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**BY**

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## RECENT RESEARCH ON WIND FORCES ON TALL BUILDINGS

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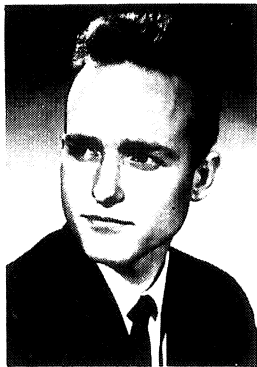


The co-authors of this paper are staff members of the Division of Building Research, National Research Council, Ottawa, where considerable fundamental and applied research supports Canada's construction research programme.

Swiss-born

W. R. Schriever joined NRC in 1948 after obtaining his M.Sc. degree from the Graduate School of Engineering at Harvard University. He received his earlier engineering education at the Swiss Federal Institute of Technology, Zurich, Switzerland, where he obtained his diploma in Civil Engineering. He specialized first in soil mechanics and more recently has concentrated on building research, particularly in the study of loads and forces acting on structures.

ment of wind pressures and suctions on high-rise office buildings. He was recently awarded the degree of M. Eng. (Civil) from Carleton University, Ottawa.



W. Alan Dalgliesh studied under a General Motors Scholarship at the University of Alberta where he obtained his B.Sc. in Civil Engineering in 1959. He joined the NRC staff following graduation. His work at the Division of Building Research since 1962 has been concerned primarily with the measure-

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When tall buildings rise above the average roof level of neighbouring structures they receive the full force of the wind over most of their height, unless they happen to obtain partial shelter from other tall buildings. Their numbers have grown at an ever-increasing rate since the beginning of this century. As early as 1929 there were already nearly 400 buildings of more than 20 storeys and 10 buildings surpassing 500 feet in the U.S. A.

It is therefore not surprising that wind loads and wind bracing of tall buildings were topics of considerable interest for structural engineers during the 1920's and 1930's. Two well-known practising engineers published full-length texts (1,2) on this subject alone, and articles appeared regularly in the Proceedings of the ASCE. Several approximate design methods were proposed and a committee of the ASCE worked on the problem over a period of 10 years, publishing the final report in 1940(3).

The results of wind tunnel research on many simple building shapes were also reported during the thirties, notably by Irminger and Nøkkentved(4) in Denmark, Flachsbarth(5) in Germany, and Dryden and Hill(6) in the United States. In most of these tests, small-scale models (1:200) were exposed to a low-turbulence flow in which the wind speed did not increase with height. Most experimenters were aware of the difference between the wind tunnel flow and the gusty natural wind for which windspeed does increase with height above ground. Although the effects of these differences could not

easily be predicted, the limitations were at least recognized in the research reports.

The importance of wind bracing was confirmed by a full-scale demonstration of wind forces on tall buildings provided by the great Florida hurricane of 18 September 1926(7). Passing right over Miami, the centre of the storm generated wind speeds exceeding 100 mph, and some permanent deformations in the steel frame of the 17-storey Meyer-Kiser Bank Building gave convincing evidence of wind pressures as high as 60 psf. On the other hand, design loads throughout the United States at that time ranged from 15 to 30 psf, and in Miami there were approximately two dozen buildings over 10 storeys that were designed for 20 psf. Except for the Meyer-Kiser Building, which was damaged beyond repair, and the 15-storey Realty Board Building, which suffered extensive damage to exterior walls and partitions, these tall buildings came through the test essentially unharmed.

The need for answers to a number of questions was apparent. Buildings were then designed for a static load that was apparently much lower than the loads consistent with the probable maximum pressures of the wind, and yet many structures did not fail. Rigid, reinforced concrete frame buildings were undamaged in the hurricane, whereas many flexible structures such as radio masts or chimneys were completely wrecked. Witnesses spoke of the frequent violent gusts superimposed on the steady force of the wind that caused extreme swaying of (for example) the Realty Board Building and the Meyer-Kiser Building. In their tests on wind stresses and wind bracing for tall buildings, Robins Fleming(1) and Henry Spurr(2) emphasized the necessity of sufficient rigidity as well as strength. Both authors recommended measurements on actual tall buildings during strong winds in order to build up a fund of experience on the behaviour of buildings and the sufficiency of their designs.

