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A PRELIMINARY APPRAISAL OF WIND LOADING CONCEPTS OF THE 1970 NATIONAL BUILDING CODE OF CANADA

BY

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UNE ÉVALUATION PRÉLIMINAIRE DES CONCEPTS DE CHARGES DUES AU VENT DANS LE CODE NATIONAL DU BÂTIMENT DU CANADA DE 1970

SOMMAIRE

On décrit les principes de base et la formulation des méthodes simples et détaillées concernant les charges dues au vent dans le Code national du bâtiment de 1970. On compare les prédictions de la réponse dynamique à la succion et des pressions sur le revêtement avec des mesures à l'échelle grandeur de plusieurs grands immeubles. On conclut que les prédictions de la réponse à la succion et de la pression au vent sont satisfaisantes. On examine les domaines qui exigent une étude plus poussée.

A PRELIMINARY APPRAISAL OF WIND LOADING CONCEPTS OF THE 1970 CANADIAN NATIONAL BUILDING CODE

UNE EVALUATION PRELIMINAIRE DES CONCEPTS DE CHARGES DUS AU VENT DANS LE CODE DE CONSTRUCTION NATIONAL CANADIEN DE 1970

by
A. G. DAVENPORT* and W. A. DALGLIESH**

SUMMARY

This paper describes the philosophy and formulation of the simple and detailed procedures for wind loading of the NBC 1970. Predictions of dynamic drag response and cladding pressures are compared with full scale measurements on several tall buildings. It is concluded that the predictions of drag response and windward pressure are satisfactory. Areas requiring further definition are discussed.

INTRODUCTION

The National Building Code of Canada(1) (abbreviated herein as NBC) is a model building by-law published by the National Research Council as a service to provincial and municipal governments. Over 90% of the 162 cities in Canada have adopted this code (in whole or part) and approximately 80% of all Canadians live in areas where the NBC is in use.

The NBC is revised every five years. The 1970 revision embraces the "Canadian Structural Design Manual"(2): in this several major changes were made in the subsection dealing with wind effects for building design. These changes introduced several new concepts to improve the understanding and formulation of some of the complex effects of wind, particularly the interaction of turbulence with dynamically responsive structures.

Previously, in the third edition issued in 1960, the NBC contained only brief instructions on how to determine design pressures from the reference gust velocity pressure and pressure coefficients (detailed values of which were provided in supplements) and a factor accounting for the increase in the velocity pressure with height above ground: in addition a warning was given of the danger to tall slender structures of dynamic overloading and vibrations at critical frequencies.

In the 1970 edition of the NBC the design pressure, p, is defined by the equation

$$p = q\, C_g\, C_e\, C_p \qquad (1)$$

where q is a reference mean velocity pressure (averaged over an hour) having a specified probability of occurrence, C_g is a *gust effect factor*, C_p is a *mean pressure coefficient* and C_e an *exposure factor*.

Substitution of the mean velocity pressure instead of the previously used gust velocity pressure allows the complex fluctuating response due to gusts to be considered separately through the factor C_g. The exposure factor C_e allows for the modifying effects of both height and a new factor, the terrain roughness. The pressure coefficient C_p is used conventionally and allows for the influence of structural shape.

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The NBC permits two design procedures; a simple procedure and a detailed procedure. In the simple procedure $C_g = 2.0$; for most places in Canada the quantity $C_g\ q$ is then close to the "gust velocity pressures" used in previous climate supplements[3]; also C_e is based on a 1/10 power law profile, again providing continuity with previous code editions[3]. Simplified pressure coefficients C_p are tabulated.

The detailed procedure is intended mainly for use with somewhat taller structures and, as will be shown later, for a broad class of structures offers economy over the simple procedure. For structures over 400 ft. high the detailed procedure is obligatory since the simple procedure may then be inadequate. Original wind tunnel testing using dynamic models in appropriate turbulent flow is permitted under the detailed procedure. There is also a recommended theoretical procedure (similar to that provided for in the Danish Standard[4]) the innovative features of which are now described in greater detail.

