives of accumulating a representative sample of wind load data on a variety of buildings in realistic surroundings and to use reliability calculations to determine appropriate design wind loads.

2. PILOT STUDY

A pilot study was carried out to study in more detail the effects of the surroundings on wind loads. Four identical rectangular flat-roofed buildings were placed randomly within a suburban commercial/industrial area in the wind tunnel and the same load variables were measured on each of the four test buildings. These included local and structural loads.

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The different building locations within the statistically-similar surroundings produced significant variability in the loads as illustrated in Figure 1, where the aerodynamic data from the 4 buildings are displayed together, oriented relative to a common building reference system. These aerodynamic data are referenced to the mean roof height dynamic pressure in an open exposure. Hence, comparison between open and suburban exposure data gives relative magnitudes of loads for the same storm condition. Aerodynamic data for one particular building shows a reversed trend due to a significantly larger building beside it. This illustrates the inadequacy of the isolated building data for code use, at least philosophically. A more detailed discussion of the effects of the surroundings on wind loads can be found in an earlier paper by the authors [8]. This paper will present an overview of the complete methodology and some preliminary results.

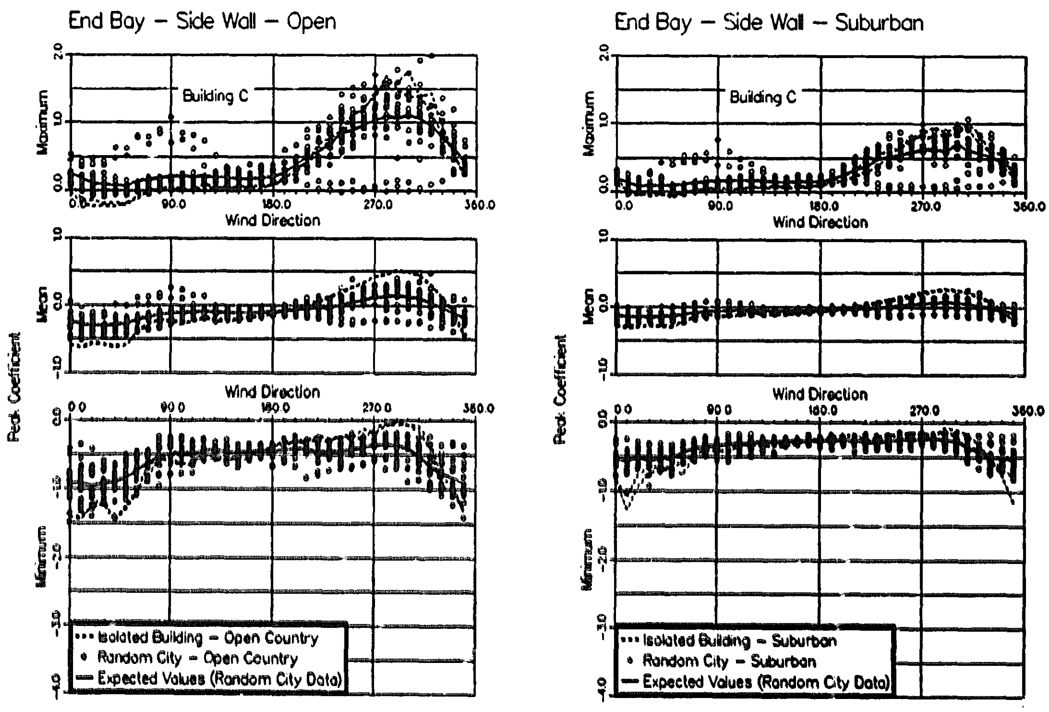

Figure 1: Aerodynamic Data For the Integrated Load on the Side Wall of the End Bay From Four Identical Buildings

3. 'MONTE CARLO' EXPERIMENTS

In order to establish a statistics-based code with specifications determined based on risk level, a statistical description of the wind loads is required. Clearly, not enough reliable wind load data can be obtained by full scale measurements for statistical analysis, and it is prohibitive to test all buildings in the wind tunnel. Thus, estimates of the statistical distribution of the true wind loads must be obtained by sampling. Previous studies achieved this by choosing representative buildings and surroundings by simplifying. While the pilot study shows that previous studies were correct in choosing the case with isolated buildings in open exposure as the worst case scenario, it also shows that this approach does not take into account the highly variable loads due to the surroundings.

