FULL-SCALE STUDY OF WIND LOADS ON A FLAT ROOF WITH PARAPETS

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ABSTRACT

FULL-SCALE STUDY OF WIND LOADS ON A FLAT ROOF WITH PARAPETS

A number of studies have been carried out to examine the effect of parapets on roof wind loading. Most of these studies have been carried out in the wind tunnel and rarely has an effort been made to study this effect in full-scale. A systematic and extensive research has been carried out in the present study to evaluate the wind loads on a full-scale building roof with and without parapets. The study has been carried out mainly on an Experimental Building located at Loyola Campus of Concordia University. In the first stage, wind loads were measured on a simple flat roof, and parapets were subsequently placed on the roof in order to study their effect. Wind-tunnel testing of a scale model of the building was carried out at the Building Aerodynamics Laboratory of the Centre for Building Studies. Mean pressure coefficients have generally been recorded for an open country type of exposure.

The analysis of experimental results indicates that for all different parapet configurations tested in full-scale, parapets reduce high suctions on the roof corner. However, results of wind-tunnel studies reveal that in the presence of

parapets corner suctions increase for ratio h/L (height of parapet / building length) less than 0.02.

The study recommends that wind standards and codes of practice consider specifying pressure coefficients for roof corners with parapets in terms of h/L rather than h alone, as it is currently the case.

ACKNOWLEDGEMENT

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To my parents and brothers, I owe my deepest appreciation for their understanding and continuous encouragement.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

In the last few years, new materials and new structural systems have made the building structures aesthetically more appealing and also cost effective and faster to construct. These innovations in the building practices due to the advent of new materials and construction technology, put pressure on design engineers to design all elements of the building to resist forces of nature like wind, earthquake, rain, ice, etc which affect the stability, integrity, safety and economical life of the structure.

Wind forces on structures occur more frequently than seismic forces. Wind is due to the difference in the amount of solar heat received by the atmosphere over various areas of the earth's surface, which causes pressure difference and hence motion of air. Wind of varying magnitude is always present in the atmosphere. Wind forces of concern in structural design are generated both by large scale systems like extratropical cyclones and by local storms like thunderstorms, Foehn winds, winds of bora type, jet effect winds and tornadoes.

Every year thousands of buildings are damaged as a result of strong winds. From a survey of damaged buildings two things are clearly evident :

- Roofs and cladding systems are the elements most prone to damage.
- Majority of damaged buildings fell into the category of low-rise buildings, i.e., their height is less than or equal to 20 metres and their horizontal dimension is greater than their vertical dimension [National Building Code of Canada (1990)].

Low-rise buildings have high natural frequencies and, in general do not vibrate under wind action. However, since they are in the lower region of atmosphere where atmospheric turbulence and speed gradients are stronger, the wind loads on these buildings are highly fluctuating and difficult to be determined. On the other hand high-rise buildings have low natural frequencies and are faced with different problems like that of resonance, etc.

In order to estimate the value of design wind loads and to study the wind structure interaction, three techniques are generally used:

-Wind Tunnel Technique

-Full-scale Technique

-Numerical & Analytical Methods

The present research work has been devoted to the study of wind pressures on flat roofs of low-rise buildings using mainly the full-scale testing technique. In particular, the effect of parapets on the roof pressure has been investigated.

1.2 WIND AND LOW-RISE BUILDINGS

Low-rise buildings, which form the larger percentage of buildings, are more prone to wind damage. A survey of damage of low-rise buildings indicates that roof elements are the most critically loaded from the wind and the majority of building failures initiate at the roof. Case studies of the wind damage around the world show:

- Much damage due to wind can be completely avoided by having a better understanding of the wind-structure interaction, proper design of construction joints and proper anchoring of roofs to the main structure.

- Traditional building methods are inadequate to cope with the occasional extreme wind storms of 70 m/sec, e.g. Cyclone Tracy which occurred in Darwin, Queensland, Australia on 25 December, 1974.

The study of wind loads on low-rise buildings, requires the knowledge of flow patterns caused on and around the building. Figure 1.1 shows the flow pattern over the roof of a building in the atmospheric boundary layer flow. Wind patterns are for wind direction normal to the face of the building, but the incident wind is more likely to be skewed at an angle, so that the flow separating from the upwind

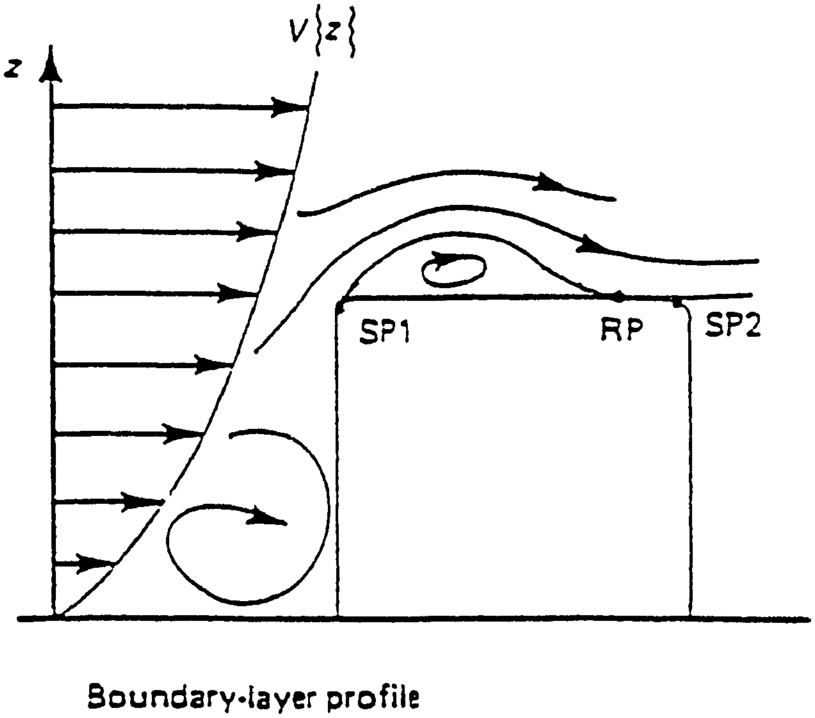


Figure 1.1 Flow Separation and Reattachment on Roofs, after Cook (1985) (SP: Separation Point, RP: Reattachment Point)

edge of the roof will have a component of velocity along the line of separation. Figure 1.2 shows the vortex formation at roof corner and pressure distribution on the roof for such cases. The flow marked 1 will be separating on the windward edge and tends to be displaced under the flow marked 2 as the flow 2 separates immediately downwind of flow 1. The vorticity of shear layers from 1 adds to that of 2 and this process continues along the roof edges (windward), resulting in a strong conical vortex called the Delta Wing vortex. These vortices generally occur in pairs, one on each windward edge of the roof. The centre of each vortex is a region of high negative pressure. The pair of vortices produce negative pressure behind each windward edge of the roof. These vortices acting directly or interacting with incident turbulence are the main cause of high uplift pressure on roof edges, and are the principal cause of damage to the roofs (Cook, 1988) .

1.3 FULL-SCALE AND WIND-TUNNEL TESTING

Measurements of wind effects on full-scale structures provide quantitative input information for development of small-scale modelling techniques and for the routine testing of models for design purposes. On the other hand, the planning of field measurements and the interpretation of the field results can be much easier with the help of an appropriate model study in a wind tunnel. In wind-tunnel testing, models of buildings to geometric scales of 1:100 to 1:500 are made and instrumented to measure pressures. Full-scale and model scale experiments are,

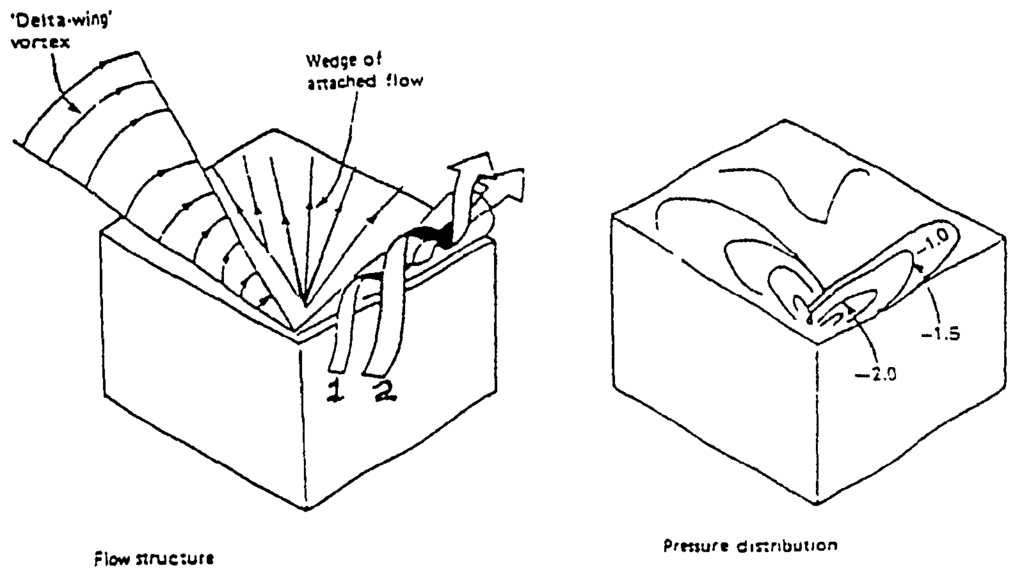


Figure 1.2 Vortex Formation on the Edges of the Roofs and Pressure Distribution on the Roofs, after Cook (1985)

therefore, two mutually supportive techniques for deriving and checking design information and analytical procedures. Large scale testing of structures to ambient conditions is expensive and should be undertaken judiciously. In contrast to well controlled wind-tunnel studies, the naturally turbulent forcing function on the structure cannot be duplicated for checking purposes in repeated measurements. In full-scale measurements, a building is instrumented to measure the wind loads as they occur. For such measurements the following points are of importance (Chiu and Dalgliesh, 1975).

1. Type of Terrain and Wind Climate :

The test site should experience sufficiently strong winds for most part of the year in order to have maximum number of observations and good response of the instruments. An open terrain type i.e., with no tall trees, buildings and other obstructions in the vicinity is ideal for testing low buildings.

2. Reference Static Pressure :

For design purposes, the pressure on the roof, windows, cladding, etc is in fact a pressure difference from the static pressure. In order to measure the difference, the reference input of each pressure sensor is connected to a common reference, measured at a point on ground level upwind of the structure at a sufficient distance so that it is not affected by the building.

1.4 THESIS ORGANIZATION

The following chapter justifies the need of the present study and discusses, the various works done in full-scale and wind tunnel to evaluate the effect of wind loads on roofs. In Chapter 3, which is divided into two parts, the first part describes the Experimental Station, instrumentation, data collection and analysis, while the second part describes the wind tunnel test. Chapter 4 presents the results of the full-scale and wind-tunnel studies and compares them with other studies. The last chapter gives recommendations and scope for future work.

CHAPTER 2

REVIEW OF LITERATURE AND NEED FOR PRESENT STUDY

The earliest full-scale measurements on low-rise buildings date back to as early as 1930. Bailey in 1933 carried out an experiment on a railway car shed to determine wind pressures on buildings. Wind tunnel testing of building models started much earlier. Irminger in 1890 carried out a series of experiments on small models of gabled houses. However all the earlier experiments in the wind tunnel were carried out in uniform flow until Jensen in 1958 introduced the model law for phenomena in natural wind and the requirement of modelling the atmospheric boundary layer was established.

2.1 REVIEW OF FULL-SCALE STUDIES

One of the most well documented full-scale works is the Aylesbury study carried out in England by a team of Building Research Establishment scientists. Eaton and Mayne (1974) studied the mean and peak pressure coefficients on a sloped roof with pitch variable from 5 to 45 degree. The study found that suction loads on roofs become more severe with decreasing roof pitch. The study also pointed out that the areas of high suction on the roof are in a localized zone, a short distance from the windward corner. Figure 2.1 shows the experimental results of the study

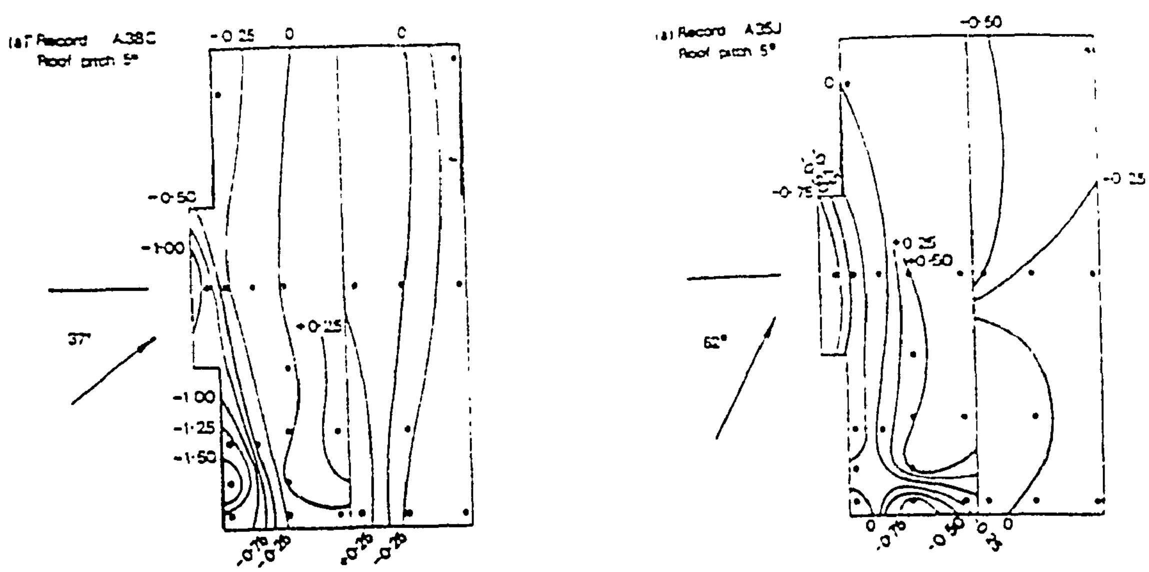


Figure 2.1 Pressure Distribution on the Aylesbury House Roof, after Eaton and Mayne (1974)

in the form of contours of mean pressure coefficients. The study does not refer to any results with zero pitch, i.e. flat roof.

Marshall (1975) carried out wind pressure measurements on a single family dwelling with a pitched roof of 11.5 degrees. Comparison with a 1:50 scale model in turbulent boundary layer has also been presented. The study shows that the fluctuating component of surface pressures far exceeds the mean values of pressures. The study points out that improper simulation of lower portion of atmospheric boundary layer is one major cause for discrepancy between the wind tunnel and full-scale results. The comparison of the results with the American National Standards Building Code A58.1-1972 reveals that the negative design pressures for the total leeward and windward roof areas exceed the observed mean pressures for measured locations.

Hoxey et al (1983) carried out experiments in full-scale to study the effect of geometric parameters that influence wind loads on low-rise buildings. The parameters considered were length, span, eaves height and roof slope. The study did not evaluate the effect of parapets.

Leicester et al (1983) carried out some pressure measurements on large models (2.44 m by 2.44 m and 1.3 m high) of low-rise buildings. The buildings tested had a pitch of 14 degrees. Load cells were used to measure force coefficients on the roof.

Waldeck et al (1989) carried out full-scale measurements on the roof of an airplane hangar. The results were later compared with a 1:300 model tested in a turbulent boundary layer wind tunnel. The comparison of wind tunnel and full-scale data showed good agreement for mean and peak pressures, although for some data sets a shift was observed between the data. According to the authors, the shift may be attributed to possible differences in the reference pressures and to errors which have occurred in modelling the mean speed wind in the wind tunnel. However, the trends in the pressure coefficients for these data sets were similar in full-scale and wind tunnel. Figure 2.2 shows typical results from this study.

Stathopoulos et al (1990) carried out pressure measurements on the flat roof of a low-rise building. The study reported mean pressure coefficient values of -2.0 to -2.5 for corner taps.

Kim and Mehta (1979) carried out pressure measurements for roof uplift loads on a full-scale building at Texas Tech University, Lubbock, Texas. The building under study had a flat roof and load cells were used to measure the roof uplift loads. The analysis of spectra of wind speed and wind loads showed peaks and lows at the same frequencies. A statistical model was developed from the study which concluded that the fluctuating component of roof uplift load is best represented by a Gamma probability density function.

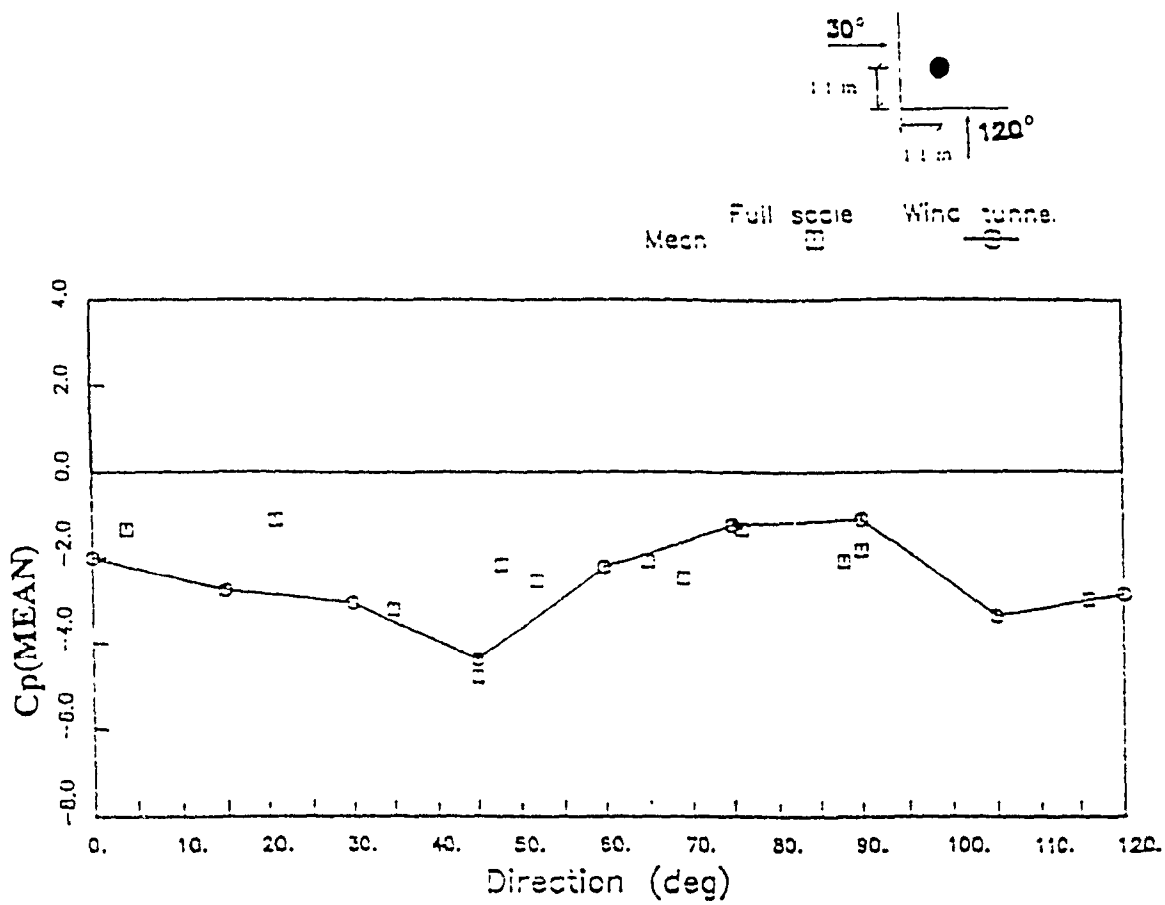


Figure 2.2 Mean Pressure Coefficients on the Roof of an Airplane Hangar, after Waldeck et al (1989)

Levitan et al (1986) studied mean pressure coefficients on the roof of another full-scale building at Texas Tech University. The building has a flat roof with pressure taps as shown in Figure 2.3 and it is mounted on rails so that it can be rotated. The study indicates that mean and peak pressure coefficients on the windward roof area are somewhat greater for $\theta = 60$ degrees angle of attack than those for $\theta = 90$ degrees. Typical results of the study are presented in Figure 2.3 in terms of mean pressure coefficients.

Surry (1986) compared pressure measurement results on the full-scale building at Texas Tech University with those obtained from a 1:500 scaled model tested in a turbulent boundary layer wind tunnel. The study shows that for winds nearly normal to the ridge, the model and full-scale data are in good agreement, however for oblique winds the data indicate significant differences in the peak coefficients. The study has also examined the effect of terrain roughness on mean and peak pressure coefficients.

Mehta et al (1991) have carried out several studies in the area of wind loads on low-rise buildings. In this particular research, the Texas Tech University experimental building was instrumented with additional taps on the roof corner. Pressure taps were located as close as 0.36 metres to the edges. For oblique wind directions mean pressure coefficients were higher than those for other wind

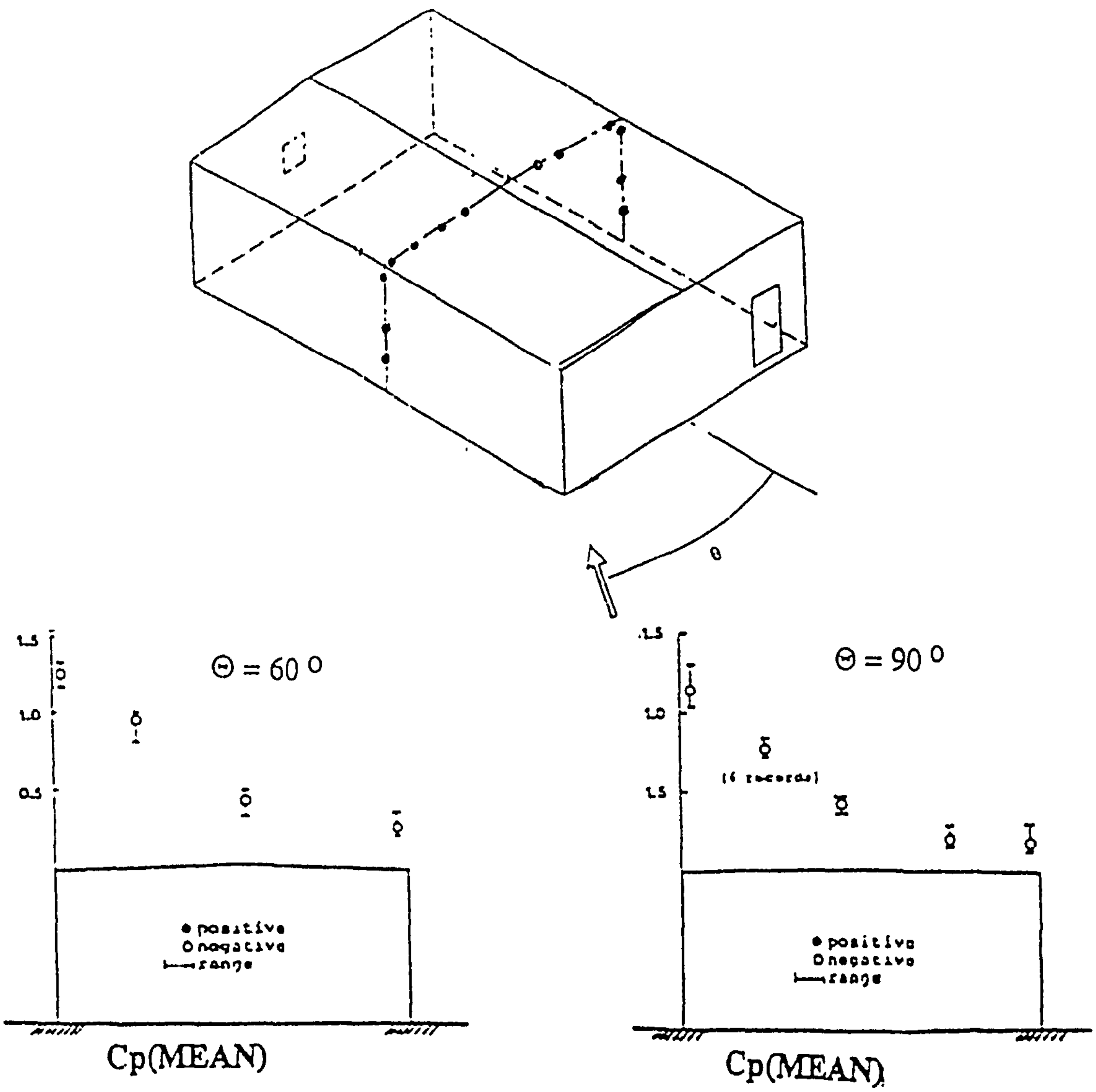


Figure 2.3 Mean Pressure Coefficients on Roof of Texas Tech Facility. after Levitan et al (1986)

directions. The results were also consistent among different records for similar wind conditions. Figure 2.4 shows typical results of the study for two pressure taps.

2.2 REVIEW OF WIND-TUNNEL STUDIES

In the wind tunnel several, studies have been carried out to investigate the wind loads on roofs of models of low-rise buildings. All studies concerned with the effect of parapets have been carried out in the wind-tunnel.

Davenport and Surry (1974) have tested the effects of parapet on low-rise building models in the boundary layer wind tunnel. They concluded that local mean suctions near the corner become higher when parapets are added, in particular for cornering wind.

Kramer et al (1978) found that parapets change the pressure coefficients significantly only in the corner regions of the roof. For square buildings (B*B) with parapets of $h / B > 0.04$ the pressures were reduced by more than seventy percent.

