4649

Transient Wind-Induced Internal Pressures

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Abstract: The paper refers to a new experimental approach applied in a boundary layer wind-tunnel experiment that tests the transient response of the wind-induced internal pressure in a building when a sudden opening occurs. This topic has been examined analytically in the past. It has been found that the internal pressure may become much higher than the external pressure when a large window breaks during a windstorm. The present study examines this question experimentally by imposing a sudden opening on the front wall of a square building. The internal pressure was monitored at a number of points inside the model building, which could be tested at various internal volumes by using airtight partitions. A continuous record of the internal pressure variation was thus obtained while a data acquisition system was sampling it at a high rate to determine its statistics. The results of the experiments are compared with the analytically predicted data and form a basis to examine the influence of the air flow and the internal volume on the transient responses of the wind-induced internal pressures in buildings.

Introduction

The transient response of the wind-induced internal pressure in buildings to a sudden external pressure increase, such as that caused by a sudden window failure during a windstorm, has been examined only analytically in the past. It has been found that the breakage of a window on the windward side of a building could raise the internal pressure momentarily to a level exceeding the stagnation pressure. According to Liu and Saathoff (1982), "This may have serious effects on building safety and, thus, should be taken into account in the design of buildings."

In reality, however, the critical question is whether or not the sudden overshooting of internal pressure may be higher than the peak values of the steady-state internal pressure fluctuations. If it is, then special provisions should be made in the wind standards and codes of practice to accommodate this potential effect. The present study has attempted to answer this question by performing tests under simulated wind conditions.

The paper first reviews the analytic approaches and presents the results of a parametric study that indicates the effects of internal volume and wind speed on the magnitude of transient internal pressure coefficients. This is followed by a description of the experimental procedure and test results. Experimental data are finally compared with analytically evaluated internal pressure coefficients.

Theory

The problem of transient response of internal pressure in a nonporous building with a windward wall opening was first examined by Euteneuer

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Note. Discussion open until December 1, 1989. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on March 7, 1988. This paper is part of the *Journal of Engineering Mechanics*, Vol. 115, No. 7, July, 1989. ©ASCE, ISSN 0733-9399/89/0007-1501/$1.00 + $.15 per page. Paper No. 23681.

(1970). Based on the assumptions of isentropic fluid flow (while neglecting mass forces and damping effects), a simple equation for the response time—the time required for the internal pressure to reach its maximum value—was derived. Euteneuer's approach, however, excluded the possibility of overshooting the internal pressure, the maximum value of which was assumed to be equal to the stagnation pressure.

Holmes (1979) described the transient response phenomenon by a second-order, nonlinear, ordinary differential equation by treating the building as a Helmholtz resonator. With this approach, the general behavior of the internal pressure—before, during, and after the sudden change—can be described. The maximum value of the internal pressure and the instance of its occurrence can thus be predicted.

A different approach, based on an application of the Bernoulli equation for unsteady isentropic flow, has been described by Liu and Saathoff (1981), who have also derived a second-order, nonlinear, ordinary differential equation to describe the transient response of wind-induced internal pressure. While Holmes' equation is only applicable to small pressure variations, the equation derived by Liu and Saathoff is applicable to any pressure variation. In fact, it has been shown that Liu and Saathoff's equation reduces to Holmes' equation when the pressure variation is small (Liu and Saathoff 1982).

The present investigation starts with the solution of the following differential equation (Liu and Saathoff 1981) for the internal pressure p_i developed in a rigid building with a single windward opening:

$$\frac{d^2p_i}{dt^2} = Dp_i(p_e^n - p_i^n) + \frac{1}{p_i}\left(\frac{dp_i}{dt}\right)^2 - \frac{E}{p_i}\left|\frac{dp_i}{dt}\right|\frac{dp_i}{dt} \quad (1)$$

where

$$D = \frac{k^2A_ep_a^{1/k}}{(k-1)L_eV_o\rho_a} \quad (2a)$$

$$E = \frac{V_o}{2kA_eL_e} \quad (2b)$$

$$n = \frac{k-1}{k} \quad (2c)$$

In Eqs. 1 and 2*a*–*c*, p_a = initial internal pressure (ambient pressure); p_s = stagnation pressure [$p_s = p_e - p_a = (1/2)\rho_a v^2$]; p_e = total external pressure; ρ_a = air density; v = wind velocity (at the opening's height); A_e = effective area of the single windward opening; L_e = effective length of the air slug; V_o = internal volume of the building; and k = polytropic exponent (specific heat by constant pressure/specific heat by constant volume). If one makes the substitutions