A full parametric study would be prohibitively time-consuming and expensive. This variability study intends to establish a representative sample of wind loads including the effects of the surroundings by realistically sampling all types of building geometry, immediate surroundings and upstream exposures. A 'Monte Carlo' type approach is adopted where major variables affecting the wind loads are represented in the sampling according to their statistical occurrence in reality. In this case, the size, roof slope and the shape of the buildings (limited to rectangular and L-shaped), the immediate surroundings and the upstream exposures were treated as variables in the wind tunnel tests.

3.1. Wind load parameters

The statistics of the size of the buildings, defined in terms of length, width and height, were established from the geometric properties of buildings supplied by several building manufacturers in the United States. This sample of statistics contains mostly larger, engineered buildings found in commercial and industrial areas. The most common building size is 125 ft × 80 ft × 16 ft. They have been grouped into discrete distributions of 50 feet increments for lengths and widths and 5 feet increments for heights. Only specific roof slopes are routinely used with the most common being 1 in 12.

Statistics of the characteristics of the immediate surroundings and upstream exposures come from empirical estimates based on city size as well as building density statistics for urban areas and land use statistics. The statistical relationship between the characteristics of the immediate surroundings and those of the upstream exposures is not critical (except in the case of an open exposure with isolated buildings) because of the dominant effects of the immediate surroundings. Three 'typical' immediate surroundings were used; namely, isolated, suburban and city center with tall buildings Three types of upstream exposures were represented in combination with the immediate surroundings; namely, open, suburban and urban. Transition zones among these discrete cases are also included using an empirical estimate of their probabilities of occurrence.

Because of limited time and funding, a total of 20 building/surroundings/exposure combinations were tested. The parameter combinations were selected randomly but statistical distributions of each chosen parameter for the 20 cases matched that of the base statistics. Chi-square tests were carried out to test the target and selected distributions and they were found to match satisfactorily.

3.2. Wind tunnel experiments

The 20 wind tunnel experiments were carried out in the boundary layer wind tunnel (BLWT II) at the University of Western Ontario. The boundary layer wind with a geometric scale of 1:250 was generated for the open, suburban and urban exposures by varying roughness element heights with all cases using three 5-foot spires at the entrance of the wind tunnel. The measured mean velocity and turbulence intensity profiles give equivalent full scale aerodynamic roughness lengths of 0.022 m, 0.3 m and 0.7 m respectively. Tests were carried out at wind tunnel speeds of 45 ft/sec and an overall sampling rate of 500 Hz was used. Equivalent full scale sampling speed was about 0.6 Hz.

Instrumentation of the buildings was designed to give a good description of the spatial pressure distributions of local peak pressures on all building walls and roofs. Modules of two basic sizes (50 ft × 50 ft and 100 ft × 100 ft) were instrumented with a 10 × 10 grid of pressures taps on the roofs and 10 taps on each wall of the 10-foot high modules. This was done to ensure sufficient resolution of spatial pressure distributions over corner quadrants of buildings.

Structural loads were measured using on-line spatial averaging with influence coefficients for the desired structural effects. Each line of taps across the narrower building dimension was used as a unit. Influence coefficients were supplied for on-line weighting to give structural loads including overall drag, overall lift, overturning moment about the edge of the roof, overturning moment about the footing of the building, internal bending moments at the eaves and the ridge for a two-pinned frame and internal moments at the eaves for a three-pinned frame. Overall end wall loads were also measured.

Since this paper is intended primarily to outline the methodology, illustration of the results will be limited primarily to the local roof suctions.

4. EXPECTED PEAK LOADS

In order to compare aerodynamic data from wind tunnel tests at this laboratory, wind tunnel results at other facilities, and full scale results, it is important that they have a common reference dynamic pressure. It is convenient to follow NBCC format in which the dynamic pressure in open country is chosen. This reference also means that comparison of coefficients gives a true load comparison. The reference conditions in the NBCC are taken as open exposure with aerodynamic roughness length of 0.03 m, and the reference dynamic pressure taken at 10 m above ground.

