WIND PRESSURE MEASUREMENTS ON FULL-SCALE BUILDINGS

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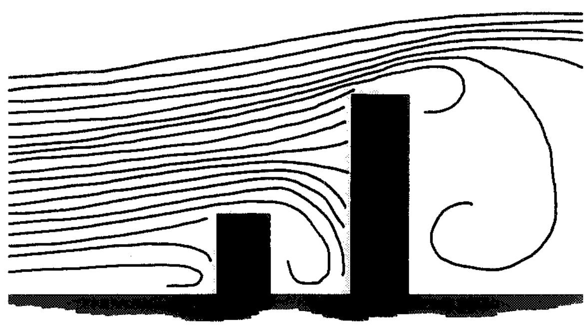

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MESURES DE LA PRESSION EXERCEE PAR LE VENT SUR LES EDIFICES

SOMMAIRE

Les observations directes des effets du vent sur les édifices sont nécessaires si l'on veut recueillir des renseignements fiables servant à évaluer la charge due au vent, mais ces observations ne sont pas suffisantes. Leur rôle essentiel est de fournir des données en vue d'une recherche systématique. Celle-ci peut être effectuée avec une plus grande efficacité dans des tunnels à vent. On examine brièvement les instruments utilisés dans le cas particulier d'un édifice élevé, ainsi que la méthode employée dans l'interprétation des mesures obtenues. Cet examen montre les possibilités et aussi quelques problèmes des mesures sur place visant à fournir des renseignements pratiques sur les charges dues au vent. Enfin, on résume certains résultats et on en étudie les implications pour la conception des constructions.

WIND PRESSURE MEASUREMENTS ON FULL-SCALE BUILDINGS

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Abstract

Direct observations of wind effects on real buildings are necessary, although not sufficient, for the development of reliable information for wind load estimation. Their essential role is to supply data for the guidance of systematic investigations that can be accomplished more effectively in wind tunnels than in full scale.

The instrumentation used in a particular tall building and the methods employed to interpret the measurements are briefly reviewed. This review illustrates the potential, as well as some of the problems, of field measurements in providing practical information about wind loading phenomena. Selected results are summarized and their implications for design are discussed.

INTRODUCTION

High-rise construction has provided a strong incentive for research on wind effects. The importance of turbulent wind loading on tall and slender buildings demands a more sophisticated design approach than is used for lower or more massive buildings. Consequently, building codes are becoming more detailed in an effort to reflect the conditions of exposure (in terms of height and terrain roughness) and the dynamic response of the structure. In addition, significant improvements have been made in the two main sources of design data - climatological information for design wind speeds and model tests in wind tunnels for pressure coefficients. In the end, however, we must always ask: how valid - or at least how accurate - are our design methods?

Wind pressure measurements on full-scale buildings thus take on a crucial role in checking both the loading of the structural frame, and of the cladding. In broad terms, the object of measurements on real buildings is to ensure that the wind tunnel, climatological, and building code information does in fact lead to reliable estimates of wind effects.

The purpose of this paper is to show, by three examples, how full-scale measurements can be usefully applied to the checking of design information. In the first example pressures measured on a 34-storey building are compared with measurements in a wind tunnel test. The second example suggests the need for new instrumentation for measuring dynamic response of full-scale high-rise buildings, and in the third example, full-scale measurements of gust pressures are used to assess two code methods of calculating gust effect factors for cladding design.

COMPARISON OF MODEL AND FULL-SCALE PRESSURE COEFFICIENTS

In checking the accuracy of wind tunnel simulation of wind action on real buildings one compares the pressures measured at corresponding points on the building in model and full-scale. Pressures may be represented by non-dimensional coefficients referred to a single reference wind pressure measured at corresponding locations in model and full-scale.

Figure 1 is a view from the north of a 34-storey high-rise office building located in downtown Montreal, surrounded on all sides by other tall buildings ranging from 10 to 45 storeys. Wind pressures were measured on the two mechanical equipment floors by the Division of Building Research and were related to the velocity pressure of the wind speed measured on an available mast, 1500 feet to the west and 800 feet above the street.