Stathopoulos (1982) carried out a wind tunnel test on a 1:250 scale building model of 1:12 sloped roof. Parapets of relative height (h/H) in the range of 0.125-0.250 were tested. The study concludes that for roof corners, parapets induce high

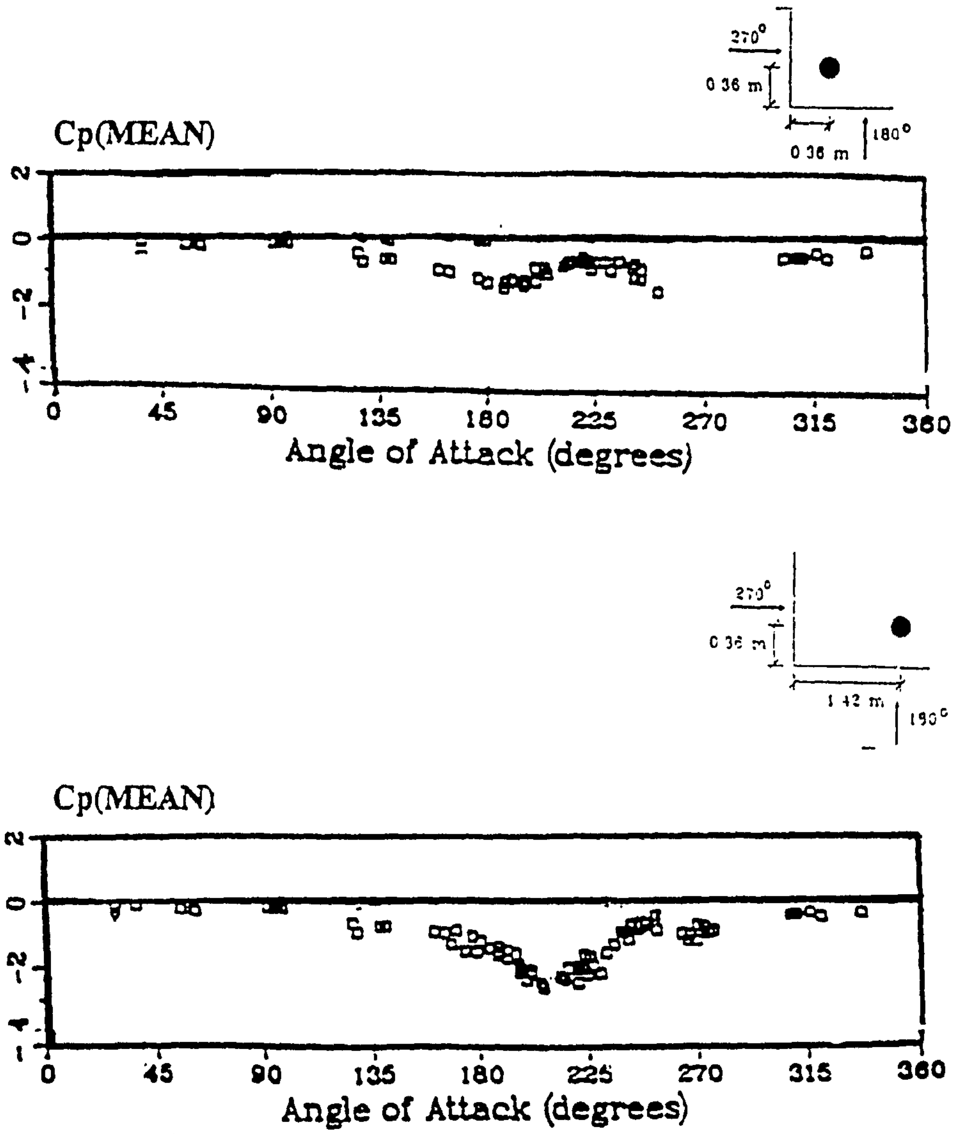


Figure 2.4 Mean Pressure Coefficients on the Roof Corner of Texas Tech Facility, after Mehta et al (1991)

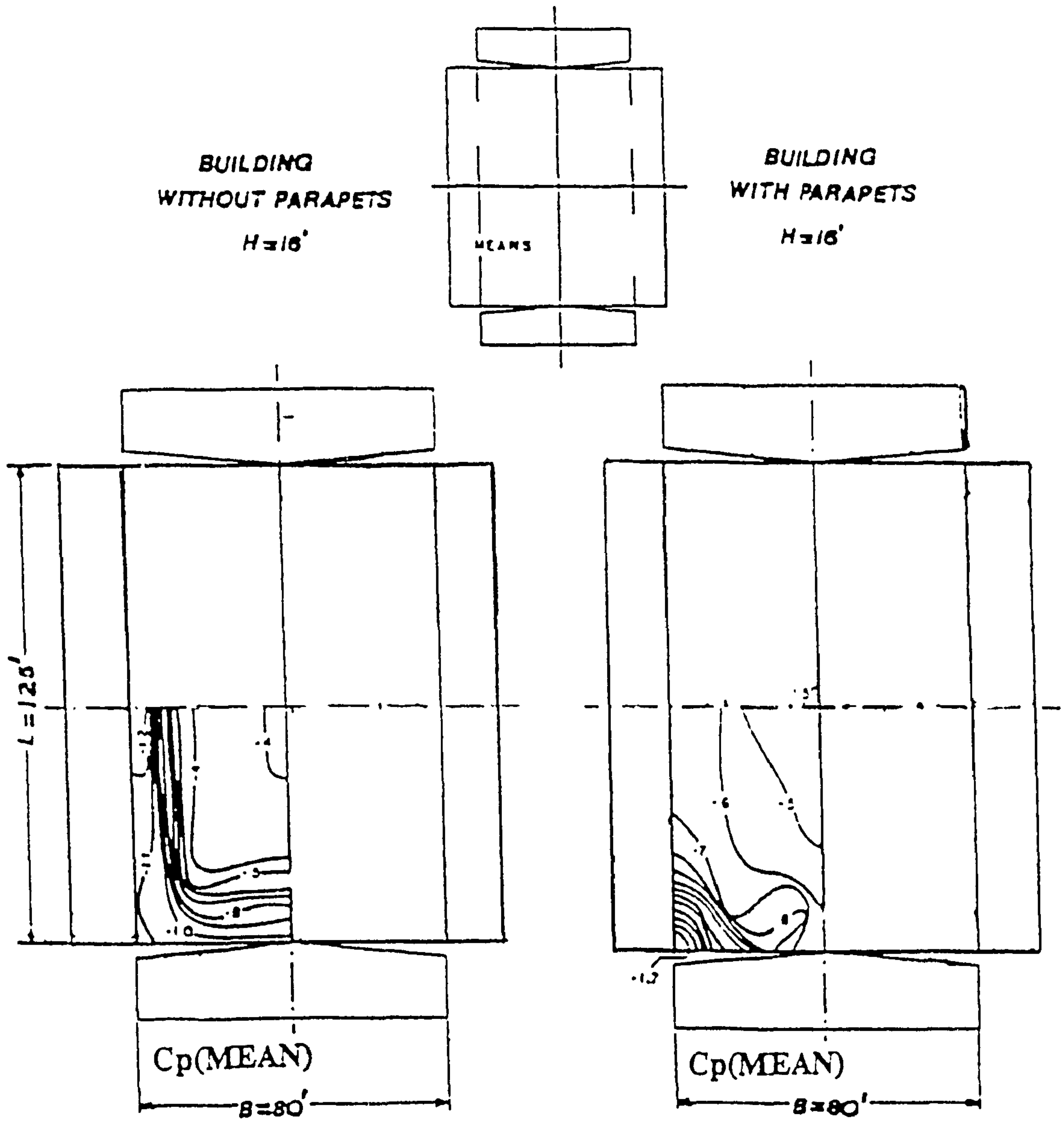


Figure 2.5 Mean Pressure Coefficients on 16 feet High Building Building Model with Open Country Terrain, after Stathopoulos (1982)

suctions as shown in Figure 2.5.

Kind (1986) found that with low parapets and a wind angle near forty five degrees, the suction peaks occur very close to the upwind edges of the roof and are very narrow in extent. The worst suctions decrease monotonically with increasing parapet height. Figure 2.6 shows mean pressure coefficients for a 1:20 scale model with flat roof.

Kind (1988) carried out experiments on a 1:20 scale model of a low-rise building (47 m * 32 m * 9.1 m) in a boundary layer wind tunnel. Parapet configurations of h/H from 0.24 to 1.83 were tested. The study concludes that a very high density of pressure taps is required in the upwind corner region of the roof if suction peaks are to be reliably captured. The study supports the conclusions of the Kind (1986) study.

Baskaran (1986) carried out research on models of low rise buildings of 12 and 24 metres as a part of his Masters thesis at Concordia University. He studied the effect of 0.75 m, 1.5 m and 3.0 m high parapets on these models. This study concluded that roof corners with low parapets experience significantly high mean and peak suctions. It has been shown that the influence of parapets on wind-induced loads on buildings appears to be independent of the terrain roughness. Figure 2.7 shows the results in terms of mean pressure coefficients for 0, 30 and

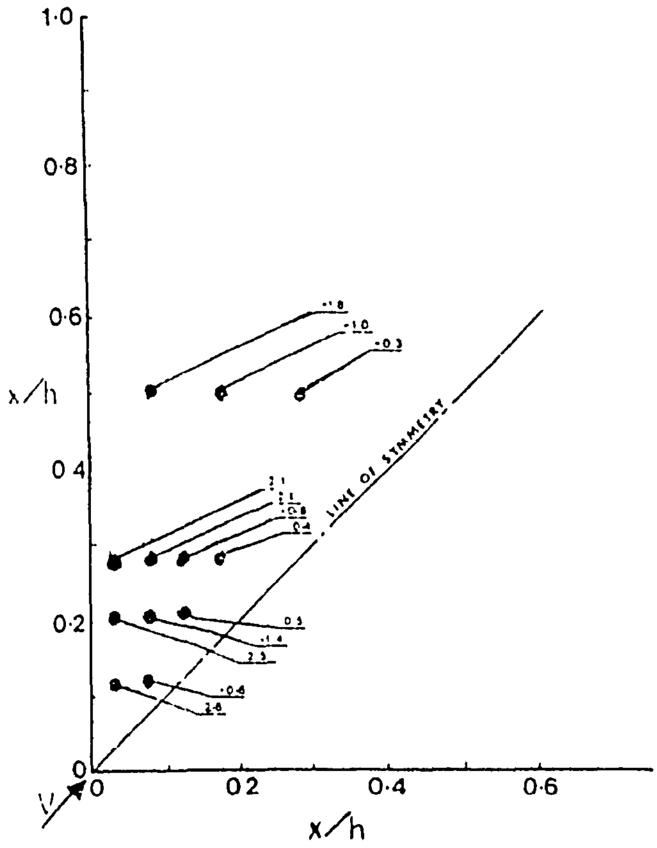


Figure 2.6 Mean Pressure Coefficients on Roof of a 1:20 Scaled Model, after Kind (1986)

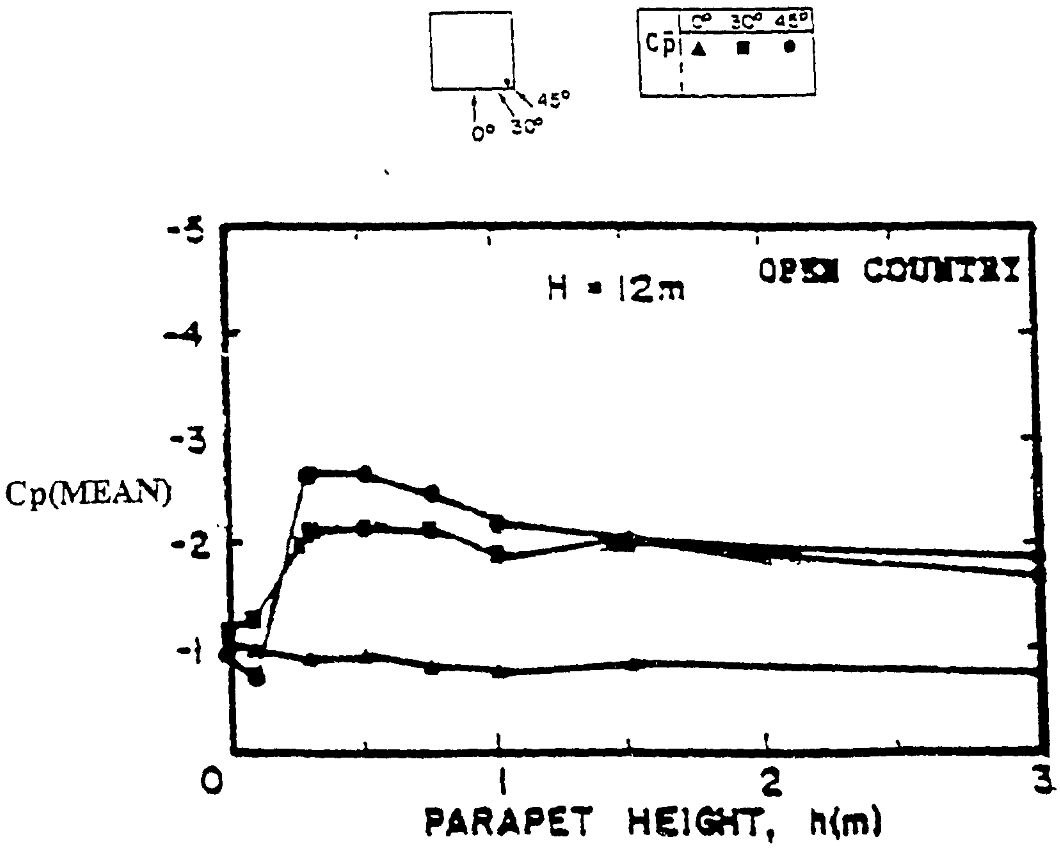


Figure 2.7 Effect of Parapets on Mean Pressure Coefficients, after Stathopoulos and Baskaran (1987)

45 degree incident winds.

Stathopoulos (1987) carried out a wind tunnel test on a flat roof model (6 in * 6 in * 1 in) with a very high density of pressure taps on one of its corners. The study concludes that regardless of building height, the pressure coefficients are little affected by the distance of the pressure taps from the edge of the roof for azimuths of 0-15 degrees, whereas the influence becomes much higher for oblique wind directions.

Stathopoulos and Baskaran (1987) have studied additional parapet configurations like slotted parapets, parapets with cuts around corners and a variety of schemes to reduce the high local corner suctions. Parapet cuts and slots around roof corners have been found effective in this regard.

Badian (1992) in his Masters thesis at Concordia University carried out pressure measurements on models of low-rise buildings with pressure taps very near the corner and then studied the effect of parapets up to equivalent of 3 m high on the roof corner wind loads. He concluded that parapets may increase suctions on the roof corner. Figure 2.8 shows results for the corner taps of the model tested with different parapet heights. It is clear that parapets increase suctions on roof corners for quartering winds.

H = 10m

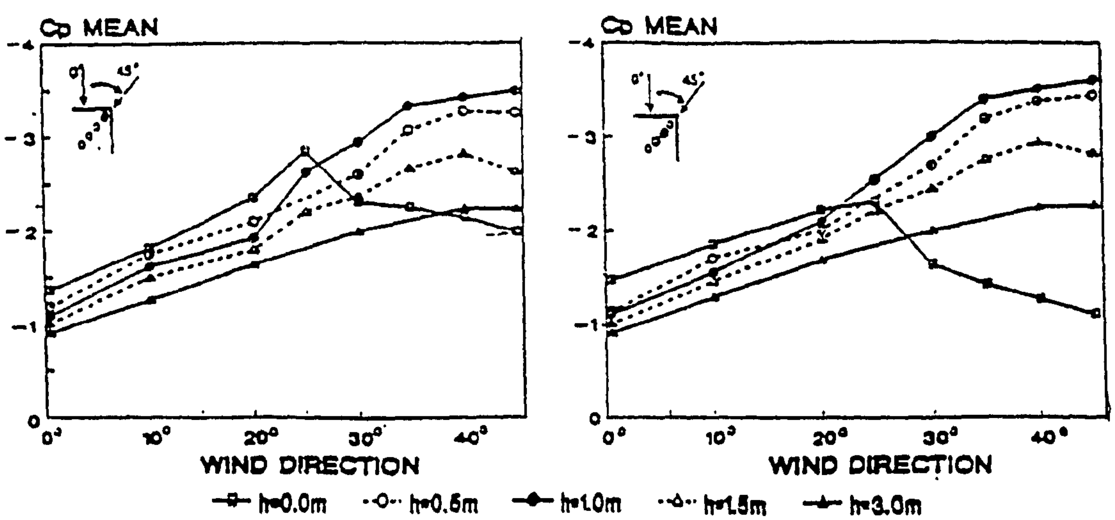


Figure 2.8 Mean Pressure Coefficients for Taps Very Close to Edges, after Badian (1992)

The literature survey has shown that there have been no full-scale studies to evaluate the effect of parapets on roof corners and edges of flat roofs of low-rise buildings. However, several wind tunnel studies have been carried out to evaluate the effect of parapet on the roof wind loading and most of them found a significant increase of corner suctions with the addition of low parapets. Therefore, the present study has been undertaken to examine the effect of parapets on the wind loading of a flat roof in the field. Additional experiments were carried out in the wind tunnel for further investigation and validation purposes.

CHAPTER 3

EXPERIMENTAL WORK

The chapter discusses the experimental work carried out in the present study. The first part of the chapter deals with the ˊ ,ll-scale experimental work while the latter part covers the wind tunnel work.

The experimental station to carry out the full-scale testing is located on the corner of football field of Loyola Campus of Concordia University. It consists of a test building and a meteorological tower. The site layout of the experimental building is shown in Figure 3.1.

3.1 DESCRIPTION OF TEST BUILDING

The test building was constructed in 1985 for another research project dealing with the Control of Rain Penetration through Pressurized Cavity Walls. The building had a sloped roof, which was modified to a flat roof for the present study.

The test building is a one-storey rectangular building 3.70 metres long, 2.60 metres wide and 3.30 metres high and is shown in Figure 3.2. The building's roof has slightly larger dimensions than the base of the building. The test building also houses the major instrumentation required for the experimentation. The building

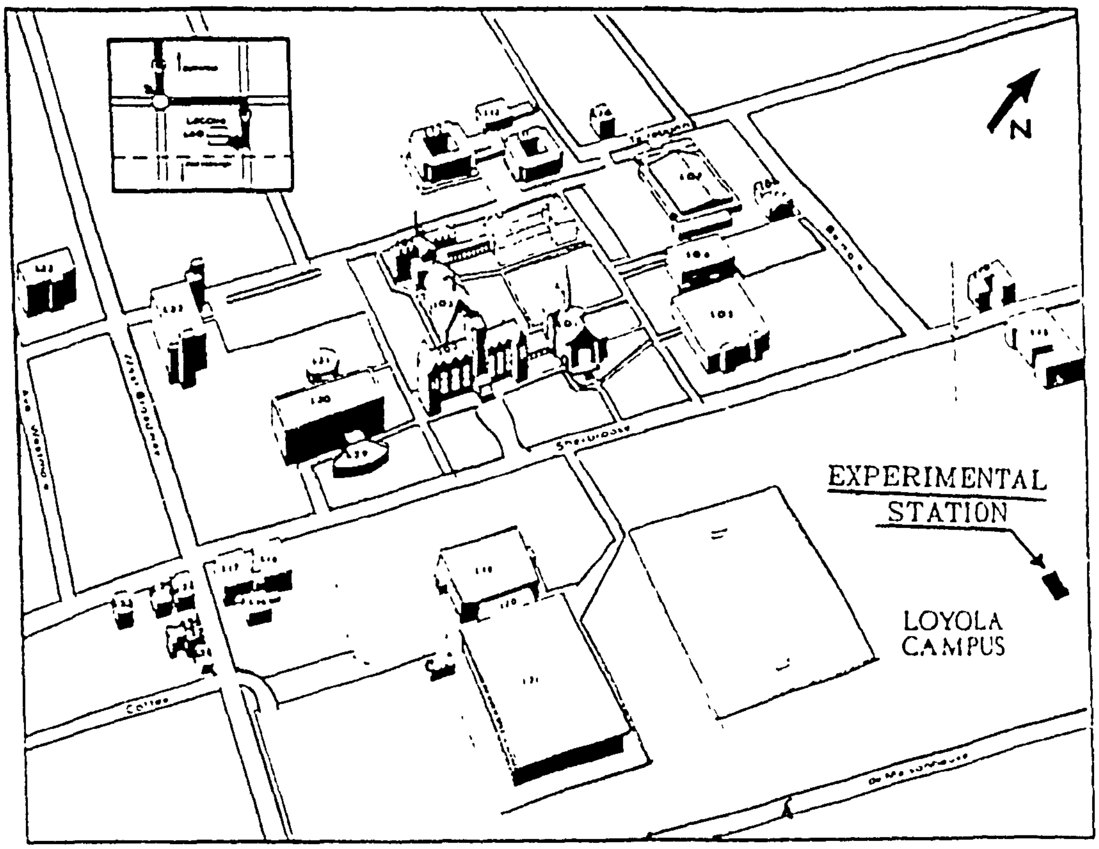


Figure 3.1 Site Layout of the Experimental Station

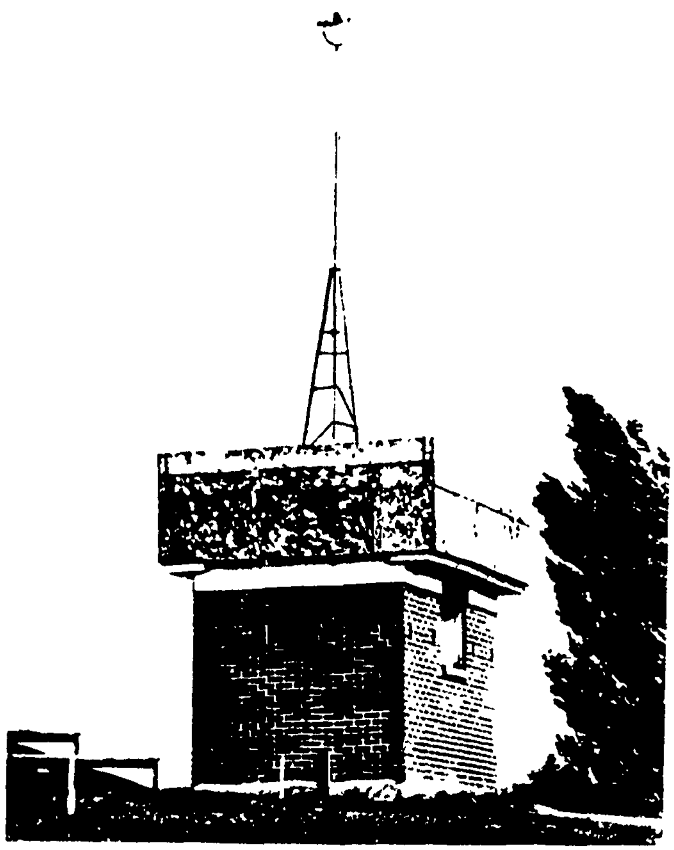


Figure 3.2 The Experimental Building

has one door and a non-openable glass window. The corners of the roof can be fitted with a retractable panel which carries the pressure taps. Figure 3.3 shows the plan and elevation of the experimental building. The exposure to north is generally suburban with largely two or three-storey houses. The area to the south is open with scattered trees, six hundred metres away from the building. The land to the west is open (direction of prevailing winds) and the football field is located in this direction. The land to the east is relatively open with scattered trees and few houses. Figures 3.4 and 3.5 show the terrain in the west and south directions respectively. Appendix 1 discusses the climate of Montreal and the variation of wind speeds over the year.

3.2 METEOROLOGICAL INSTRUMENTS AND TOWER

A three cup anemometer and a wind vane were the meteorological instruments used in the present work. Anemometers and wind vanes in full-scale studies are placed in a position near the location of measurement that is not affected by the wind flow around the building. The anemometer in the present study was mounted on a movable lattice mast. In the early stages of experimentation, the position of anemometer was tested for various locations on and around the building. It was finally decided to mount the mast on the top of the test building. The height of the anemometer on the top of the building is chosen in accordance with the ASHRAE recommendation included in the fundamentals(1989) i.e., the anemometer should

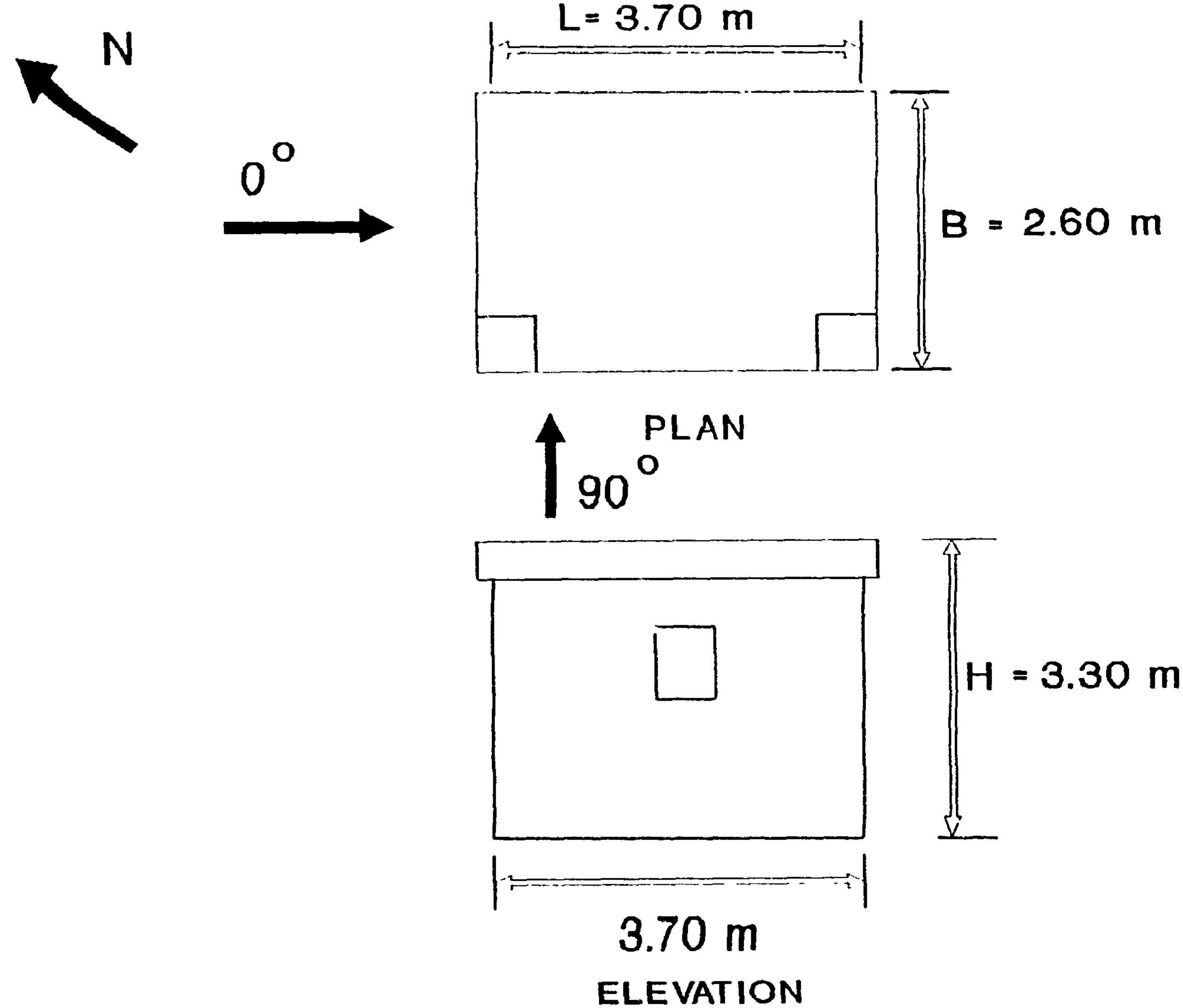


Figure 3.3 Plan and Elevation of the Experimental Building

Figure 3.4 The Terrain Facing the West of the Experimental Building

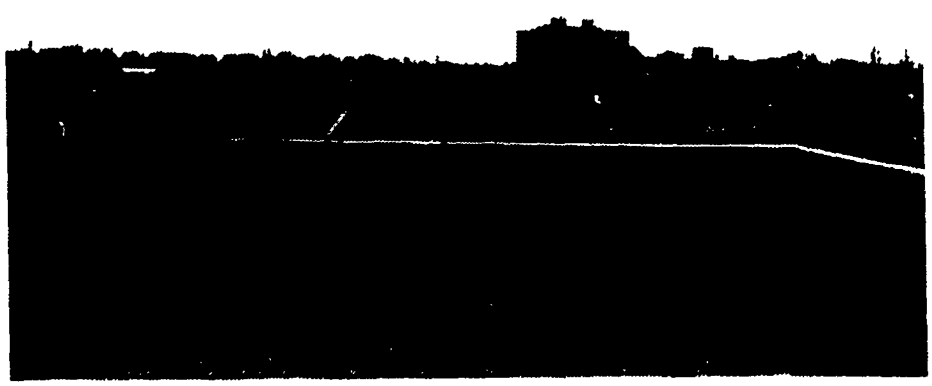


Figure 3.5 The Terrain Facing the South of the Experimental Building

be placed at a height of **1.5** times **A** where

$$A = (H * W)^{0.5}$$

in which

H = Height of the Building and

W = Width of the Building as

shown in Figure 3.6.