By equating the loads obtained from the wind tunnel tests with a simulated roughness length, z_0, and wind loads specified in the NBCC, the conversion is written

$$C_pC_g = C_L \left(\frac{\bar{V}_{z_0,H}}{\bar{V}_{r,10}}\right)^2 \frac{1}{\left(\frac{H}{10}\right)^{0.2}} \tag{1}$$

where C_pC_g is the peak pressure coefficient defined in the NBCC, C_L is the measured aerodynamic data referenced to mean roof height dynamic pressure in the simulated terrain, z_0 is the aerodynamic roughness length for the tested exposure, H is the height of the building (mid-roof height in case of buildings with 4 in 12 roof slope), r denotes the standard open condition with z_0 of 0.03 m and 10 denotes 10 m height above ground. $(H/10)^{0.2}$ is the exposure factor, C_e, used in the NBCC to account for the dependence of wind pressure on height and exposure. This gust pressure profile is used for all exposure conditions for design of low buildings.

The aerodynamic data over the full range of wind angle at 10° increments were combined with a circular wind climate model to obtain the expected peak loads. This synthesis of aerodynamic data with wind climate model using the upcrossing method is well established. Interested readers can find more details in reference [9]. This procedure reduces the aerodynamic data over all wind directions to expected peak loads independent of wind direction.

An effective peak load coefficient, C_pC_g is defined by normalizing the calculated expected peak loads by the dynamic pressure represented by the wind climate model used and the exposure factor used in the NBCC.

$$\text{Effective } C_pC_g = \frac{\text{Expected Peak Loads}}{\frac{1}{2}\rho V_r^2 C_e} \tag{2}$$

where V_r is the wind speed corresponding to the predicted wind loads and C_e is the height dependent factor specified in the code. Only these coefficients were used throughout the following steps towards code specifications. For brevity, these effective C_pC_g will be referred to simply as C_pC_g for the remainder of this paper.

5. ORTHOGONAL DECOMPOSITION

The NBCC and most other building codes have higher specified local and structural loads near the edges of the walls and the roofs as well as the corners of the roofs. This follows the expected aerodynamic behaviour of low buildings. In built-up surroundings, the question arises as to whether this increase in loads, mostly suctions, would be significant enough to warrant the complexity of the current code format, in light of the highly variable loads over all regions of the building. For illustrative purposes, the statistical distributions of the measured roof suctions on all twenty buildings are shown in Figure 2. It shows the statistical distributions of roof suctions measured for all the corner taps (within a $0.1w \times 0.1d$ area at roof corners, where w and d are horizontal dimensions), all edge taps (within an edge strip of $0.1w$ or $0.1d$ area excluding corner taps) and interior taps (all taps excluding corner and edge taps). Also shown is the statistical distribution of roof suctions for all pressure taps on all buildings. The interior areas clearly have lower loads, but differences between corner and edge areas are small.