THE DETAILED PROCEDURE

Elements of the detailed procedure for design of the overall structure are summarized in Fig. 1. Two innovative features are of particular note:

1) The exposure factor C_e is set forth in Fig. 1(a); it is defined as a function of height z for three degrees of terrain roughness: open country (Zone A), intermediate (wooded or suburban areas) (Zone B) and heavily built-up city centres with many tall buildings (Zone C). The roughness of the terrain of the zone assumed in design should exist for a considerable distance upwind of the structure. The considerable reductions in pressure near the ground in rough terrains implied by the reduced exposure factors are partly offset by the greater turbulence and gust effect factors described below.

2) The gust effect factor C_g appropriate for the design of the overall structure is determined from the statistical theory for the dynamic response to turbulence and defined in Figs. 1c-f (For cladding, C_g is 2.5 universally). The basic formulation for C_g given in Fig. 1, can also be written in the form

$$C_g = \frac{\mu + g\sqrt{\sigma_B^2 + \sigma_R^2}}{\mu} \qquad (2)$$

Here μ denotes the mean response amplitude, g the peak factor, σ_B^2 is the variance of the response due to "background" gust excitation at frequencies below the natural frequency, acting quasi-statically, and σ_R^2 is the variance of the response resonant with the fundamental frequency of the structure. It follows that in terms of the basic formulation

$$\frac{\sigma_B^2}{\mu^2} = \frac{K}{C_e} B \text{ and } \frac{\sigma_R^2}{\mu^2} = \frac{K}{C_e} \frac{SF}{\beta} \qquad (3)$$

The parameters B, S, F and g and their functional dependencies on the height of the structure H, aspect ratio D/H and mean velocity at the top of the structure, $\overline{V}_H$, are indicated in Figs. 1c-f. ($\overline{V}_H$ is readily calculated from the reference velocity pressure viz. $\overline{V}_H = \sqrt{2C_e\ q/\rho}$). Suggested critical damping ratios, β, are .01 for steel framed buildings and .02 for concrete.

