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ESTIMATION OF AIR INFILTRATION IN MULTI-STORY BUILDINGS USING WIND TUNNEL TESTS

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SYNOPSIS

When carrying out pressure tests of models of multi-story buildings in The Boundary Layer Wind Tunnel, the external mean and RMS pressures are measured at 400 to 800 different locations over the building surface. The tests are originally carried out in order to determine the net wind loads for the design of cladding and glazing, but the results can also be used to estimate the internal pressures, and then calculate the air infiltration. Two mathematical models are used to estimate the wind-induced air infiltration in three multi-story buildings. One of the mathematical models is used to estimate the infiltration in the case that the internal pressure is optimally controlled (i.e.when the mean differential pressures all over the building surface equal zero) and the only infiltration will be that due to turbulence. The importance of including the turbulence in infiltration calculations is discussed. The effectiveness and potential advantages of carrying out these studies is referred to as well as the limitations presented by current practices.

1. MODEL AND BUILDING DESCRIPTIONS

The three buildings in question are of different shapes but of similar heights. The surroundings are different as well, roughly they experienced three different exposures to the wind: exposed, intermediate and built-up. Photographs of the models are shown in Fig.1 and Fig.2.

A) The first building is located at a lake shore, and only one other high-rise building is located close to it, so it is exposed. In full scale it rises to 136 meters, and the plan is shaped almost like a four-leaf clover. (Pressure taps are not shown in photographs of building A)

B) The second building is square with cut-off corners. The corners are increasingly cut off near the top. It rises to a full scale height of 184 meters and it is located on a lake shore but a number of high-rise buildings are located north of the building. The terrain is later referred to as intermediate.