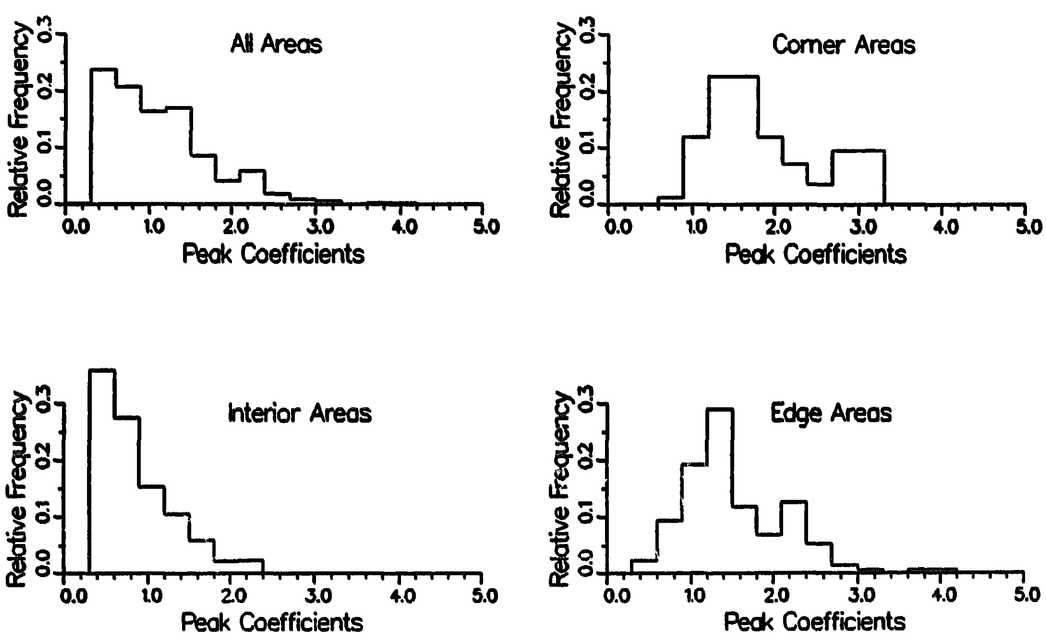

Figure 2: Statistical Distributions of Local Suctions In Different Roof Regions

It is therefore very useful to determine the prevailing spatial distributions of peak loads on low buildings, particularly the gradient of the expected peak loads near the edges and corners of the roof. A code model can then be developed for further consideration of the magnitudes of specified peak coefficients within each chosen zone.

Using the roof suction distribution as an example, the non-simultaneous spatial distribution of peak pressures can be described by a 10×10 matrix for each building[1]. These are highly variable in both magnitude (due to exposure condition in the far field and the near field) and spatial distribution (due to relative orientation and size of the neighbouring buildings). Each of these spatial distributions can be described by an expansion series,

$$C_p C_{g_k}(x,y) = a_{k_1}\psi_1(x,y) + a_{k_2}\psi_2(x,y) + a_{k_3}\psi_3(x,y) + \cdots + a_{k_n}\psi_n(x,y) + \cdots \tag{3}$$

for the kth building. The common shapes for all distributions, $\psi(x,y)$, describe only the spatial variation over the roof. The amplitudes, a, describe the overall magnitude level of the roof suctions. A technique called 'Proper Orthogonal Decomposition' [10, 11, 12, 13] extracts orthogonal mode shapes from an ensemble of distributions by solving an eigenvalue problem formed by the mean covariance between the points in the distributions. Mathematical details of the technique will not be presented here because of space limitations, but some of the essential features of this technique are discussed. This technique does not require pre-determined input shapes as in the case of Fourier, Legendre or Chebychev series, but rather extracts the most common shape among the inputs for the first mode, the most common among the remaining for the second mode and so on. All mode shapes are orthogonal and hence the amplitudes calculated for the expansion series to reconstruct the input distributions using these mode shapes are independent of the shapes. This is particularly useful for code applications. The eigenvalues provided in the solution give the relative contribution of each mode in identifying the common structures of the distributions in the ensemble.

The amplitudes of the results for all buildings in each mode are combined to form statistical distributions. The first mode amplitudes give the general level of peak pressure coefficients and the statistical distributions of the higher mode amplitudes give close to zero means because they represent corrections to the first mode. In this case where the ensemble of input distributions are similar, the higher mode amplitudes also have low variability.

Figure 3 shows the first two mode shapes for roof suctions. The first mode shape shows increases of loads towards the edge of the roof but the loads at the corners are not significantly higher than those at the edges. Second and higher mode amplitudes are very low and therefore add little to the overall effect. For code application, this provides a good basis for truncation of the expansion series formed for the specified peak coefficients. A possible code model would therefore be uniform loads on an edge region (including both the current edge strips of the roof and the roof corners) and uniform loads on the interior region. It should be noted that the above uses the non-simultaneous local peak pressure coefficients and the results cannot be subsequently used to determine structural loads. Analysis of independently-measured structural loads uses the same technique using the distribution of loads over the length of the building.

[1]The 10×10 matrix does not describe the spatial distribution of some longer buildings nor L-shaped buildings and other considerations have to be made. For illustrative purposes, it is assumed that all buildings within the sample can be described with a 10×10 matrix.

