

INTERNAL PRESSURE CHARACTERISTICS OF LOW-RISE BUILDINGS DUE TO WIND ACTION

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SUMMARY

Wind-induced internal pressures have been experimentally determined using models of low-rise buildings of different geometry and internal volume. Three different uniform porosities (0.0, 0.5 and 3.0% of the total surface area) have been examined in combination with openings in a wall ranging from 0 to 100% of that wall's area. Tests have been carried out in a simulated atmospheric boundary layer over two terrain roughnesses corresponding to open country and suburban regions. Results show that internal pressures are dynamic but their magnitudes are generally lower than those of local external pressures. For windward openings, internal pressure coefficients are generally positive with the exception of cases with high background porosity combined with small openings, when they become zero or slightly negative. The lower the background porosity, the smaller the size of the wall opening necessary to make the internal pressures insensitive to further increases of the wall opening. For all cases, high correlation has been found between those components of external and internal pressures which participate in loading the primary structure.

INTRODUCTION

Most full-scale and wind tunnel studies dealing with wind loads on buildings are designed to provide external pressure coefficients only. As such they define the external surface loading relative to a reference static pressure well away from the building. The total wind loading, even for a building which has minimal leakage and hence a steady uniform internal pressure, must include the contribution of the internal pressure to both local and distributed loads. In reality, a building may have considerable inherent leakage as well as the potentiality for large openings due to the presence of doors or windows. The resulting internal pressures can be a significant proportion of the total loading. Thus, it is important for the structural designer to account for the internal pressures for all likely conditions of permeability and wall openings. Note that a precise description of the net load would require knowledge of the correlation between external and internal pressures.

Although the significance of the internal pressure is well recognized, very few studies have dealt with it. Among those that have, only one or two are either full-scale cases or model cases in appropriate atmospheric simulations. No study, to the writers' knowledge, exists that deals with the determination of internal pressures in buildings with various uniform porosities combined with different wall openings. As a result only limited comparisons of the results of this study with others' findings can be made.

METHODOLOGY AND MODELS

The Boundary Layer Wind Tunnel at the University of Western Ontario has a working section about 24.5 m (80 ft.) long, 2.4 m (8 ft.) wide and about 2.1 m (7 ft.) high. Most of this fetch is required for the natural production of a boundary layer which grows in a manner paralleling the atmospheric process under neutral conditions. The surfaces in the wind tunnel can be changed to represent different terrains. Boundary layer depths ranging from about 0.5 to 1 m (2 to 4 ft.) are obtained at the test section with different surface roughnesses. In relation to the atmospheric boundary layer this implies that geometric scales of between 1:400 and 1:500 are most appropriate for studies of wind effects on buildings and structures; however, in the present study, models at this scale posed considerable difficulties because of their small size. Instead, most of the tests were carried out at a somewhat relaxed scale of 1:250, after an intensive set of experiments had been completed to verify that such a relaxation in scale did not materially affect the results (1). For the tests reported here, two terrain models have been used. The 'smooth' exposure represents open country conditions whereas the 'built-up' exposure corresponds to suburban conditions.

Three basic models were constructed, all providing variable side-wall and end-wall openings and three background porosities of 0%, 0.5% and 3.0% of the total surface area. The models shown diagrammatically in Figures 1 and 2, are sealed underneath so that the pressure inside the model is determined completely by the flow conditions within the tunnel. The two 'small' models are 1:250 scale models of 24.4 x 38.1 m (80 x 125 ft.) buildings with 1:12 and 4:12 roof slopes. The 'large' model is a 1:250 scale model of a building geometrically similar in plan, and having 2.5 times the plan dimensions. The small models could be tested at 4.9, 7.3 and 9.8 m (16, 24 and 32 ft.) eave heights whereas the large model could be tested only for a 9.8 m (32 ft.) eave height. It was found to be unnecessary to test all possible configurations. The background porosity or permeability of the models was achieved by a series of holes of various sizes which could be left open or closed. Although this simulates porosity in a manner somewhat different to reality, local effects were found to be small and hence for pressure measurements at locations a reasonable distance from the holes, the difference is not likely to be significant.

The chosen background porosity ratios (0.0, 0.5 and 3.0% of the total surface area) arose from the following considerations. First, it is very difficult to measure or even to estimate actual building permeabilities since they vary significantly even for the same type of buildings. Tamura (2) measured air leakages through six different one or two-storey houses in Canada. From his reported results, overall porosity values up to 0.09% can be calculated, although this permeability ratio does not include leakages through doors and windows. Newberry and Eaton (3) suggest porosity ratios of the order of 0.01 to 0.1% or more, as for instance 0.2% for the study of Royex House (4) in England. An ad hoc survey among several members of the Metal Building Manufacturers Association suggested typical values of about 0.5% for metal buildings without windows. For buildings with windows, it was estimated that the porosity could be as large as 1.0 to 3.0%, although these upper bounds are likely to significantly decrease with increasing awareness of energy losses. Furthermore, it is obvious that the various climatic conditions and construction techniques in different countries naturally yield a variety of building permeability ratios. Thus the range of 0.0 - 3.0% appears to include most cases of practical interest.

All models are equipped with pressure taps on both the internal and external surfaces. Each tap is connected to a pressure transducer through a length of plastic tubing of 1.6 mm (1/16") I.D. which contains a restrictor to optimize its frequency response characteristics (6). A 610 mm (2 ft.) length of tubing provides a frequency response flat to about $\pm 6\%$ up to 100 Hz. Such tubes were used for the larger model. The small model used tubes of half this length which improved the frequency response to 120 Hz. Comparisons of external pressure measurements made using both tubing configurations show no significant differences (1,7).