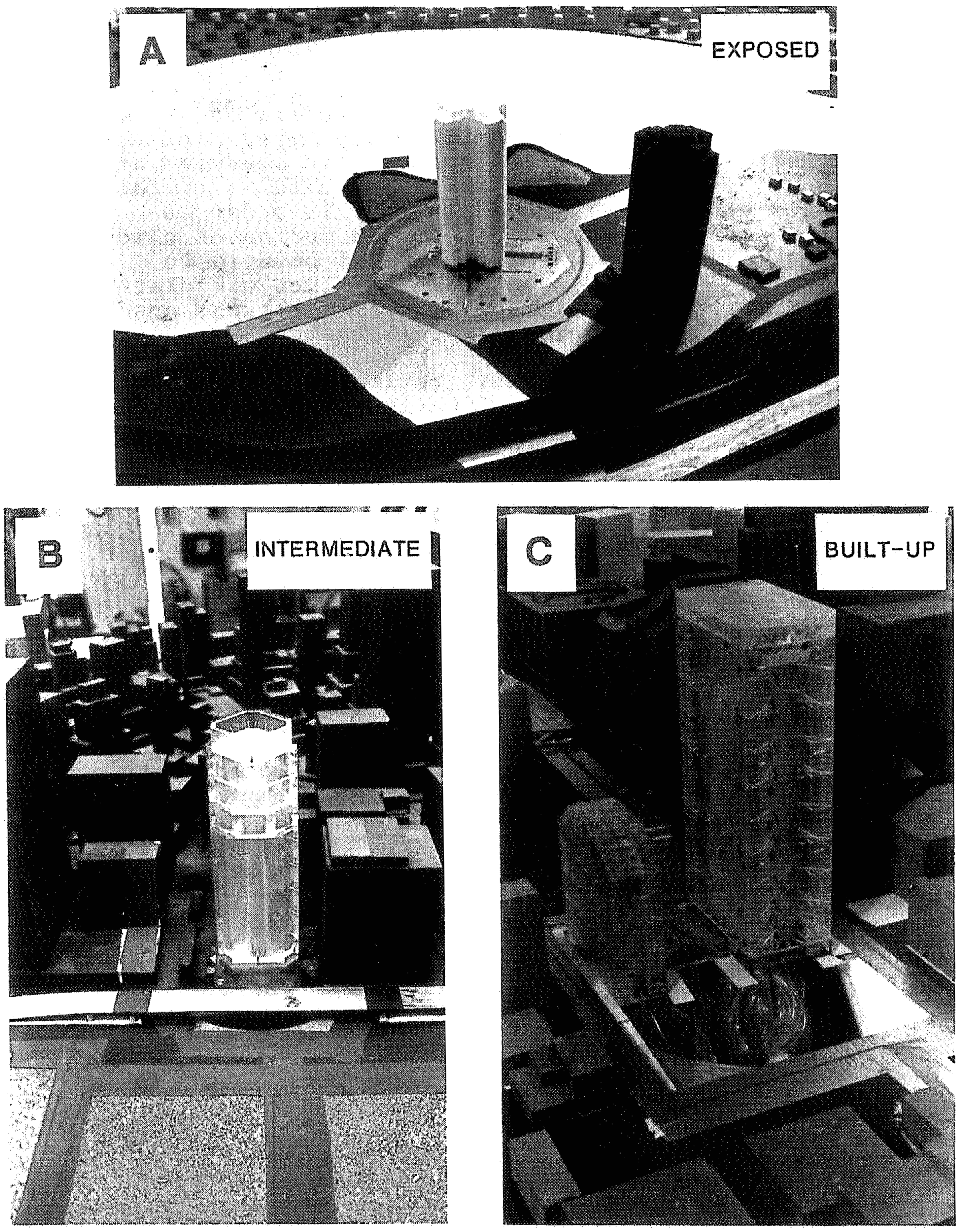

FIG.1 PHOTOGRAPHS OF THE THREE WIND TUNNEL MODELS

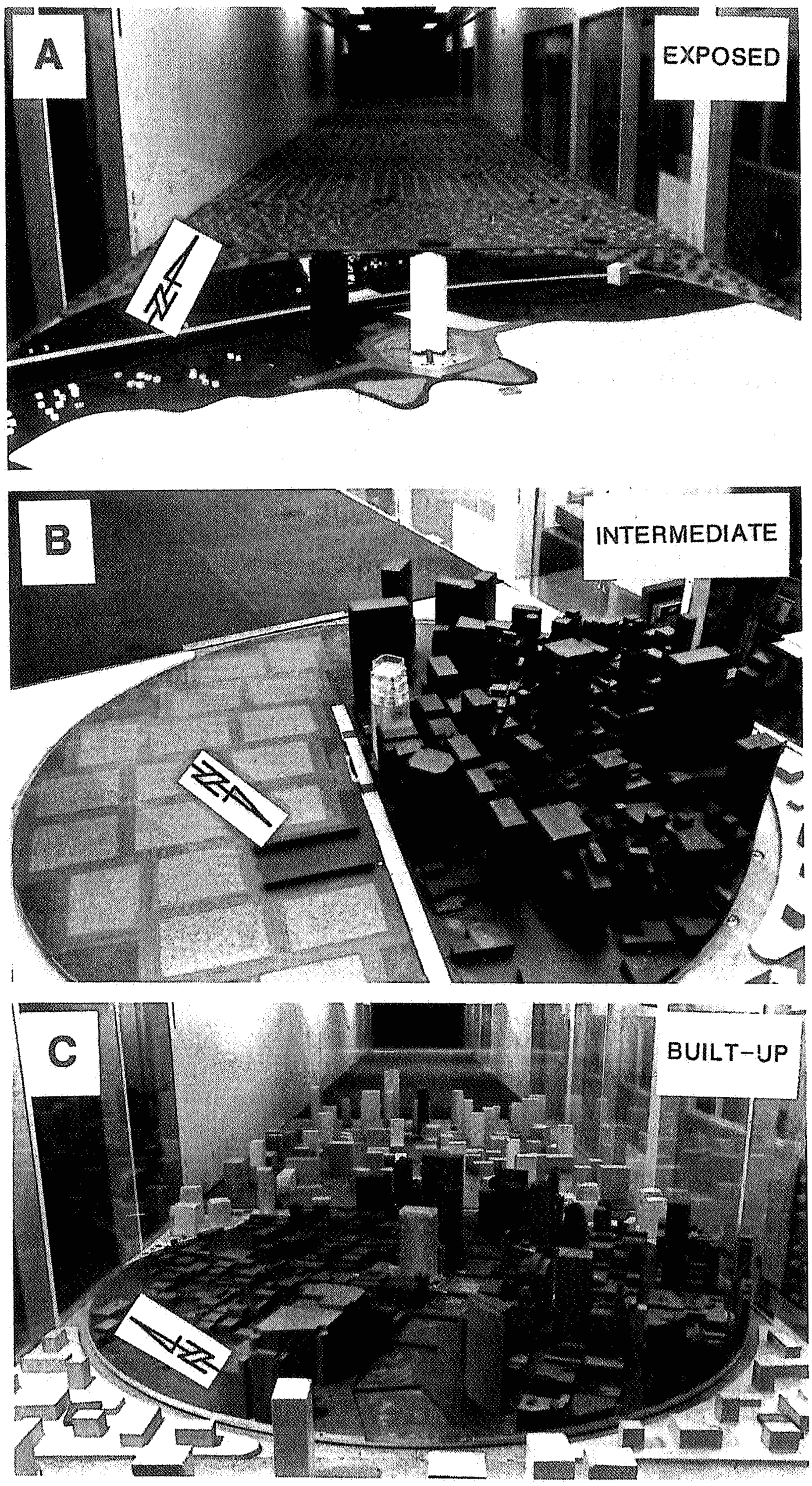

FIG.2 PHOTOGRAPHS OF THE THREE WIND TUNNEL MODELS WITHIN THE PROXIMITY MODELS

C) The third building tested has a full scale footprint of 38 x 65.5 meters and rises to a height of 147 meters. It is surrounded by high-rise buildings, so the terrain is referred to as built-up. (Only the tallest of the two buildings in Fig.1C was used in this study).

2. TEST PROCEDURE

Models of the three multi-story buildings have been tested in The Boundary Layer Wind Tunnel Laboratory at The University of Western Ontario, London, Ontario, Canada, in order to determine the accelerations, deflections and moments of the buildings. The net wind loads acting on the building used in the design of the cladding and glazing were also determined. The test results of the latter are used to calculate air infiltration rates. Models of the buildings in question were built in detail at a scale of 1:500 in plexiglass and equipped with pressure taps for measuring the mean and the root-mean-square (RMS) values of the external pressures at a large number of locations over the surfaces of the buildings. These measurements were taken at 10 degree intervals for a full 360 degree range of azimuths. The model of the immediate surroundings included all major buildings within a full scale radius of 610 meters. The overall textures of the upstream terrains were modelled but not the detailed geometry.

3. INSTRUMENTATION

Measurements of wind-induced surface pressures at a point are accomplished by allowing the surface pressure to act on a transducer which provides an electrical analogue of the pressure. The electrical signal is then processed using standardized instrumentation techniques and digitized to allow on-line analysis by a small computer and peripherals.

In practice, the transmission of surface pressure to the transducer is complicated in two ways. First, there are usually a large number of measuring positions requiring the use of multiple pressure switches - in this case scanivalves - to provide a reasonable trade-off between a large number of transducers and a lengthy testing time. Second, the model is generally too small to allow the pressure switches and transducers to be very close to the measuring locations. The resulting use of long lengths of pneumatic tubing leads to modification of the pressure at the transducer compared to that at the model surface.

These problems are dealt with as follows: pressure taps on the model are connected pneumatically to one of several scanivalves, each capable of handling 48 different taps. Each scanivalve contains a pressure transducer to which individual taps are connected on computer command. The pneumatic connection between model and scanivalve is typically 1/16'' ID plastic tubing containing a restricting insert of small bore at a specific point along its length. The function of the restrictor is to add damping to the resonant system made up of the pressure tube and the connecting volume adjacent to the pressure transducer. The resulting pressure system with two-foot long tubes responds with negligible attenuation or distortion to surface pressure fluctuations with frequencies up to about 100 Hz. Although some response is obtained for signals of several hundred Hertz, these higher frequencies suffer increasing attenuation.