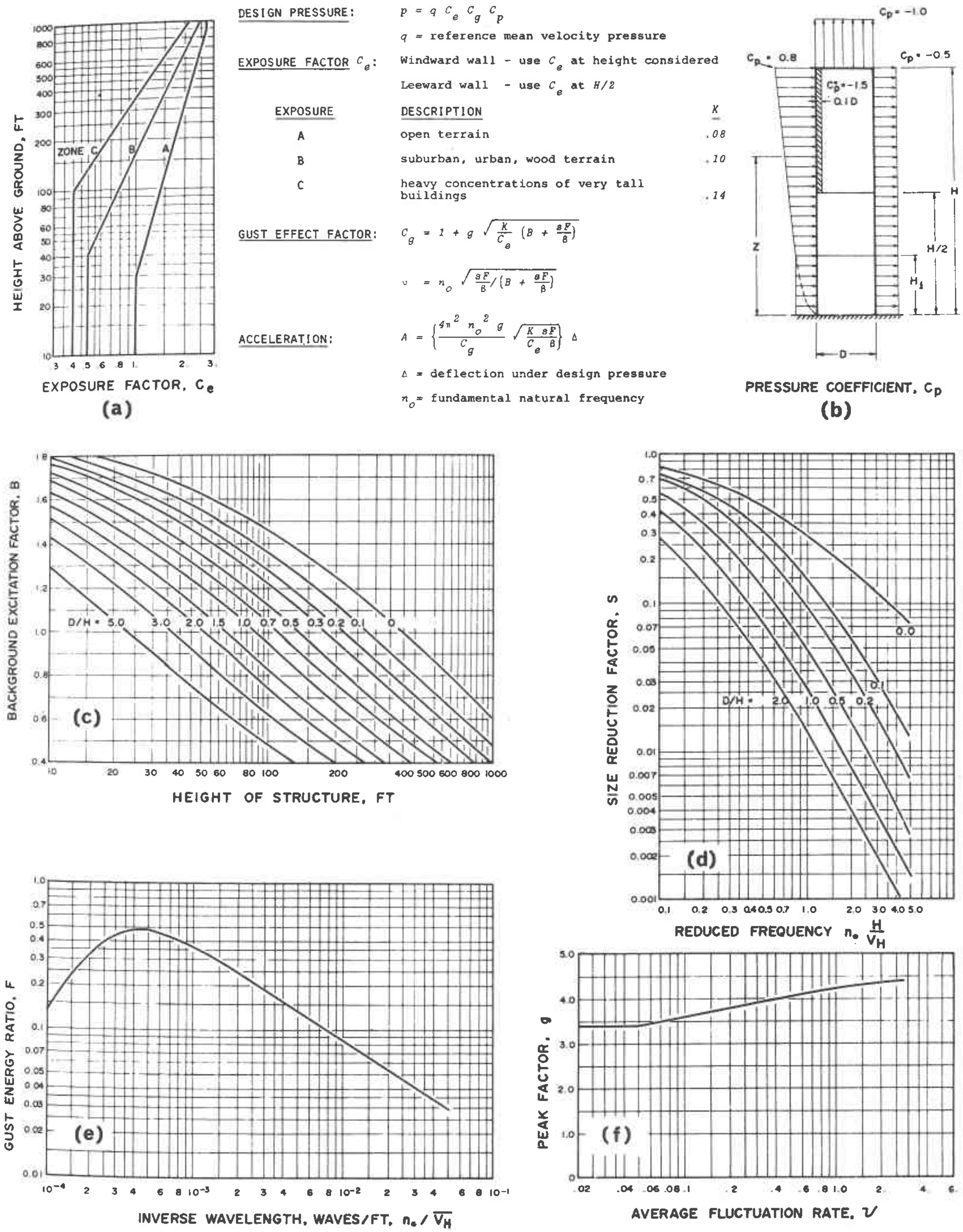

FIG. 1 THE NBC DETAILED APPROACH TO WIND LOADING

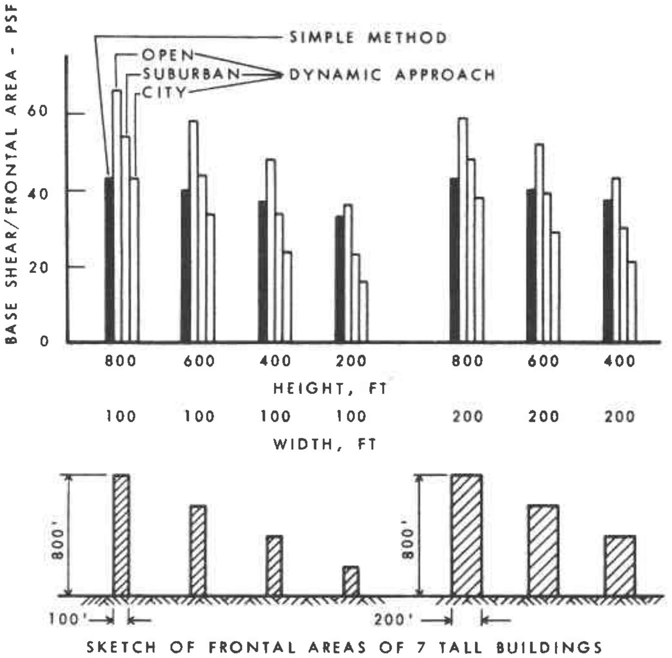

FIG. 2 COMPARISON OF SIMPLE AND DETAILED PROCEDURES OF NBC FOR CALCULATING WIND LOADS ON TALL BUILDINGS

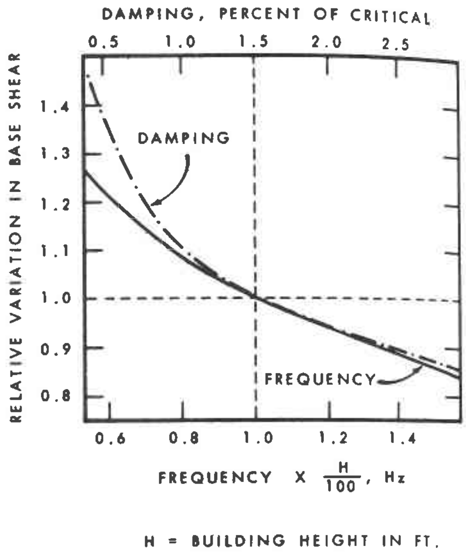

FIG. 3 RELATIVE EFFECTS OF FREQUENCY AND DAMPING ON BASE SHEARS OF TALL BUILDINGS

IMPLICATIONS OF THE DYNAMIC APPROACH FOR DESIGN OF TALL BUILDINGS

It is found that the gust effect factor follows the following general trends. Larger values of C_g are found with i) slender structures (due to the greater spatial organization of the gusts; ii) structures having lower natural frequencies; iii) higher mean wind speeds and iv) lower values of damping. These factors also effect the relative contributions of the resonant response σ_R^2 and the background response σ_B^2.

The overall effect of the detailed procedure is illustrated in Figs. 2 and 3. In Fig. 2 comparisons are made of base shears per unit frontal area for 7 tall rectangular building shapes as indicated. For the analysis a reference mean velocity pressure at 30 ft. (10 m. is $10\ psf \sim 50\ kg/m^2$), the structural damping, $.015$ of critical and the frequency in hertz is $100/H$ where H is the height in feet.

It is seen that, for the open exposure, the detailed procedure gives larger loads than the simple procedure for all buildings whereas in the suburban or intermediate zone it gives lower loads for buildings below 500 ft. for the 100 ft. width, and below 700 ft. for the 250 ft. width.

Figure 3 demonstrates the sensitivity of the base shear to variations in frequency and damping: it is greatest when the resonant component is dominant and the gustiness is greatest - as with tall structures in the city exposure.

EXPERIMENTAL CONFIRMATION