Both local pressure and 'generalized area loads' were measured. Local loads were determined using conventional techniques (1,6). For area loads, differences of external and internal pressures were

measured simultaneously at ten locations. These were integrated together with appropriate influence factors to provide sets of structural 'outputs' or generalized loads, corresponding typically to horizontal and vertical forces or bending moments acting on building frames. Since this sampling and multiplication is done on-line at a high rate (200 times/sec) the result is the time-varying behaviour of the total wind-induced structural reactions which are of primary design interest (1,6,8). For both local and generalized loads, sampling is continued for a period of up to about a minute in real time during which the computer records, for each output, the maximum (max) and minimum (min) values that occur, and computes the mean and root mean square (rms) values. The reference dynamic pressure is monitored similarly. At the end of the sampling period the resultant measurements, consisting of the max, min, mean and rms pressure or load for each channel are put into coefficient form by dividing each by the mean dynamic pressure at eave height.

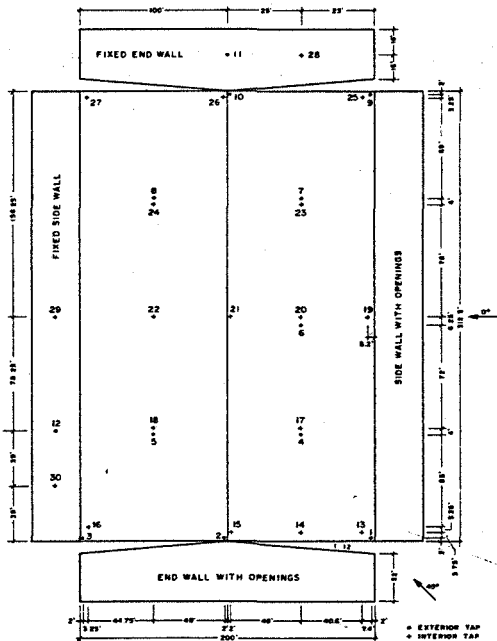


Fig. 1 Exploded plan view of the large model for internal pressure measurements showing the positions of pressure taps

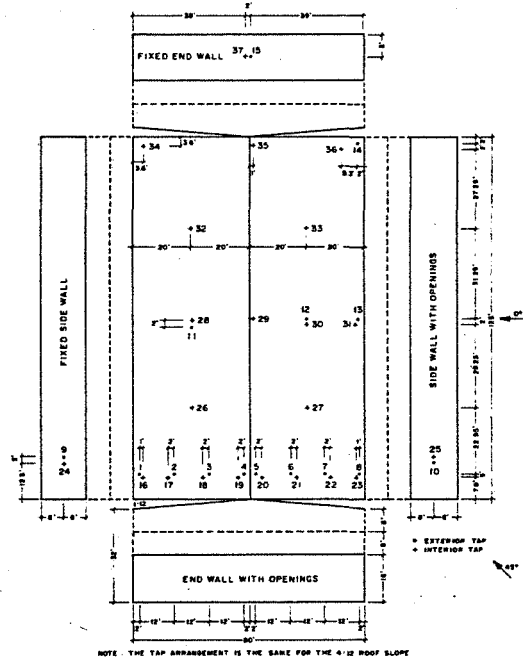


Fig. 2 Exploded plan view of the small model (3 heights, 2 roof slopes)

Scaling and similarity requirements for models designed for wind tunnel determination of external loads have been thoroughly discussed elsewhere (see (9) for example). Such similarity considerations lead to the determination of velocity and time scales of the order of 3:10 and 1:100 respectively for typical full-scale design speeds. Consequently, the use of a 30 second or one minute wind tunnel sample under flow conditions where the speed above the boundary layer is about 14 m/sec provides a statistically stable estimate of mean and rms pressures and an assessment of peak values associated with a full-scale period of about an hour.

Additional scaling requirements related to modelling internal pressures for flexible buildings have been discussed in (10). For rigid buildings of low height where gravitational terms are unimportant, the unsteady pressure change induced in the building by the wind essentially requires the Mach number to be simulated. This ensures that propagation of pressure fluctuations occurs similarly in model and full scale, and hence internal pressure fluctuations maintain a correct phase relationship with external pressures. Essentially, this reduces to maintaining the same velocities for model and full scale. For the cases examined here, a Mach number discrepancy equal to the velocity scale has been introduced;

however, the consequences are likely to be small since a typical propagation time for a full-scale pressure wave would be about one-fifth of a second in the larger building, and about one-thousandth of a second in model scale. These periods correspond to turbulent fluctuations within the wind which have very small spatial correlation. Hence, for larger gusts likely to have significant impact on the internal pressures, these pressures will respond essentially instantaneously; the fact that the model's interior responds three times too quickly for the high frequency components of small spatial correlation will be of little importance. The above is supported by Euteneur's work (11) on the estimation of time required for the transmission of pressures inside volumes not totally enclosed. Also the results reported below for the two model sizes verify that the internal pressures reflect gusts which essentially envelop the buildings. Furthermore, the results for the larger model indicate that the combined effect of a larger open frontal area (which will be sensitive to less of the gust content within the wind) and the longer times required for the highest frequency components to propagate throughout the volume, together produce little significant change when compared to the data from the smaller model.