The on-line digital data acquistion system, consisting of a small computer and peripherals, simultaneously samples the signals from each of the pressure transducers at a rate of about 500 times per second for sixteen inputs. Typically, sampling is continued for a period of up to about a minute in real time during which the computer records, for each input, the maximum and minimum values that occur, and computes the mean and the RMS values. Other statistics such as probability distributions can also be gathered. The reference dynamic pressure, usually measured in the free stream above the boundary layer, is monitored similarly. At the end of the sampling period, the measured maximum, minimum, mean and RMS pressure for each channel are converted to pressure coefficients by dividing each by the reference dynamic pressure. These are then stored on disk for later analysis. In addition to the sampling and on-line calculation, the computer controls the experimental hardware such as the stepping of the scanivalves, the rotation of the turntable on which the model is mounted and the wind speed.

4. THE MATHEMATICAL MODELS

Tamura and Shaw[4] and Shaw[5] developed some valuable information on the leakage of Canadian buildings using measurements of the flow into buildings from a fan pressurization system. They found the leakage proportional to $c(\Delta p)^n$ where Δp is the pressure difference, c an empirical flow coefficient and n an empirical flow exponent. The flow coefficient, c, was found to have a mean and range of 0.018 ± 0.010

$[m/s/(kPa)^{-0.65}]$. These values were found from the testing of 8 high-rise buildings. The flow exponent, n, can vary over the range 0.5 to 1.0, but it appears to converge on a value of 0.65. In the following the value of c is set to 0.018 $[m/s/(kPa)^{-0.65}]$, and the value of n is set to 0.65. The three mathematical models used in this study, are derived from this expression and the model to calculate total infiltration described by Davenport and Surry[3] :

$$Q_{in} = \int_A \int_{z_1}^{\infty} c(r)\{\Delta p(r,z)\}^n \; f_z(z)dz \; dA(r)$$

where the fluctuations of the pressure are described in statistical terms by a probability density function $f_z(z)$ that can be taken as Gaussian. The parameter z is a random variable with mean zero and standard variation of unity, and z_1 is the value of z at which $\Delta p = 0$. The flow coefficient, c(r), is a function of the position, r, since the leakage is, in practice, not uniformly distributed.

4.1 The internal pressures

The time average internal pressure coefficients for distributed leakage are found by using the continuity condition Q = 0, and the two first terms of the Taylor expansion as described by Davenport and Surry[3] :

$$C_{pi} = E(C_p) - m \; RMS(C_p) \int_{-\infty}^{\infty} \theta \; \ln|\theta| \; f_\theta(\theta)d\theta$$

in which the reduced pressure term is represented by

$$\theta = (C_p - E(C_p))/RMS(C_p).$$

$E(C_p)$ is the expected value of the external mean pressure coefficient, and it is a first approximation to C_{pi} and the second term gives a correction usually of around 10 %. The parameter $m = 1 - n$ and $\theta \ln|\theta|$ is a weighting function.

4.2 Model 1

In this model the turbulence is not included in the infiltration calculations but only the mean differential pressures. The velocity pressure is $q = 1/2\ \rho\ V^2$ where ρ is the density of air and V the mean velocity, and when expressing Δp by $q\ \Delta C_p$ and when n is the number of pressure taps, the equation for the total leakage flow into the building is:

$$Q_{in} = c\ q^{0.65} \sum_{i=1}^{n} A_i\ \Delta C_p^{\ 0.65} \quad (\text{for } \Delta C_p > 0)$$

where A_i is the tributary area and the summation is done for those areas where $\Delta C_p > 0$ only.

4.3 Model 2

In this model the turbulence is included, and the equation is

$$Q_{in} = c\ q^{0.65} \sum_{i=1}^{n} A_i \int_0^\infty z^{0.65}\ f_z(z)dz$$

where

$$f_z(z) = (1/(RMS(C_p)\sqrt{2\pi}))\ \exp[-0.5(z - \Delta C_p/RMS(C_p))^2].$$

4.4 Model 3

This model is the same as model 2, but the mean differential pressure coefficients (ΔCp) are all set equal to 0, so the model simulates the infiltration corresponding to the lowest possible air change rates, when the internal pressure is controlled, but not fluctuating. In other words the only infiltration is that due to the turbulence.

$$Q_{in} = c\ q^{0.65} \sum_{i=1}^{n} A_i \int_0^\infty z^{0.65}\ f_z(z)dz$$

where

$$f_z(z) = (1/(RMS(C_p)\sqrt{2\pi}))\ \exp[-0.5(z-0/RMS(C_p))^2].$$

4.5 Infiltration and Exfiltration Estimates

The calculations of the internal pressure coefficients are not exact. In order to obtain a better estimate of the infiltration into the building the following is done. First the infiltration is calculated as indicated above and then the exfiltration is calculated by reversing the sign of the differential mean pressure coefficients, and then recalculating the infiltration. The mean of these two is taken to be the best estimate of the infiltration. The difference is not found to be significant though.