Two independent projects were carried out, one to check the structural design data(1), and the other to obtain information about climatic effects on the operation of the mechanical services of a typical high-rise building(5). The two projects were done by the Building Structures and the Building Services Sections of the Division of Building Research respectively.

Later, a model of the building and the other prominent structures surrounding it were tested in a boundary layer wind tunnel.

Model and full-scale pressure coefficients are compared in Figures 2 and 3 for two different wind directions. Although there is certainly room for improvement, the agreement is reasonably good considering the complicated nature of the air flow around the various tall buildings that had to be modelled. The agreement between the full-scale measurements of the Services Section (shown as open circles in the figures) and those of the Structures Section (solid points) is reasonably good, considering that naturally the wind conditions were not identical for the two sets of measurements.

DYNAMIC RESPONSE OF STRUCTURES

Wind pressure measurements alone are not the best way of determining the dynamic response of structures to wind action, either in model or full-scale experiments. Ideally, the displacement of the structure at various levels should be recorded as a function of time to give the integrated effect of the whole spectrum of gust sizes and durations over the entire surface of the building.

Unfortunately, little information is at present available from actual buildings. One reason for this is a lack of appropriate instrumentation for measuring and recording the absolute displacements of tall buildings. Sensitive accelerometers and seismometers have been used with a fair degree of success for estimating natural frequencies and mode shapes, but not for actual displacements. The Division of Building Research is planning to instrument a 58-storey office tower now under construction in Toronto. A system for measuring displacement of the top of the building using a laser beam for reference will be used in addition to strain measurements in columns and beams and pressure measurements on the building surface. Strain measurements on the structural frame itself can give useful indications of structural behaviour; this method was used with some success for one project in Holland(6).

STATISTICAL NATURE OF GUST LOADS ON CLADDING

Gust action on cladding is best visualized as random turbulent fluctuations superimposed on the mean wind. The wind effect of primary concern for cladding design is the maximum pressure or suction that can reasonably be expected to occur during the useful lifetime of the cladding, and this quantity is most conveniently expressed in statistical terms.

Figure 4 shows a short portion of a record of fluctuating pressure measured on the north wall near the top of a 45-storey building. The instrumentation and results will be briefly described below, but first several features of gust pressures will be noted.

The mean value of the pressure is represented by C_{mean}, which corresponds to the usual local pressure coefficient obtained from any wind tunnel test, whether of the smooth-flow or the boundary layer variety. Although C_{mean} is necessary to describe wind action at a point on the building, from Figure 4 it is evidently not sufficient by itself to estimate maximum pressures.

A second coefficient is therefore used in describing full-scale and boundary layer type wind tunnel measurements, the rms (root-mean-square) pressure coefficient, C_{rms}. This is a measure of the average amplitude of fluctuations about the mean pressure. Finally, a peak factor is defined which gives the number of standard deviations (C_{rms}) by which the maximum peak pressure is expected to exceed the mean value. C_{mean} and C_{rms} can usually be treated as fixed for any given building shape and topography. The maximum peak, however, is a random variable whose numerical value fluctuates from one repetition to the next of the same experiment.

The conventional simple procedure for estimating the amount by which the peak pressure exceeds the mean pressure is based on the "wind gust factor." The wind gust factor represents the average ratio of the maximum gust registered by a particular fast-response anemometer to the mean wind speed on which the design value is based. By this procedure C_{peak} is obtained by multiplying C_{mean} by the square of the wind gust factor (since wind pressure is proportional to wind speed squared).

A more detailed procedure based on measurements of fluctuating cladding pressures can be expected to give more realistic results than the simple procedure. In principle, measurements in a wind tunnel in which the turbulence characteristics are correctly simulated should give such information, but as in the case of mean pressures and dynamic response, full-scale information is required to give confidence in the applicability of the results.