At this height the anemometer is generally not affected by the disturbances caused by the building. The height of the tower is 6.4 metres and the height of the anemometer from the base of the building is 9.7 metres.

3.3 LOCATION OF REFERENCE PRESSURE POINT

Ambient atmospheric pressure is used as reference for the pressure measuring devices. The reference pressure is collected at a point upstream located 10-15 metres away from the building and at the ground level. The reference pressure is transmitted by a 5.0 mm (0.2 inch) internal diameter PVC flexible tubing to the test building and then branched and served to the transducers.

Reference pressure in full-scale is not quasi-steady as in wind tunnel experiments and hence requires special consideration. In the initial stages of the study, the reference pressure was measured at various locations around the building to

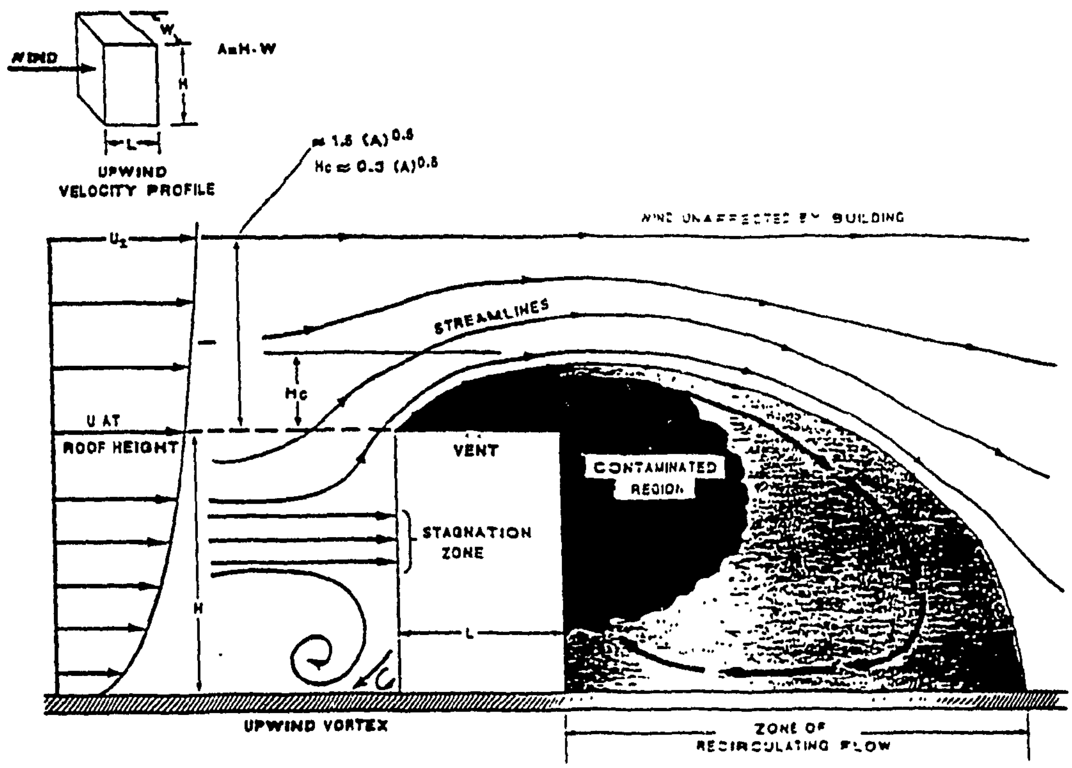


Figure 3.6 Wind Flow Around a Square Building, after ASHRAE Fundamentals (1989)

ensure stability and negligible effects on the measured pressures. A common way of checking the reference pressure fluctuations is to connect the reference pressure to both ends of a transducer and measure the fluctuations. The reference pressure point and the building are sufficiently separated so that there is no effect of the building on the measured reference pressure.

3.4 LOCATION OF PRESSURE TAPS ON THE ROOF OF THE BUILDING

As mentioned earlier, each roof corner can be fitted with a retractable panel which houses the pressure taps. On each of these panels twelve pressure taps are located. The pressure taps are numbered from 1 to 12 as shown in Figure 3.7.

Each pressure tap has 9.5 mm (3/8 inch) diameter hole and is connected by a flexible PVC tubing to the pressure measuring device. The flexible PVC tubing has an internal diameter of 3.2 mm (1/8 inch) and 9.5 mm (3/8 inch) outer diameter. The maximum length of the tubing is 5 metres. The retractable panels have a cover so that rain, water and dust can be prevented from going inside the taps after the data acquisition is over.

The test building in the first stage of the experiment is tested with its flat roof without parapets. In the second stage of the experiment, parapets 0.25 m and 0.50 m high were placed on the roof.

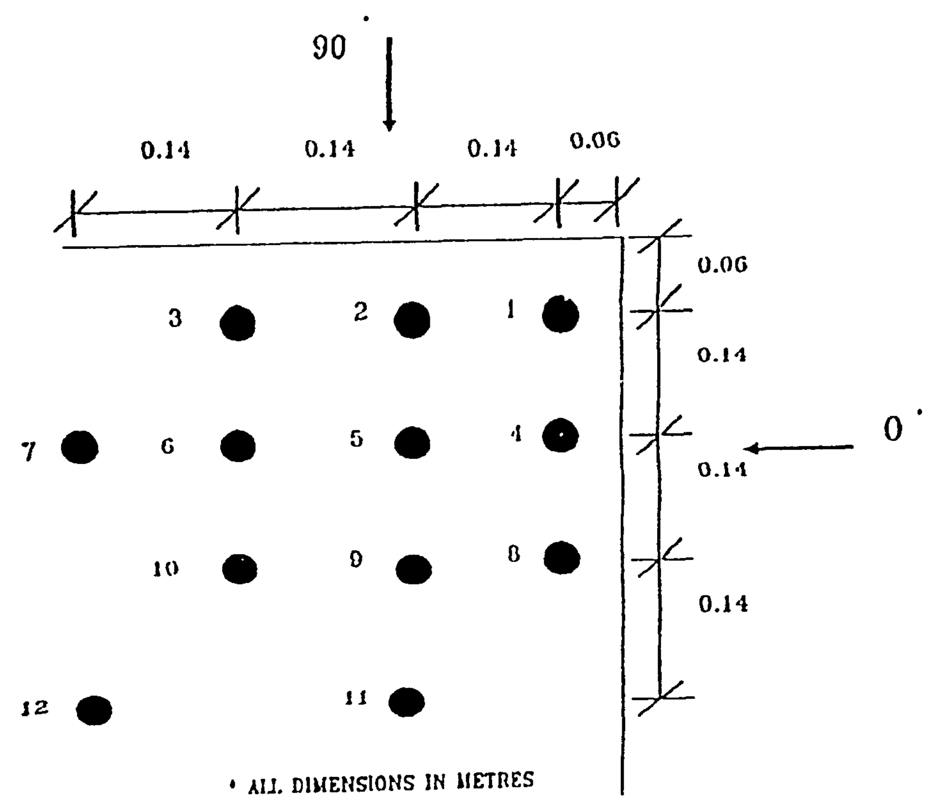


Figure 3.7 Details of Pressure Taps on Roof Corner

3.5 DETAILS OF PARAPETS

When the parapets are placed on the roof the tap numbers 1, 2, 3, 4 and 8 are covered with the parapet and so the taps left for measurement with parapets are 5, 6, 7, 9, 10, 11 and 12. Figure 3.8 shows pressure taps on the roof with parapets.

The parapets are made of 11.12 mm (7/16 inch) Aspenite Board separated by a 5 cm * 7.6 cm (2 inch * 3 inch) stud. The parapet section is shown in Figure 3.9. The parapets are constructed with slots so that additional parapet sections could easily be fitted to change the parapet height as shown in Figure 3.10. The parapets have a thickness of 0.10 meters and they are fixed to the roof by plate connection fastened with screws to hold them together.

3.6 INSTRUMENTATION

3.6.1 Measurement of Wind Speed and Direction

For measuring the wind speed, a commercial three cup anemometer was used. The anemometer was supplied by Sierra Methods Inc. of Berkeley, California. The three cup anemometer is provided with a compact box which shows wind speed in miles/hour. The output from the anemometer is in volts and is directly

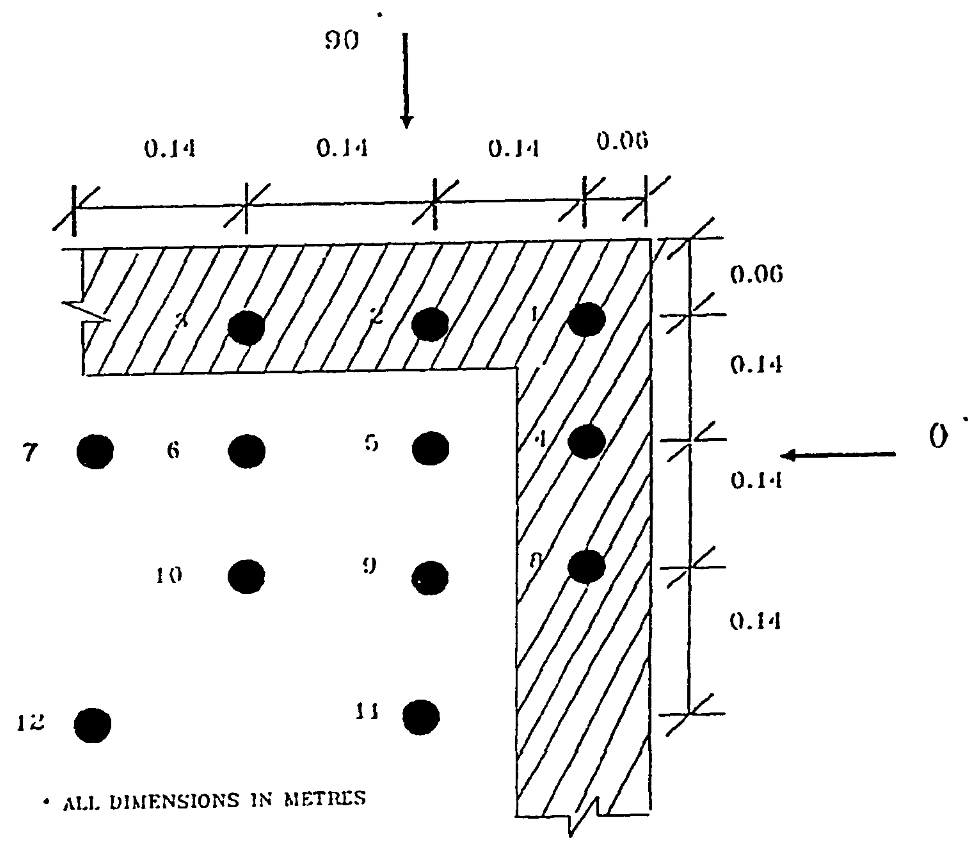


Figure 3.8 Pressure Taps on the Roof with Parapets

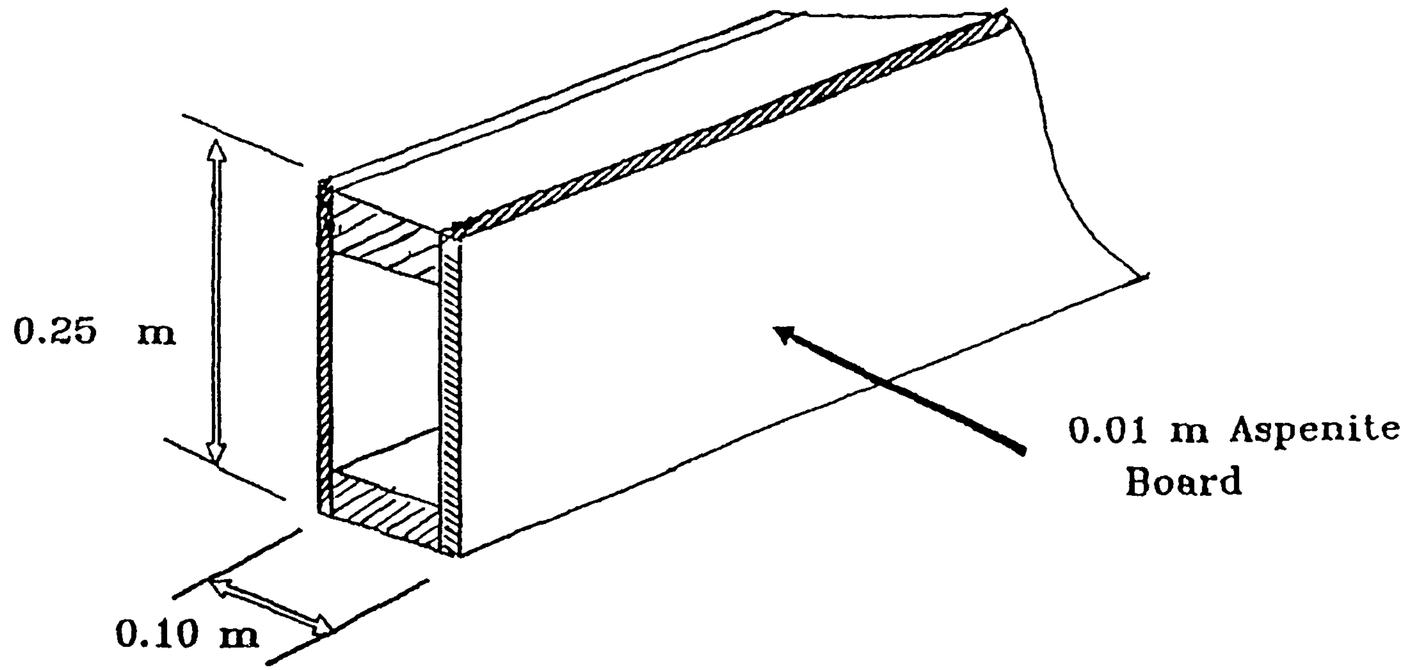


Figure 3.9 Parapet Section of 0.25 Metres

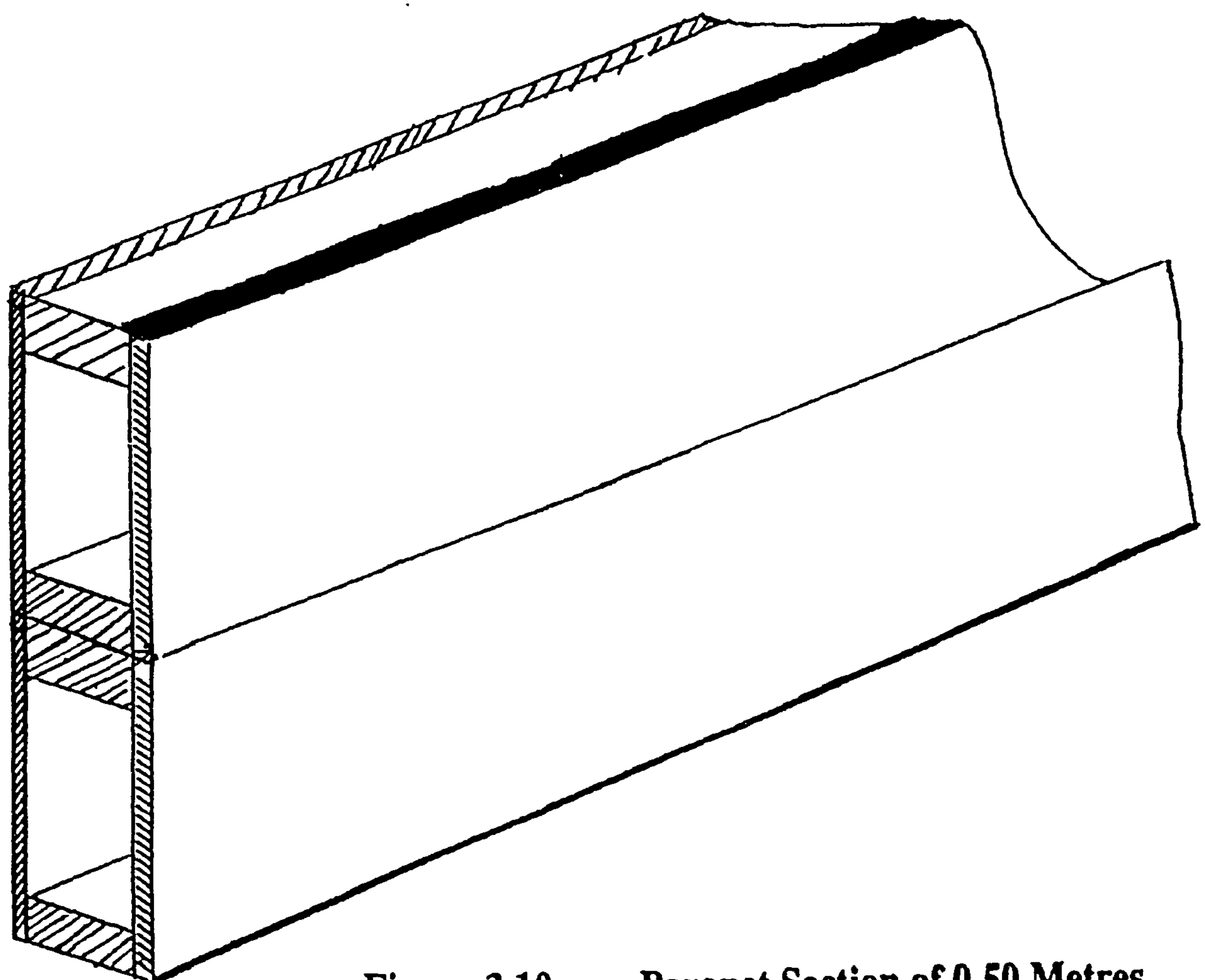


Figure 3.10 Parapet Section of 0.50 Metres

proportional to the wind speed. The three cup anemometer was calibrated in the Boundary Layer Wind Tunnel of the Centre for Building Studies, Concordia University. The calibration consists of placing the anemometer in the wind tunnel and recording the corresponding output in terms of volts for various speeds. A graph is then plotted of volts vs wind speed in m/sec . The points are fitted by a straight line as shown in Figure 3.11.

For measurement of azimuth of the incident winds, a wind vane attached on the same mast with the anemometer is used. The wind vane is supplied from the same company with that of the anemometer. The direction is indicated on the compact box in the same way as the wind speed. The wind vane was calibrated by using a magnetic compass. For calibration purposes, the wind vane is pointed to a particular direction e.g., North and the output in volts is measured. A similar process is repeated for other directions. The calibration of the wind vane is shown in Figure 3.12. The wind vane shows some non-linearity for winds mainly from easterly and southeasterly directions. This non linearity had no effect on the measured azimuth since all the records considered in the present study correspond to south and southwesterly wind directions. The present calibration was checked repeatedly at regular intervals during the experimentation, to confirm its steadiness. The calibration showed no changes during the experimentation process.

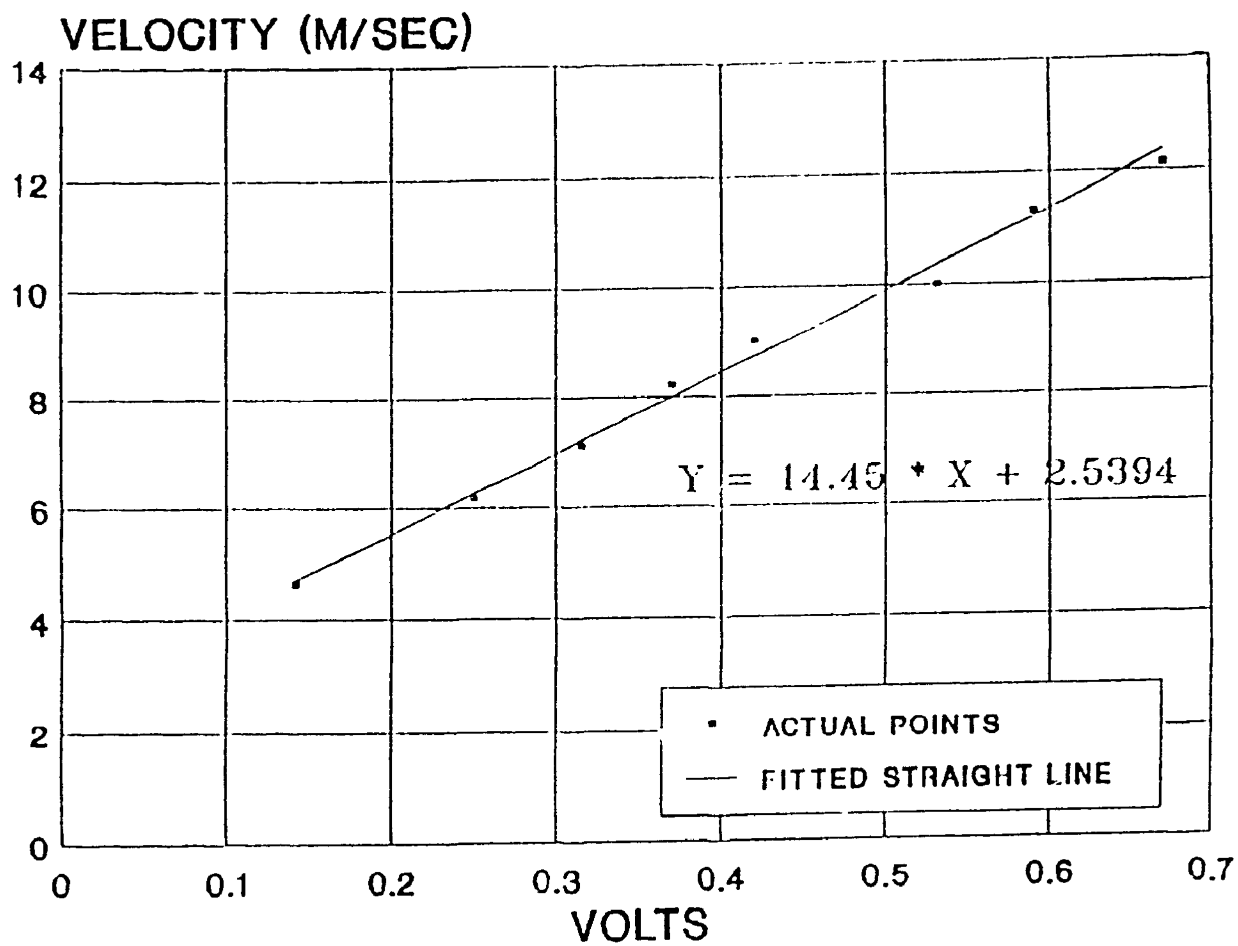


Figure 3.11 **Calibration of the Anemometer used in the Present Study**

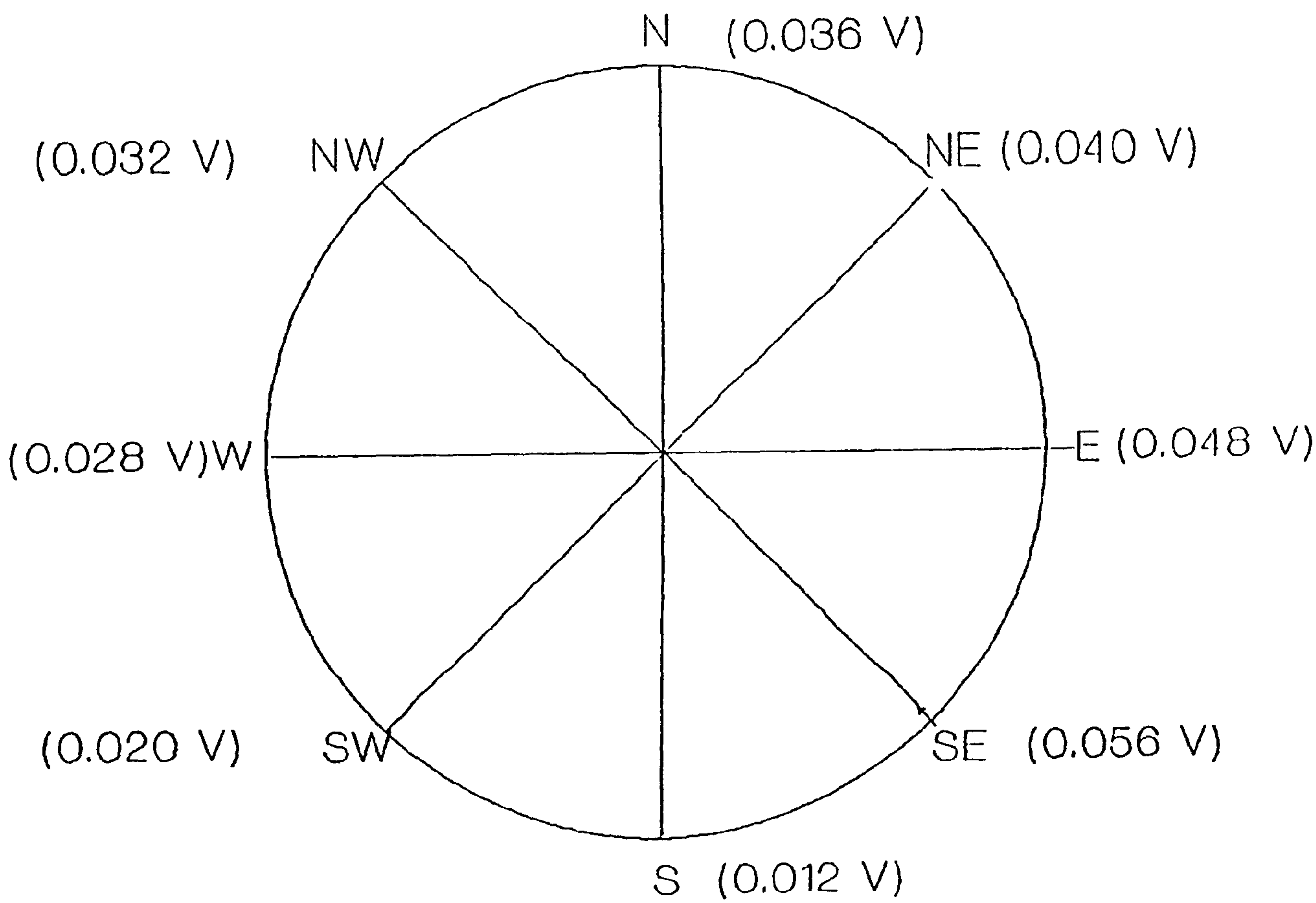


Figure 3.12 Calibration of Wind Vane for Direction

3.6.2 Measurement of Pressure

For measuring pressure in this particular experiment, pressure sensors 160 PC manufactured by Micro-switch (a Honeywell Division) were used. 1 psi sensors provide output voltage proportional to the applied pressure. They operate from a single, positive supply voltage ranging from 6.0 to 12.0 volts D.C.. Figure 3.13 shows the pressure sensor along with the relevant details. The pressure sensors were calibrated in the Buildings Aerodynamics Laboratory of the Centre for Building Studies, Concordia University. The calibration is done by using a manometer, a syringe with tubing and a T-joint. With the help of syringe, pressure is applied and measured in inches of water by a manometer. For each pressure level applied, the corresponding output voltage is recorded. A graph is plotted between pressure in inches of water and the output in volts. The points are fitted by a straight line as shown in Figure 3.14.