5. RESULTS FROM THE THREE MATHEMATICAL MODELS

In Fig.3 are the results from model 1 and model 2 for gradient wind speed equal to 10, 20 and 30 m/s. The overall influence of including the turbulence does not seem very significant, but including the turbulence seems always to result in slightly higher infiltration rates. When Building B was subjected to winds from the north, the inclusion of turbulence resulted in more than twice as much infiltration. This is a significant difference,though. The results of model 3 are shown in Fig.4 for the same wind speeds as those looked at in the previous models. In order to determine how much the infiltration rates will decrease, the results from model 2 are shown again. It is, of course, impossible to control the internal pressure so that it will equal the external mean pressure at all points of the exterior wall, but by individual pressure control in all rooms, one can come close. The results from model 3 is, therefore, the absolute minimum air change rates we can obtain by internal pressure control. Since the infiltration rate always seems to be at least half as much for model 3 as for model 2, a better air barrier system might be the way forward rather than a better pressure control. None of the models above includes the stack effect, which is a significant factor for high rise buildings. The results show that we can expect only a minor reduction in the overall wind-induced infiltration rate in the case of a building located in a built-up area. For wind coming from sea or lake, we can expect to halve the infiltration rate.

6. AN EXAMPLE OF A WIND CLIMATE

Since the overall infiltration rates can vary by a factor four or more due to changes in wind direction alone, the annual heat losses and heat gains for a building will be very dependent on what the predominating wind direction is for the area in question. The wind climate for Columbus, Ohio is taken as an example. There is a predominating gradient wind direction between 225 and 270 degrees (Southwest to West). The wind data from records in the period 1960 to