GUST PRESSURES ON A 45-STOREY BUILDING

The statistical investigation of gust pressures on cladding involves the measurement of pressures whenever high winds occur, and the storage of data for analysis after sufficient records have been accumulated. To appreciate the magnitude of the data handling problem, consider that a modest sample of 25 maximum pressure peaks drawn from 30-minute records requires 90,000 readings per cladding position.

In September of 1968, the Division of Building Research installed a digital data acquisition system in a 45-storey building in Montreal (see Figure 5). The building, 100 x 140 feet in plan and 607 feet in height, was instrumented with twelve pressure transducers, and a wind vane and anemometer on an existing 200 foot mast on the roof.

The transducers measured pressure differences between six outside taps on each of two levels and a common internal reference pressure. The pressures were converted into electrical signals and conducted to the data system where the 12 channels plus wind speed and direction were scanned every 1/2-second and recorded on magnetic tape. After ten months of operation during which 30-minute records were automatically taken whenever the wind speed exceeded 90 ft/sec, over 30 hours of measurements has been collected.

Referring once again to Figure 4, it will be seen that the rms pressure coefficient and the peak factor are needed in addition to the mean pressure coefficient for calculating peak pressure coefficients. An estimate for the peak factor of 4.5 was made on the basis of 43 maximum peak pressures for each of the 12 cladding positions and the rms pressure coefficient was shown to be approximately linearly related to the mean pressure coefficient(2).

COMPARISON OF MEASURED AND CALCULATED GUST PRESSURES

Two design methods from the forthcoming 1970 edition of the Canadian National Building Code(4) were used to calculate the relationship between mean and peak pressures. One, called the detailed method, is based on the gust loading factor proposed by Davenport(3). The simple method makes use of a "gust effect factor" of 2.5(based mainly on judgement and on wind gust factors) and a 1/10th power law velocity profile, suitable for gust speeds in open terrain.

The measured and calculated gust pressures are compared in Table 1 in the form of peak pressure coefficients with reference to the mean velocity pressure at 30 feet in open terrain. The coefficients apply only for a north-west wind and are not necessarily the critical ones for the cladding positions considered.

The greatest discrepancy between measured and calculated results occurred on the east wall at the lower level where a relatively calm area in the wake of the building would normally be expected. The high peak suctions probably resulted from buffeting by turbulence generated around the neighbouring buildings. Apart from this, the detailed method was within about 20% of the measured values, whereas the simple method is, as intended, somewhat more conservative for all points.

CONCLUDING REMARKS

Field experiments are time-consuming and costly to undertake. They require a relatively large input of research and data-processing effort for interpretation of the results, in proportion to the output of practical design data. As a result, designers rely mainly on (a) a broad geographical network of climatological information for basic design wind speed, and (b) systematic and carefully executed wind tunnel tests for translating the basic wind speed into equivalent static loads for structural design, cladding pressures, or any other wind effects required in the design of tall buildings.

Full-scale measurements, however, provide the only sure means for checking the validity of our design information. This checking can be done in many ways, but two of the most direct methods are comparisons of pressure coefficients obtained on actual buildings with those measured on a model in a wind tunnel, and actual building deflections with the deflections of a spring mounted model representing the fundamental dynamic behaviour of the building.

Perhaps the most pressing problem now facing the designer is the determination of peak gust pressures and suctions for cladding design. An example has been given which shows the inadequacy of even a detailed method for relating peak gusts to mean pressures. The lack of reliable information on the characteristics of wind at typical building sites in cities stands as the main obstacle to progress in further improving design procedures.

The complicated interaction of the wakes from surrounding buildings with the structure being designed also raises difficult questions for the designer. For example, to what extent should he be expected to anticipate future changes in the environment? The erection of new buildings may create serious buffeting problems. One possible solution would be to specify one or more "standard exposures" incorporating representative configurations for surrounding buildings.

It must be concluded that full-scale measurements, in spite of their relatively high cost and low output in terms of direct design data, are most urgently needed. They supply the basic information about real-life conditions, which is essential for solving the wind loading problems now facing the designer of high-rise buildings.