$$t = x \quad (3a)$$

$$p_i = y \quad (3b)$$

$$\frac{dp_i}{dt} = y' = z \quad (3c)$$

Eq. 1 takes the general form

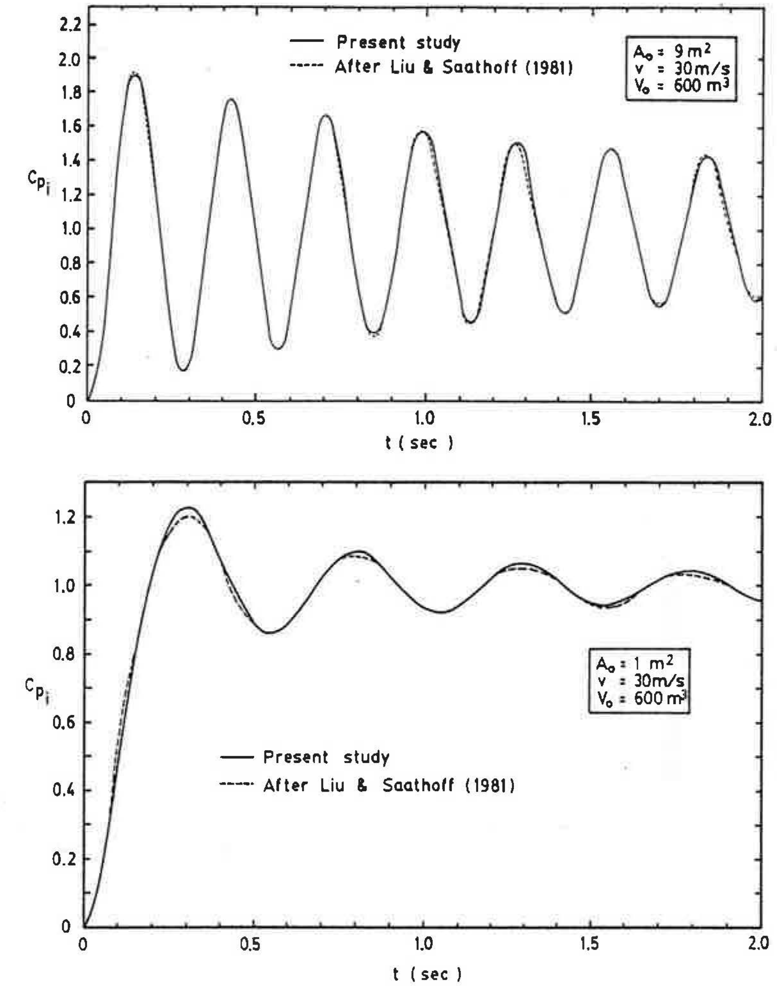


FIG. 1. Transient Response of Internal Pressure Coefficient Due to: (*a*) Sudden Large Opening; (*b*) Sudden Small Opening

$$\frac{dy}{dx} = F(x,y,z) \quad (4a)$$

$$\frac{dz}{dx} = G(x,y,z) \quad (4b)$$

where

$$F(x,y,z) = z \quad (5a)$$

$$G(x,y,z) = Dy(p_e^n - y^n) + \frac{1}{y}z^2 - E\frac{1}{y}|z|z \quad (5b)$$

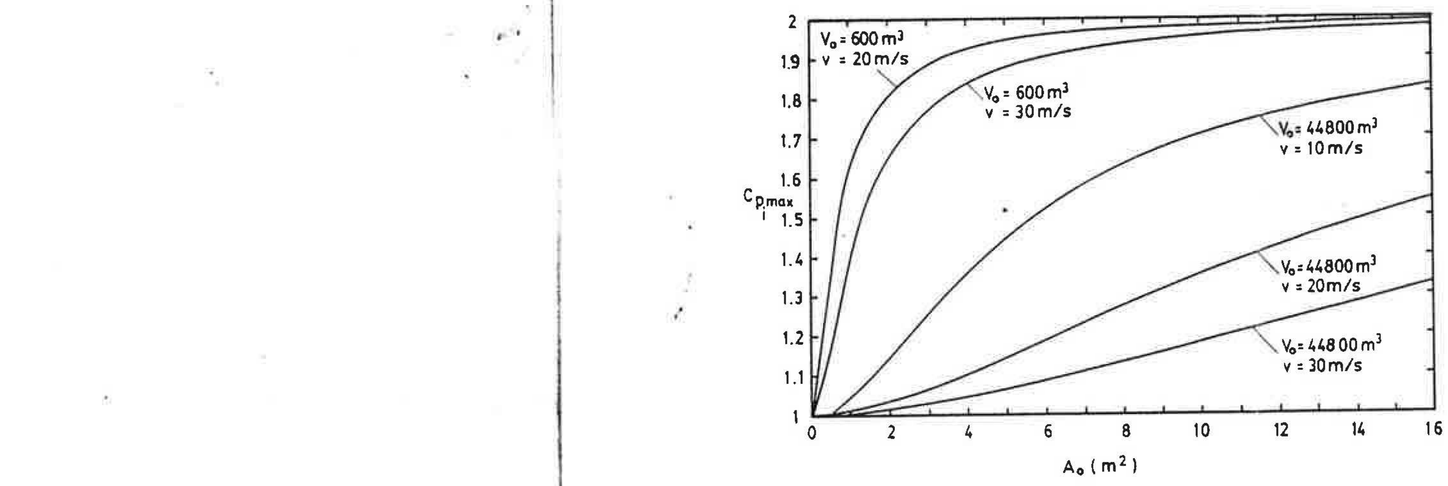


FIG. 2. Maximum Internal Pressure Coefficient Calculated for Various Openings, Internal Volumes and Wind Speeds