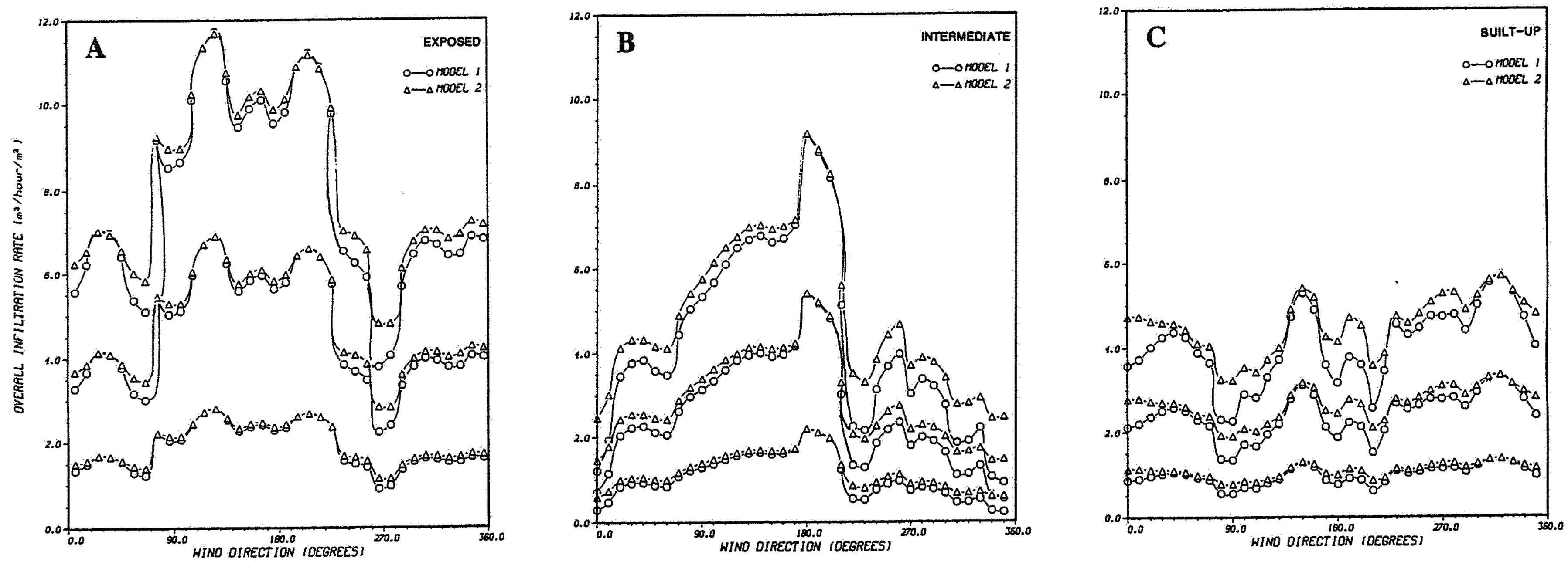

FIG.3 THE VARIATION OF OVERALL INFILTRATION RATES WITH GRADIENT WINDSPEED.

THE THREE CURVES CORRESPOND TO WIND SPEEDS OF 10, 20 AND 30 m/sec.

THE TURBULENCE IS INCLUDED IN MODEL 2 BUT NOT IN MODEL 1

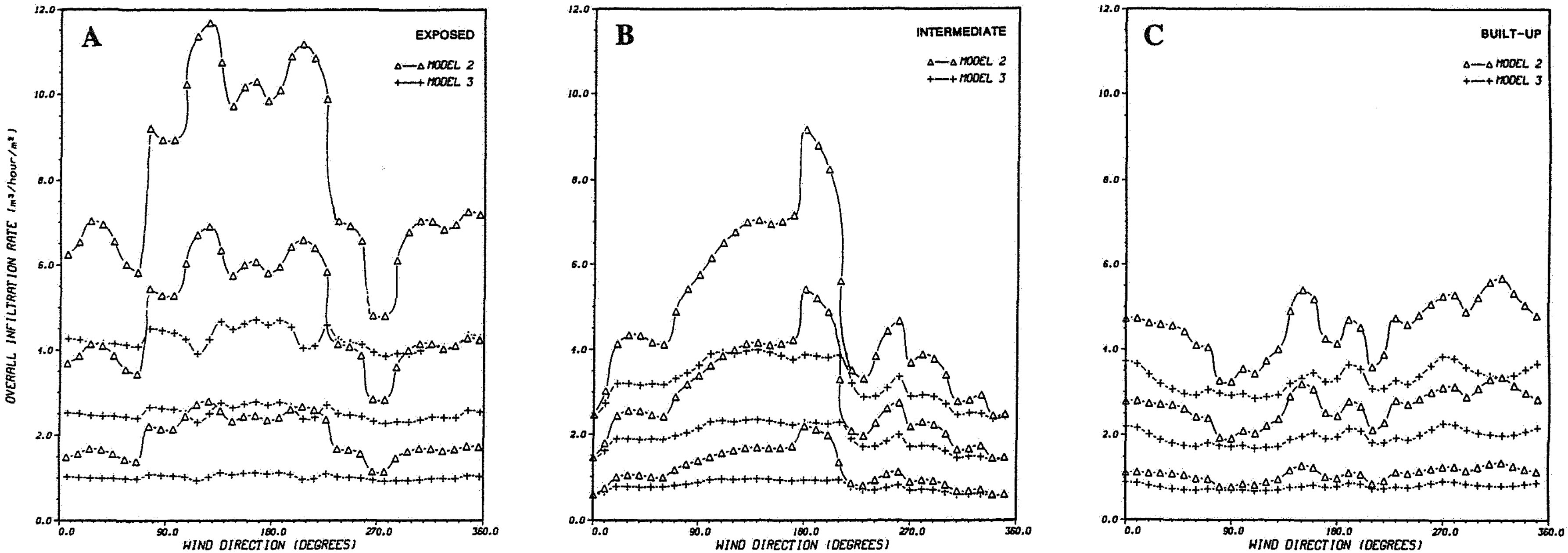

FIG.4 THE VARIATION OF OVERALL INFILTRATION RATES WITH GRADIENT WIND SPEED. THE THREE CURVES CORRESPOND TO WIND SPEEDS OF 10, 20 AND 30 m/sec. MODEL 3 INDICATES THE LOWEST RATE POSSIBLE WHEN CONTROLLING THE INTERNAL PRESSURE. IN MODEL 2 THE INTERNAL PRESSURE IS NOT CONTROLLED

1978 are fitted to a Weibull distribution as described by various authors (ex. Conradsen et al[1] and Davenport[2]) and Fig.5 illustrates the resulting distribution. P(>Vg) = the probability of exceeding the hourly mean gradient wind speed, Vg, within an azimuthal sector of 10 degrees.