3.7 INSTRUMENTS FOR ACQUISITION OF DATA

For the collection of data, various instruments were used during experimentation. Details of the equipment are as follows :

Squirrel/Meter Logger from Grant Instruments Limited, Barrington, Cambridge, U.K.. The instrument is a portable, 2 channel data acquisition system operated on

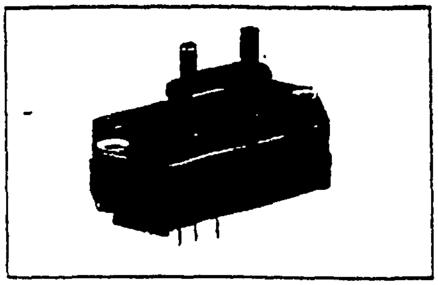
MICRO SWITCH
a Honeywell Division

1 psi pressure sensors

PK 8772 3

GENERAL INFORMATION

160PC 1 psi sensors provide an output voltage proportional to applied pressure. They operate from a single, positive supply voltage ranging from 6.0 to 12VDC. Signal conditioning results in directly usable outputs: temperature compensation results in predictable performance over specified temperature ranges.



160PC SPECIFICATIONS at 8.0 ± 0.01VDC, 25° C

PARAMETER	Min	Typ.	Max.	UNITS
F S O (Full Scale Output)*	4 85	5 00	5.15	Volts
Null Offset	0 95	1 00	1 05	Volts
Excitation	6 0	8 00	12.0	VDC
Output Current Source Sink	 10 0 5 0			mA
Supply Current (10K ohm load)		8 0	20 0	mA
Overpressure			5	psi
Operating Temperature	-40° C to -85° C (-40° F to -185° F)			
Storage Temperature	-55° C to -125° C (-65° F to +257° F)			

*F S.O. is the algebraic difference between end points (null and full pressure outputs).
Output voltage at full pressure equals 6.0 ± 0.20 volts at 8.0VDC.

Figure 3.13 Pressure Sensor used in the Present Study

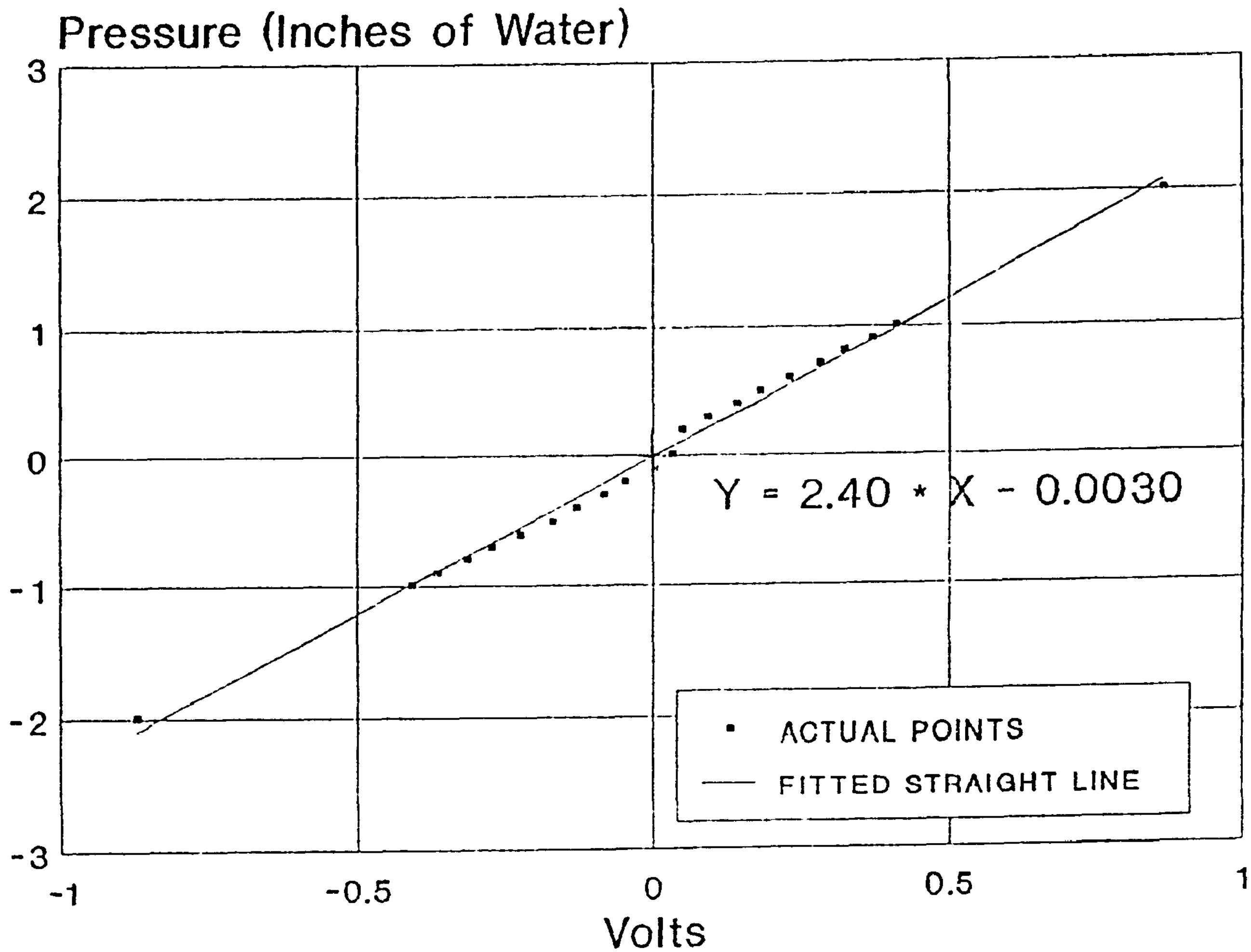


Figure 3.14 Calibration of Pressure Transducer used in the Present Study

a 9 V battery. The maximum sampling rate is 1 sample per channel per second. The instrument can be connected to an IBM compatible Personal computer(PC) by a RS-232-C cable. The instrument was used to measure the wind velocity and wind pressure from the transducer. The wind velocity and the pressure were recorded in volts. Overall range limits were -25/25 volts and possible range of span for volts is 10 mV to 25 V. Up to 1900 readings per channel can be recorded. In conjunction with the Squirrel/Meter Logger, a standard compact recorder was also used to measure the wind direction.

Standard Compact Recorder from Philips(Model No. PM8252 A), Netherlands was used. The instrument is a two channel strip chart recorder in which the signal is recorded. The input sensitivity can be adjusted to any desired signal amplitude from 1 mV up to 50 volts. Chart speeds are adjustable from 10 mm/h to 300 mm/h. The equipment was used to measure the wind direction.

The two pieces of equipment as described above were used in the initial stages of experimentation to measure wind direction, wind speed and pressure from one tap. The Squirrel/Meter Logger had only two channels resulting in significant time delays. Therefore, a new data acquisition system from Fluke and Philips was purchased to overcome the limitation.

Hydra Data Logger Unit (Model 2620 A) from Fluke and Philips was used for data acquisition during a major part of the experimentation. The instrument is a multi-channel data acquisition unit capable of measuring both ac and dc voltages. It has 21 measurement channels. The maximum sampling rate for each channel is 1 sample per second. The system can be connected to an IBM compatible Personal Computer through a RS-232 cable. The instrument is shown in Figure 3.15. The unit is portable and can only operate with a 120 V power source. The unit comes with its own menu driven software, which can be used in conjunction with an IBM PC compatible for data collection and analysis.

3.8 DATA COLLECTION

On a typical windy day, the data collection consists of the following steps :

Step 1: Check if the wind velocity is over 5.5 metres/second at the anemometer height and the winds are westerly to southwesterly, as the terrain for these directions is ideal for the present full-scale study.

Step 2: Put the power "on" to the transducers, data acquisition and other instruments.

Step 3: Go to the roof of the building, and remove the covers over the retractable unit so that the pressure taps are exposed to the atmosphere and ready for measurement.

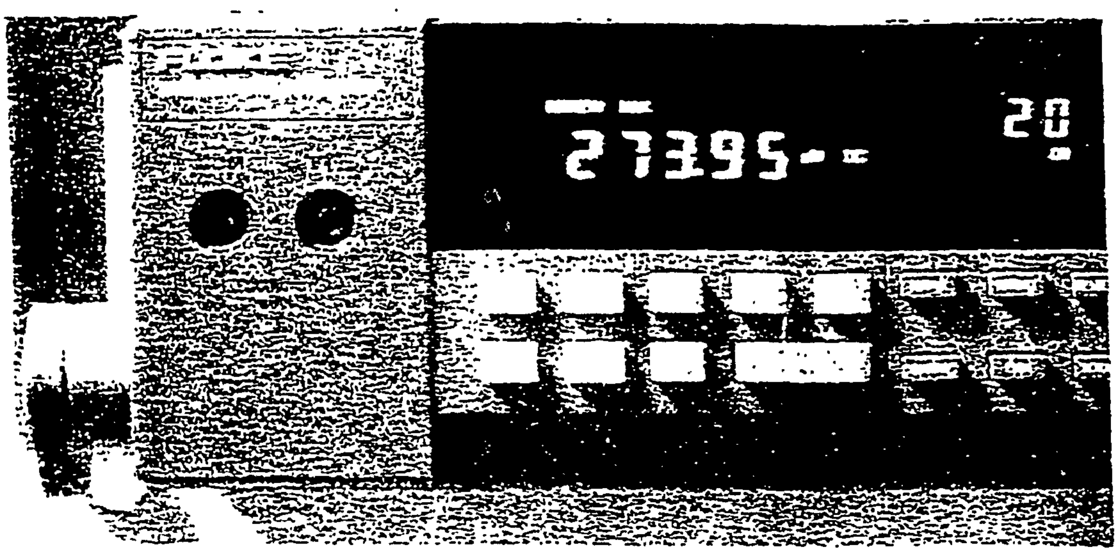


Figure 3.15 Data Acquisition Unit from Fluke and Philips Used in the Present Study

Step 4: Check the calibration of all the transducers, and set them to zero reading.

Step 5: Check the data acquisition unit and all the connections to verify o.k. status. Set the sampling rate for all channels at 1 sample per channel per second. Set the desired unit, i.e. volts for all the channels.

Step 6: Connect the four pressure taps to the transducer heads, for which the data is desired. The wind velocity and direction inputs are connected to the data acquisition unit for measurements.

Step 7: Record the time at the initiation of recording and carry on recording for a period of 15 minutes.

Step 8: Disconnect the pressure taps and connect other taps for which data is desired. Repeat step 7. At the end of 30 minutes, the data acquisition unit memory is full.

Step 9: Disconnect the data acquisition unit, and take it to the Loyola Computing Services for uploading the data to an IBM PC Computer. It takes 20 minutes to upload a 30 minute recording.

For further recording carry steps 2 through 9.

About forty records were collected over a period of two years. Out of these forty sets of data thirty were found good for further analysis. The data records typically have 15-minute mean wind speeds at the anemometer height (9.7 m). This velocity at anemometer height was reduced to the roof height (3.3 metres) by using the Power Law with an exponent (α) equal to 0.15. Stationarity of the wind speed and direction was a ɔ checked for all records, before they are picked up for further analysis. For stationarity check of wind speed and direction, the data of 15 minute interval was divided into three equal time intervals of 5 minute duration each (Bendat, J.S., and Piersol, A.G.,1971). For all these three sets, mean and mean square values are calculated. If the data set is stationary, then the statistical properties computed for each of these intervals (5 min) will not vary significantly say within 10% from one time interval to the next. The data which passed the test was processed for the calculation of mean pressure coefficients and turbulence intensity. The average (of 15 minute record) longitudinal turbulence intensity at roof height was found to be around 22 %. For a full-scale study it is difficult to get winds for same azimuth repeatedly. Thus, for repeatability check, the two sets of data compared are within +/- 5 degree range.

3.9 DATA ANALYSIS

As previously mentioned, after the data was collected, it was transferred from the Data Acquisition unit to an IBM PC (80386 Processor). The data was saved in a ASCII format file, which was then imported in Lotus 1-2-3 spreadsheet for further analysis.

In order to calculate the value of Cp(Mean) for each record, the value of pressure at the instant was divided by the value of dynamic velocity pressure at that instant to get a Cp value. Such values were calculated for all the 900 samples (15 min * 60 samples/minute) and averaged to provide the Cp(MEAN) reported in the present study. Figure 3.16 shows typical calculations for mean pressure coefficient and mean velocity. Turbulence intensity for the 15 minutes period is also reported.

The other method of calculating Cp(MEAN) was to divide the average value of pressure for the 900 samples by the average value of the velocity recorded over the 900 samples. Both methods gave almost the same result for ninety percent of the records with a difference of less than 4 percent. For example, the earlier method reported the value of Cp(MEAN) for tap 5 as 0.89 while the latter method reported the value as 0.86.

The wind speeds measured in the experiment were also cross-checked with the wind data from the Dorval Station of Environment Canada. The data was checked for 12 days of recording, selected at random and the percentage variation of the two data was less than ten percent. The difference in the speeds could be attributed to a number of factors like trees and buildings in the vicinity of the test building and difference of geographical features at the two sites. A typical record of wind velocity, wind pressure and mean pressure coefficient are presented in Figure 3.17, 3.18 and 3.19 respectively. All the three figures correspond to data

JULY 16, A, 1991	SAMPLE SIZE	:	15 MIN
TIME: 13.45 HRS	SAMPLING RATE	:	1 SAMPLE SEC CH
	WINDS	:	SOUTH-WESTERLY
	PARAPET	:	0.25 METRES

SET 1

MEAN VELOCITY : 4.476879 M SECS
MEAN DIRECTION : 53.25 Degrees
TURBULENCE INT.: 0.190751

TAP (#)	PRESSURE (Pa)	Cp(MEAN)
TAP 5	-10.43	0.89
TAP 9	-11.97	-1.02
TAP 6	-11.06	-0.94
TAP 10	-12.01	-1.03
TAP 7	-11.34	-0.99

AVERAGE OF EVERY FIVE MINUTES

TIME (SEC)	VELOCITY (M SEC)	PRESSURE (PASCALS)				
		TAP 5	TAP 9	TAP 6	TAP 10	TAP 7
0-300	[illegible].30	ERR	-10.47	-11.71	-10.63	-11.93
301-600	4.46	ERR	-10.47	-12.05	-11.21	-12.[illegible]9
601-900	4.63	ERR	-10.47	-11.96	-11.40	-11.9[illegible]

Figure 3.16 A Typical Data Analysis on Lotus 1-2-3

of tap 5 for July 19, 1991. The mean value for each parameter measured is also shown in the figure. Figure 3.16 has already shown the calculation for the same tap along with other taps for this particular date.

3.10 WIND-TUNNEL EXPERIMENTATION

After carrying out the full-scale study of wind pressures on the building it was decided to model the building in the wind tunnel and carry out measurements in order to compare the results with those of the full-scale building.

The section discusses the wind tunnel testing facility of the Centre for Building Studies, the details of the building model and the data acquisition system used in the laboratory.

A Wind Tunnel can be defined as a facility to blow air through an enclosed pathway (tunnel) instrumented to study the interaction between the wind and the object in consideration or study.

There are several types of wind tunnels and can be divided into four categories:

(1) Aeronautical Tunnels, in which the flow is uniform and smooth. Earlier types of wind tunnels were always of this type and buildings were tested in

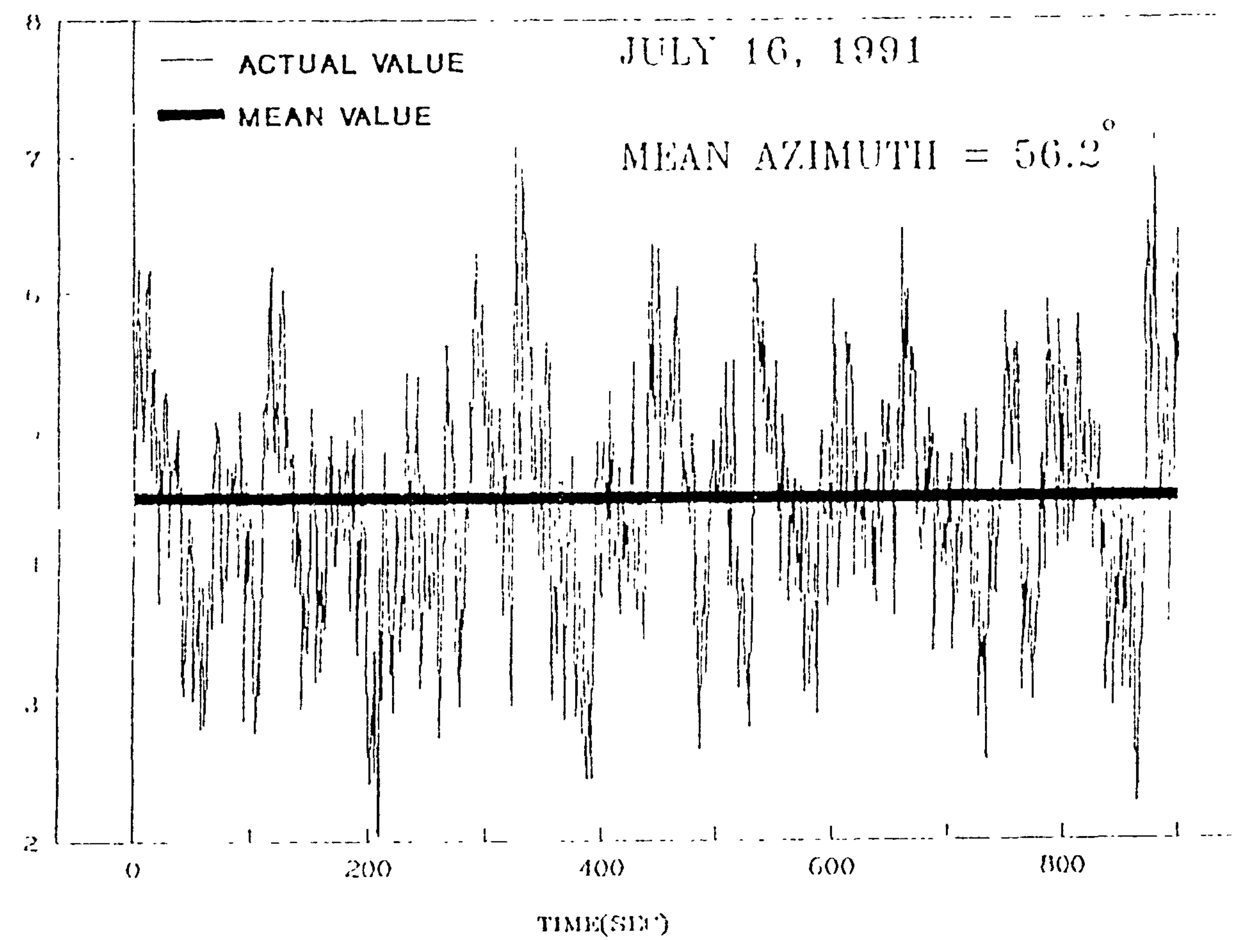


Figure 3.17 A Typical Record of Longitudinal Wind Velocity at Roof Height (3.3m)

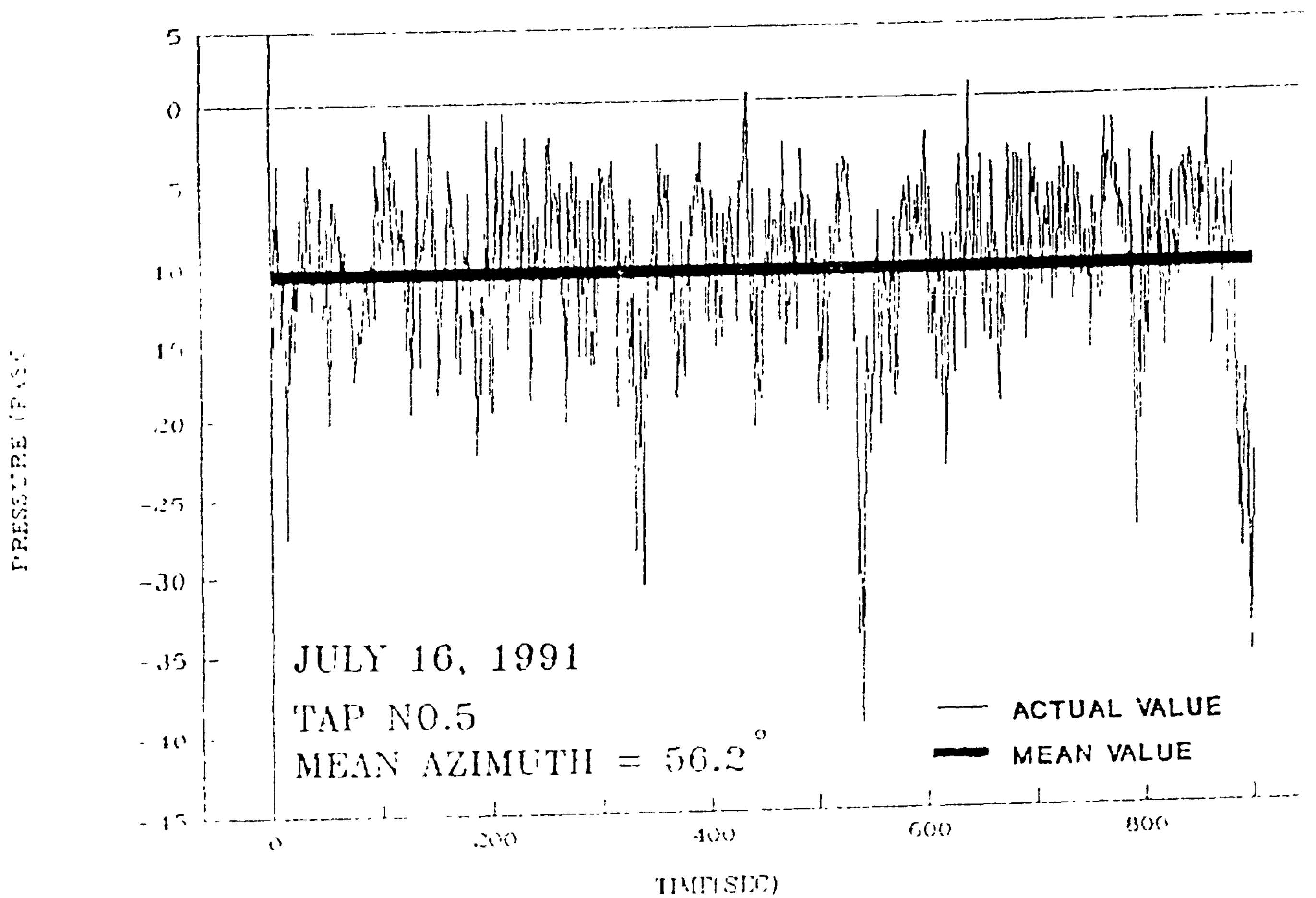


Figure 3.18 A Typical Record of Wind Pressure on Roof Tap

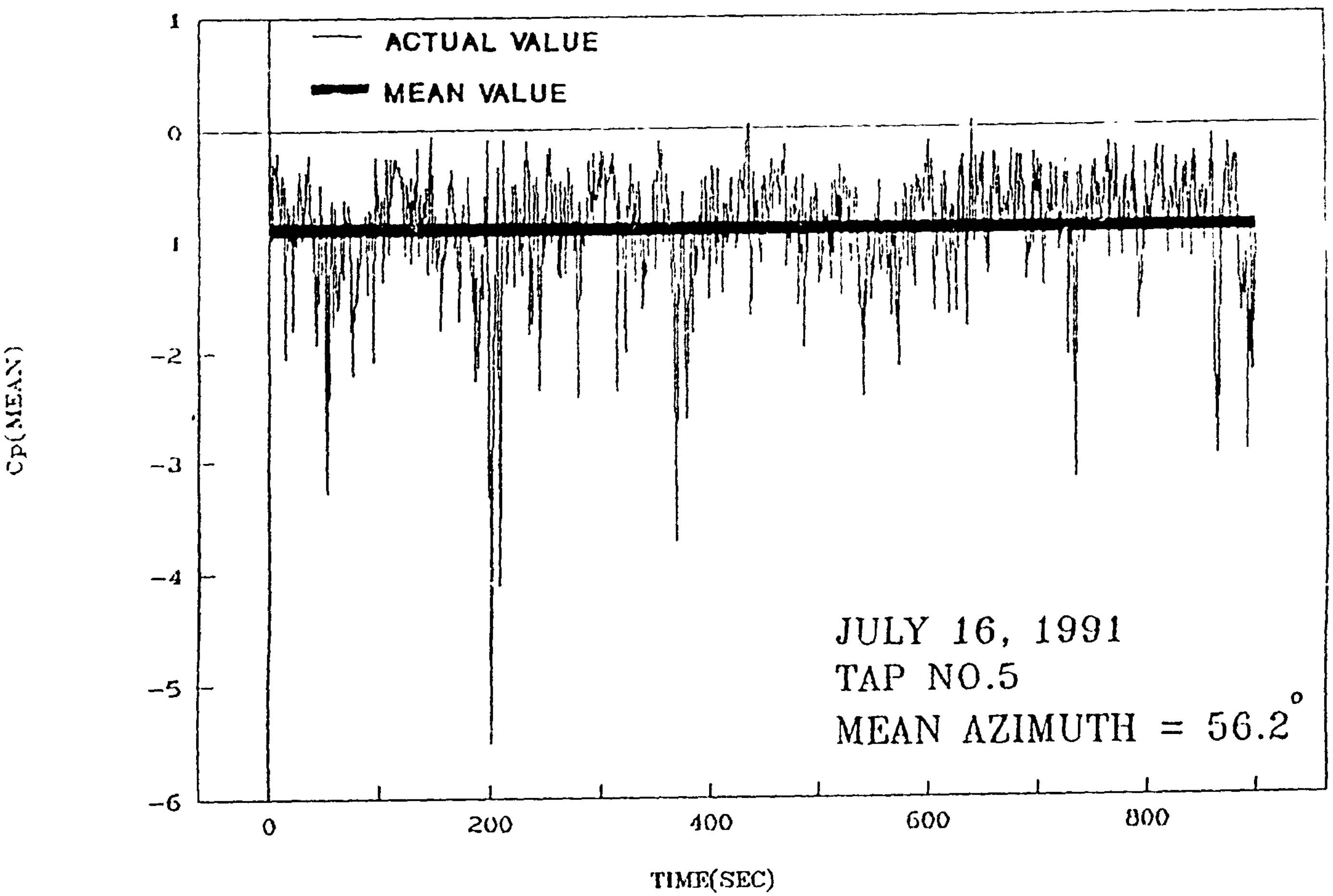


Figure 3.19 A Typical Mean Pressure Coefficient Profile (Tap # 5)

uniform flow only.