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TABLE 1

MEASURED VS. CALCULATED PRESSURE COEFFICIENTS REFERRED TO MEAN WIND AT 30 FT. IN OPEN TERRAIN

Height in feet	Centre of Wall	Measured	Calculation Method	
			Detailed	Simple
545	West	1.55	1.69	1.79
	North	.88	1.07	1.12
	East	- .90	-1.00	-1.14
195	West	1.31	1.12	1.50
	North	.96	1.12	1.50
	East	-2.21	-1.47	-1.98

FIGURE 1

34-storey office building looking south-east. Dark bands are at 10th and 33rd floors, where the mechanical services are located and wind pressure measurements were taken.

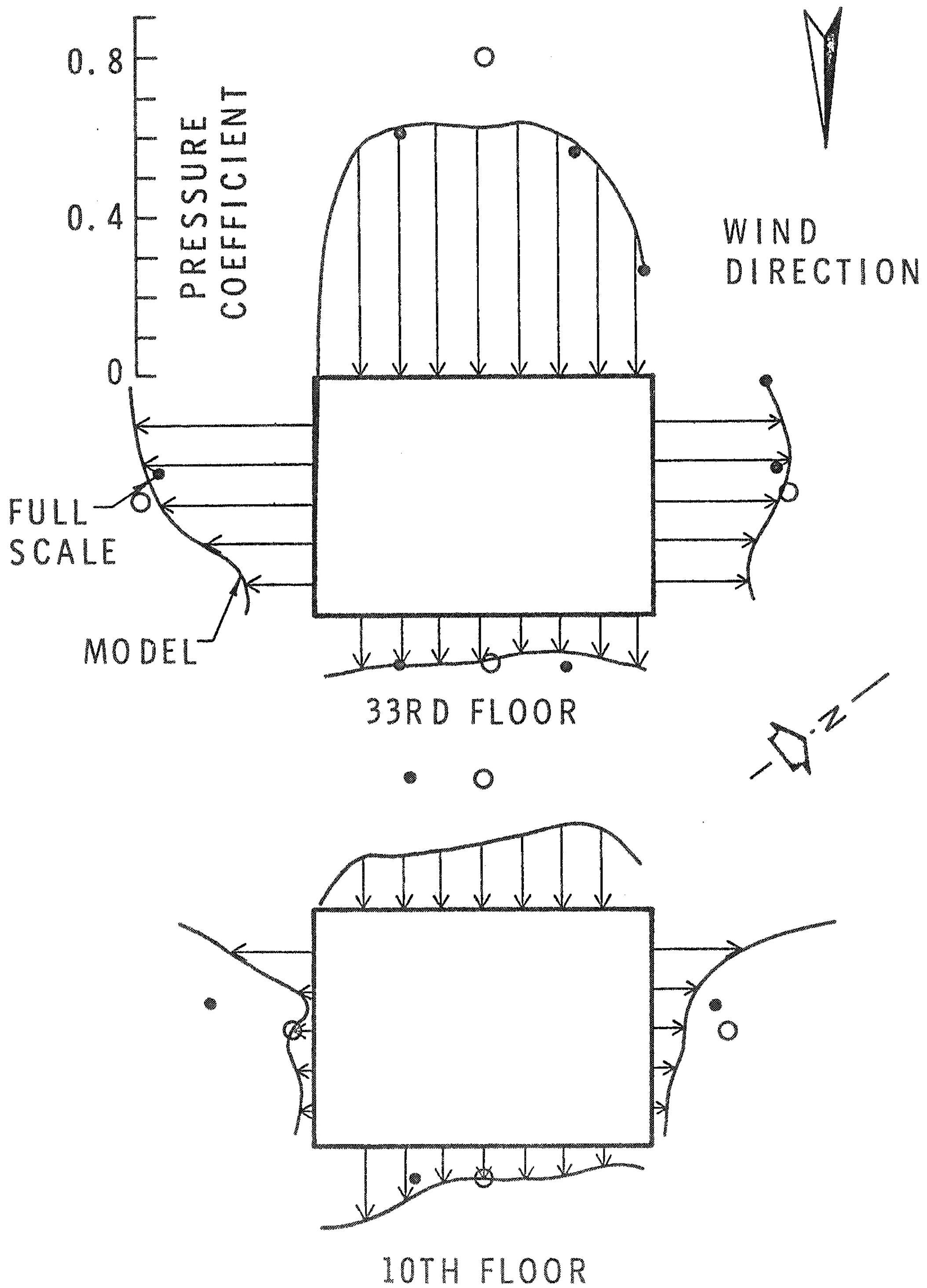

FIGURE 2