Consequently, Eq. 1 has been transformed into the system of two first-order, ordinary differential equations (Eqs. 4*a* and 4*b*) that can be solved by means of a second-order, Runge-Kutta method (Baines et al. 1976). The solution has been carried out on an IBM PC with a BASIC compiler. Typical results of the variation of internal pressure coefficients with time appear in Figs. 1(*a*) and 1(*b*) for the case of a large and a small opening, respectively. The same data presented by Liu and Saathoff (1981) have been used for comparative purposes and the results agree fairly well. It is also noteworthy that the overshooting of internal pressure is higher and the response time faster in the case of a larger windward opening.

To study in detail the effect of various parameters on the magnitude of the maximum internal pressure coefficient, Eq. 1 has been solved for a number of cases, consisting of buildings with windward wall openings, whose effective areas are always considered equal to the nominal areas of opening (A_o). In addition, the effective length, L_e, is calculated by the equation

$$L_e = L + \alpha\sqrt{A_o} \quad \text{(6)}$$

where L = the wall thickness; and α = a jet-related empirical coefficient equal to 0.89 in the case of a circular opening and equal to 0.86 for a square opening (Vickery et al. 1984). An intermediate value of α = 0.875 has been used for irregular openings. Thus, the effective length is different from that used by Liu and Saathoff (1981), who assumed that $L_e = 0.8\sqrt{A_o}$.

Fig. 2 shows the results of the solution of Eq. 1 in terms of maximum internal pressure coefficients (with peaks first occurring at transient response) versus the nominal area of the windward wall opening for various wind speeds and two values of building volumes. In all cases, a polytropic exponent k = 1.4 has been used, assuming isentropic flow. Clearly, the maximum value of internal pressure coefficient increases with increasing the nominal area of the windward opening and decreases with increasing the wind velocity and/or the building internal volume. Moreover, it has been

found that the transient internal pressure decreases slightly by decreasing the wall thickness and/or the polytropic exponent (between isothermal and isentropic) but this influence appears insignificant.

Experimental Approach

The experimental work is aimed at verifying the results of the theory and comparing the transient with the steady-state internal pressure fluctuations. The experiments were carried out at the boundary layer wind tunnel of the Centre for Building Studies (CBS) of Concordia University. The wind tunnel has a working section approximately 12.20 m long × 1.80 m wide, and has an adjustable roof height averaging roughly 1.60 m. A geometric scale of 1:400 has been suggested for the simulation of the most important variables of the atmospheric boundary layer under strong wind conditions. More details about this wind tunnel and its simulation characteristics are given by Stathopoulos (1984). The present measurements are carried out in a simulated open country exposure with a velocity profile represented by a power-law equation with an exponent equal to 0.15.

Fig. 3 shows a longitudinal cross section of the building model used in this study. The model, which is a cubic box with a 0.152-m-long side is made of 0.012-m-thick plexiglass. It is equipped with a number of internal and external pressure taps and has a circular opening on one wall 0.051 m in diameter. The front part of the opening has a circular seat 0.004 m thick and 0.056 m in diameter. A thin aluminum ring, having an outer diameter of 0.056 m and an inner diameter of 0.019 m, is located in the front seat, serving as a support for the polyethylene circular membrane simulating the window or the door to be broken. The membrane was kept tight to the seat by means of two circular rings. A partition wall inside the building reduced the effective volume to approximately one-third of the total. The wind-tunnel tests, reported in this paper, have been carried out with an internal volume, V_o, equivalent to 44,800 m³ in full-scale terms, with nominal opening areas,