(2) Long tunnels in which the atmospheric flows are simulated by a thick boundary layer that develops naturally over a rough floor.

(3) Tunnels with passive devices, in which a thick boundary layer is generated by grids, fences or spires placed at the test section entrance.

(4) Tunnels with active devices, such as jets or machine driven shutters with flaps. In jet tunnels it is possible, within certain limits, to vary the mean velocity profile and the flow turbulence independently of each other.

The boundary layer can be described as a thin region near a solid surface, in which the effect of internal friction in a fluid cannot be neglected. In other words the frictional effect of the solid boundaries on the flow is confined to the boundary layer, in which the fluid velocity changes from zero at the solid surface to the free flow velocity at the boundary layer.

At the wind tunnel of the Centre of Building Studies, the boundary layer develops naturally over a rough floor with the assistance of some passive devices. This implies that different wind tunnel floor roughness develop conditions representative of different terrain exposure.

The carpet on the floor of the tunnel represents Exposure A as per the National Building Code of Canada i.e., Open Exposure. The vertical distribution of the mean velocity and the longitudinal turbulence intensity for the open country terrain is shown in Figure 3.20. By using the power law equation, the best fitted velocity profile exponent is estimated as 0.15 for this open country exposure. The set up of the wind-tunnel along with the instrumentation is shown in a schematic diagram in Figure 3.21.

Appendix 2 provides the basic definitions of the terms used in the present study. The parameters of the full-scale and the wind-tunnel simulation are shown in Table 3.1. The parameter Z_0 represents the roughness length, Z_g is the gradient height, α is the power law coefficient and C_g is the geostrophic drag coefficient. They imply a geometrical scale of about 1:400.

3.11 DETAILS OF THE MODEL

For the present study, three models of scale 1:100, 1:200 and 1:400 of the experimental building were made. All the three models were made out of special sheet metal. The dimensions of the various models are shown in Figure 3.22. The tap location for various models is shown in Figure 3.23. Parapets of 0.05, 0.10, 0.15, 0.20 and 0.25 m were tested on each of these building models. Parapets for so small models posed a challenge. The parapets were made by a very thin sheet

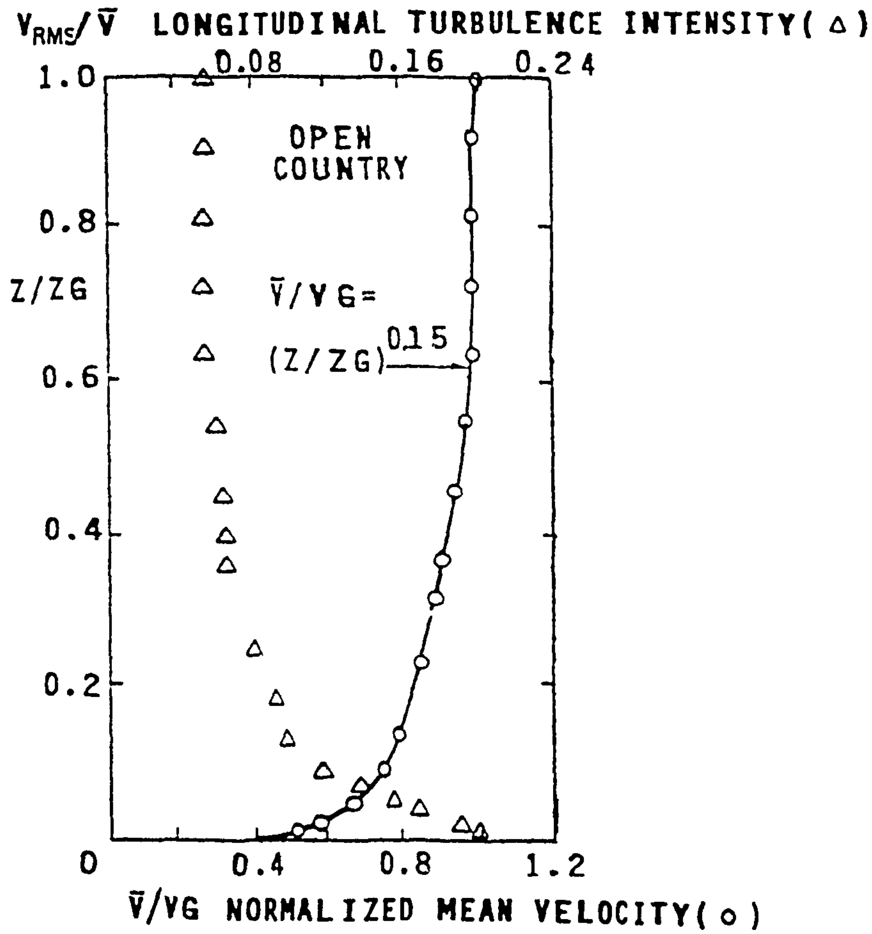


Figure 3.20 Mean Speed and Turbulence Intensity Profiles for Open Country Terrain Exposure at CBS Wind Tunnel

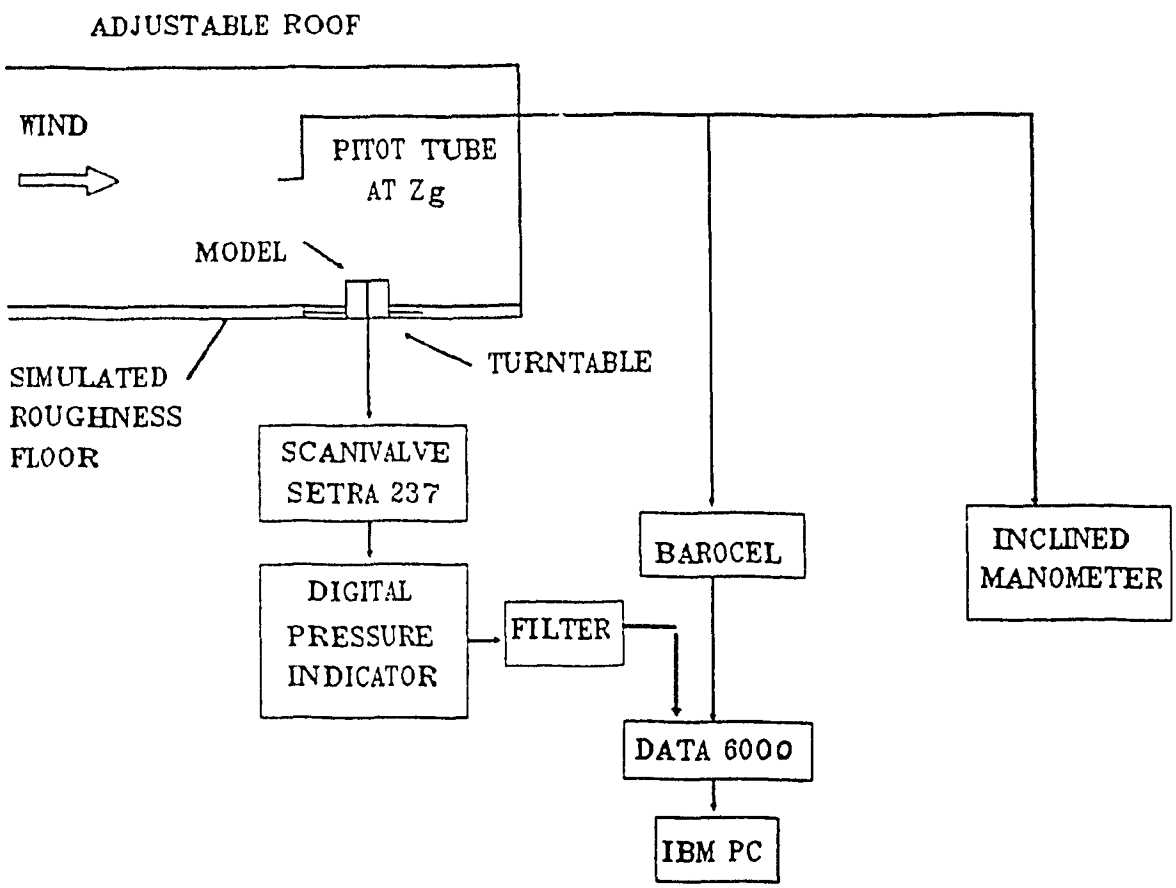


Figure 3.21 **Experimental Setup for Present Study at CBS Wind Tunnel**

of metal and were fixed around the roof of the building models with scotch tape. Various parapet heights were marked on the sheet metal to facilitate the attachment of the parapets at the correct height.

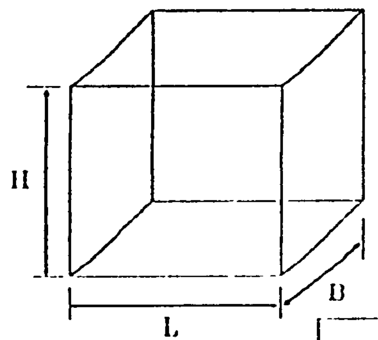
3.12 DATA ACQUISITION AND INSTRUMENTATION

The objective of the measurements was to evaluate the mean pressure coefficient for each of the pressure taps. The pressure was measured by using Setra 237 dynamic pressure transducers (0.1 psid range) placed in a scanivalve. Pressure taps on the roof of the model were connected to the scanivalve through a short plastic tubing with internal diameter 1.6 mm. The velocity in the tunnel was measured by a pitot tube, placed at a height of 600 mm above the floor of the tunnel.

The data collection was done using a DATA 6000, a Uniform Wave Form Analyzer facility. The instrument has 4 input channels, and is equipped with a small screen to view the signal. Programs are available to find the mean, maximum, minimum, rms, etc. of the input signal. For the present experimentation, two programs were written, one for the calibration and the other for the evaluation of Cp(Mean). The mean pressures obtained were normalized by the velocity at the pitot tube height and then reduced to the roof height by using the height factor listed in Table 3.2. The height factor is calculated in the following manner(for 1:200 model) :

PARAMETERS	FULL-SCALE (Open Country)	WIND-TUNNEL (Open Country)
Zg	200-270 m	0.60 m
Zo	0.001-0.20 m	0.0001
α	0.16	0.15
Cg	0.042	0.042

Table 3.1 Parameters for Full-Scale and Simulated Flow Conditions



	FULL SCALE (m)	MODEL SCALE 1:400 (mm)	1:200 (mm)	1:100 (mm)
L	3.7	9.2	18.5	37.0
B	2.6	6.5	13.0	26.0
H	3.3	8.2	16.5	33.0

Figure 3.22 Building Models Tested

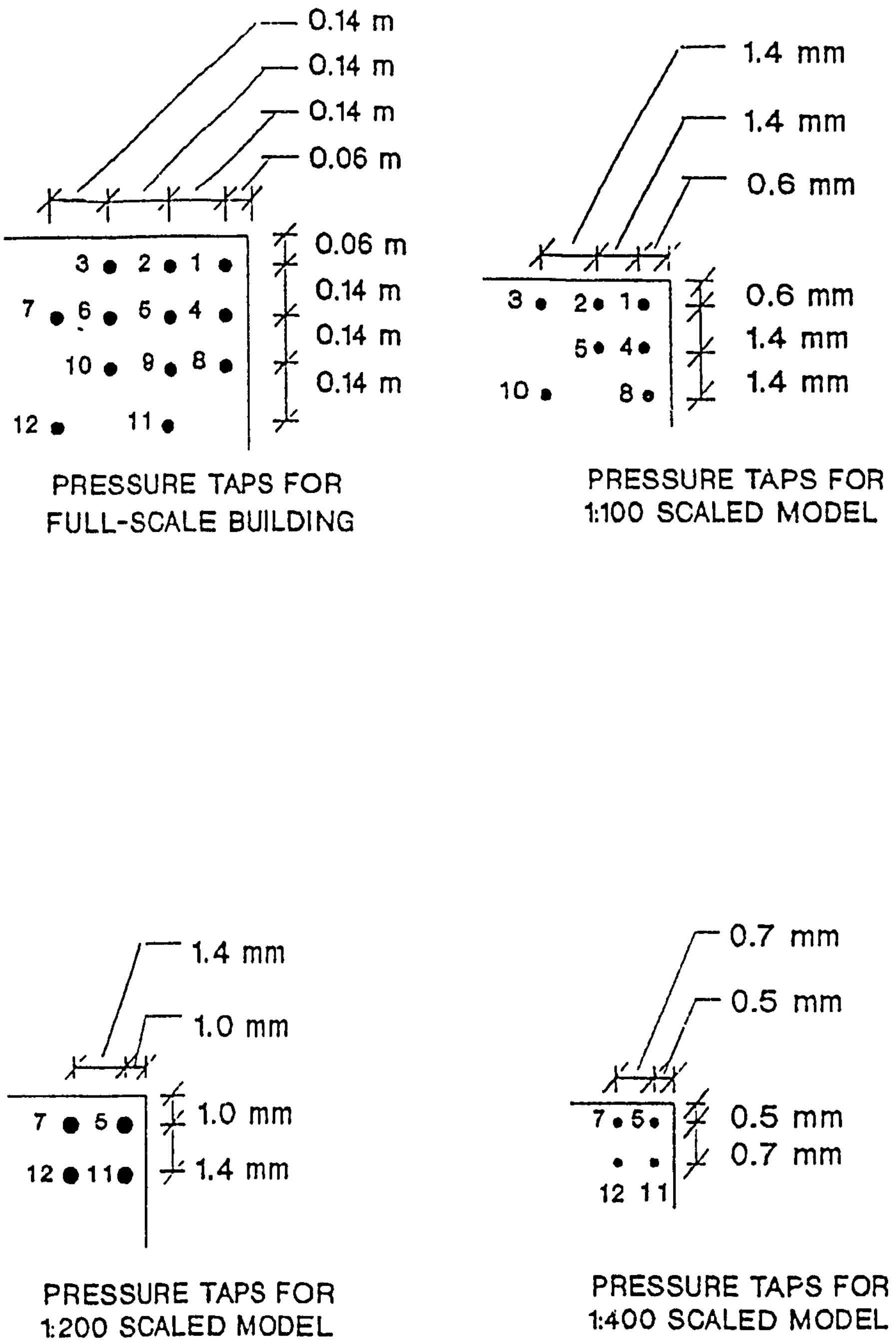


Figure 3.23 Tap Locations for Various Models and Full-Scale

Using the Power Law as defined in the Appendix 2,

$V_r = V_z * (16.5/600)^{0.15}$

$(V_r)^2 = V_z^2 * (0.58)^2$

in which

z = Height at which wind speed is measured (600 mm)

z_r = Height of Roof (16.5 mm)

V_z = Velocity at height z

V_r = Velocity at height z_r

Now, substituting the value of $(V_r)^2$ in the equation of Cp(Mean) as defined in Appendix 2, the value of Cp(Mean) obtained in the wind tunnel at the height of pitot tube can be reduced to the roof height by multiplying by a factor $1/(0.58)^2$ i.e., 2.93 as written in the Table 3.2.

The data for the evaluation of Cp(Mean) was acquired for a period of 16 seconds with a sampling rate was 500 samples per second.

SIZE	BUILDING HEIGHT	HEIGHT FACTOR
1:100 MODEL	33 mm	2.38
1:200 MODEL	16.5 mm	2.93
1:400 MODEL	8.2 mm	3.64

Table3.2 Factors Relating Dynamic Pressure at Roof Height to Dynamic Pressure at Gradient Height

CHAPTER 4

RESULTS AND DISCUSSION

4.1 GENERAL

This chapter presents the results of the full-scale experimental work and their comparison with other full-scale and wind-tunnel studies. It also presents the measurement results of the model of full-scale building tested in the Boundary Layer Wind Tunnel of the Centre for Building Studies. The results of this test are compared with other wind tunnel studies as well. Experimental data are presented in terms of mean pressure coefficients and they all correspond to an open terrain exposure.

For better understanding of the full-scale and wind-tunnel results and their comparisons, this chapter has been divided unto three sections. Full-scale experimental results are presented in the first section. The results of the models tested in the Boundary Layer Wind Tunnel of the Centre for Building Studies are in the second section while the last section deals with the comparison of the full-scale and the wind-tunnel results. At the end, a comparison of the results of the present study with other wind-tunnel studies is made.

4.2 REPEATABILITY OF DATA

During the entire experimentation process, periodic checks were applied to the data to confirm repeatability. Figure 4.1 shows the repeatability of data for various taps. The two sets of mean pressure coefficient data marked 1 and 2 in parenthesis were measured at a time interval of at least one month. The data shows good repeatability at the various stages of experimentation which also provides a further check for the proper functioning of various instruments and the data collection system. The agreement between the two sets of data is particularly satisfactory considering the uncertainties in the evaluation of wind direction.

4.3 CONFIRMATION OF THE PRESENT STUDY RESULTS

It is important to establish the validity of the experimentation. This section deals with the comparison of data of the present study with some other full-scale and wind-tunnel studies. A brief review of the studies being compared is as follows:

The present study results are compared with the full-scale study of Mehta et al (1991) carried out on a roof with taps on the roof corner. In the study one of the roof corners was instrumented with 11 pressure taps. The tap closest to the corner was at a distance of 0.36 m from the edges. The results of this tap are compared with tap 10 of the present study.

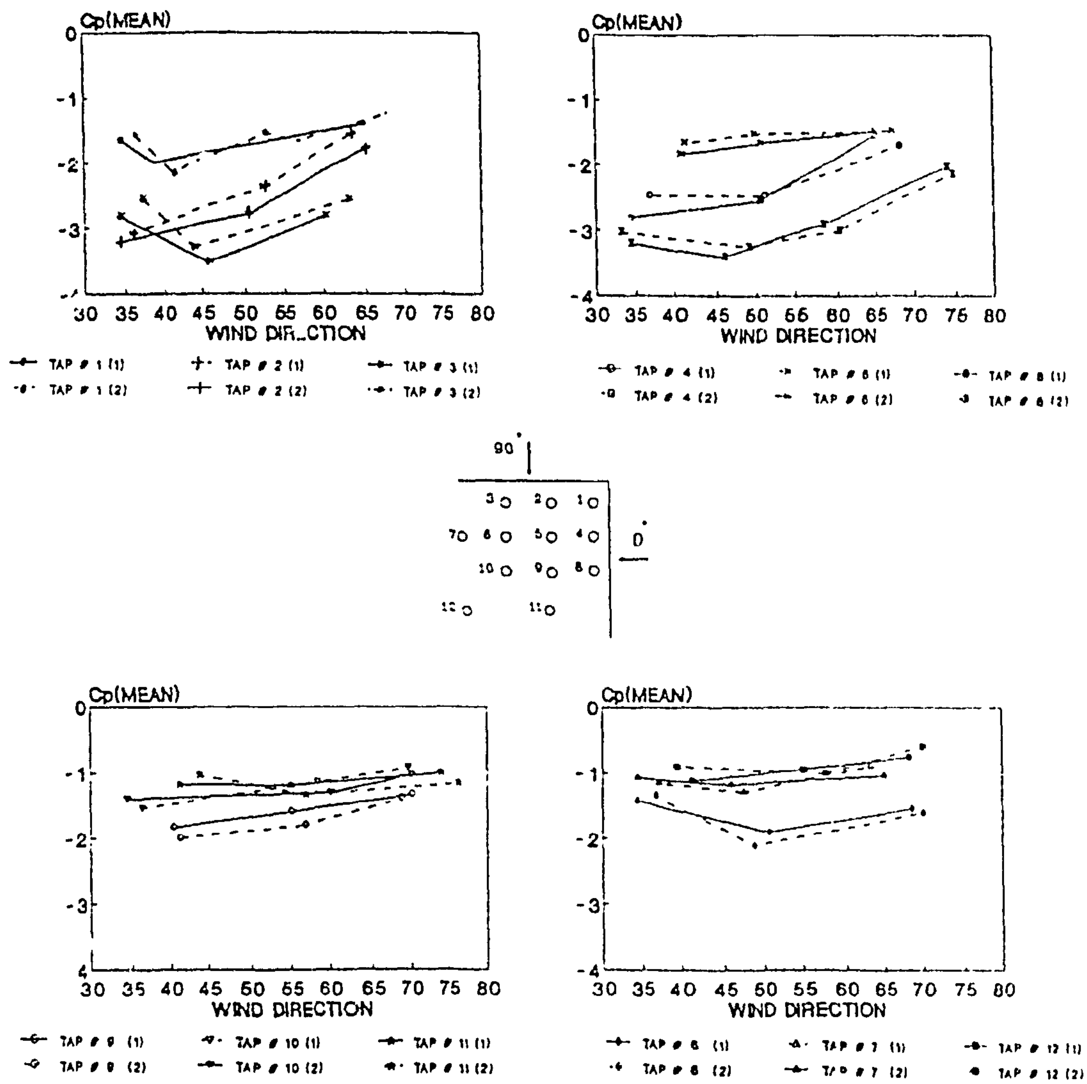


Figure 4.1 Repeatability of Data for Various Taps

Stathopoulos et al (1990) carried out some full-scale experiments on the same building with the same location and numbering of the taps with the present study.

Baskaran (1986) carried out a wind-tunnel study on a 1:400 scaled model of a 61 m by 61 m and 10 m high building with a flat roof. In the study, the tap closest to the roof corner was at a distance corresponding to 0.50 m (full-scale) from the corner of the roof. The results of this tap are compared with tap 12 of the present study.

Badian (1992) also carried out a wind-tunnel study on a 1:400 scaled model of the 61 m by 61 m and 12 m high flat-roofed building. In this work, the taps were very close to the roof corner and the closest one was at a distance corresponding to 0.30 m (full-scale) from the edges. The results of this tap are compared with tap 5 of the present study.

Data of the present study is available for a limited fetch ranging from 35 degrees to 75 degrees. Figure 4.2 compares the data for the taps 5, 10 and 12 of the present work with the results of the studies mentioned above. The selection of taps has been made on the basis of tap location availability in the previous studies. The figure on the left top side compares the data of tap 5 with those of Badian (1992) and Stathopoulos et al (1990). The data compares satisfactorily with Stathopoulos et al (1990) for 30 through 45 range azimuth , while there is some discrepancy

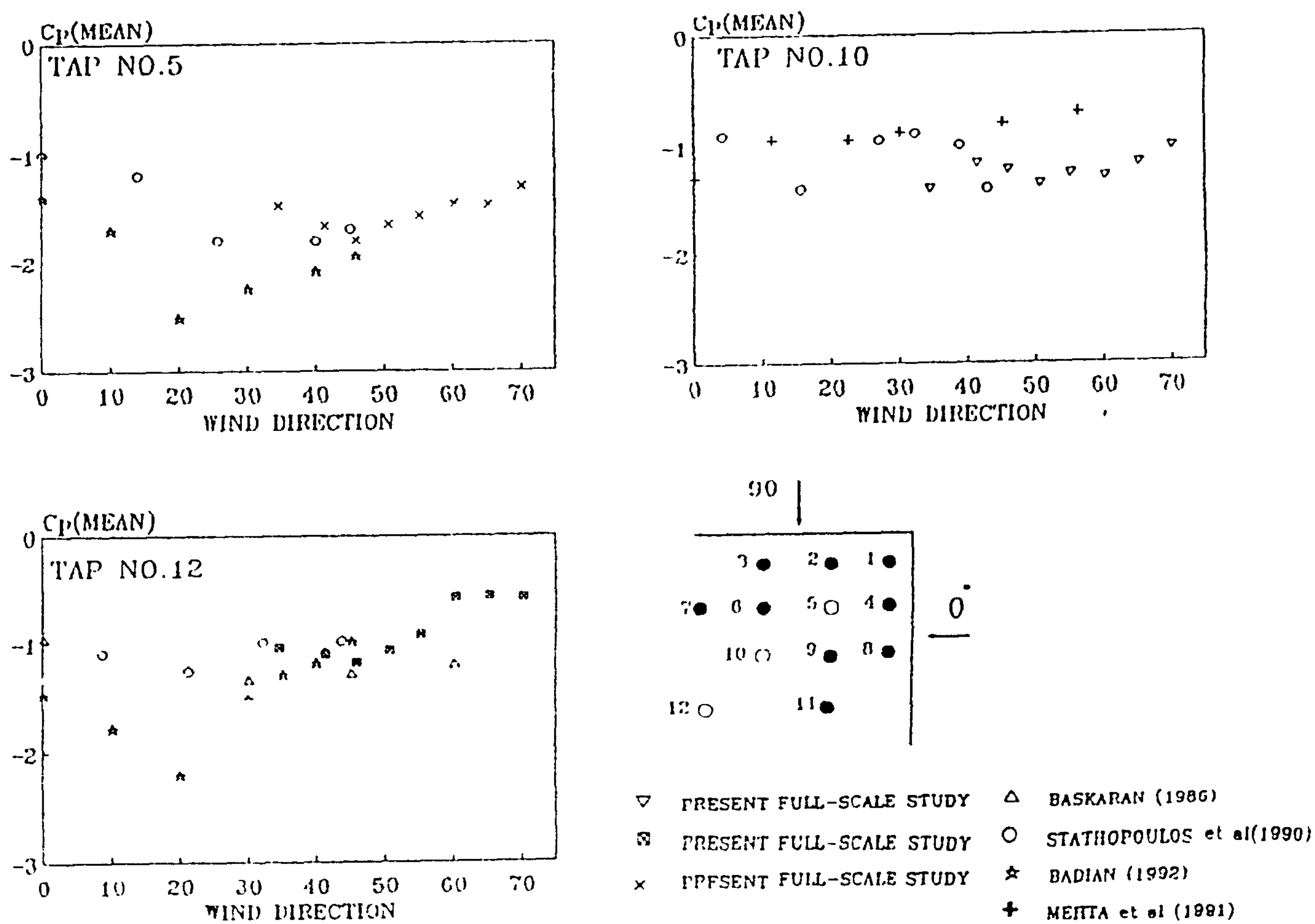


Figure 4.2 Comparison of Present Study Results with Other Studies

when compared with those of Badian (1992). This discrepancy can be attributed to the difference of building dimensions and the flow conditions. Results for tap 10 are compared on the top right hand side with the data of Stathopoulos et al (1990) and Mehta et al (1991). Again, the agreement with Stathopoulos et al (1990) is quite satisfactory, while there is difference with Mehta et al (1991). Data have been compared only for the 30 through 45 degree range of azimuth, the data have been compared. Comparison for tap 12 is made with studies of Baskaran (1986) and Stathopoulos et al (1990). All the three sets of data agree satisfactorily for the range of 30 through 50 degree azimuth.

4.4 WIND LOADS ON FLAT ROOFS

The present section shows the results of the full-scale study conducted to evaluate the effects of wind on flat roof corners of the experimental building. The results are presented in terms of mean pressure coefficients measured for different wind directions ranging from 35 degrees to 75 degrees, i.e., the most critical azimuths. The stability of the Cp(Mean) values, which are suctions referenced to the dynamic velocity pressure at roof height, is confirmed after extensive repeatability checks as shown in section 4.2. For better understanding of the variation of mean pressure coefficients. the taps along the edges, diagonal and more interior taps are organized separately in the presentation of the results.