THE EFFECT OF POROSITY AND WALL OPENINGS ON LOCAL EXTERNAL PRESSURES

Before measuring internal pressures, the variation of the external pressures with various porosities and/or wall-opening ratios was examined. Results are shown in Figure 3 for the case of the large building, where two different roof pressure taps are examined. Similar data were also recorded for the small building. All data show that the external pressure coefficients are insensitive to the wall-opening ratios. Extreme values show somewhat more scatter but the data are within the repeatability expected for successive runs under nominally identical conditions. Some discrepancy is evident in Figure 3 for pressure tap 1 for different porosities. This is probably due to the fact that tap 1 is located very close to the uniformly distributed holes which provide the porosity. These holes are relatively large for the 3.0% porosity case and probably create local flow disturbances. No such discrepancy occurs for the other tap on the same building (located further away from these holes) or in the case of the small building where the porosity holes are significantly smaller. A similar insensitivity of the external pressure distribution was also found in a recent study by Kandola (12), who examined the effect of leakage characteristics of a building on the external wind-induced mean pressures, and by Surry et al (13) in the study of some large hangars. Consequently it can be reasonably concluded that the external wind pressure distribution is not significantly affected by either the porosity or the wall openings for cases similar to those considered here in which the openings do not permit large flows through the buildings.

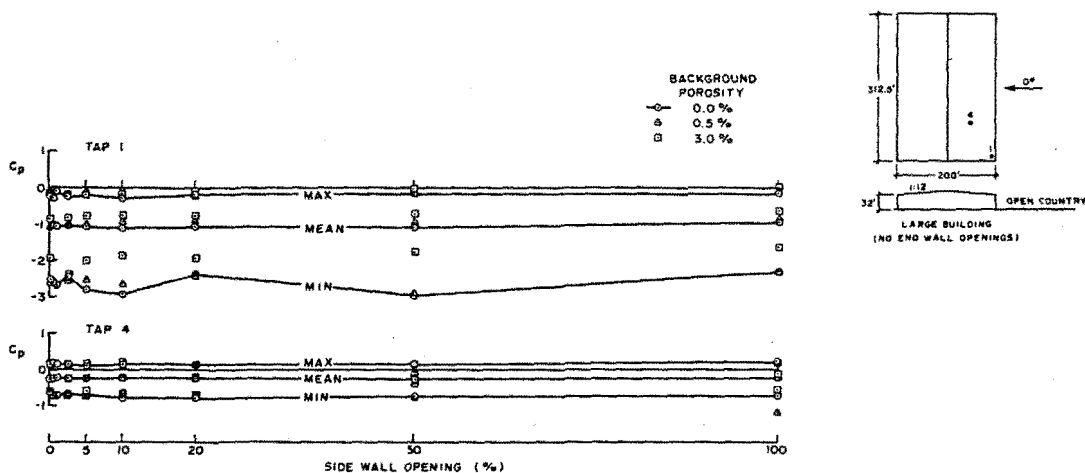


Fig. 3 Variation of external pressure coefficients with wall openings – large building, three porosities, open country exposure

LOCAL INTERNAL PRESSURES

Figure 4 illustrates the high degree of correlation of the internal pressures. Typical time traces of pressures from two internal taps located at opposite ends of the large building are shown. The traces are virtually identical. This characteristic is quite general for all the various configurations examined and leads to the conclusion that the spatial variation of the internal pressures is minimal. This was also observed in the substantially larger buildings studied in (13). Hence characteristics of the internal pressure can be given below without reference to the particular location within the building. The only exception to the above was found for points inside the building located in regions very close to openings or other architectural details of odd geometry. However, the uniformity of internal pressures is likely to be somewhat reduced in buildings with significant openings on more than one wall.

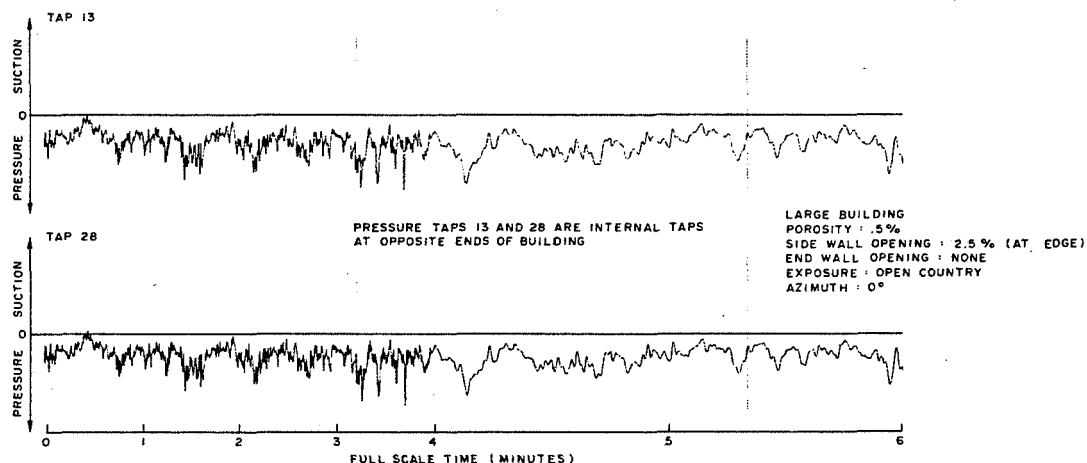


Fig. 4 Simultaneous time traces of internal pressures for two different taps

Comparison between traces of external and internal pressures not recorded simultaneously is made in Figure 5. The two pressure taps considered are located at the corner of the roof of the building, one on the inside and the other on the outside. The internal pressure appears to be as dynamic as the external pressure but its magnitude is significantly lower (notice the different scale of the two traces).