Some experimental evidence confirming the general response characteristics predicted by the gust effect factors is available from firstly full scale studies and secondly boundary layer wind tunnel experiments.

Observations are available of the dynamic response of several tall buildings whose measured properties are listed below:

TABLE 1

Building	*Ref.*	*H ft.*	*D/H perp. to wind*	*B/H parallel to wind*	n_o H_Z	*Damping* β	*Exp. ass'd*
A. John Hancock Building, Chicago	5	1107	.15 to .09	.24 to .14	.21	.0045	C
B. Delft Apartment Building	6	149	1.72	.36	.70	.015	B
C. C.I.B.C. Building, Montreal	7	603	.17	.23	.21	.016	B
D. C.I.L. House, Montreal	7	430	.26	.39	.25	.015	B
E. Post Office Building, Ottawa	7	148	1.8	.5	1.44	.010	B

Figure 4 shows recordings of column strains at ground floor level in Buildings A and B. The dynamic response of these two very dissimilar buildings in a 40 mph mean wind at the top predicted by the gust effect factor of the NBC is tabulated below:

TABLE 2

Building	*Exposure*	$\frac{\sigma_B^2}{\mu^2}$	$\frac{\sigma_R^2}{\mu^2}$	$\frac{\sigma_T^2}{\mu^2}$	$\frac{\sigma_B^2}{\sigma_T^2}$	$\frac{\sigma_R^2}{\sigma_T^2}$	$\frac{\sigma_T}{\mu}$ *Pred.*	$\frac{\sigma_T}{\mu}$ *Observ.*
A	C	.029	.043	.072	.40	.60	.26	---
B	B	.068	.0036	.072	.95	.05	.26	.26

$$\sigma_B^2/\mu^2 = \frac{K}{C_e} B \qquad \sigma_B^2/\mu^2 = \frac{K}{C_e}\frac{sF}{\beta} \qquad \sigma_T^2 = \sigma_B^2 + \sigma_R^2$$

It is apparent that although the ratio of the rms fluctuating response to mean response $(\frac{\sigma_T}{\mu})$ is the same for both buildings, for the John Hancock Building the contribution to the total variance (σ_T^2) from the resonant component is 60%, while for the Delft Apartment Building it is negligibly small - only 5%. This is confirmed by the traces themselves as well as by the response spectra sketched in Fig. 5 from the original experimental results. It is noted that the predicted value of σ_T/μ is in agreement with observation.