COMPARISON OF FULL SCALE WITH MODEL RESULTS-
MEAN PRESSURE COEFFICIENTS ON 34-STORY
OFFICE BUILDING, NORTH-WEST WIND

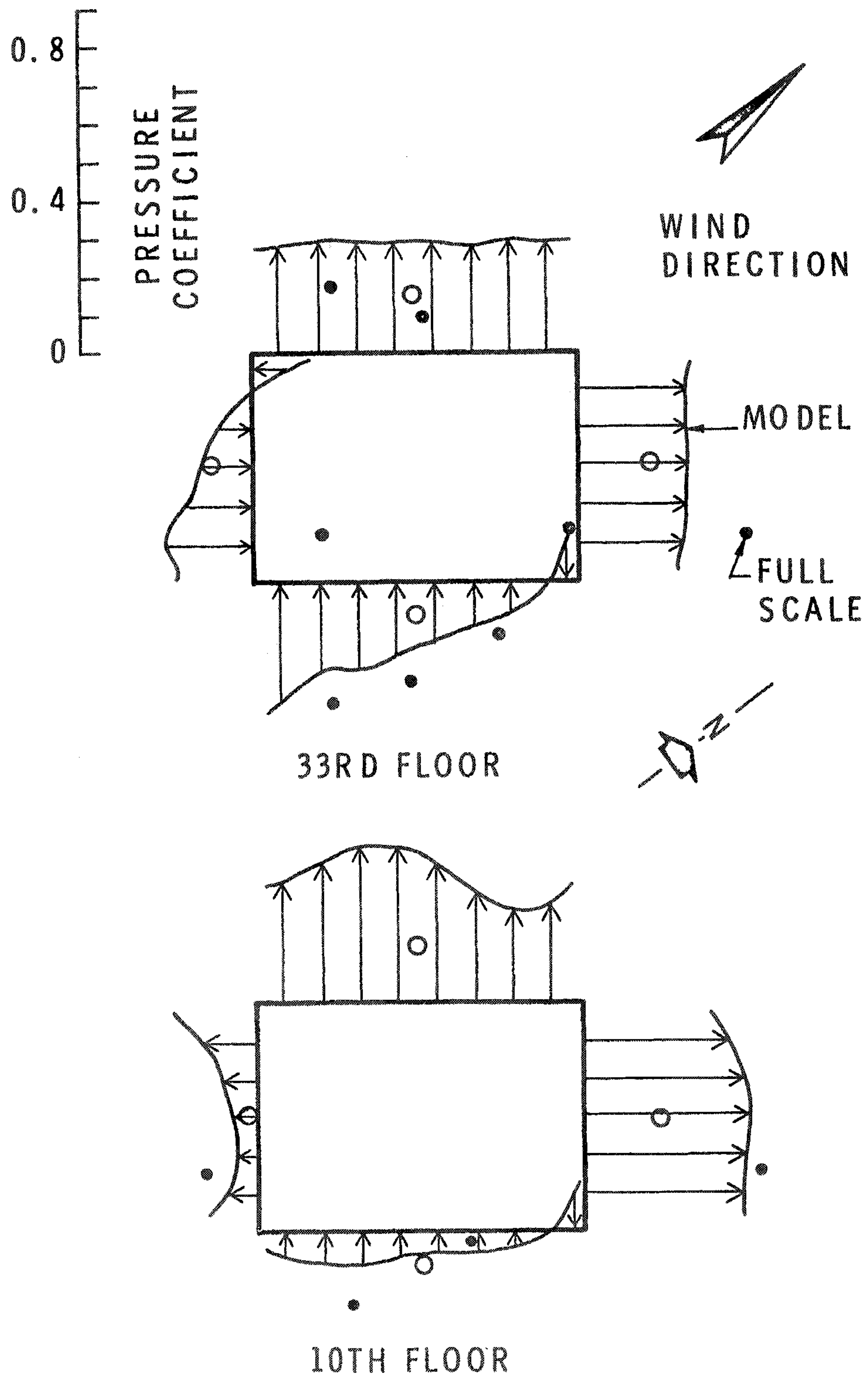

FIGURE 3

COMPARISON OF FULL SCALE WITH MODEL RESULTS-
MEAN PRESSURE COEFFICIENTS ON 34-STOREY
OFFICE BUILDING, SOUTH WIND

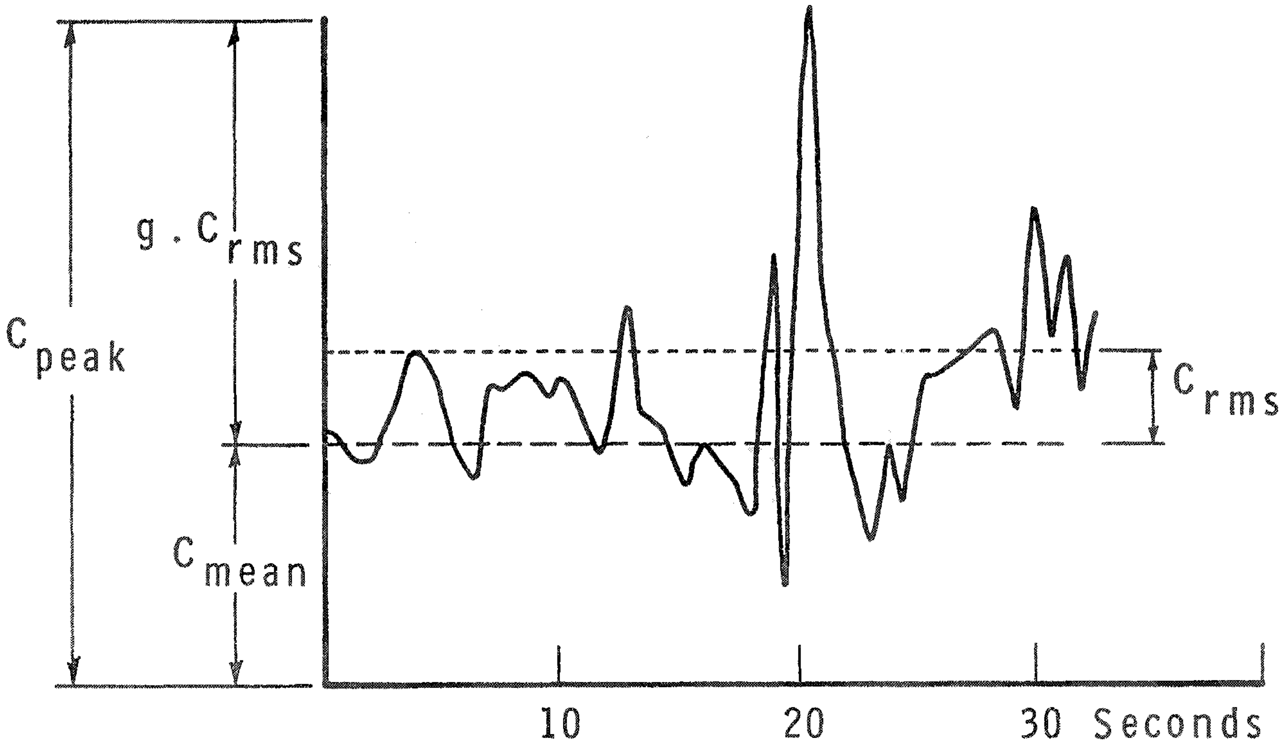

FIGURE 4