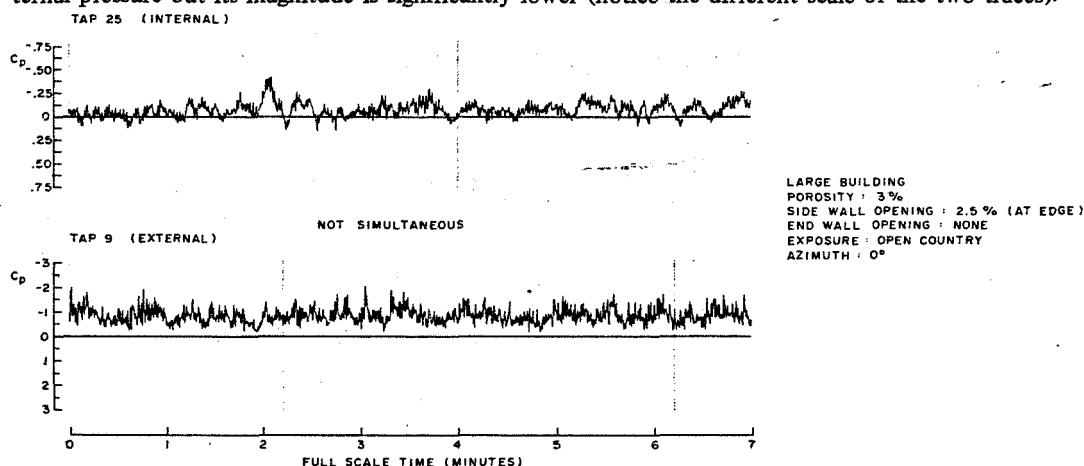


Fig. 5 Time traces of external and internal pressures (non-simultaneous)

Numerous configurations were examined in detail, as discussed in (7). However, much of the data were

made redundant by the high spatial correlation of the internal pressures. Figure 6 shows a typical example of the variation of extreme and mean values of internal pressure coefficients with azimuth. As expected, the maximum values occur when openings are on the windward wall. These and the data for other cases indicate that the influence of the wind direction is greater for the extreme values than for the mean values; Furthermore, little difference was found in either the mean or peak internal suction between wind directions of 90° and 180° . This differs from results found in (13) for a substantially higher hangar building. In those tests, peak internal suction were nearly twice as large for 90° as compared to 180° . This presumably reflects the more severe suction induced near the wall corners for taller buildings.

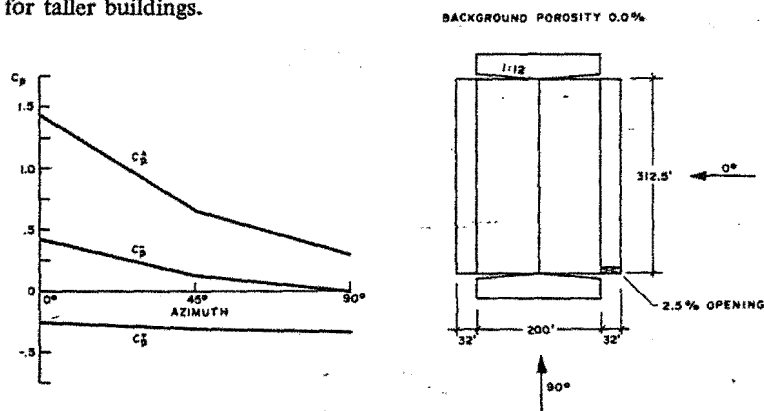


Fig. 6 Variation of internal pressure coefficients with wind direction

For the wind blowing directly onto the wall with openings, which is often the critical design case, results of internal local pressure coefficient measurements have been compiled in Figures 7 to 10 for the large and small building exposed to both open country and suburban terrains. For example, Figure 7 presents max, min, mean and rms internal pressure coefficients for the large building exposed to an open country terrain. Each point on the graphs represents a typical value of internal pressure coefficient for one particular configuration, i.e. a particular combination of background porosity and side wall opening. For all cases shown in Figures 7 to 10, mean internal pressure coefficients are generally positive with the exception of the case of high background porosity combined with small or no openings, when they become zero or slightly negative. For wall openings of significant size (more than 20% of the wall area) the internal pressure coefficients depend little, if at all, on the background porosity. The lower the background porosity, the smaller the necessary size of the wall opening before the internal pressure coefficients become insensitive to further increases of the openings. Some increase of the maximum pressure coefficient values appears for small openings, particularly for the larger building in a built-up exposure. This is attributed to the effects of small scale gusts whose integrated impact becomes smaller as the wall opening becomes larger. For very small openings ($< 1\%$), large changes occur in the data for the zero porosity case. These changes are not significant since under conditions approaching nominal impermeability the slightest leakage between the building and the outside of the wind tunnel contaminates the data. The residual leakage was estimated and found to be insignificant for the wall openings and finite values of porosities considered. Although the unsteady component denoted by $C_{p_{rms}}$ decreases for some cases with very low wall-opening ratios (implying that the internal pressure

becomes more nearly static for such configurations), the data suggest that internal pressures are normally dynamic in nature, with a typical value of internal gust factor of about two for the open country exposure. It is interesting to note that this is similar to the value of the gust effect factor often taken for overall external loads, suggesting that the reduced internal pressure fluctuations nevertheless include the quasi-steady components which are encompassing the major part of the structure. The higher external intensities are then primarily local effects. For the built-up terrain, the major difference is the larger magnitudes of the coefficients compared to those for open country terrain, due to the lower reference mean dynamic pressures at eave height. For similar flow speeds above the boundary layer (i.e. the same

full-scale storm system) the actual pressures induced are lower. Comparison of the results for the small and large buildings indicate little significant difference in the general trends of the data for the two model sizes. The internal mean pressure coefficients are similar (a little bit higher for the small building) whereas the peak and rms values are somewhat higher for the small building, particularly for the lower background porosities. Some differences in the model instrumentation, as described earlier, might have led to shorter response times for the peaks, together with the effect of the smaller volume itself; however, the effect does not appear significant over the range of typical low-rise building geometries investigated.