Observations of the response of buildings C, D and E to wind were made using Willmore seismometers. These instruments are velocity sensitive and the indicated response is principally that at resonance - σ_R. In Fig. 6 a comparison is made between the indicated resonance response ratios $\frac{\sigma_R}{\mu}$ and the ratio predicted using the gust effect factor approach of the NBC. To make this comparison an estimate

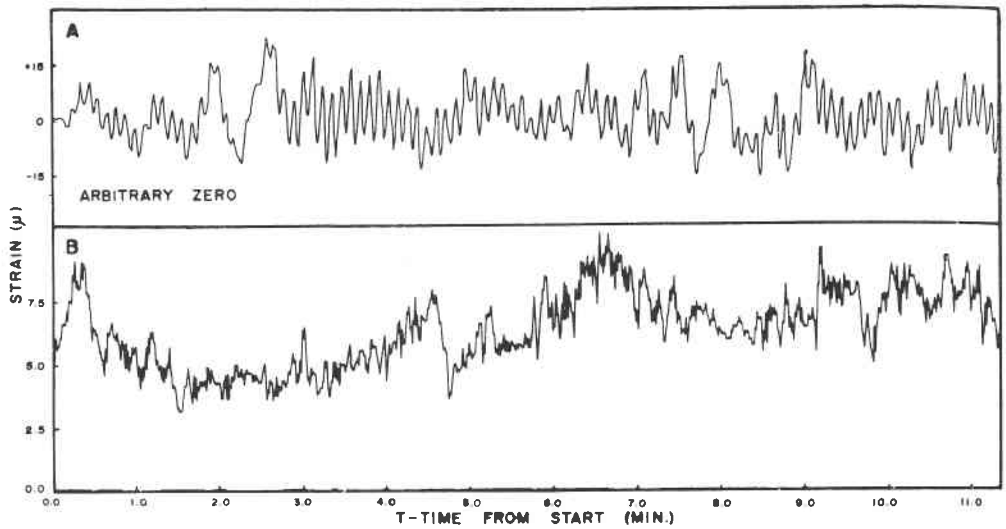

FIG. 4 COMPARISON OF WIND INDUCED COLUMN STRAINS ON (A) JOHN HANCOCK BUILDING, CHICAGO AND (B) APARTMENT BUILDING, DELFT

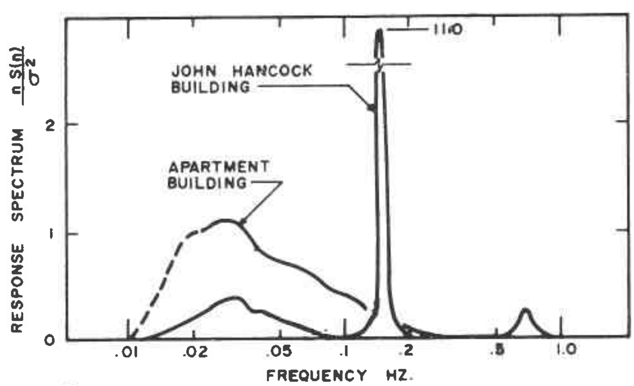

FIG. 5 COMPARISON OF SPECTRA OF RESPONSE OF BUILDINGS A & B

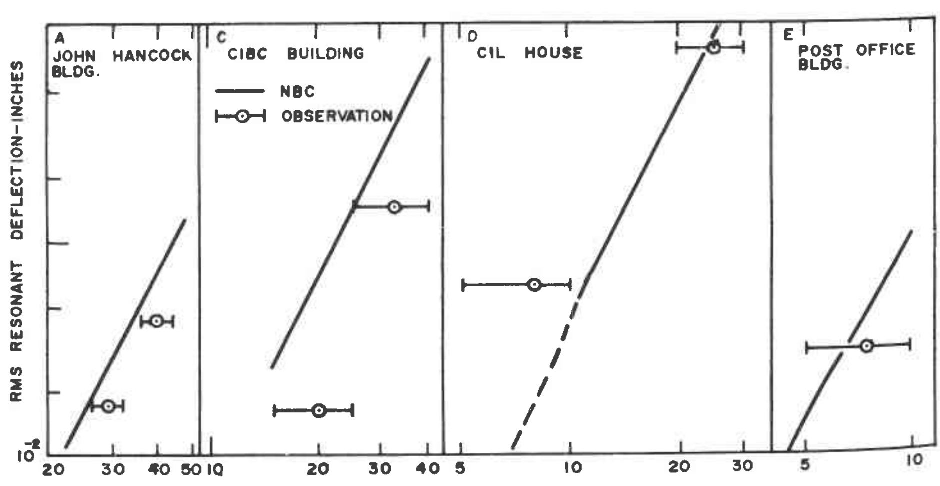

FIG. 6 COMPARISON OF OBSERVED RMS RESONANT RESPONSE OF TALL BUILDINGS AND NBC PREDICTIONS

of the mean response (deflection at top) is necessary and the following approximate expression was used

$$\mu = \frac{q_o \int_o^H C_F(Z)\ D(Z)\ \phi(Z)\ dZ}{4\pi^2\ n_o^2 \int_o^H \gamma(Z)\ \phi^2(Z)\ D(Z)\ B(Z)\ dZ}\ \phi(H) \simeq \frac{q_o}{4\pi^2\ n_o^2\ \bar{\gamma}\ B_e} \qquad (4)$$

in which q_o is the reference velocity pressure, $C_F(Z)$ is the drag coefficient at height (Z), $\phi(Z)$ is the mode shape, $D(Z)$ and $B(Z)$ the width and downwind length of the building, $\gamma(Z)$ is the average building density at height (Z), and $\bar{\gamma}\ B_e$ is defined by the ratio of the integrals they replace. Very approximately it can be shown that B_e can be taken as the along wind dimension of the building. In the analysis of buildings C, D and E there was some uncertainty concerning the direction of the wind and the generally prevailing wind direction was assumed. Due to the large expanses of the St. Lawrence River upwind of building C and D exposure B was assumed. It is seen from Fig. 6 that the NBC approach results in predictions that are generally slightly conservative - (a result partly to be expected from certain simplifications concerning the form of the wind speed spectrum).