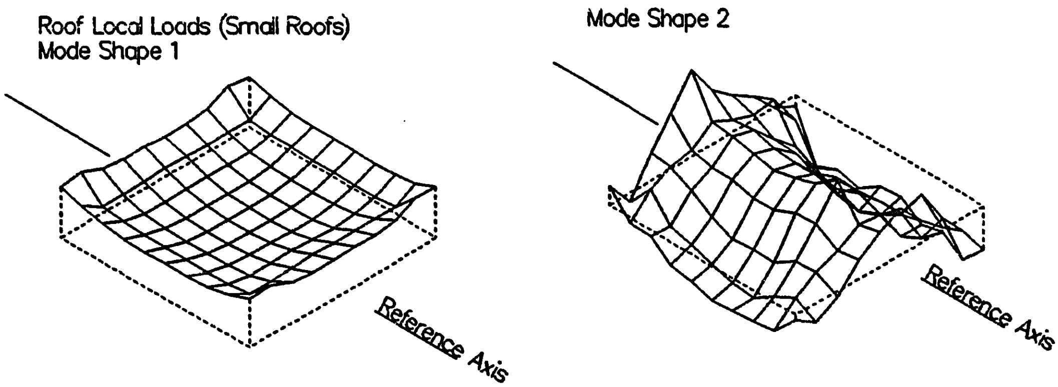

Figure 3: Mode Shapes For Local Roof Suctions

6. RELIABILITY ANALYSIS

6.1. Second moment reliability

Second moment reliability theory is used to calculate the suitable level of specified peak coefficient based on acceptable risk level. Considering only wind loads, from the loading equation following the NBCC format,

$$L = qC_eC_pC_g\mu \tag{4}$$

where L is the total wind load, q is the reference dynamic pressure at 10 m height in open exposure, C_e is the exposure factor, C_pC_g is the peak coefficient and μ is a model uncertainty factor used in this equation to take into account uncertainties such as using wind tunnel data as the data base, assumptions made throughout the procedure and also some of the uncertainties involved in estimating internal pressures[2].

The wind load, L, formed by a number of highly variable parameters, will take on a lognormal distribution, following the Central Limit Theorem. A reliability index, β, is defined as the number of standard deviations from the mean of the statistical distribution for L. In the NBCC, the design requirement is simply that the factored resistance has to be higher than the factored loads. Considering only wind loads, the factored wind load is the product of a load factor, γ_L (=1.5 in the NBCC) and the specified loads, L_s. The requirement therefore is that the factored wind loads match the load level which is a distance of β standard deviations from the calculated mean. It can be approximated as

$$\gamma_L L_s = \bar{L}\exp(0.75\beta V_L) \tag{5}$$

where $\bar{L}$ is the mean from the statistical distribution of the wind loads and $\exp(0.75\beta V_L)$ is the mean load factor determined by the reliability index and the variability of the wind loads.

Combining the loading equation (Equation 4) and the expansion series (Equation 3), $C_pC_{g_s}$ can be evaluated based on the first and second moments of the parameters, q, C_e,

[2]Internal pressures will not be discussed in this paper, but are included in the overall study.

C_pC_g and μ as well as the ratio of the mean to specified values for q, C_e and C_pC_g.

$$C_pC_{g_s} = \frac{\bar{q}}{q_s}\frac{\bar{C}_e}{C_{e_s}}\frac{\bar{\mu}}{\mu_s}\overline{C_pC_g}\frac{1}{\gamma_L}\exp(0.75\beta V_L) \tag{6}$$

$$1+V_L^2 = (1+V_q^2)(1+V_{C_e}^2)(1+V_{C_pC_g}^2)(1+V_\mu^2) \tag{7}$$

where V denotes the coefficient of variation and the subscript s denotes specified values. Some useful characteristics of the mode shapes and amplitudes can be used in simplifying the reliability calculation which uses the peak pressure coefficient distribution represented by the expansion series, $C_pC_g(x,y) = a_1\psi_1(x,y) + a_2\psi_2(x,y) + a_3\psi_3(x,y) + \cdots$. Because of the low variability of amplitudes for the second and higher modes, overall variability of loads, V_L, calculated using Equation 7 is almost constant whether using one or more modes. The mean C_pC_g also does not change significantly with the number of modes used although the higher modes can be easily incorporated into the calculations. Unlike the variable mode shapes, the specified shapes for codes are all uniform and normalized to unity. The magnitude of the specified peak coefficients comes from the specified amplitudes. Equations 6 and 7 become