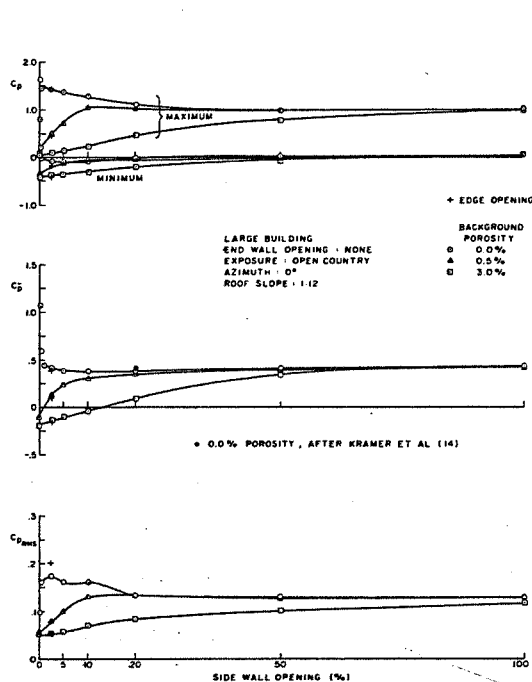


Fig. 7 Extreme, mean and rms internal pressure coefficients for various side wall openings and background porosities — large building, open country exposure

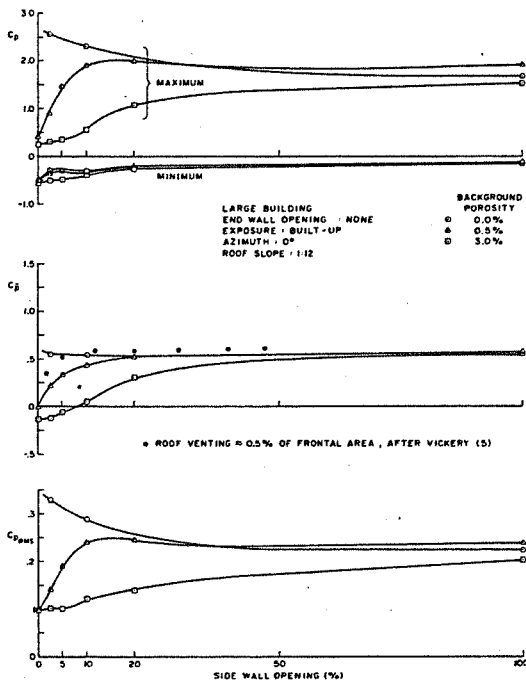


Fig. 8 Extreme, mean and rms internal pressure coefficients for various side wall openings and background porosities — large building, built-up exposure

Kramer, Gerhardt and Scherer (14) measured mean internal pressure coefficients for buildings of various geometries and wall-opening ratios but with no background porosities. Their results, added to Figure 7, are in very encouraging agreement with the results presented here for cases of similar geometry. Vickery's results (5) for internal pressure coefficients measured on a large low-rise hangar also show a fair agreement with the present data as shown in Figure 8. In Vickery's work the hangar roof had a permeability estimated at 0.3 to 1.0% of the frontal area due to instrumentation requirements, and was tested for various wall opening ratios in flow over a rough terrain.

Several internal pressure measurements were made for wind acting perpendicularly to the closed wall (the wall with openings being in the wake). In these cases the variation of internal pressure coefficients versus background porosity or size of openings is not large. Typical values of pressure coefficients referenced to eave height for this case are as follows:

Exposure	C_{pmax}	C_{pmin}	$C_{\bar{p}}$	$C_{p_{rms}}$
Open Country	0.10 to 0.20	-0.30 to -0.45	-0.05 to -0.15	0.05 to 0.10
Built-up	0.30 to 0.45	-0.40 to -0.55	0.00	0.10

These values are also representative of different size buildings (different internal volumes).

Spectra of internal pressures were also measured (7). Their characteristics are very similar to the spectral characteristics of external pressures, which indicate the rapidity with which pressure fluctuations are transferred to the interior of the building. This was also noticed by Eaton and Mayne (15) in their full scale experiments in England.

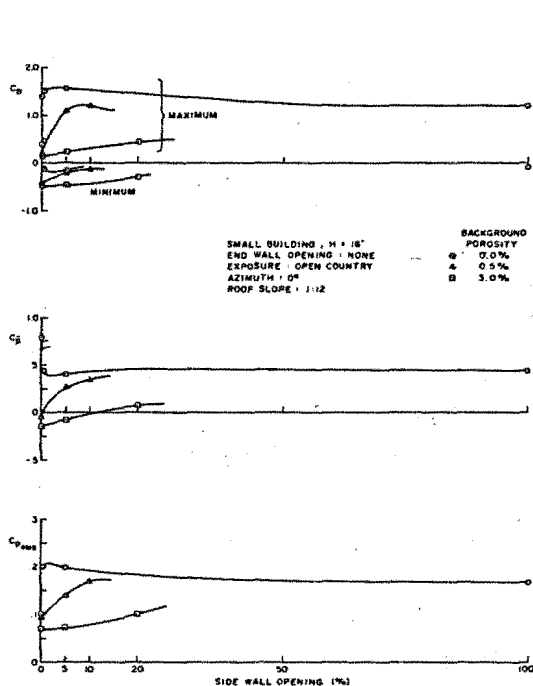


Fig. 9 Extreme, mean and rms internal pressure coefficients for various side wall openings and background porosities – small building, open country exposure