Earlier studies by Vickery and Davenport(8) and Vickery(9) have related the results of wind tunnel studies at The University of Western Ontario Boundary Layer Wind Tunnel Laboratory with predictions of drag response of the NBC with generally satisfactory agreement.

WIND PRESSURES FOR CLADDING DESIGN

The NBC does not in its detailed method specify a comparative dynamic approach for the establishment of the gust factor for the design of cladding as it does for the design of the overall structure; as noted a factor of 2.5 is applied universally. A further innovation is the adoption of a reference velocity pressure q_o for cladding design (and deflections) having a higher risk of occurrence (annual probability of 1/10) than that for structural design (annual probabilities of 1/30 and 1/100 respectively for "normal" and "important" structures).

The cladding pressures computed according to the simple procedure differ little from the pressures specified by previous codes. The cladding pressures complimentary to the structural loads described in Figs. 2 and 3 are shown in Fig. 7 (a reference pressure of 8 psf instead of 10 psf is used corresponding to the permitted increase in risk or annual probability of occurrence).

We may speculate on the possible formulation of a more detailed approach to gust factors for cladding. If it is assumed that the dynamic response of the loading is comparatively insignificant, the form of the gust factor is

$$C_g = 1 + g\,\frac{\sigma_p}{\bar{P}} = 1 + g\,\frac{C_{rms}}{C_{mean}}$$

where g is the peak factor, σ_p the rms pressure, $\bar{P}$ the mean pressure and C_{rms} and C_{mean} the corresponding pressure coefficients. Theory suggests that $g \simeq 4.3$. On windward faces, the pressure intensity $\frac{\sigma_p}{\bar{P}}$ might be expected to be approximately equal to twice the velocity intensity which is related to the roughness and height. Approximately, $\sigma_p/\bar{P} \simeq 2\,\frac{\sigma_v}{\bar{V}} \propto \sqrt{\frac{K}{C_e}}$. On leeward faces the assessment is more complex.