$$\sum_i a_{s_i} = \frac{\bar{q}}{q_s}\frac{\bar{C}_e}{C_{e_s}}\frac{\bar{\mu}}{\mu_s}\sum_i(\bar{a}_i\cdot\bar{\psi}_i)\frac{1}{\gamma_L}\exp(0.75\beta V_L) \tag{8}$$

$$1+V_L^2 \simeq (1+V_q^2)(1+V_{C_e}^2)(1+V_{a_1\psi_1}^2)(1+V_\mu^2) \tag{9}$$

6.2. Variability of the parameters

Equations 8 and 9 show clearly that the level of specified peak coefficients depend on the statistics of the parameters as well as the risk level represented by the reliability index. The statistical mean and variability of each of the parameters is summarized in Table 1 and discussed briefly below. The ratios of statistical mean to specified values define how accurately the parameters are nominally specified in the code. The COV's define how well deterministic specified values or expressions represent variable parameters.

Table 1: Summary of the Variability of the Loading Parameters

Load Equation : $P = qC_eC_pC_g\mu$

	mean/specified	coefficient of variation
q	0.9	0.20
C_e	1.0	0.1
C_pC_g	see Table 2	
μ	1.05	0.14

Reference dynamic pressure, q

All regionally or nationally based wind loading codes specify the modes for various return periods, e.g. 10, 30, 50 years, etc. of the extreme value distribution of wind speeds [2, 14] from historical wind records, usually measured at airports. The statistical mean and variability (COV) of these skewed extreme value distributions can be calculated from information on the dispersions and the modes of the distributions. The characteristics of extratropical wind climates and hurricane wind climates are slightly different, mainly due to differences in the cycling rate.

Additional adjustment was made to the statistics of this parameter because of the use of an empirical circular climate model which gives equal probability of wind coming from different directions to calculate expected peak loads. The effects of random orientation within a directional wind climate is not accurately produced by that assumption and can only be determined by rotating a directional wind climate model with respect to the building orientation. This effect was investigated using several characteristic directional climate models on some typical aerodynamic coefficients such as those with high response for only a few wind directions (expected for local suctions) and those which are more slowly varying with wind direction (structural loads).

The total effects due to the above give a mean to specified ratio and COV of about 0.9 and 0.2 for extratropical wind climates and about 1.0 and 0.3 for hurricane wind climates. It is proposed that the values for extratropical wind climates are used for specification purposes and an empirical factor be applied to take into account the higher specifications required for hurricane-prone sites.

Exposure factor, C_e

The statistics of the wind loads using this approach are independent of the definition of the exposure factor since the same definition was used to normalize the wind tunnel data. Additional variability, however, arises due to the use of discrete exposure conditions in the wind tunnel experiments to represent the entire range of typical terrain categories. For example, the use of only the single experimental z_o value of 0.022 m to represent open exposure conditions, in which z_o probably ranges between 0.007 m and 0.1 m, provides only nominal values in terms of roof height dynamic pressures. Investigation of the variation of dynamic pressures over the range of open, suburban and urban exposures separately shows that the variation is in the order of 10%. The values used for reliability calculations are therefore, 1.0 and 0.1 for the mean to specified ratio and the COV of the exposure factor.

Peak coefficient, C_pC_g

The statistics of the peak coefficients were obtained through the 'Monte Carlo' wind tunnel experiments on the 20 buildings selected. They were found to be highly variable. As expected, the effects of the surroundings give lower mean and higher variability than previously estimated through isolated building test results. Table 2 summarizes the statistical means and COV's obtained for measured structural and local loads.

Model uncertainty factor, μ

The model uncertainty factor takes into account the bias and the variability of using wind tunnel studies to determine wind loads. This factor may be adjusted based on the confidence placed on the wind tunnel data, as derived from model/full scale comparisons. For example, when a larger data base including wind tunnel data from other facilities and full scale wind load data are compiled, this bias may be reduced. Through the study of the Aylesbury model and full scale comparison, Davenport [15] estimated that this effect has a mean bias of 1.05 and COV of 0.14. With increasing sophistication in full scale and model scale measurements of wind loads, e.g. the recent Texas Tech Building full scale experiment [16] and the use of high speed solid state pressure scanning systems, the model uncertainty factor may be adjusted.