The first measurements of this kind were made on the Empire State Building by Rathbun and reported in a paper to the ASCE in 1940(8). In addition to providing valuable information about the behaviour of the frame and the additional stiffness contributed by the heavy stone cladding, these measurements afforded the first real opportunity to check the applicability of a small-scale model test to full-scale conditions. The results were disappointing; in Rathbun's words, "A comparison of the pressures on the model and those on the building shows clearly that the natural wind move-

ering the effects of the strongest wind measured during several months or even a few years, they have been found to be of the same order of magnitude, i. e. in the range  $0 \pm 10$  psf.

Difficulty with the static reference pressure does not affect the calculation of the net force on the building as a whole (i. e. evaluation of a drag coefficient  $C_d$ ), but for the extrapolation of measured local suction on cladding to higher wind speeds it is important to distinguish between wind-induced pressure differences and those from other causes.

The third objective is concerned with building displacement, velocity, or acceleration under wind excitation. Measurements in this area can add valuable information about wind forces on tall buildings; and it is also possible to derive information from strain measurements on some of the main framing members. Such measurements are useful in the determination of the over-all loading of the frame, and in investigating the behaviour of the structure itself when acted on by a dynamic load.

Finally, as an over-all objective to be considered in conjunction with the three specific ones, full-scale measurements on tall buildings are required to assess the results of conventional wind tunnel tests and to permit the development of new flow modelling techniques that will give more realistic answers for building aerodynamics problems.

#### Methods of Measurement and Analysis

The most common method of measurement, and the one used in three of the four projects to be described, is to make a grid of pressure taps through the exterior walls of the building and record pressures and suction (relative to some internal reference pressure) during strong winds. In this respect the measurements are similar to those made in a wind tunnel study using a smooth air flow, except for the differences already mentioned with regard to reference pressure.

The most obvious difference between pressure measurements in the smooth flow of a low-turbulence wind tunnel and those made in real wind is that the former are (for practical purposes) constant with time, whereas the latter are constantly varying. As a result, full-scale measurements must be recorded simultaneously for all pressure taps and continuously for periods of at least 5 minutes in order to provide adequate information about the pressure distribution on a

building.

The next problem encountered concerns the analysis of the great quantities of information contained in simultaneous and continuous recordings of pressures at several pressure taps. Fluctuations of pressure about some mean values are essentially random in nature, and a statistical approach is needed to reduce the data to some manageable form. The quantitative characteristics of the pressure records are summarized by the mean pressures (averaged over several minutes) and the standard deviation or RMS (root-mean-square) value of the pressures. The RMS pressure is the square root of the variance of the pressure record, and the variance can be further described by its graph of power spectral density plotted against frequency divided by the mean wind speed. The latter quantity (wave number) can be thought of as the inverse of wave length, a measure of the physical dimensions of a gust. The graph of power spectral density vs. wave number, therefore, gives the distribution of variance according to the spatial extent of the gusts. Spectral analysis also plays an important role in the recently developed analytical methods for handling loadings produced by random phenomena.

The statistical treatment of pressure records applies equally well to measurements of displacement of the building and deformations in the main framing members. Such measurements are necessary for the accomplishment of the third objective of investigating the behaviour of the structure under dynamic loading.

#### Full-Scale Measurements in Four Countries

London, England: Newberry, Eaton and Mayne (A)

The Building Research Station in England, after conducting a survey in 1957 of the general problems of wind load on buildings, decided to concentrate a major part of its efforts on a full-scale study of wind effects on tall buildings. A building 194 feet high and 142 feet by 58 feet in plan was chosen for instrumentation at three levels with wind pressure gauges (see Fig. 1). The building was completed in 1963, and readings were taken at 48 gauge points simultaneously during periods from 1964 to 1966 whenever the wind speed exceeded approximately 35 mph. Recordings were made on two synchronized multi-channel oscillographs and varied in length up to about half an hour.