Uncertainties in the estimation of design pressures on cladding render experimental results both full scale and model valuable.

In the absence of appreciable resonant response theory suggests that for cladding panels the peak factor $g \simeq 4.3$. This value appears to be supported by experimental evidence from a statistical investigation of pressures recorded over a 10-month period at two levels of six locations (Fig. 8) on a 600-foot tall office building in Montreal[11,12]. The measured values, shown in Table 3, range from 3 to 5 with one exception; at one point in the centre of the wall in the wake region, 200 feet above the street, the peak factor was *6.6*. Probably the main cause for such a large value was intermittency in the flow; this exceptional condition illustrates one difficulty in the prediction of cladding pressures. The averages of the peak factors for five locations (excluding point E1) are *4.0* for the upper level and *4.5* for the lower level. The probability distribution of peaks is a relatively narrow one, so that the observed peaks tend to be grouped rather closely about the "central", or location measure, "g".

TABLE 3

Cladding Position (see Fig. 8)	*Height (ft.)*	g	C_{rms} *	C_{mean} *	C_{peak} *
W1	545	3.2	.14	.49	.94
	195	4.2	.13	.21	.76
W2	545	3.5	.13	.46	.92
	195	4.3	.12	.22	.74
W3	545	4.7	.11	.35	.87
	195	4.6	.11	.19	.70
W4	545	4.2	.09	.32	.70
	195	4.7	.09	.13	.55
N2	545	4.2	.07	.23	.52
	195	4.6	.07	.19	.51
E1	545	3.9	.05	-.17	-.36
	195	6.6	.13	-.22	-.86

* The reference velocity pressure (measured on a mast on the building at 800 feet above ground) ranged from 3 to 8 psf.

Table 3 also indicates measurements of $C_{rms}/C_{mean} = (\sigma_p/\bar{P})$ measured on the same building. Fig. 8 compares these measurements for windward cladding positions with predictions of peak pressure and wind tunnel tests by Cermak[16] on a similar building. The main deviation from the field data arises from an apparent over-estimate of the increase in C_{rms} with height and possibly a slight under-estimate of the increase in C_{mean} with height. These two tendencies combine to produce an over-estimate of approximately 25% in the peak pressures at the upper level. The decreased rms component and the increased mean component of pressures measured at the upper level (545 ft.) are, in fact, both consistent with the hypothesis of the growing "inner" boundary layer of the very rough city centre not having yet reached the upper level. Other pertinent factors are the decrease in stagnation pressure predicted and measured by Bearman[13].

CONCLUDING REMARKS

In summary experimental evidence gives encouragement that both overall structural design loads and windward cladding pressures due to wind can be predicted to a reasonably accurate degree by the detailed procedures of the National Building Code of Canada. Further full scale, and wind tunnel information and theoretical guidelines are needed to provide a more detailed evaluation of lateral responses suction pressures and effects of complicated shapes and interactions with other buildings.