Figure 4.3 shows the variatic of mean pressure coefficients, for edge taps, for

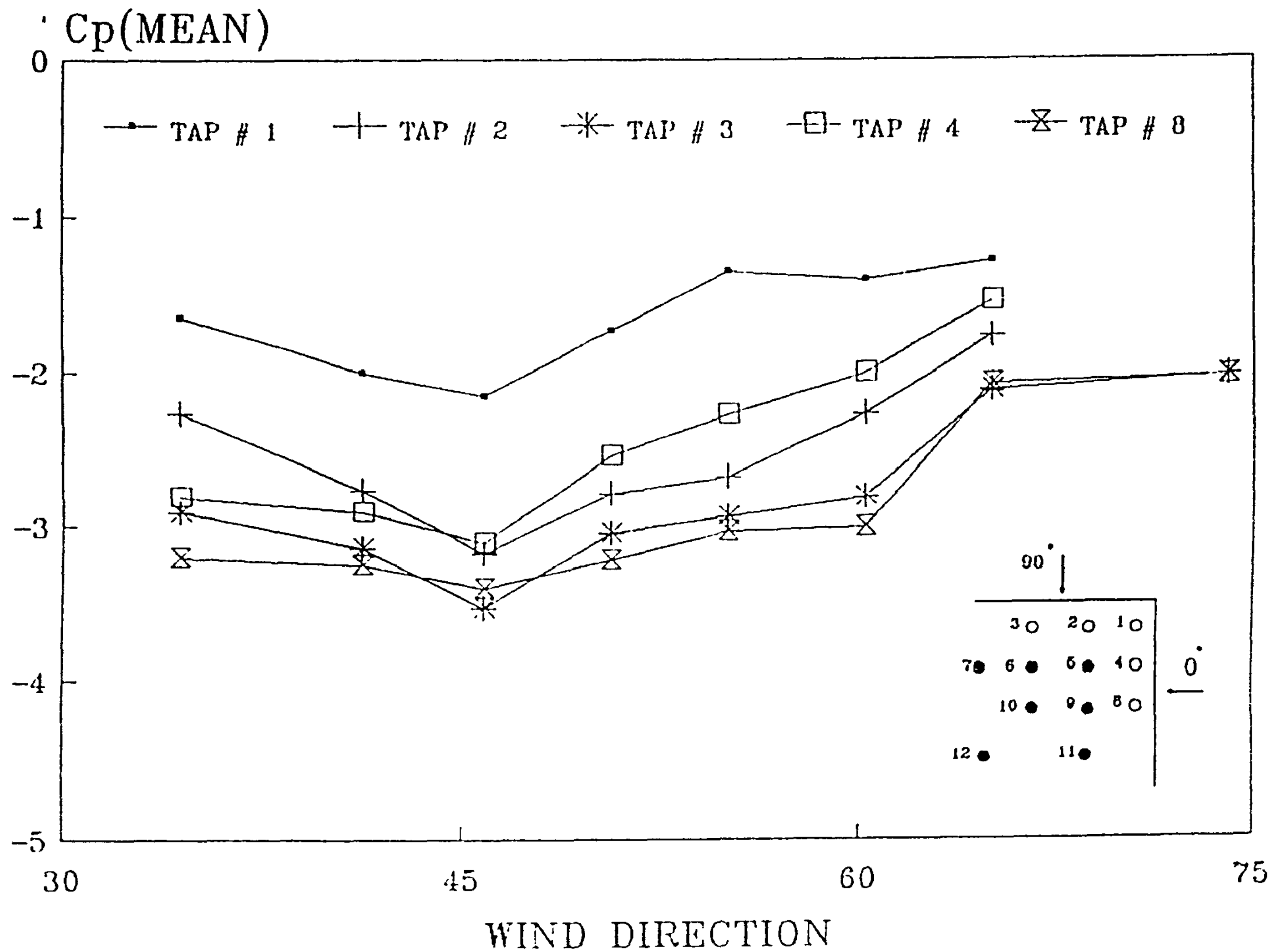


Figure 4.3 Mean Pressure Coefficients for Edge Taps (Flat Roof)

different wind directions. It is observed that the very corner tap 1 indicates lower suctions than the adjacent edge taps, which has been noticed in previous wind-tunnel studies, and attributed to the formation of the delta wing conical vortices gaining strength somewhat downstream along the roof edges after their formation. For instance, all the edge taps yield maximum suctions for 45 degree incident winds. This indicates that the strength of delta wing vortices formed at the corner is the highest for 45 degrees, which eventually leads to highest suctions in all the edge taps. Pressure taps 2 and 4 as well as 3 and 8 are symmetrical to the flow for 45 degrees, which leads to very similar Cp(Mean) values at the corresponding pairs of taps as expected.

The variation of mean pressure coefficients, for diagonal taps, for different wind directions is shown in Figure 4.4. For these taps, the Cp(Mean) suction is also maximum for 45 degrees. It is interesting to note the clear decrease of suctions for diagonal taps as compared to the edge taps. Because of the formation of the delta wing vortices at the edges which are far from the diagonal, the diagonal taps experience lower strength vortices yielding lower suctions. It should also be noticed that mean pressure coefficients decrease as the distance of the diagonal taps from the corner increases. Clearly, the effect of vortices developed at separation becomes less effective away from the corner.

Figure 4.5 shows the variation of mean pressure coefficients, for more interior taps

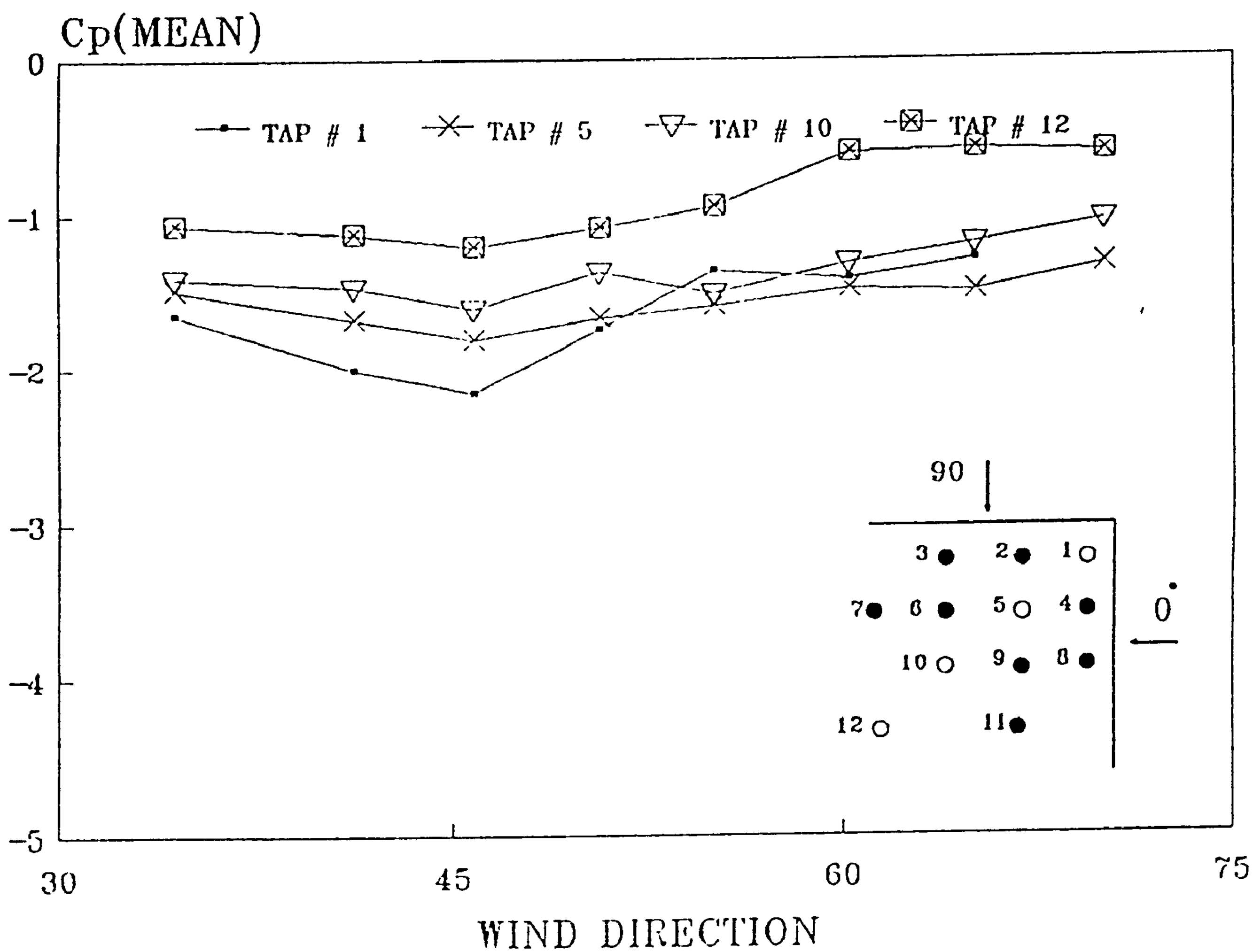


Figure 4.4 Mean Pressure Coefficients for Diagonal Taps (Flat Roof)

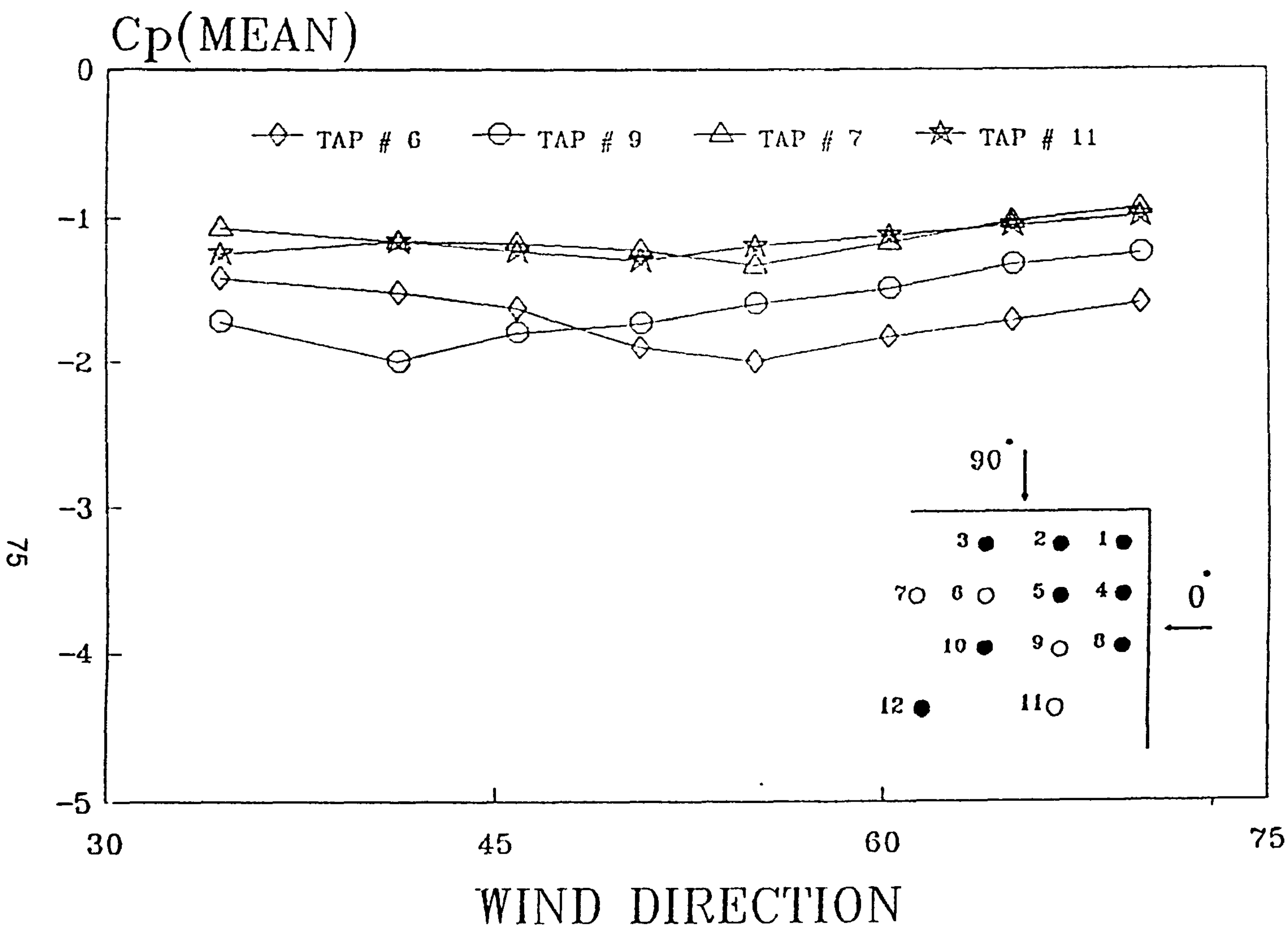


Figure 4.5 Mean Pressure Coefficients for Taps away from Edge (Flat Roof)

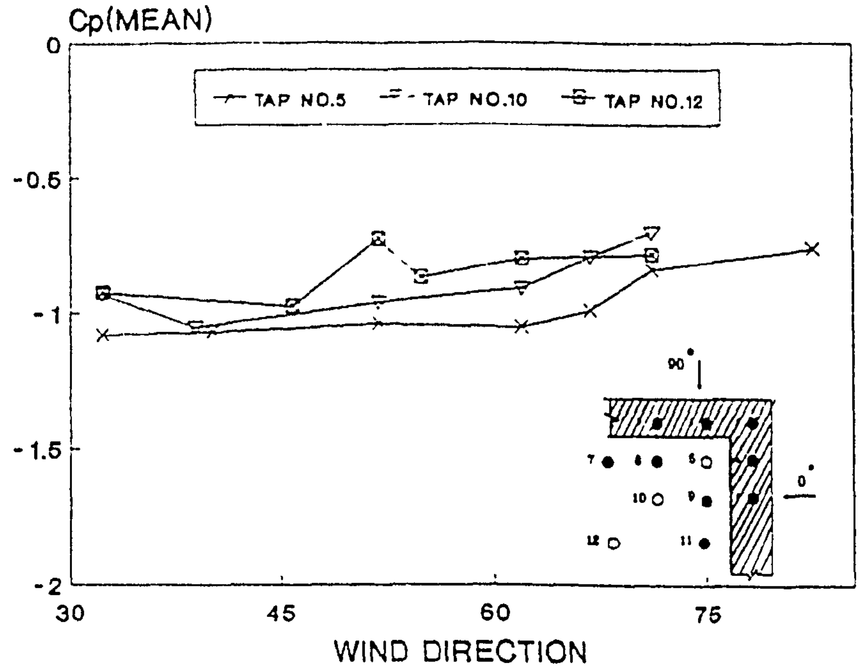
(6, 7, 9 and 11) for different wind directions. Taps 6 and 9 show higher suctions than those of 7 and 11, as they are closer tc the edge where the flow separates. For 45 degree oblique winds, Taps 7 and 11 show almost identical Cp(Mean) values as expected due to symmetry.

4.5 WIND LOADS ON FLAT ROOF WITH PARAPETS

In the second phase of the study, parapets were fixed on the roof. The objective of the study was to evaluate how the parapets affect the wind pressures on flat roof corners. As mentioned in Chapter 3, parapets of 0.25 m and 0.50 m high have been chosen. Due to the thickness of these parapets, some pressure taps are covered as shown in Figure 3.8. Only taps 5, 6, 7, 9, 10, 11 and 12 are available for pressure measurements in the case of parapets.

Initially 0.25 m parapets were fixed on the roof . Mean Pressure Coefficients for taps 5, 6, 7, 9, 10, 11 and 12 are plotted versus wind direction in Figure 4.6. The top graph covers the diagonal taps 5, 10 and 12; for tap 5 the highest suction is observed and the suction generally decreases as the distance from corner increases. This is similar to what has been noticed in the non-parapet case.

The bottom graph presents Cp(Mean) for taps 6, 7, 9 and 11. Taps 6 and 9 have higher Cp(Mean) values than taps 7 and 11. Taps 9 and 11 exhibit almost



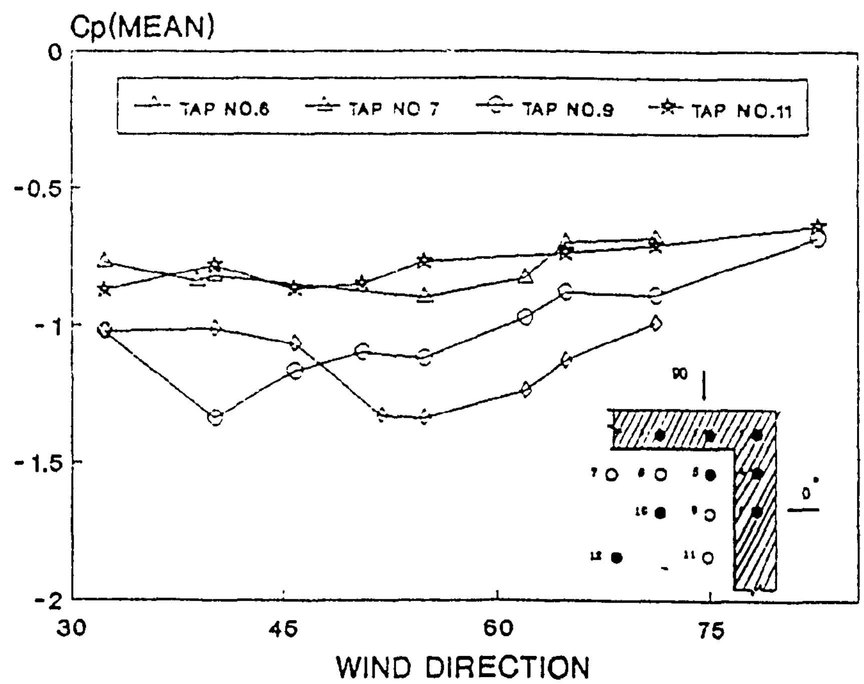


Figure 4.6 Mean Pressure Coefficients with h=0.25 m Parapets

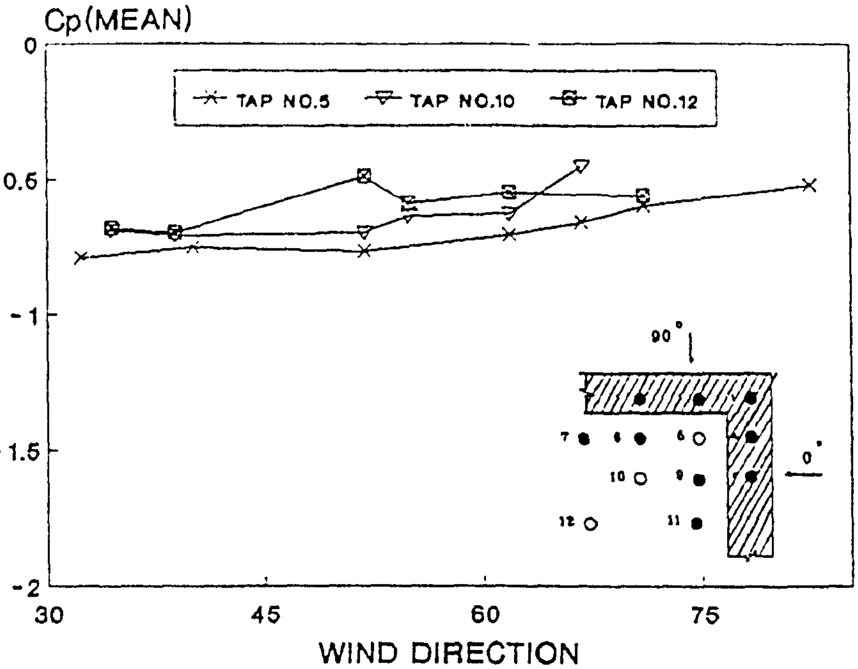
identical Cp(Mean) values over a range of azimuth. By comparing the top and bottom graph, it can be observed that taps 6 and 9 have higher Cp(Mean) values than tap 5. This phenomenon may be attributed to the vortices developed in the region.

Parapets of 0.50 m were also fixed on the roof in the second phase. Results for taps 5, 6, 7, 9, 10 and 12 are presented in Figure 4.7 in the same format with Figure 4.6. Tap 5 has higher mean suction values as compared to the taps 10 and 12, and taps 6 and 9 also display higher suctions as compared to taps 7 and 11. The trends are identical with those for the 0.25 m parapet case.

4.6 COMPARISON OF RESULTS OF FLAT ROOF WITH AND WITHOUT PARAPETS FULL-SCALE

In this section a comparison is made between the results obtained for flat roof with those for the 0.25 and 0.50 m parapets. This comparison sheds light on how parapets affect the roof corner wind loading. The results are presented for taps 5, 6, 7, 9, 10 and 11 and they are shown in Figures 4.8 and 4.9.

Figure 4.8 shows the comparison for taps 5, 6 and 7. All data show a decrease in suctions when the parapets are placed. With 0.25 m parapets, there is a clear reduction in suction by 25-30 percent of the values obtained for the flat roof case.



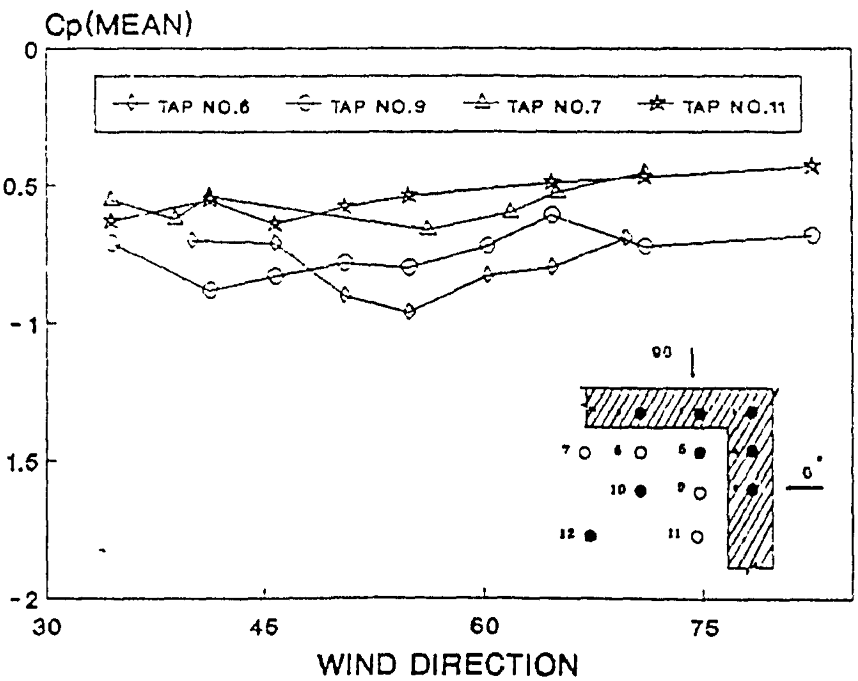


Figure 4.7 Mean Pressure Coefficients with h=0.50 m Parapets

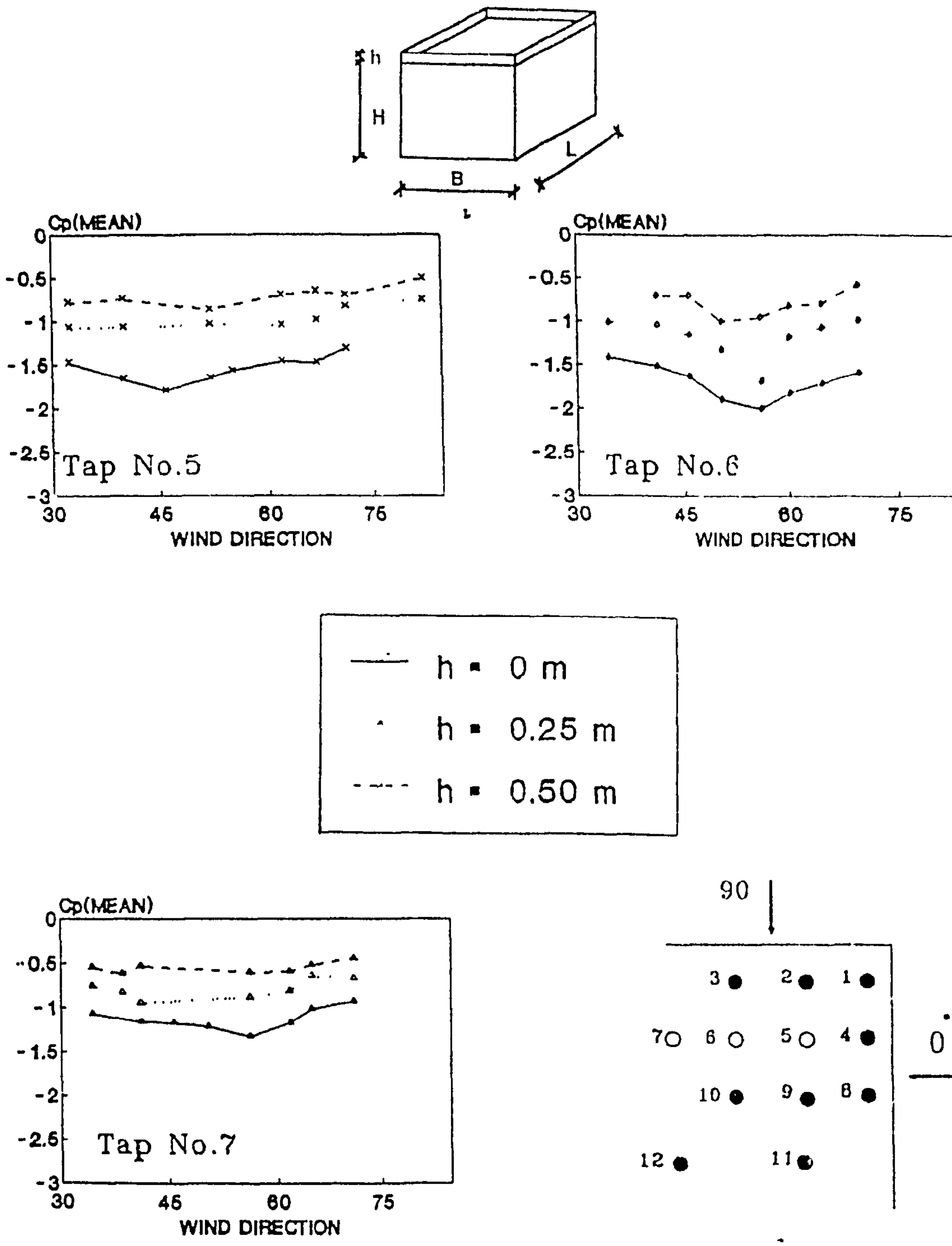


Figure 4.8 The Effect of Parapets on Mean Pressure Coefficients for Taps 5, 6 and 7

A further reduction in suction by 20-25 percent (of 0.25 m parapet values) is observed.

Figure 4.9 shows the results for taps 9, 10 and 11. These taps exhibit a similar trend of reduction in suctions for 0.25 and 0.50 m parapets as was observed in case of taps 5, 6 and 7 .

Thus, it can be clearly concluded that for the experimental building, low parapets 0.25 and 0.50 m high cause a reduction in the wind loads on roof corners. It appears that the higher the parapet, the higher the reduction. Similar trends of reduction of corner loads due to parapets have been reported by Columbus (1972), Kind (1974), Sockel and Taucher (1980) and Kramer (1985). For instance Sockel and Taucher (1980) did some wind tunnel experiments with models of 1.4 m high parapets on a tall building and found that parapets reduced mean pressure by about 50 percent.