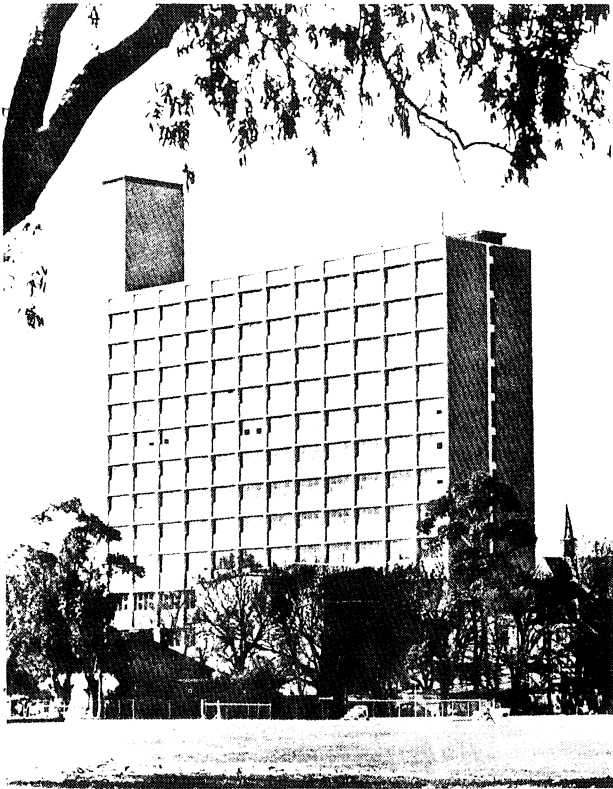


Fig. 2. The Barry Building at University of Melbourne showing the north face (Plate 1, Joubert (B) )

building. Pressure readings were taken by observers watching banks of manometers attached to 65 pressure taps at five levels of the building.

Gusts of relatively long duration (approximately 30 seconds) and steady velocity at the tower were selected for correlation with pressures measured at the building after a suitable delay. Fifteen test runs were performed. The problem of the internal reference pressure was circumvented by dealing only in terms of pressure difference across the whole building, using readings from corresponding pairs of points on the north and south walls.

The dynamic wind pressure at the top of the tower (two-thirds of the building height) was used to determine drag coefficients for the whole building. The drag coefficient for the fifteen individual large gusts was found to vary from 0.8 to 1.6. In addition, it was noted that the contours of pressure were in most cases unsymmetrical, contrary to model test results. The mean value for the

drag coefficient was 1.1 and the centre of pressure was found at 53 per cent of the building height.

Wind tunnel tests were carried out in which the velocity profile and turbulence were produced by a series of horizontal rods across the flow upstream of the model. The centre of pressure agreed with the full-scale tests, but the pattern was symmetrical and the drag coefficient 1.0. The authors concluded that differences in the contours of pressure distribution could perhaps be explained by differences in the lateral distribution of wind velocity. They recommended that further results be collected on similar buildings and that both lateral and vertical distributions of velocity should be measured.

Another explanation was advanced at the Seminar for the lack of agreement between model and full-scale pressure distributions. It was suggested that pressure distributions for each of the fifteen individual large gusts were, in effect, fluctuations about a mean pattern that would possibly agree better with the model pressure pattern.

Delft, Holland: Van Koten<sup>(C)</sup>

The measurements and the method of analysing the results applied by Van Koten to another slab-like tall building form a remarkable contrast to the two projects already described. The building chosen is 150 feet high, 255 by 40 feet in plan (see Fig.3) and has an open exposure. The structure consists of a steel frame skeleton with prefabricated concrete floor slabs. Deformations produced by wind action were measured in one of the steel columns instead of recording the pressures on the walls of the building. The only other wind measurement used in the analysis was a record of wind speed registered several kilometers away by a different institute.

Two types of deformation records were taken. The first consisted of recordings of deformation for 3 or 4 minutes out of each 3-hour period for three months. This slowly varying phenomenon was compared with corresponding readings of wind speed made by the other institute. The second type of measurement was made during periods of high wind and consisted of continuous recordings lasting for 20 or 30 minutes at a time.