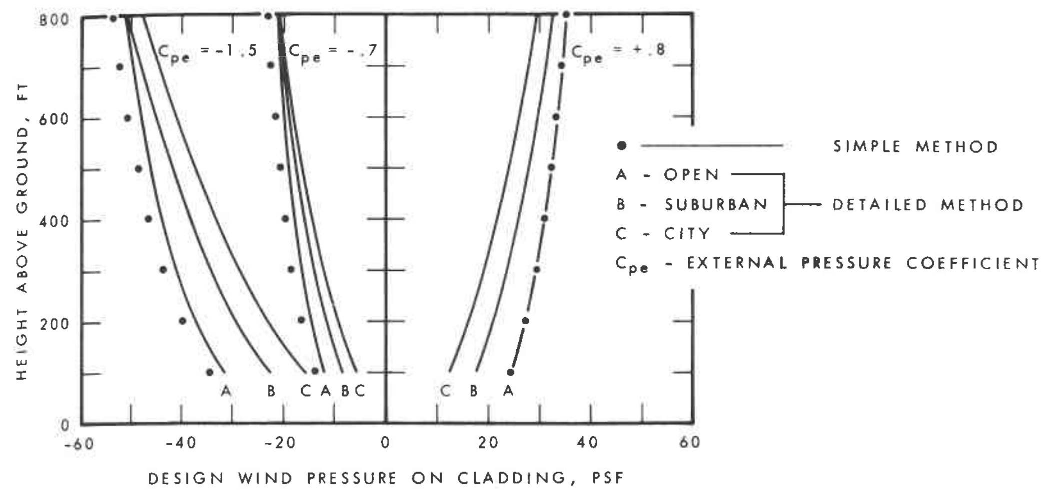

FIG. 7 COMPARISON OF CLADDING DESIGN WIND PRESSURES ACCORDING TO THE 1970 NBC

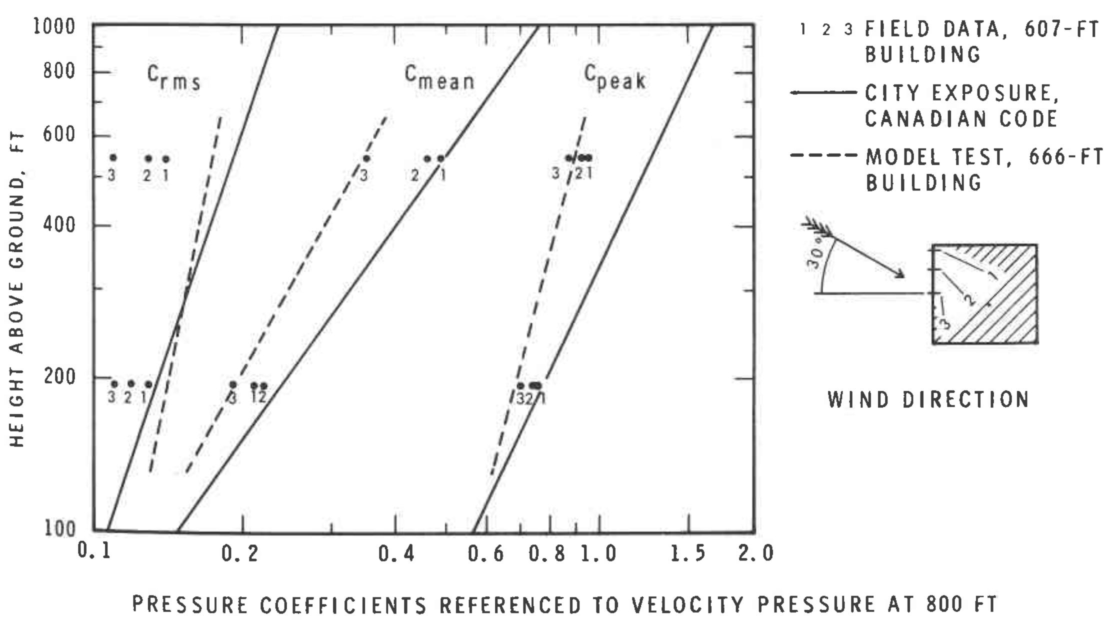

FIG. 8 A COMPARISON OF PEAK PRESSURE COEFFICIENTS OBTAINED FROM FIELD DATA, MODEL TEST, AND THE NBC

In spite of the increase of sophistication the detailed procedure still omits consideration of several influential factors(14,15). These include the assessment of directional effects of the wind and the interaction of "prevailing wind directions" and "critical response directions"; the interaction of neighbouring structures on pressures and structural response; and the effect of the surface texture; transverse vibrations and the affects of fatigue. The code formulation is appropriate for free standing structures, such as tall buildings and chimneys, but not guyed towers and long span bridges.

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