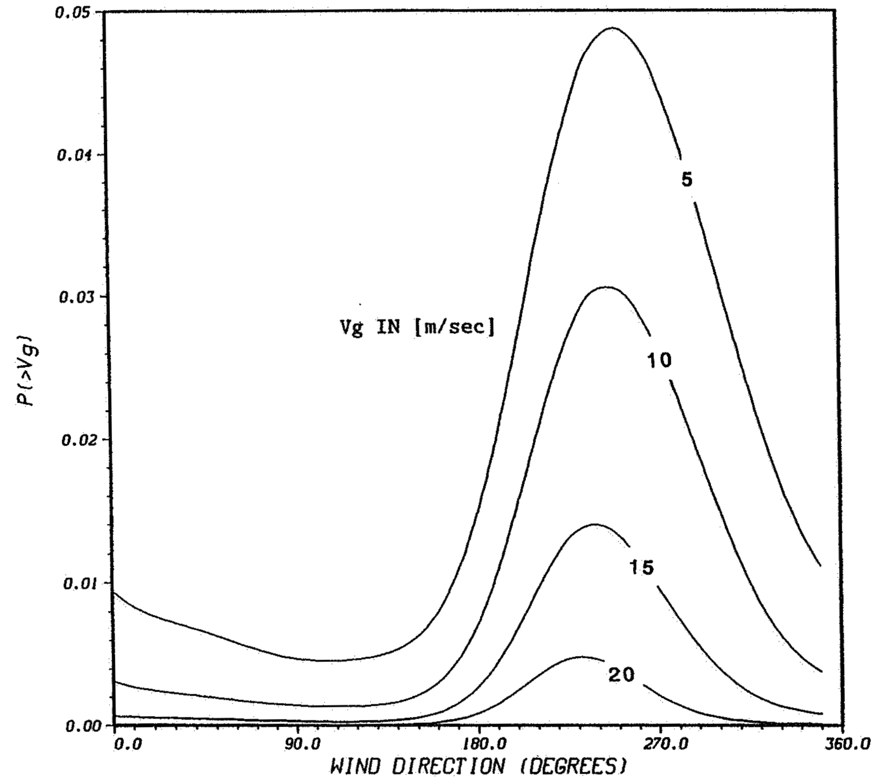

FIG.5 PROBABILITY OF EXCEEDING THE HOURLY MEAN GRADIENT WIND SPEED, Vg, AS INDICATED, WITHIN AN AZIMUTHAL SECTOR OF 10 DEGREES FOR COLUMBUS, OHIO

The results from the infiltration calculations (model 2) are combined with the probability distribution in Fig.6. Also in Fig.6 are the same results but with the probability distribution turned 180 degrees. The probability distribution is seen to be the most dominating factor. Since most of the air infiltration will take place on the wind ward walls, more heating and cooling is needed in certain areas of the building. Designing HVAC systems in high-rise buildings, by including informations as those in FIG.6, could be beneficial.