The recordings of deformation during high winds showed clearly that the building was vibrating at its fundamental frequency of 0.7 cps, with a low but significant amplitude compared with the larger deformations resulting from large gusts. This experimental

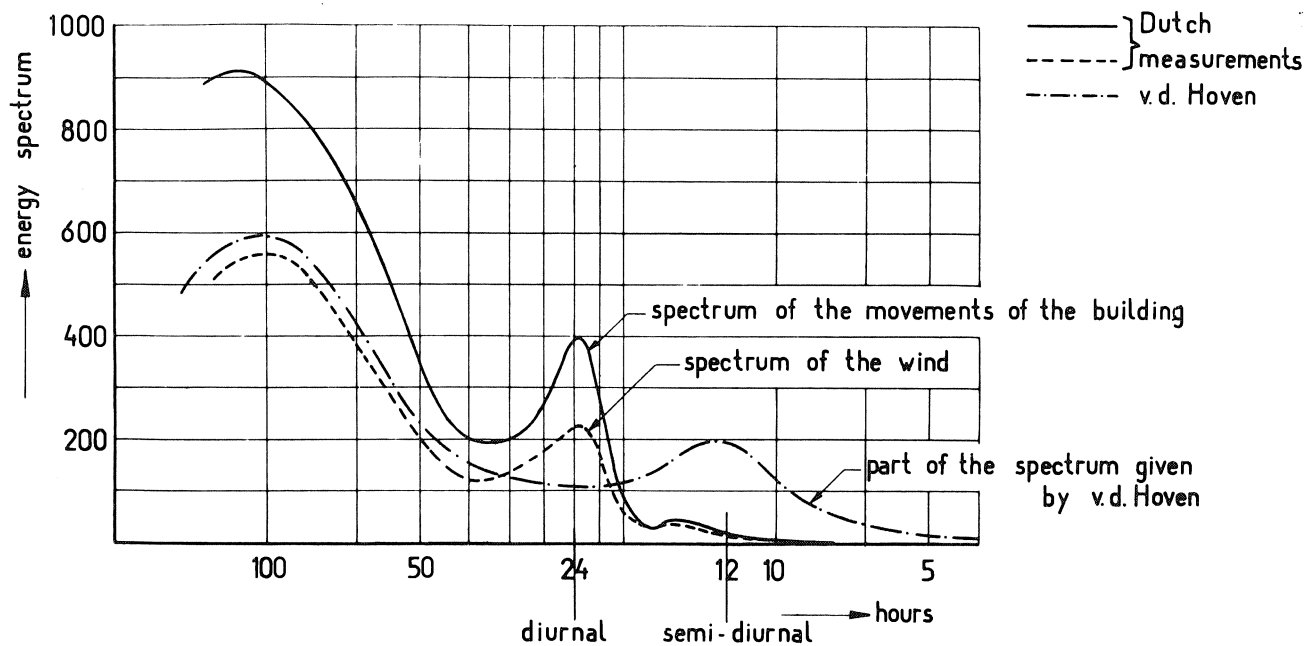


Fig. 4. Energy Spectrum of the Slowly-Varying Movements (Fig. 7, Van Koten (C) )