On the other hand, wind tunnel studies by Baskaran (1986) with a model representing a building 61 m by 61 m and 12.5 m high have shown that in the presence of very low parapets (0.4-0.5 m), roof corner suctions are increased for 45 degree incident winds on the corner tap at a distance 0.50 m equivalent full-scale from the edge. Badian (1992) carried out a wind tunnel study with a similar building size (61 m * 61 * 10 m) with a very high density of taps very close to the

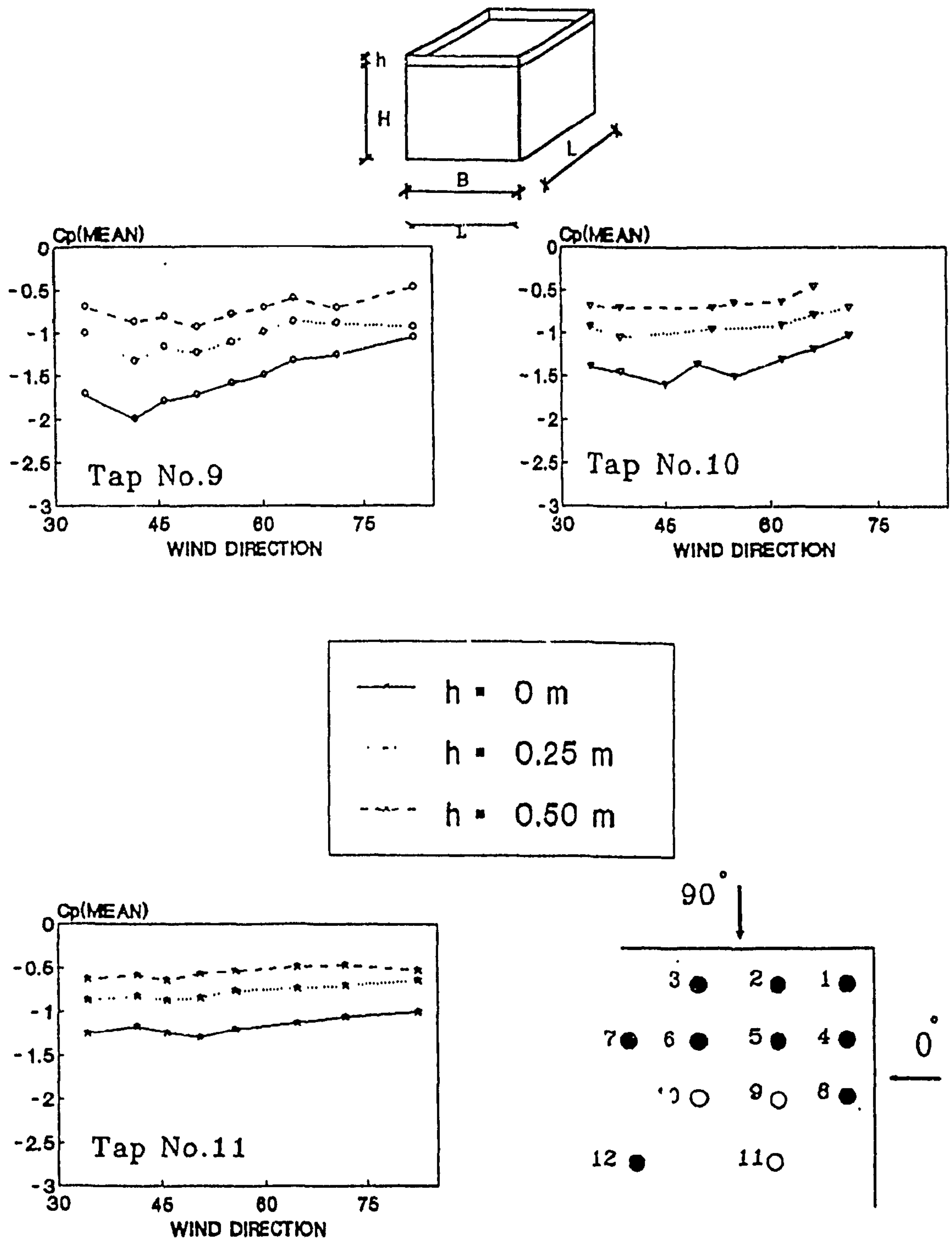


Figure 4.9 The Effect of Parapets on Mean Pressure Coefficients for Taps 9, 10 and 11

roof corner. The tap closest to the corner is at a distance of 0.30 m (full-scale). The study reported a similar trend of suction increase for corner taps in presence of very low parapets as found by Baskaran (1986). Also both studies show that for higher parapet heights there is a reduction in the roof corner suctions, probably due to the fact that the parapet tends to lift the shear layer or the vortices farther from the roof surface. This phenomenon of suction increase has been reported in a couple of other wind-tunnel studies by Davenport and Surry (1974), Stathopoulos (1982) and Stathopoulos and Baskaran (1987).

4.7 MODEL TESTING

The present full-scale study shows a decrease of roof corner suctions in the presence of low parapets, while findings of recent wind-tunnel studies appear contrary to these results. In order to resolve this inconsistency, wind tunnel tests were undertaken.

Three models (in scales 1:100, 1:200 and 1:400) of the full-scale experimental building were constructed. The 1:400 model, which is in the appropriate geometric scale for the wind tunnel of the Centre for Building Studies, is very small (9.2 mm by 6.5 mm and 8.2 mm high) and, therefore, the edge taps cannot be drilled on the roof of the model. The 1:200 and 1:100 scaled models facilitate the location of taps closer to the roof edge. A small relaxation of scale (up to a factor of 2 to

3) is not expected to critically affect the experimental results as has been shown by Lee (1982) and also shown by Stathopoulos and Surry (1983). On the other hand larger models can be fabricated and instrumented more easily, pressure taps can be located closer to the edges and pressure measurements have better frequency response. The construction of these tiny models posed a big challenge. Traditionally, plexiglass is used for the fabrication of wind-tunnel models. However, in the present case due to the very small size of the models, sheet metal was chosen as fabrication material. The construction of 1:400 scaled model required a high level of workmanship. Figure 3.22 shows the dimensions of all three models along with their full-scale dimensions. Figure 3.23 shows the pressure tap locations on the three models along with those of the full-scale building.

The flat roofed models were tested first without parapets and then for parapets of 0.05 m, 0.10 m, 0.15 m, 0.20 m, 0.25 m and 0.50 m height. Tests were run for 30, 45 and 60 degree azimuth wind. The Reynold's number for the three models based on their height was 17000, 7700 and 3400 respectively. Only for 1:100 scale model, the number was above the critical value of 10,000.

4.8 RESULTS OF 1:400 SCALED MODEL

The 1:400 scaled model corresponding to the "right scale" for the present wind tunnel setting was first tested. As shown in Figure 3.23, taps 5, 7, 11 and 12 were available for measurement. The model was tested for flat roof (h= 0 m) for azimuth of 30 through 60 degrees. Parapet configurations 0.05 m through 0 50 m high were tested for 45 degree oblique winds since earlier studies by Stathopoulos and Baskaran (1987), Baskaran (1986) and Badian (1992) along with the present full-scale results have shown that this is the most critical wind direction.

Figure 4.10 presents the results for taps 5, 7, 11 and 12. A very interesting observation from the graph is that for parapet height of 0.10 m, all the taps exhibit an increase in suctions. However, for 0.25 and 0.50 m parapet heights, there is a reduction in suction which confirms the findings of the present full-scale study. For tap 5, there is a gradual reduction in suctions for parapet heights beyond 0.10 m. Tap 12 being farther away from the roof corner shows an increase of suctions for all the parapet heights. Further results of Tap 7 show reduction in suction for all parapet above 0.15 m. Tap 11 shows a similar trend as tap 7.

4.9 RESULTS OF 1:200 SCALED MODEL

Figure 3.23 shows that taps 5, 7, 11 and 12 are also available for measurement with the 1:200 scaled model. Figure 4.11 presents the results for these taps. Parapets of 0.05 m height, show increase in suctions for all cases although only for certain azimuths for taps 7 and 11. For tap 5, there is a gradual reduction in ıction for parapets higher than 0.10 m. pressure. For tap 12, all tested parapet

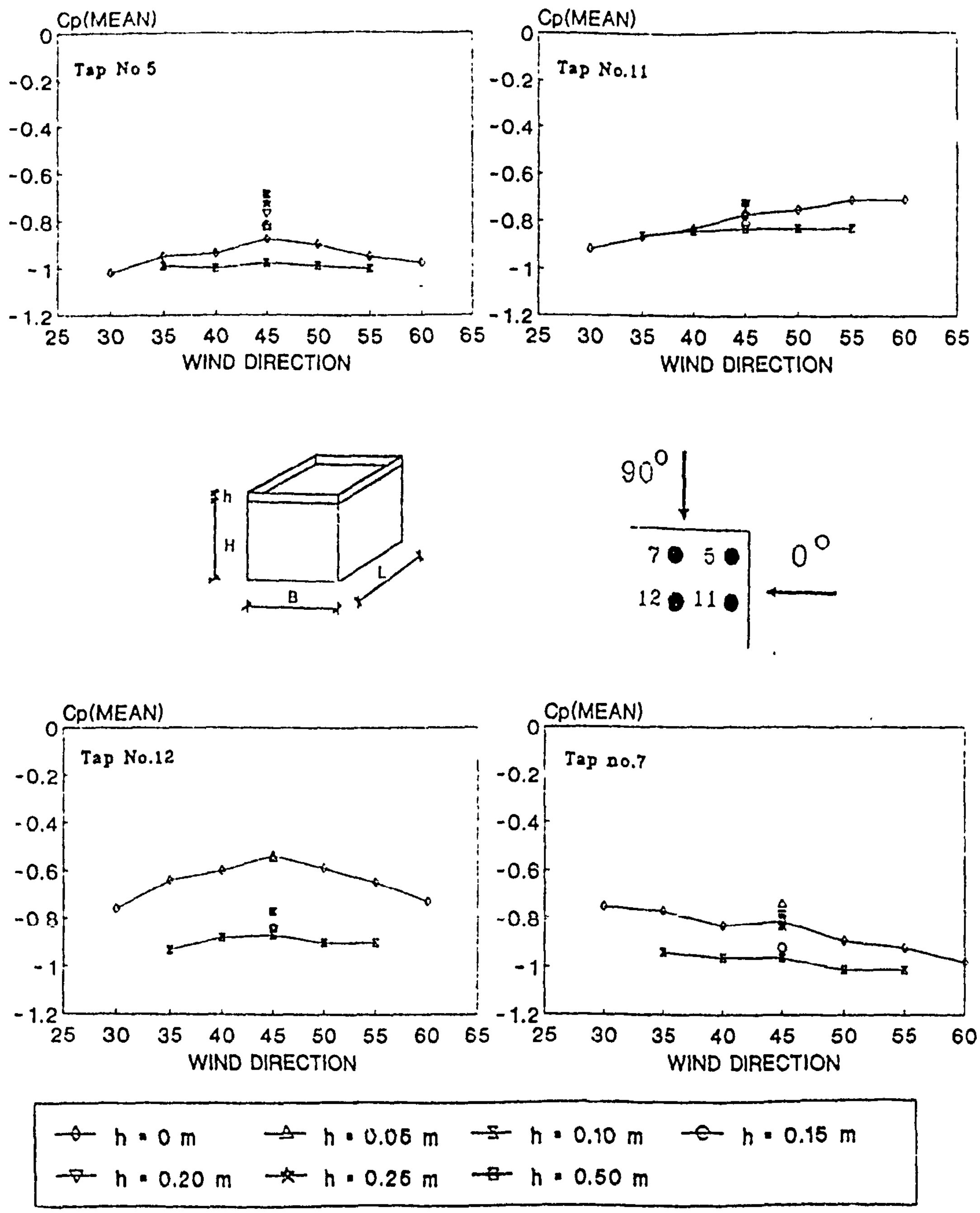


Figure 4.10 Mean Pressure Coefficients for 1:400 Scaled Model with Various Parapet Heights

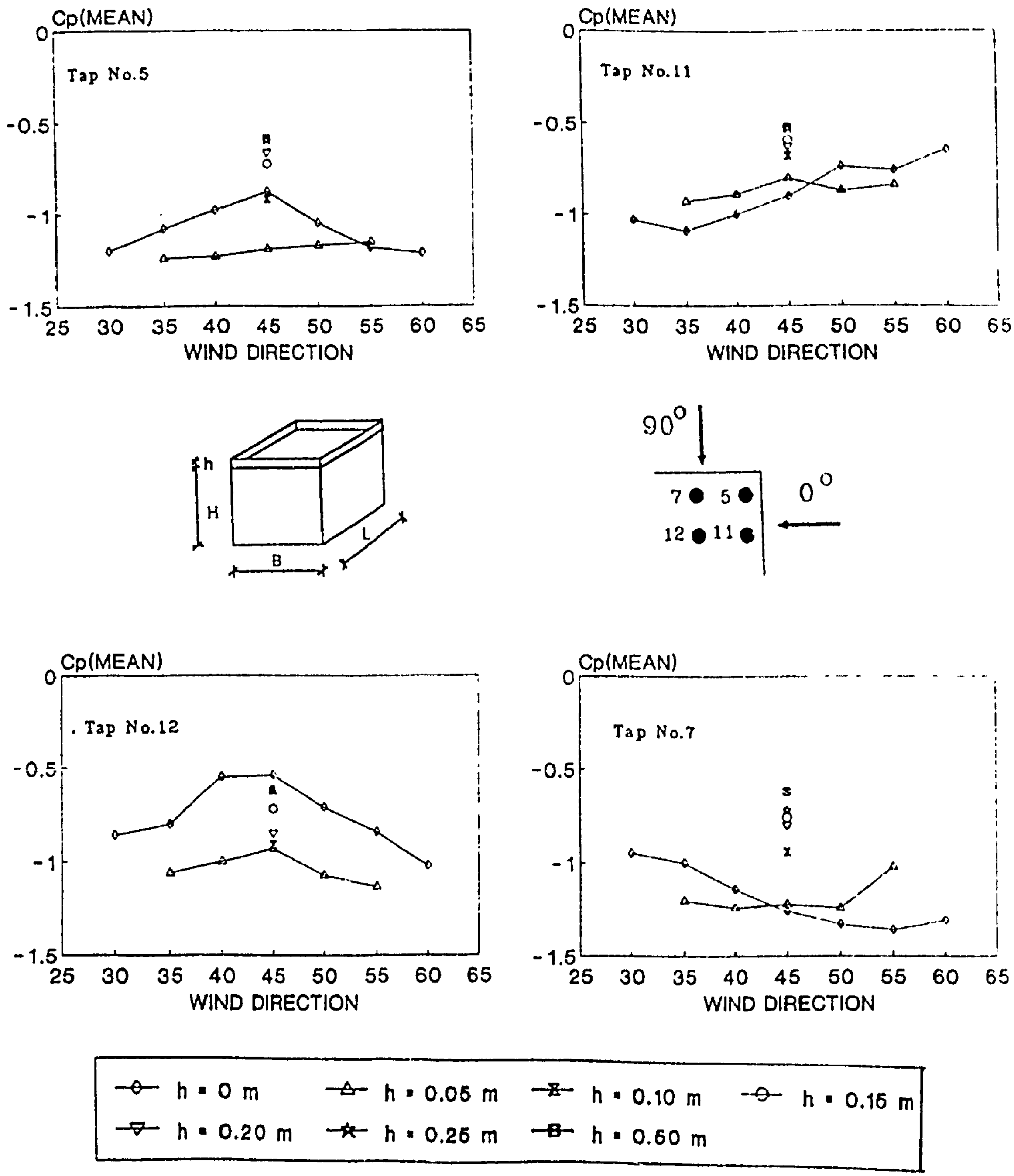


Figure 4.11 Mean Pressure Coefficients for 1:200 Scaled Model with Various Parapet Heights

heights cause an increase in suction. This phenomenon was also observed in the case of 1:400 scale model. Tap 7 shows a reduction of suction for all parapets above 0.10 m .

4.10 RESULTS OF 1:100 SCALED MODEL

The 1:100 scaled model was tested in the last stage of the wind-tunnel experimentation. Figure 3.23 shows taps 1, 2, 3, 4, 5, 8 and 10 available for measurement. Results for taps 1, 2, 4 and 5 are presented in Figure 4.12. Measurements for flat roof and 0.25 m parapet height are only for the azimuths of 30, 45 and 60 degrees. Parapets of 0.05 m height cause increase of suctions for only tap 1, while for taps 2, 4 and 5 there is reduction in suction for all the parapet heights tested. Further, for taps 2, 4 and 5 as the parapet height goes on increasing, the suction goes on decreasing. A clear trend of increase in suctions for flat roof is observed for 45 degree oblique winds for all four taps. The trend is similar to that observed for taps 1, 2, 4 and 5 in full-scale study.

4.11 COMPARISON OF FULL-SCALE AND WIND TUNNEL RESULTS FOR FLAT ROOFS WITH AND WITHOUT PARAPETS

A comparison of full-scale and wind tunnel data for flat roof and 0.25 m parapets is presented in this section. The taps included for this comparison are 5, 7, 11 and

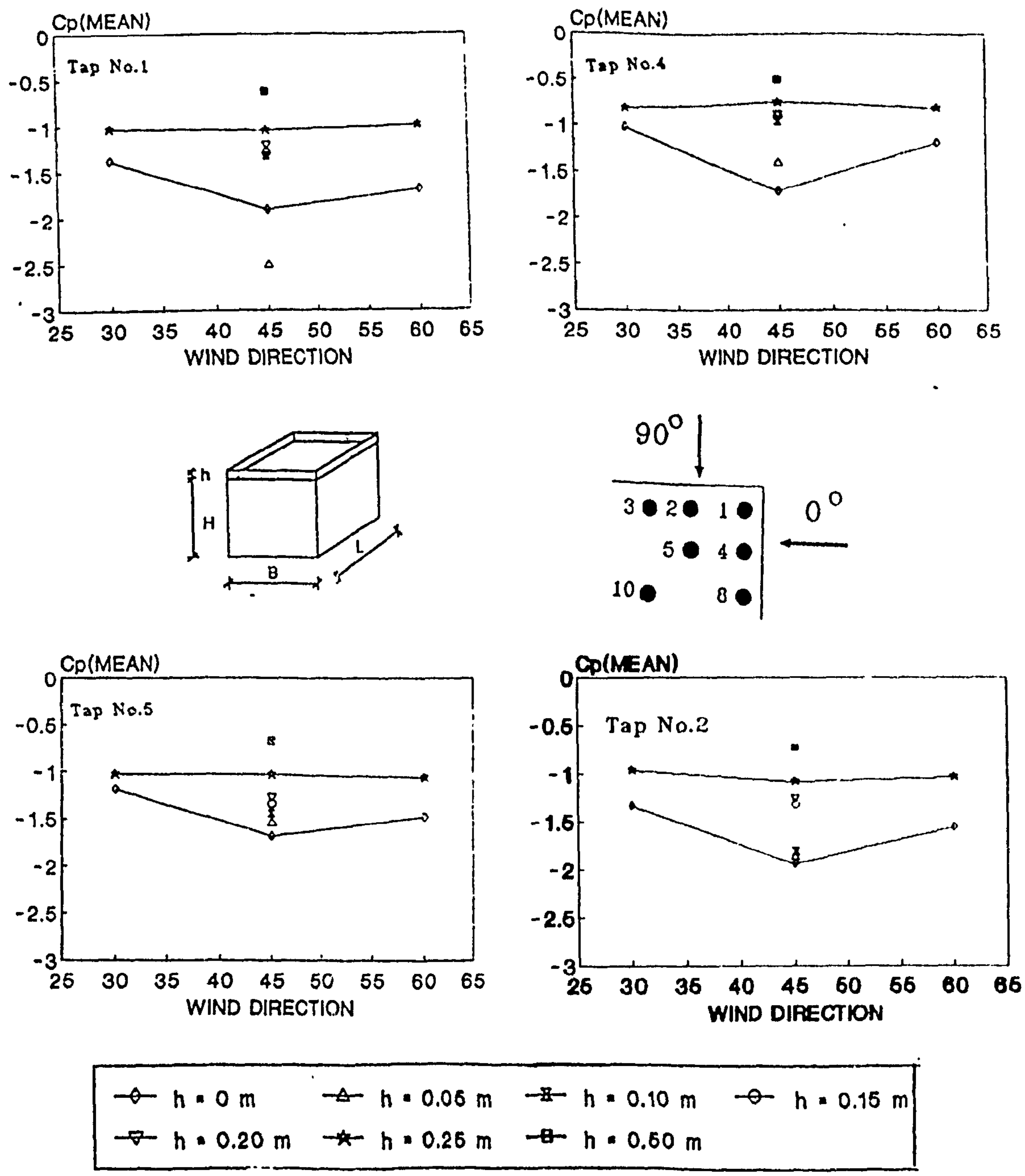


Figure 4.12 Mean Pressure Coefficients for 1:100 Scaled Model with Various Parapet Heights

12. The relevant data from taps 7 and 11 of the 1:100 scaled model is omitted since these taps are missing from the model. In addition, tap 10 results of the 1:100 model are substituted for those of tap 12 in the present comparison.

Figure 4.13 compares the results for a flat roof without parapets. Full-scale results of taps 5, 11 and 12 show highest suctions for 45 degree incident winds. The 1:400 scaled model shows generally the lowest suctions. It is observed that for each pressure tap as the model size decreases, the value of suction also decreases. A similar trend has been reported by Mohammadian (1986). For full-scale and the 1:100 scaled model, there is an increase in suctions for 45 degree incident winds. In general , the full-scale data compares reasonbly well with that from wind tunnel. Notable exceptions may be attributed to possible differences in the reference pressures, errors which have occurred in modelling the mean wind speed profile in the wind tunnel.

Figure 4.14 compares the data for 0.25 metre high parapets. For all the four taps, the data is in good agreement with the wind tunnel results.

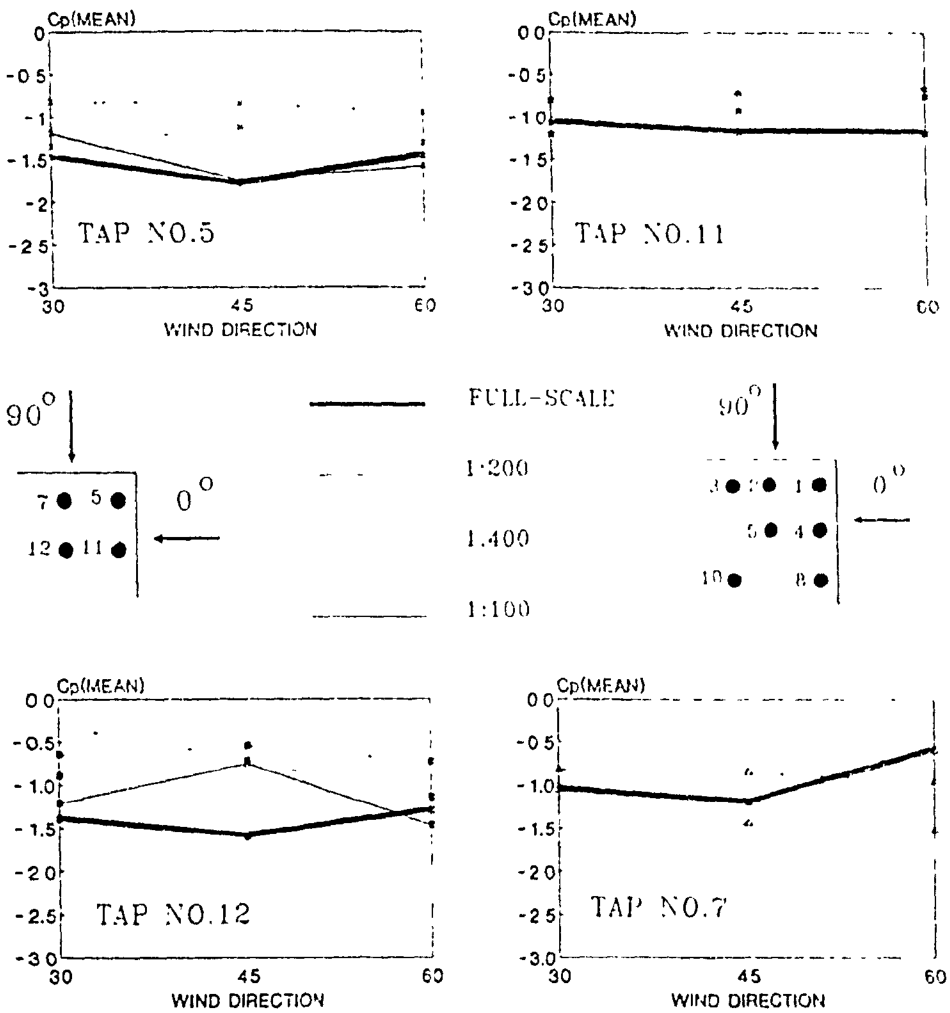


Figure 4.13 Comparison of Mean Pressure Coefficients for Various Models and Full-Scale - No Parapet

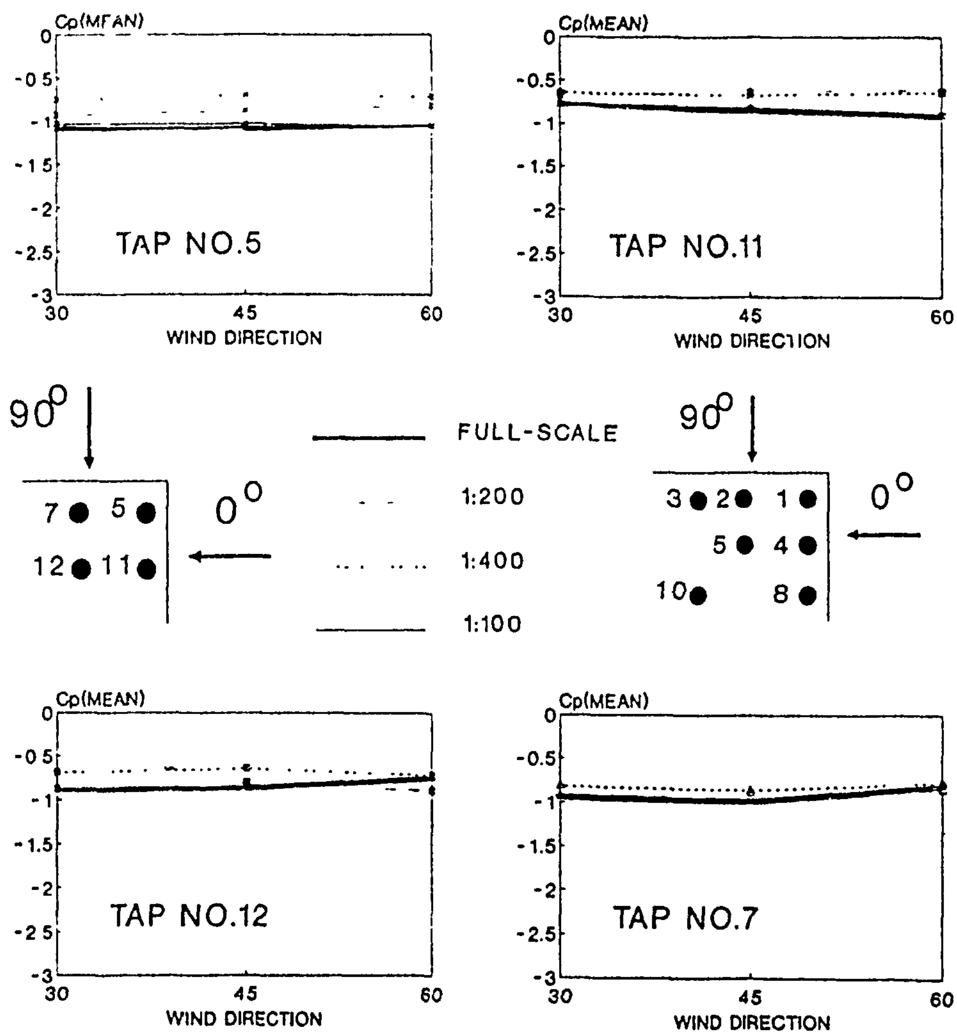


Figure 4.14 Comparison of Mean Presssure Coefficents for Various Models and Full-Scale - h=0.25 m Parapet

4.12 FURTHER COMPARISONS OF RESULTS

The wind tunnel study carried out for a model of the experimental building showed that for very low parapets i.e. 0.05-0.10 m, there is an increase in suctions as compared to those measured on the flat roof. However, wind tunnel studies by Baskaran (1986) and Badian (1992) showed that for 0.4-0.6 metre parapets the suctions increase on roof corners. This difference in the range of parapet heights prompted to look into the aspects of relative dimensions of the building tested in this study vis-a-vis the models employed in previous research works. Consequently, it was decided to plot the Cp(MEAN) results of the present study in terms of dimensionless ratio h/L (parapet height/building length). Data from Baskaran (1986) and Badian (1992) for larger building models and similar flow conditions have also been included in the comparison. Results are compared for tap 12 (distance from corner 0.48 m) because the wind tunnel studies by Baskaran (1986) and Badian (1992) have their taps closest to the corner at this (0.48 m) distance.