Table 2: Statistics of C_pC_g From Wind Tunnel Data

	Positive		Negative	
	Mean	COV	Mean	COV
STRUCTURAL LOADS				
Lift	0.86	0.56	0.19	0.64
Drag	1.30	0.34	1.30	0.34
Moment	0.47	0.52	0.10	0.58
LOCAL LOADS				
Roof				
All Areas	0.40	0.34	1.12	0.55
Wall				
All Areas				
(small tributary area)	1.28	0.33	0.84	0.46
(large tributary area)	0.94	0.41	0.67	0.50

Note: Moment = overturning moment about roof eave

Reliability Index, β

The value of the reliability index is determined through calibration of the existing design criteria. Common values are between 2.5 and 3.5 for ultimate limit states requirements. Reliability indices of 2.5 and 3.0 were used to calculate the specified peak coefficients for illustration in this paper.

7. SPECIFIED PEAK COEFFICIENTS

Specified peak coefficients were calculated using Equations 8 and 9 and the first and second moments of the parameters discussed above, based on edge strips of $0.1w$ wide and roof corners of $0.1w \times 0.1d$ area. The statistics of C_pC_g from the 'Monte Carlo' experiments (Table 2) were used. Table 3 shows the calculated specified peak coefficients for structural loads including the overall lift, drag and overturning moment about the roof edge; and local loads such as at roof corners and edges, wall edges, and roof and wall interior regions, for reliability indices of 2.5 and 3.0. The current NBCC specifications are included as reference. These values show that structural loads and wall loads are higher than currently specified while other local loads are very similar. This is probably due to the significant increase in the COV for local loads being compensated for by the significant decrease in the means of expected peaks with buildings in built-up surroundings. On walls and for structural loads, the increase in the COV is not accompanied by a similar decrease in the means of expected peaks, resulting in higher specified values.

8. CONCLUDING REMARKS

This paper utilizes a powerful technique to rationally define wind code specifications through the use of wind tunnel data and a statistical approach. The data base can be easily increased when more data on more buildings and from other facilities become available. The statistics of the parameters can also be better defined when they are better understood and described.

Table 3: Calculated Specified C_pC_g

	Positive			Negative		
	Current Study		1985*	Current Study		1985
	$\beta = 2.5$	$\beta = 3.0$	NBCC	$\beta = 2.5$	$\beta = 3.0$	NBCC
STRUCTURAL LOADS						
Lift	1.8**	2.3	1.5/1.0***	0.5	0.6	—
Drag	1.9	2.2	1.95/1.3	1.9	2.2	1.95/1.3
Moment	0.9	1.1	0.9/0.6	0.2	0.3	—
LOCAL LOADS						
Roof						
All Areas	0.6	0.7	—	2.3	2.9	—
Corner	0.9	1.1	—	2.9	3.4	4.4
Edge	0.6	0.7	—	2.5	3.0	2.5
Interior	0.5	0.6	—	1.6	2.0	1.8
Wall						
All Areas						
(small tributary area)	1.8	2.1	1.8	1.5	1.8	—
(large tributary area)	1.5	1.8	1.3	1.3	1.6	1.5
Edge	1.9	2.2	1.8	1.8	2.1	2.1
Interior	1.8	2.1	1.8	1.2	1.5	1.8

* These values are as specified in the 1985 NBCC. The 1990 NBCC does specify positive values, and the roof suctions have been increased in corner areas.

** Structural load values for Current Study are for the entire roof area.

*** End Zone / Interior Zone

The major contributor to the highly variable wind loads is undoubtedly the peak coefficients, C_pC_g, with COV's in the order of 0.6. The other major contributor, as can be seen in Table 1, is the reference dynamic pressure. Using a nominal edge zone with $0.1w$ width and corner zone with $0.1w \times 0.1d$ area and using the data base from the 'Monte Carlo' experiments, some of the specified loads using the proposed methodology would be increased over current NBCC requirements, and some would be decreased. The increases are primarily associated with the high variability of the coefficients in the real surroundings. Results presented in this paper are not complete for the purpose of code formulation; other area specifications will be examined before final conclusions can be drawn.

Acknowledgements

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