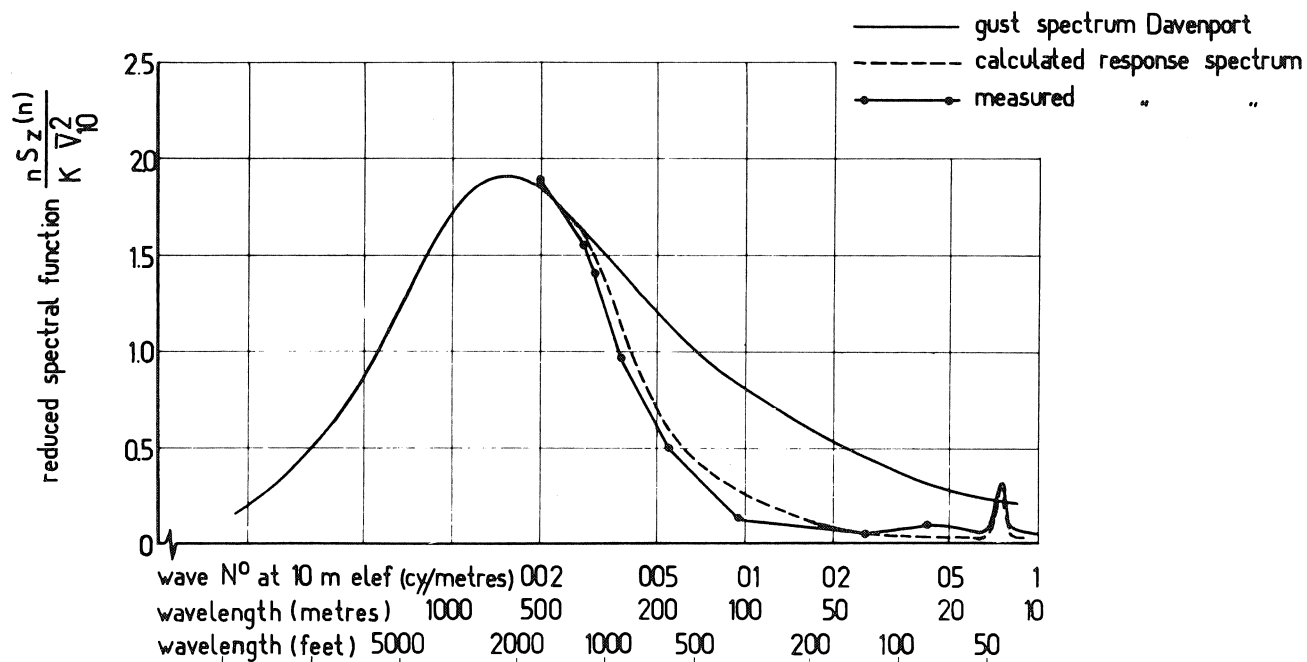


Fig. 5. Spectrum of the Horizontal Gustiness in High Winds (Fig. 17, Van Koten (C) )