Figure 4.15 shows the results for tap 12 for 30 degrees incident winds. It has been observed that for h/L ratio less than 0.02 there is an increase in the suction measured for all previous studies including the present wind tunnel study. This

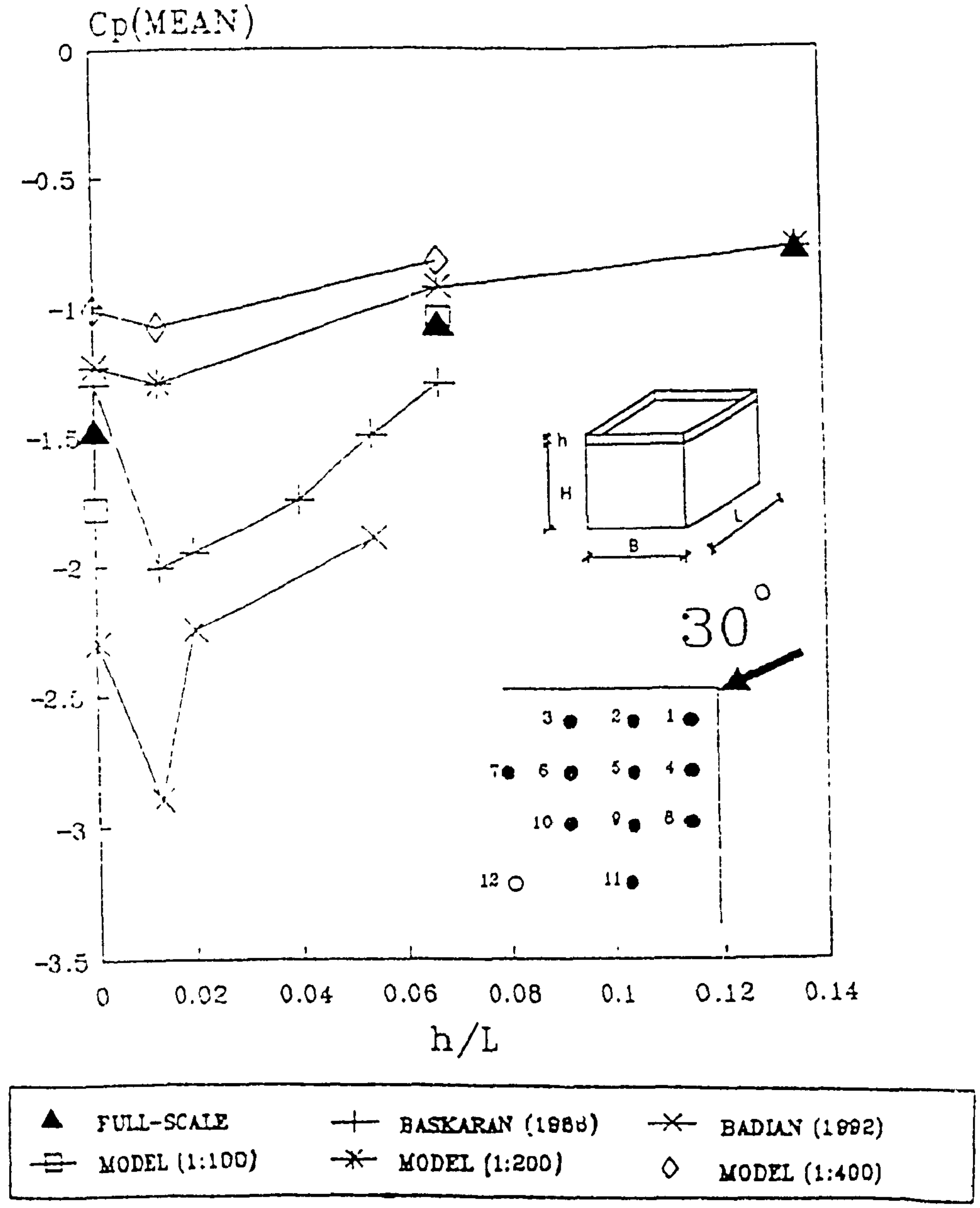


Figure 4.15 Comparison of Full-Scale, Model and Other Studies for Tap 12 - 30 Degree Azimuth

feature was not observed in the full-scale study, because no parapets less than 0.25 metre height were tested.

For 45 degree incident winds, similar results are presented in Figure 4.16. A very clear trend of increase in suctions for h/L ratio of 0.017 is observed. All studies compared, are in complete agreement with this observation, except for the full-scale, as no parapets less than 0.25 metre height were tested.

Figure 4.17 shows the results for 60 degree incident winds. Although, not much data was available for this particular azimuth, still the trend of increase in suctions for h/L less than 0.02 can be is observed .

In all studies compared, there has been difference in the values of Cp(Mean). This may be attributed to the difference in the dimensions of the buildings in the different studies and also to scaling effect as far as the present study is concerned. Kramer et al (1978) showed that for all h/B (Height of Parapet / Width of the Building) ratio less than 0.04, small parapets increase the wind loads. Only high parapets (h/B >= 0.04) will lessen the wind loads for all relative building heights. Thus, the findings of the present study are supported by the work of Kramer et al (1978).

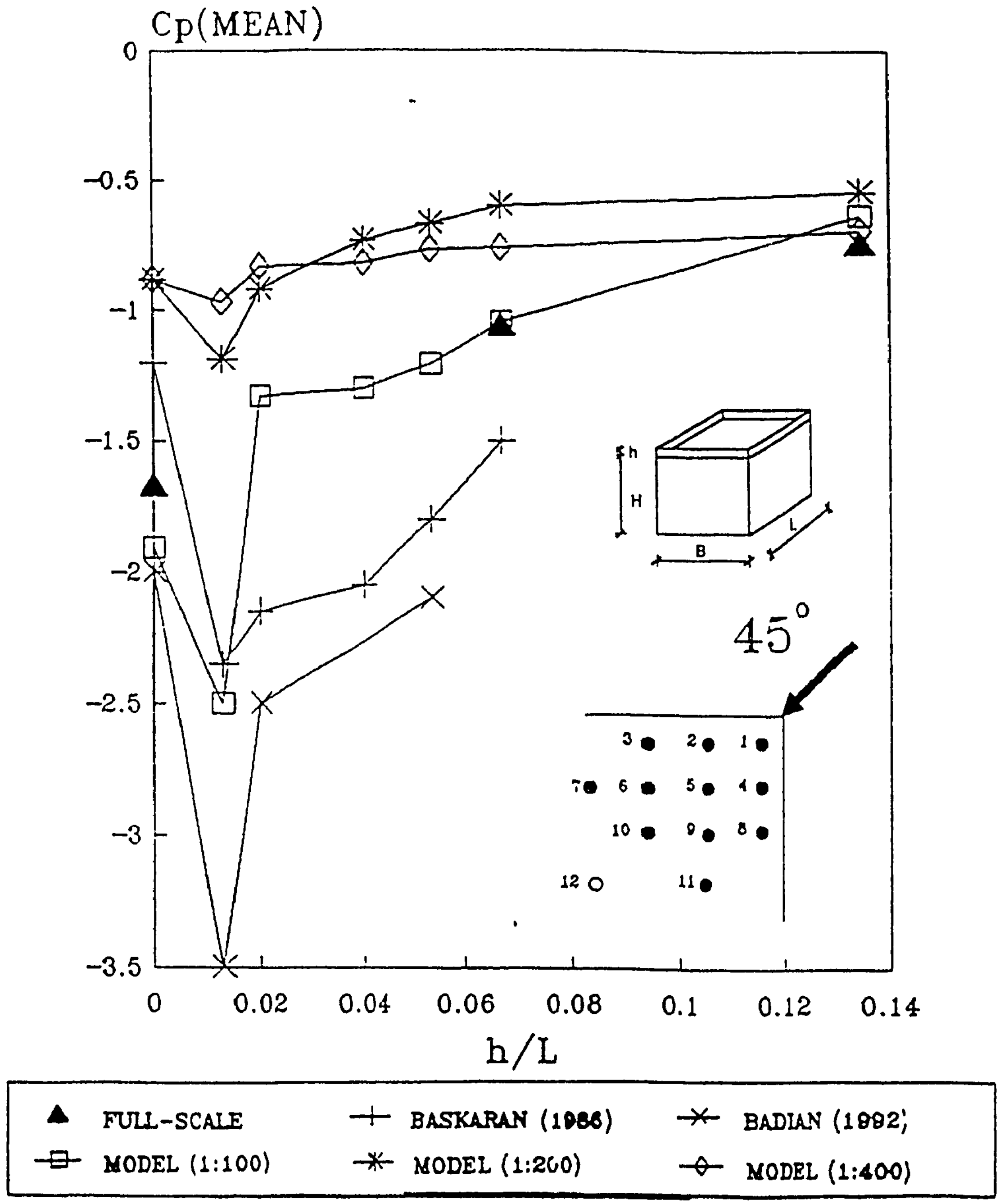


Figure 4.16 Comparison of Full-Scale, Model and Other Studies for Tap 12 - 45 Degree Azimuth

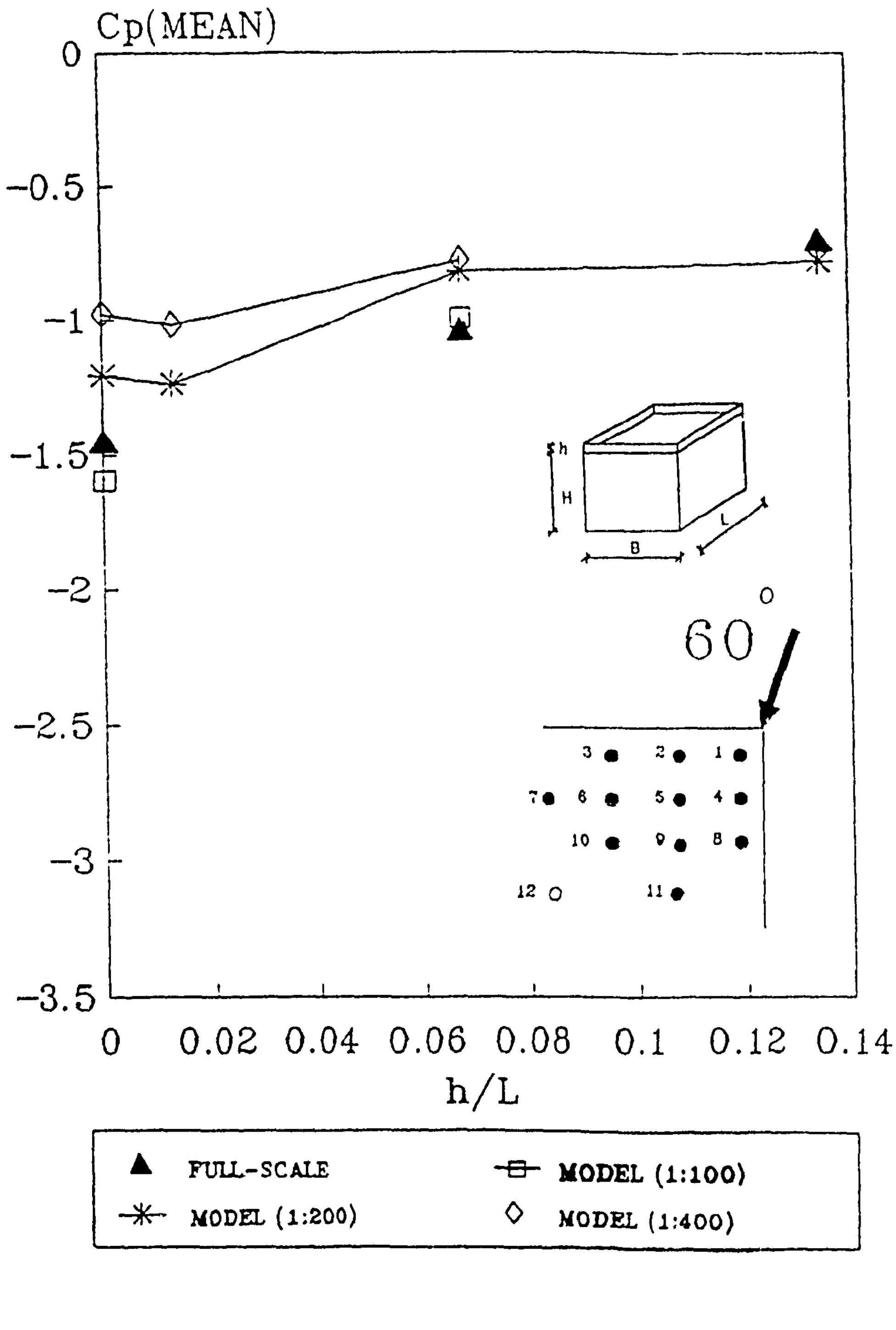


Figure 4.17 Comparison of Full-Scale, Model and Other Studies for Tap 12 - 60 Degree Azimuth

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

A full-scale study for the determination of wind loads on flat roof corners with parapets has been carried out. The study was supplemented by some wind-tunnel testing of the models. The full-scale study was carried out at the Loyola Campus of Concordia University and the wind-tunnel testing at the Building Aerodynamics Laboratory of the Centre for Building Studies.

Initially, wind loads were measured on a simple flat roof. Later 0.25 and 0.50 m parapets were fixed on the roof and again the wind loads were measured. Three models of scale 1:400, 1:200 and 1:100 were tested for flat roof and then with parapet heights ranging from 0.05 m to 0.50 m. All measurements both in the full-scale and in wind-tunnel have been for open country type of exposure and all results are expressed in terms of mean pressure coefficients.

The experimental results of full-scale experiments show that parapets of 0.25 and 0.50 m reduce the high suctions produced on the roof corners. Wind tunnel experiments with 1:400, 1:200 and 1:100 scaled models of the full-scale building revealed that very low parapets (0.05-0.10 m high), produced higher suctions than those obtained for flat roofs. With 0.25 and 0.50 m parapets, all models also showed a reduction in suctions, similar with the full-scale findings.

A further comparison with other wind-tunnel studies and plotting the data in terms dimensionless ratio h/L (parapet height/building length) have shown that the corner suction increases for h/L less than 0.02. However, this was not noticed in the full-scale data because such geometries had not been tested - the smaller parapet height gives h/L = 0.067. The results were consistent for oblique wind directions of 30, 45 and 60 degrees.

On the basis of these findings, it may be appropriate that the wind standards and codes of practice consider specifying pressure coefficients for roof corners with parapets in terms of h/L rather than h alone as it is currently the case.

More experimental results are required in order to expand these finding to medium and high-rise buildings. Much better understanding of the particular phenomena of increase in suctions can be achieved by carrying out flow visualization tests. Further full-scael measurements will be required to confirm the wind-tunnel data for low h/L values. Pressures on both sides of a parapet also need to be evaluated. The effect of parapet width must be examined in full-scale to provide more information about the roof corner wind loadings.

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APPENDIX 1

WIND CLIMATE OF MONTREAL

The city of Montreal experiences strong winds during the winter season and moderate to strong winds during the spring and fall season of the year. Because of severe winter conditions it is difficult to carry out field experiments between November and March. During the summer months the daytime temperature ranges from 15 to 35 degrees centigrade. In the present experiment the direction and speed of winds in Montreal were important.

A study of prevailing wind direction at the site is essential as the wind pressure changes with the azimuth of incident winds. The direction from which the wind blows depends on two main factors. The first is the atmospheric circulation aloft, which varies with the weather system passing over the region. The second in combination with the first, is the effect of local topography which tends to deflect the wind and slow it down.

Figure A.1 illustrates the annual frequency of each wind direction at the Dorval and St. Hubert stations as provided by Environment Canada. From the figure it can be seen that the winds coming from west-southwest blew thirty eight percent of the time, while those from north-northwest zone occur fifteen percent of the time.

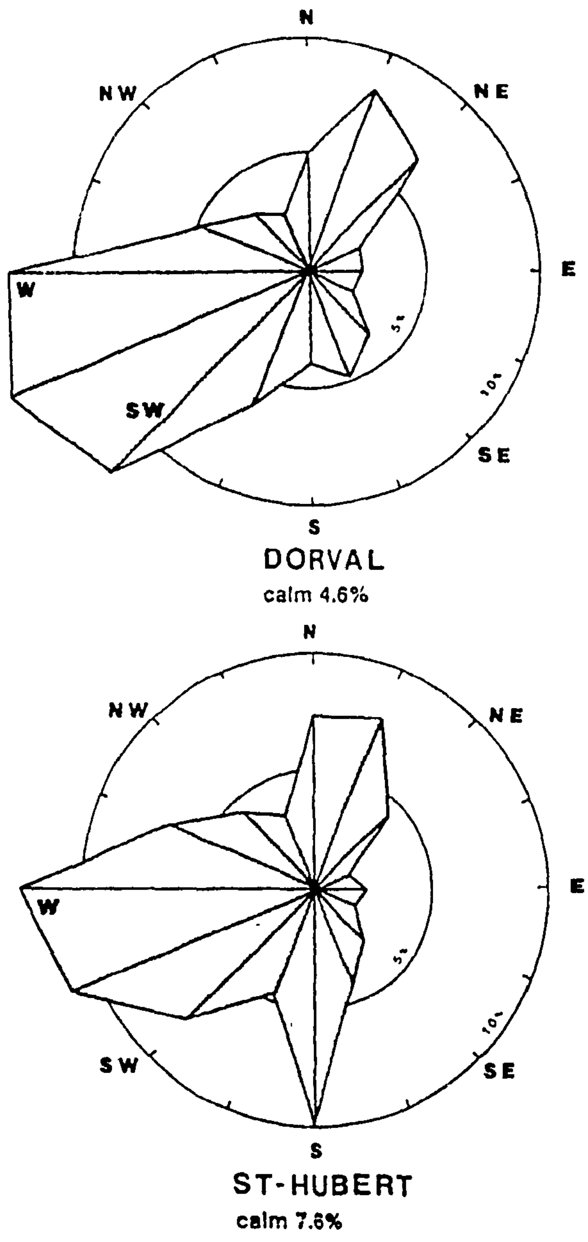
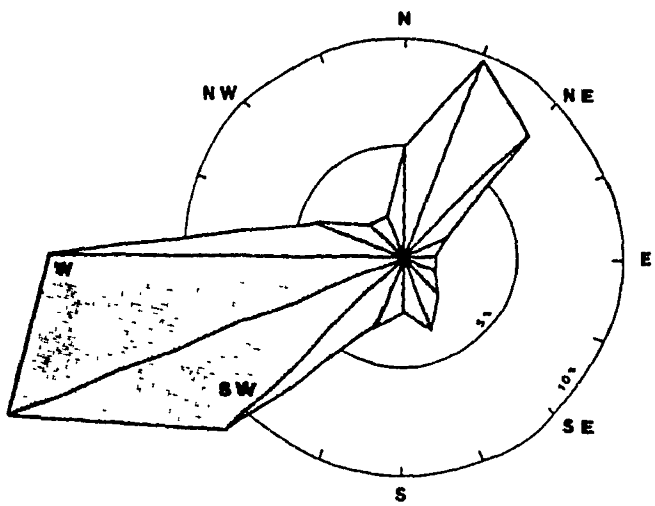


Figure A.1 **Annual Frequency of Each Wind Direction at Dorval and St.Hubert Stations, after The Climate of Montreal (1988)**

Figure A.2 shows seasonal variation in the frequency of wind direction at Dorval. As shown, only one sector predominates, centered on south-west.In winter the prevailing winds are centered on west-southwest. Figure A.3 shows the monthly variation of wind speed at the Dorval station.



JANUARY
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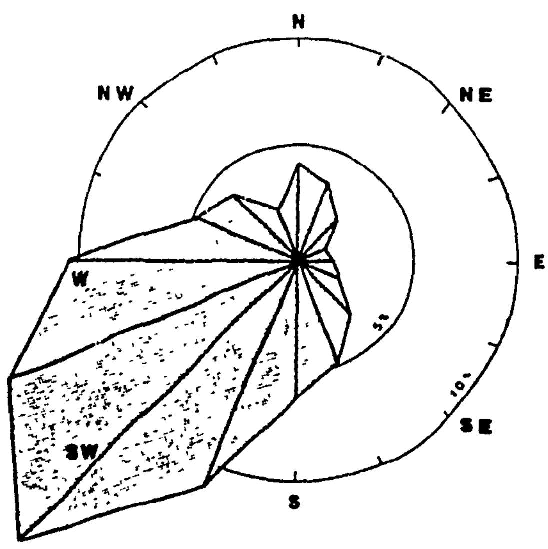

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Figure A.2 Seasonal Variation in the Frequency of Wind Directions at Dorval, after The Climate of Montreal (1988)

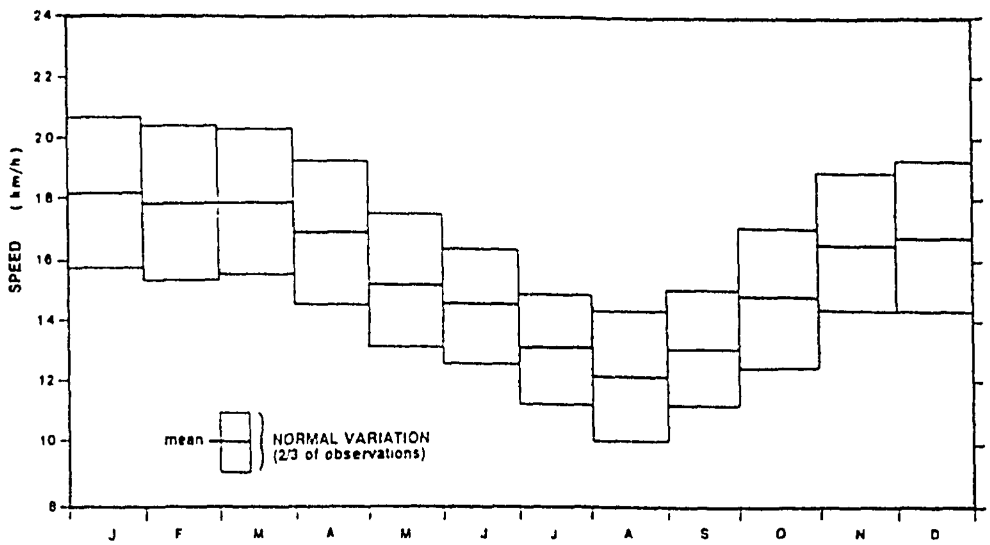

Figure A.3 Monthly Distribution of Wind Speeds for All Directions at Dorval, after The Climate of Montreal (1988)

APPENDIX 2

DEFINITIONS OF TERMS USED

Atmospheric boundary Layer : Atmospheric Boundary Layer (ABL) is the region of wind which is affected by earth's surface. Near the earths surface, the wind speed is reduced by the surface friction. At the earth's surface the wind speed reduces to zero.

Gradient Speed and Gradient height : The height at which the wind is free of earth's frictional influence is called the gradient height and the velocity of wind at the gradient height is called the gradient velocity. The upper limit of the atmospheric boundary layer is the gradient height.

Power Law: At the earth's surface the wind velocity is zero and in conditions of neutral stability, there is a continuous increase of mean wind speed from the ground to the gradient height. A number of laws for defining this wind profile have been suggested, the most widely used is the power law.

Power Law has the simple expression :

$$\frac{V_z}{V_r} = \left(\frac{z}{z_r}\right)^{\alpha}$$

V_r = Velocity at reference height, usually taken as the standard meteorological height of 10 metres.

V_z = Velocity at height z to be determined.

α = Power law coefficient its value depends upon the type of terrain above which the velocity is calculated.

Log Law : The logarithmic profile of the variation of mean wind speed with height, is given by

$$\frac{V_z}{V_*} = \frac{1}{k} * \log_e \frac{z}{Z_o}$$

where

z_o = Roughness Length

V_* = Friction Velocity

k = von Karman's Constant (0.4)

z = Height at which velocity is to be determined

V_z = Velocity at height z.

Pressure Coefficient: The pressure produced by the wind at a point on the external surface of the body acts normal to the surface, and is defined as the pressure difference between the total pressure at the point and some reference pressure. The reference pressure is usually taken as the static pressure of the approaching stream.

In non dimensional form, the pressure is expressed by a pressure coefficient defined as :

$$C_p = \frac{P - P_o}{\left(\frac{1}{2}\,\rho\, V_h^2\right)}$$

in which ρ is the air density and V_h is the wind velocity at height h.

Turbulence Intensity: A typical data of wind speed shows that it varies randomly with time. This variation is due to the turbulence of the wind flow. Information on atmospheric turbulence is useful from the structural engineering viewpoint as flexible structures may exhibit resonant amplification effects induced by the velocity fluctuations, while rigid structures and structural parts are subjected to time-dependent wind loads. On the other hand, aerodynamic test results, obtained in the laboratory may be influenced to a considerable extent by the features of turbulence in the wind flow. The turbulence intensity is defined as the ratio between root mean square of the velocity and the mean wind speed, i.e.

$$I = \frac{\sigma}{\overline{V}}$$

where

I = Turbulence Intensity

σ = Root mean square of the velocity

V = Mean wind speed