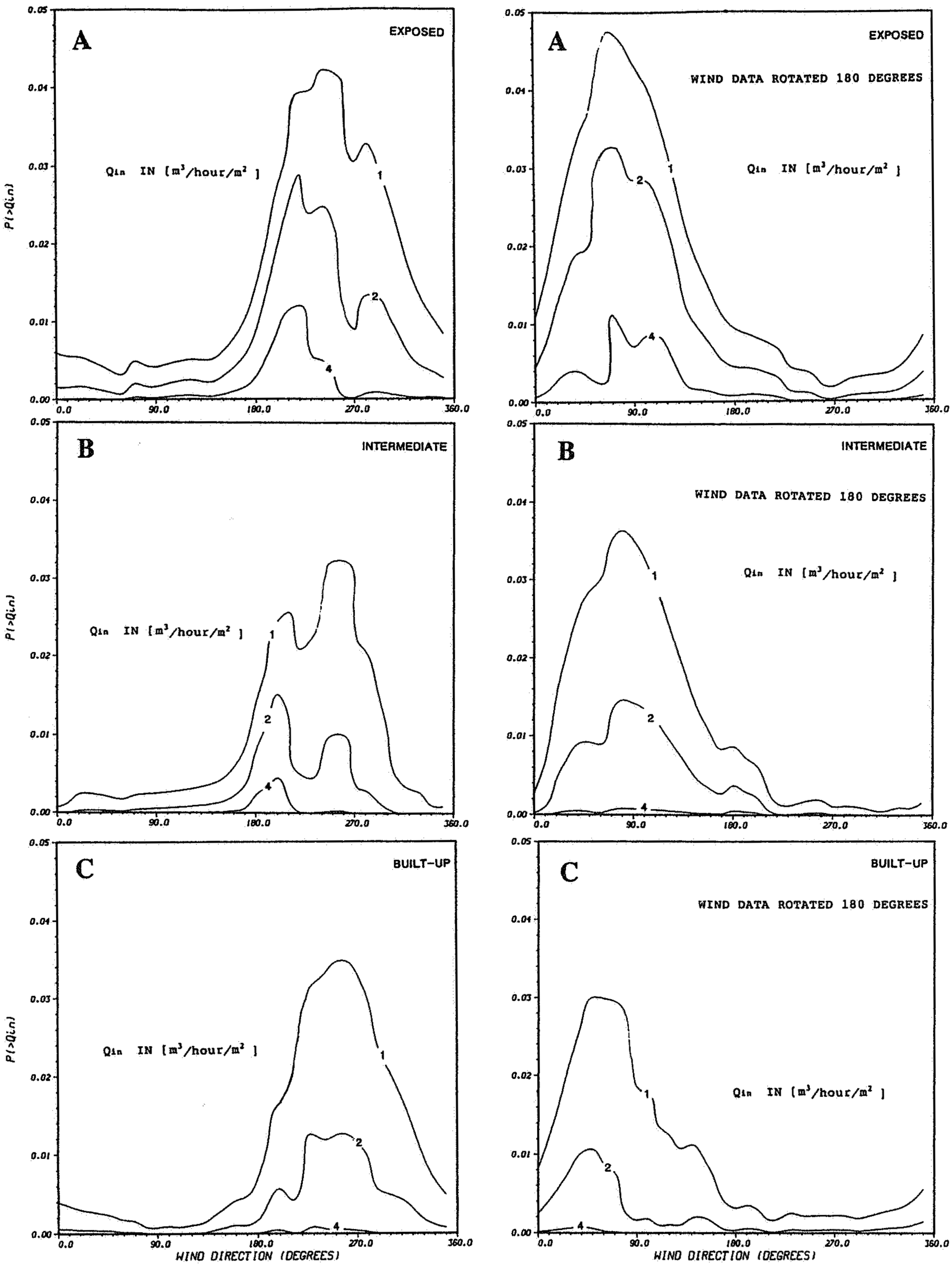

FIG.6 PROBABILITY OF EXCEEDING THE HOURLY MEAN INFILTRATION RATES AS INDICATED (BY CONTOURS 1, 2 AND 4) WITHIN AN AZIMUTHAL SECTOR OF 10 DEGREES, WHEN USING THE WIND SPEED DISTRIBUTION IN FIG.5 AND THE SAME DISTRIBUTION TURNED 180 DEGREES

7. CONCLUSIONS

Wind induced overall infiltration rates on a high-rise building can vary by a factor of four or more for different wind directions due to difference in exposure.

Estimating overall infiltration rates from mean differential pressures only, will result in a slight underestimate.

A simple approach to internal pressure control would, under some circumstances, reduce the wind induced air changes by roughly half.

Information on the wind speed and direction and the infiltration likely to result can be exploited using zone heating and cooling to improve the efficiency of the HVAC system.

8. REFERENCES

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