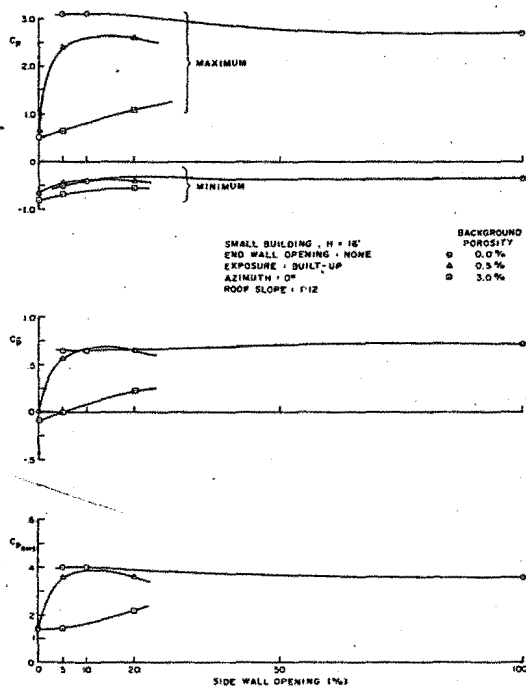


Fig. 10 Extreme, mean and rms internal pressure coefficients for various side wall openings and background porosities – small building, built-up exposure

GENERALIZED LOADS INCLUDING THE EFFECT OF INTERNAL PRESSURES

All of the above data are for local internal pressure coefficients. Measurements of generalized loads, including the simultaneous action of external and internal pressures, have also been made for the end bay of the small building. These generalized bay loads refer to forces and moments applicable to frame design; however, characteristics of the component loads which are appropriate for the design of structural elements such as wall panels, purlins and girts, were also measured. Similar results for external loads only have been obtained and described in detail elsewhere (1,7,8). In this previous work, the generalized loads were derived by measuring eight roof loads and two wall loads simultaneously, and combining them on-line using a computer to form generalized bay loads, which reflected the interaction of the wind-induced forces and the structural action. Each of the ten component loads was formed by pneumatically averaging (6) four or five pressure taps distributed over the component area of interest. In the present case, instrumentation and time constraints led to the use of a simplified approach for the determination of external purlin and wall loads by using one instead of multiple pressure taps to represent the component loads. The simplified approach was validated through successful comparisons

of external pressure data obtained by both methods (7). In all cases the simplified approach appears slightly conservative. In order to obtain the total purlin load (external – internal), the external and internal pressures at each purlin location were differenced directly across each pressure transducer. The resultant pressure load was sampled by the on-line data system and used directly in the generalized load program. The use of the pressure transducer in this way led to a slight reduction of the frequency response to internal pressures; however, this is unlikely to have any significant effect on the integrated loads.

Generalized load data were measured for the critically-loaded end bay of the small building for various porosity and wall-opening configurations. Results appear in a non-dimensional form defined as follows:

$$\text{Force Coefficient, } C_F = \frac{\text{Force per unit area}}{q}; \text{ Moment Coefficient, } C_M = \frac{M}{q w^2 b}$$

where M is the bending moment at various cross-sections of the frame
 w is the building width
 b is the longitudinal extent of the bay [taken as 7.6 m (25 ft)]
 q is the dynamic wind pressure at eave height ($\frac{1}{2} \rho V_e^2$)

Typical results appear in Figures 11 and 12 which show max, mean and min bay force and bending moment coefficients respectively, for a building with each of the three background porosities in combination with a 5% end-wall opening. Again, as with the local loads, the higher the building background porosity, the lower the critical bay loads. Both vertical force and bending moment coefficients of the building with no background porosity are significantly greater (for critical wind directions) than for cases with porosity, whereas the horizontal thrust coefficients are essentially unaffected.

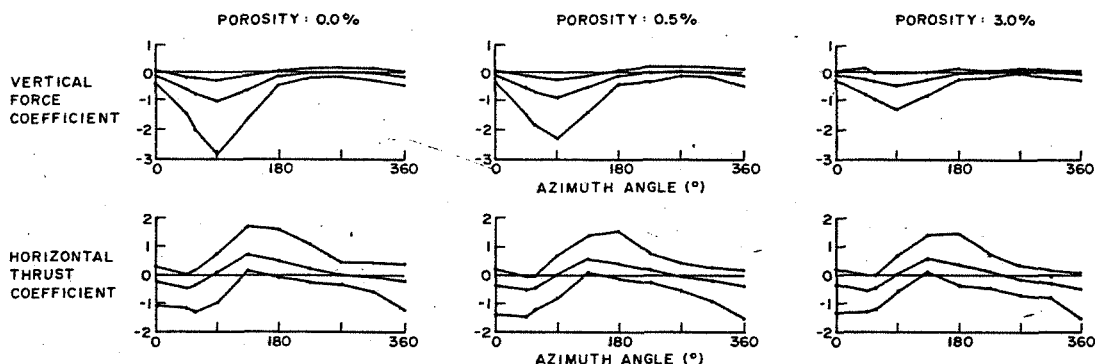


Fig. 11 End bay force coefficients for total (external – internal) load conditions – 3 porosities, 5% end wall opening (roof slope = 1:12, eave height = 16', exposure = open country)

Comparison of the data for the building with no background porosity with results of the generalized loads using external pressures only, as obtained previously (1), show the true effect of internal pressures on the loading mechanism of the structural members. In fact, this effect is crucial for some loads, as for instance the vertical forces, and not critical at all for others, as for instance the horizontal thrusts. The latter is predictable since the internal pressure uniformity cancels the overall effect on the vertical walls. In general, vertical force and bending moment coefficients for the building with no background porosity and for critical wind directions are 50 – 100% higher when the internal pressures are considered. These values are reduced for increasing porosity. Similar data obtained in suburban exposure (presented in (7)) show the same trends except that the background porosity does not appear as strong a factor for the determination of loads. All results for low background porosities are relatively insensitive to wall openings greater than about 5% of the wall area. For high background porosity the results

indicate some dependence on the size of the wall opening, as did the local loads; in fact, all the coefficients are significantly increased in the case of a missing wall.