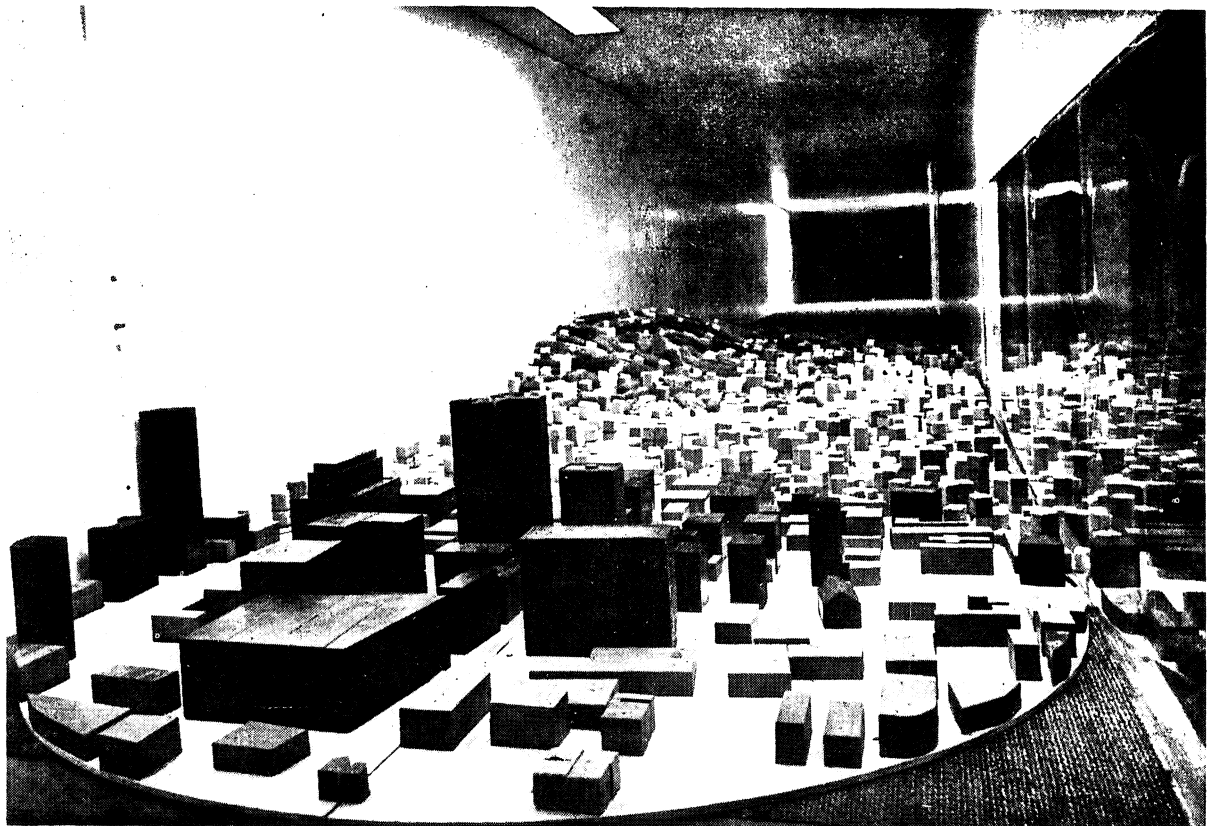


Fig. 7. Model of downtown Montreal with major topographical features in the boundary layer wind tunnel at the University of Western Ontario for comparison with full-scale measurements (photo by Ron Nelson, London, Ontario). (Fig. 4, Dalglish (D) ).

the tunnel floor upstream of the scaled section of Montreal to create similar conditions of turbulence and increase of windspeed with height. By December 1967 only a preliminary run of model tests had been completed, but there were encouraging indications that good agreement could be obtained.

Spectra of the variance of selected pressure records for the model were compared with the full-scale spectra, and with the empirical strong wind spectrum suggested by Davenport. The agreement of the spectra for one such record, shown in Fig. 8, is a good indication that the turbulence of the flow was properly scaled to simulate the actual conditions.

The preliminary model tests covered only one of the five runs selected for detailed analysis. The results are therefore limited to a comparison of twelve mean pressures and twelve RMS pressures measured for one particular wind direction (normal to the long wall), but the agreement obtained so far is very promising. For example, the linear relation found between model and full-scale mean pressures had a correlation coefficient of approximately 0.96, which indicates that

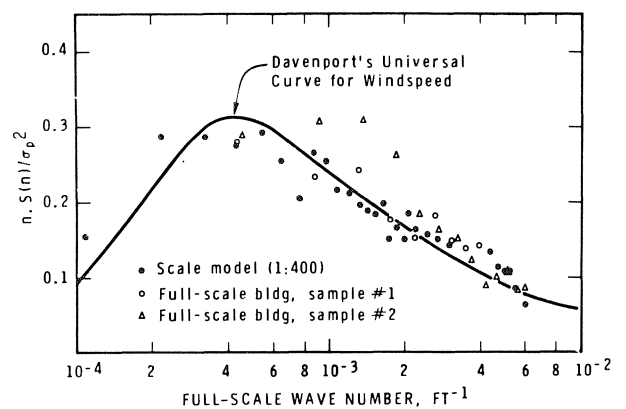


Fig. 8. Sample power spectral density curves obtained from both model and full-scale experiments on an office building in Montreal. (Fig. 10, Dalglish (D) ).

the model test results could have been used to predict the full-scale mean pressure coefficients to within a few per cent on the average. The agreement for RMS pressures was not quite so good, and the average correlation coefficient was about 0.84.

The measurements made so far were



ings for which aeroelastic modelling would provide relevant design information, and for which flexibility criteria might well govern the design.

### Conclusions

Most wind research prior to 1958 was based on the simple concept of a smooth air flow, which resulted in static design loads for most structures. Research for the past 10 years, on the other hand, has benefited from three related major innovations: (1) A start has been made on gathering the full-scale information needed to identify and evaluate properly the main features of the real wind structure; (2) A workable analytical basis for research was provided by the implementation of the statistical theory of turbulence, specifically for wind effects on buildings and structures; and (3) Experimentation with turbulent boundary layer flows to simulate the real gusty wind and with aeroelastic building models has progressed to the point where they can be used with confidence for providing design information.

The main features of the statistical approach to design are already embodied in the new Danish Code in the section on dynamic wind loads, prepared by Davenport<sup>(17)</sup>. Designers using this Code are made to adopt a realistic view of wind effects, to recognize how wind turbulence on the one hand, and dynamic properties of the building on the other, can affect design loads, and to assess their influences quantitatively. Future research will probably bring adjustments to some of the parameters or even modify the method itself. One important advantage of using such a code, even though some aspects are still only tentative, is that it promotes an awareness of the true nature of wind and its effect on buildings and structures. A similar approach is expected to be recommended in Canada by the Subcommittee on Loads of the Standing Committee on Structural Design in preparing the 1970 edition of the wind load requirements in the National Building Code of Canada.

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