PORTION OF RECORD SHOWING MEASURED PRESSURE FLUCTUATIONS AT A POINT ON A TALL BUILDING

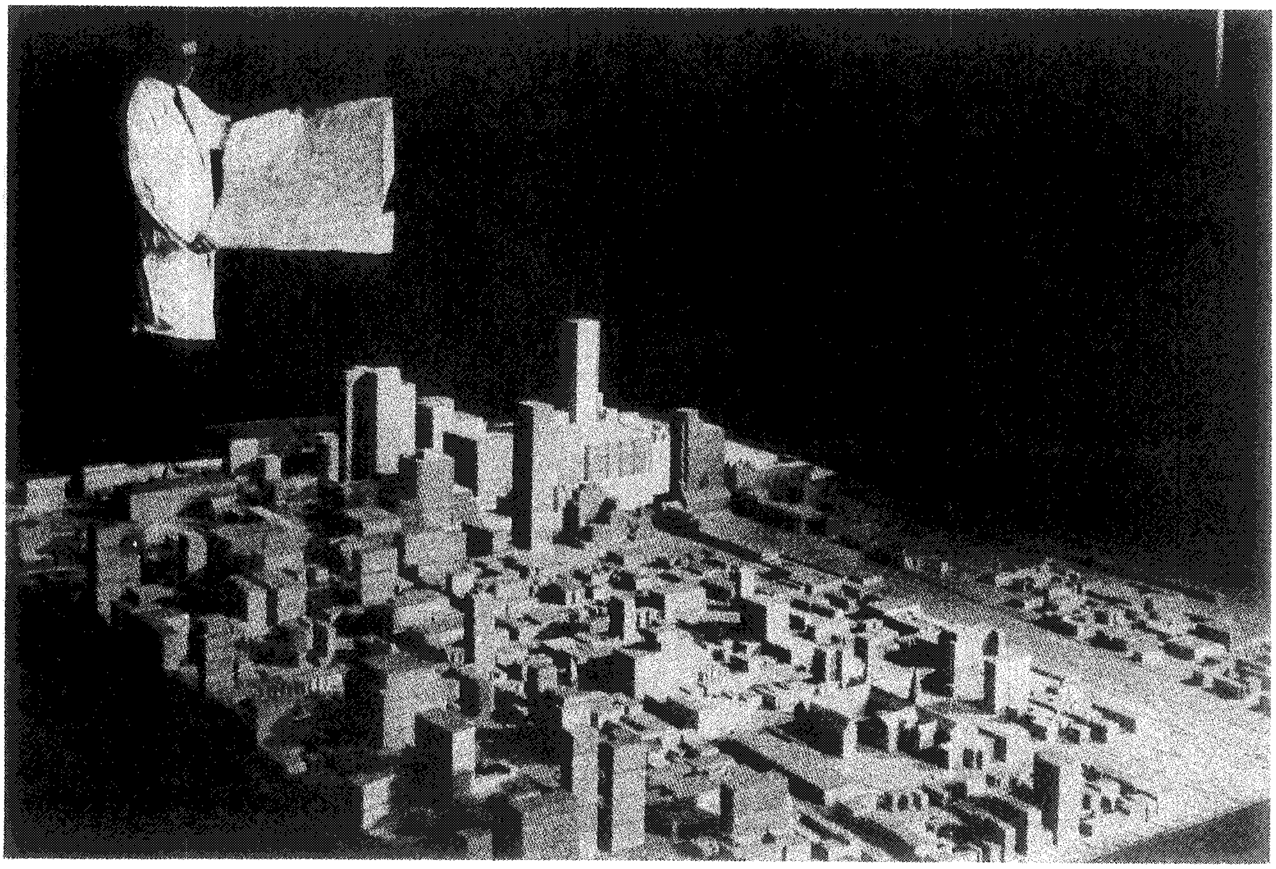

FIGURE 5

Scale model (1:400) of 45-storey building (in centre of model, identifiable by white mast on roof) and surroundings in downtown Montreal in preparation for wind tunnel test