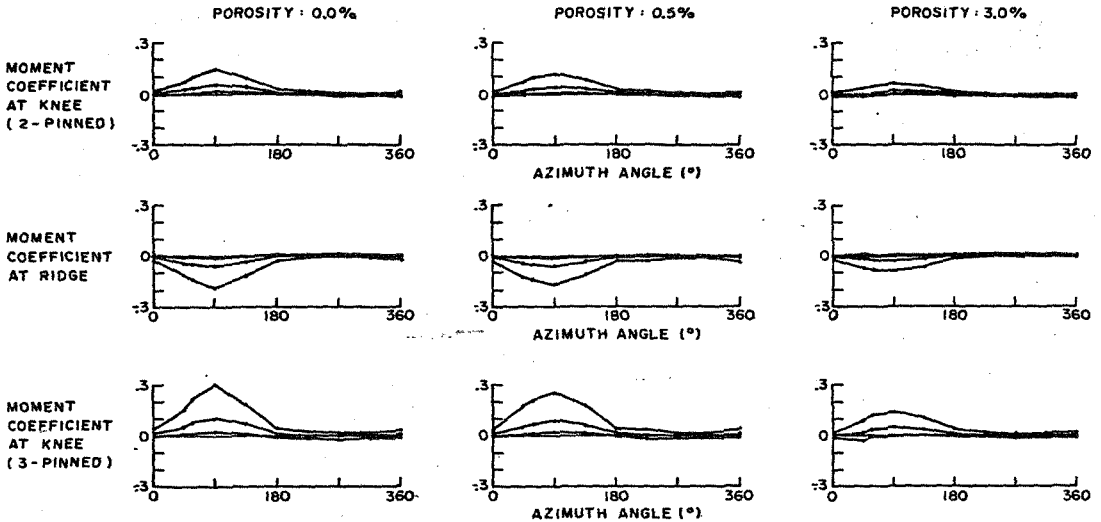


Fig. 12 End bay bending moment coefficients for total (external - internal) load conditions - 3 porosities, 5% end wall opening (roof slope = 1:12, eave height = 16', exposure = open country)

Comparison of data associated with the two roof slopes (1:12 and 4:12), some of which are not shown here, indicates higher vertical force coefficients for the steeper roof but equal or lower bending moment coefficients. There is no difference in horizontal thrust coefficients.

Although not measured directly, a high correlation between internal and external pressures has been deduced in all cases. First, the peak total (external - internal) pressure registered at any point is not very different from the total pressure derived assuming that both external and internal peak pressures, measured independently, occur simultaneously. Second, the experimental peak generalized loads, which included simultaneous measurement of the internal pressures, were found to be approximately equal to the vectorial sum of the peak generalized loads measured considering only the external pressures plus the independently measured peak internal pressures. This essentially isolates that component of the pressure which participates in overall structural loads. Similar results were found in the study on large hangars (13) where 75-80% of the internal pressure was correlated with external structural loads. These characteristics are consistent with the physical picture of the building responding essentially quasi-statically to the larger-scale wind gusts. Smaller gusts and local effects introduce contributions to local peaks which are somewhat less spatially-correlated.

COMPARISON OF INTERNAL PRESSURE DATA WITH CURRENT CODES AND STANDARDS

To provide a better perspective on the experimental internal pressure data, comparisons have been made with pressures suggested by ANSI A58.1 (16) and the National Building Code of Canada (17,18). Since both documents do not recognize the effect of building background porosity, a separate comparison for each porosity tested is shown. Since, in general, pressure coefficients are referenced to different heights and speeds, all internal pressure coefficients have been transformed to internal building pressures assuming a particular storm system which produces a fastest mile speed of 100 mph at 10 m (30 ft) and consequently $\bar{V}_{10} = 34.4$ m/sec (77 mph) and $q_{4.9} = 608$ N/m (12.7 psf) in open country

exposure (ANSI: type C, NBCC: type A). The building considered has a 1:12 roof slope and is 4.9 m (16 ft) high. Four cases of different side-wall openings have been considered. The calculations are shown in Table 1 to indicate the pressure coefficients used and the appropriate gust factors, if any. In all cases the internal pressure coefficients drawn from the current results are the worst peak values found for any wind angle. The final two columns in Table 1 indicate the ratios of the recommended values to the current results. It can be seen for this example, using data typical of all the results found, ANSI is conservative in some cases but also underestimates the internal pressure loads in some other cases. The NBCC is always conservative if, as shown, a gust factor of two is assumed.

TABLE 1

SIDE-WALL OPENING	BACK- GROUND POROSITY	Internal Pressures (psf) (1 psf = 47.88 N/m ²)			ANSI	NBCC
		BLWT	ANSI	NBCC	BLWT	BLWT
windward 50%	any	$1.0 \times 12.7 = 12.7$	$0.8 \times 26 = 21.0$	$0.7 \times 2.0^* \times 16 = 22.4$	1.65	1.76
windward 2.5%	0.0%	$1.5 \times 12.7 = 19.0$	$(0.3 + 1.67 \times .025) \times 26 = 8.9$	$0.7 \times 2.0^* \times 16 = 22.4$	0.46	1.18
	0.5%	$0.7 \times 12.7 = 8.9$			1.00	2.52
	3.0%	$0.2 \times 12.7 = 2.5$			3.56	8.96
leeward opening of any size	any	$-0.45 \times 12.7 = -5.7$	$(-0.3 - .025) \times 26 = -7.1$ $(-0.6 \times 26 = -15.6 \text{ for } > 30\% \text{ opening})$	$-0.5 \times 2.0^* \times 16 = -16.0$	1.25 2.74	2.81
0	3%	$-0.5 \times 12.7 = -6.3$	$\pm 0.3 \times 26 = \pm 7.8$	$-0.3 \times 2.0^* \times 16 = -9.6$	1.24	1.52

* left to the designer to decide whether this value will be 2.0 or 2.5 or whether a gust factor should apply at all.

CONCLUSIONS

The following conclusions may be drawn from the study of wind-induced internal pressures in low-rise buildings:

- i) Internal pressures fluctuate significantly; but their overall magnitudes are generally less than that of the local external pressures. The overall gust factor – the ratio of the peak pressure to the mean – is roughly two in open country.
- ii) The fluctuations in internal pressure show little or no spatial variation except in regions close to dominant openings.
- iii) A high correlation between external and internal pressures has been found in all cases, particularly for the component of pressure participating in the overall structural loading.
- iv) The largest internal pressures occur when the wind direction is perpendicular to the wall with dominant openings.
- v) When the dominant openings are to the lee of the structure and the windward wall is closed the internal pressures are generally negative and are not very sensitive to the size of wall openings or to the background porosity.

- vi) For windward openings, although internal pressure coefficients are generally positive, cases with high background porosity combined with small openings produce zero or slightly negative coefficients. For wall openings of significant size (more than 20% of the wall area) the internal pressure coefficients become essentially independent of the background porosity. The lower the background porosity, the smaller the necessary size of the wall opening needed to make the internal pressure coefficients insensitive to further increases of the wall opening.
- vii) Large-scale structural loads, represented here by bay loads, are also affected by the background porosity. For constant wall openings the bay loads tend to be higher for lower background porosity.

ACKNOWLEDGEMENTS

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REFERENCES

1. Davenport, A. G., Surry, D and Stathopoulos, T., Wind Loads on Low-Rise Buildings: Final Report of Phase I and II, Parts 1 and 2, Boundary Layer Wind Tunnel Laboratory, The University of Western Ontario, London, Canada, BLWT-SS8-1977, November 1977.
2. Tamura, G. T., Measurement of Air Leakage Characteristics of House Enclosures, ASHRAE Transactions, Vol. 81, Part 1, 1975.
3. Newberry, C. W. and Eaton, K. J., Wind Loading Handbook, Building Research Establishment Report, Department of the Environment, London, England, 1974.
4. Newberry, C. W., Eaton, K. J. and Mayne, J. R., Wind Loading on Tall Buildings - Further Results from Royex House, Industrial Aerodynamics Abstracts 4, July - August, 1973.
5. Vickery, B. J., Wind Loads on Low-Rise Buildings, presented at D.R.C. Seminar, Darwin, Australia, March 30, 1976, (Unpublished, 11 pages, 19 figs).
6. Surry, D., Stathopoulos, T., An Experimental Approach to the Economical Measurement of Spatially -Averaged Wind Loads, Journal of Industrial Aerodynamics, Vol. 2 (1977/1978), pp. 385-397.
7. Davenport, A. G., Surry, D. and Stathopoulos, T., Wind Loads on Low-Rise Buildings: Final Report of Phase III, Parts 1 and 2, Boundary Layer Wind Tunnel Laboratory, The University of Western Ontario, London, Canada, BLWT-SS4-1978, July 1978.
8. Surry, D., Stathopoulos, T. and Davenport, A. G., The Wind Loading of Low-Rise Buildings, Proceedings of Canadian Structural Engineering Conference 1978, The Canadian Steel Industries Construction Council.
9. Surry, D. and Isyumov, N., Model Studies of Wind Effects - A Perspective on the Problems of Experimental Technique and Instrumentation, Proceedings of the Sixth International Congress on Instrumentation in Aerospace Simulation Facilities, Ottawa, Canada, Sept. 22-24, 1975.
10. Tryggvason, B. V. and Isyumov, N., Similarity Requirements for Inflatable Structures, Proceedings

of the Third U.S. National Conference Wind Engineering Research, Gainesville, Florida, February 26–March 1, 1978.

11. Euteneuer, G. A., Druckanstieg Im Inneren von Gebauden Bei Windeinfall, Der Bauingenieur, Vol. 45 (1970), pp. 214–216.
12. Kandola, B. S., Wind Effects on Buildings with Varying Leakage Characteristics – Wind–Tunnel Investigation, Journal of Industrial Aerodynamics, Vol. 3 (1978), pp. 267–284.
13. Surry, D., Kitchen, R. B. and Davenport, A. G., Wind Loading of Two Hangars Proposed for Jeddah Airport, Saudi Arabia – A Rigid Model Study, Report to be published, Boundary Layer Wind Tunnel Laboratory, The University of Western Ontario, London, Canada.
14. Kramer, C., Gerhardt, H. J. and Scherer, S., Wind Pressure on Block Type Buildings, Proceedings of the 3rd Colloquium on Industrial Aerodynamics, Part 1, Aachen, W. Germany, June 14–16, 1978.
15. Eaton, K. J. and Mayne, J. R., The Measurement of Wind Pressures on Two-Storey Houses at Aylesbury, Journal of Industrial Aerodynamics, Vol. 1 (1975), pp. 67–109.
16. American National Standard Building Code Requirements for Minimum Design Loads in Buildings and Other Structures, ANSI A58.1 – 1972, Amer. Nat. Standards Inst., New York, 1972.
17. National Building Code of Canada 1975, NRCC No. 13982, Associate Committee on the National Building Code, National Research Council of Canada, Ottawa, 1975.
18. Commentaries on Part 4 of the National Building Code of Canada 1975, Supplement No. 4, NRCC No. 13989, Associate Committee on the National Building Code, National Research Council of Canada, Ottawa, 1975.