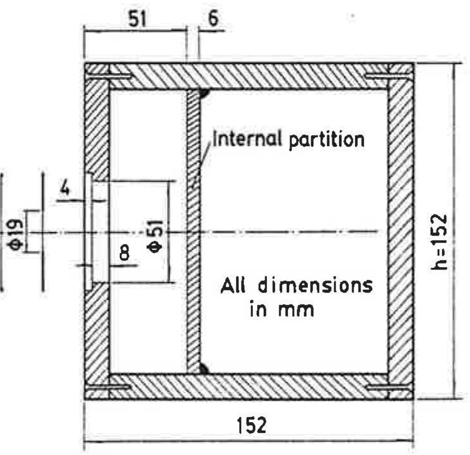
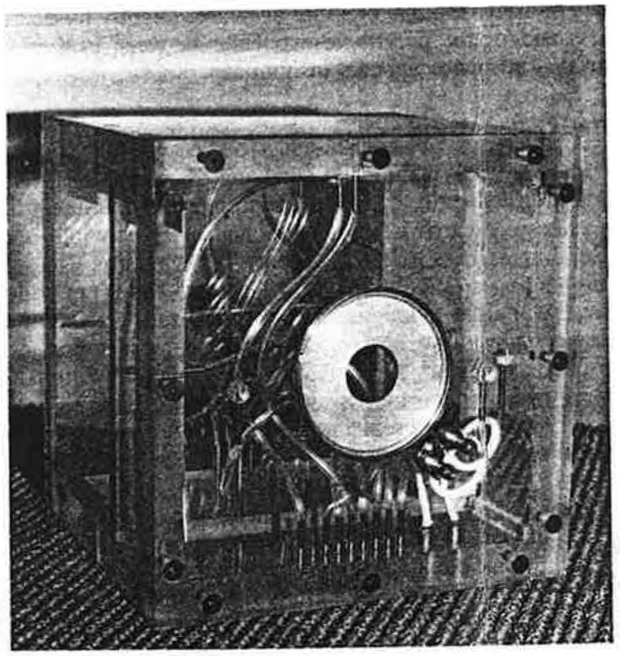


FIG. 3. Longitudinal Cross Section of Experimental Building Model with Membrane



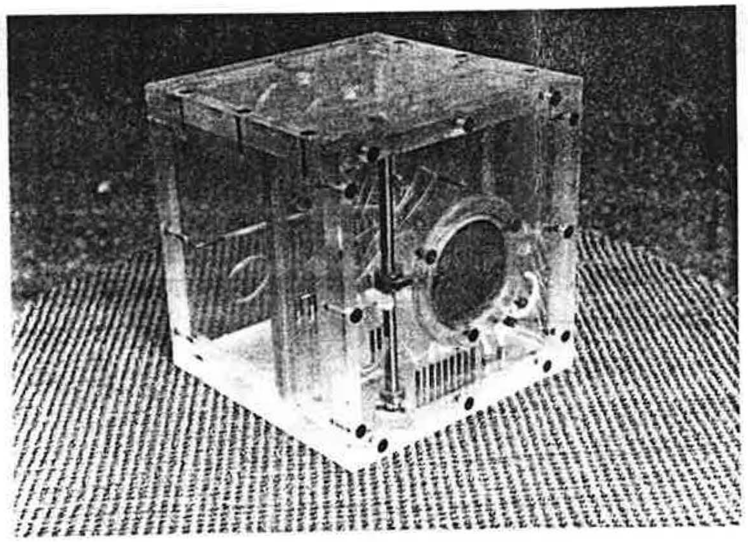


FIG. 4. Experimental Building Model with: (*a*) Membrane; (*b*) Mechanical Device

A_o, ranging from 0.32 to 16 m^2 in full scale. Fig. 4(*a*) shows a picture of the model.

The internal pressure is monitored by a SETRA-237 dynamic pressure transducer, which is connected to an internal pressure tap by means of a short segment to a thin plastic tube, 0.001 m in internal diameter. The frequency response of such a tube is flat up to several hundred hertz. An identical transducer was used to pick up the reference dynamic pressure from a Pitot tube placed at the height of the opening at some distance in front of the model. Both pressure signals were sent simultaneously to a two-pen, fast-response PM8252A Philips recorder. The data-acquisition system of the laboratory, measurement, analysis and control system (MACSYM2 of Analog Devices), was also sampling the internal pressure at a rate of 512 samples/s. A number of tests were carried out at different wind speeds in the range between 4 and 11 m/s.

The simulation of a sudden opening in the wind tunnel is a difficult task. The time scale of a wind tunnel test is given by the equation

$$\frac{t_m}{t_p} = \frac{l_m}{l_p}\frac{v_p}{v_m} \quad (7)$$

in which m and p stand for model and prototype, respectively, l_m/l_p is the length scale and v_m/v_p is the velocity scale. Assuming a length scale of 1:400 and an inverse velocity scale ranging between 5 and 10 based on very strong full-scale wind conditions—say more than 70 km/h—a time scale in the order of 1:40 to 1:80 can be estimated. This implies that, for correct simulation conditions, a phenomenon should occur 40–80 times faster in the wind tunnel than in full scale. Various methodologies were used for the creation of the sudden opening on the windward wall of the building model.

The first attempt was to destroy the central part of the polyethylene membrane by injecting a chemical through a thin pipe tightened to the windward wall of the model. That procedure was slow and resulted in irregularly shaped openings which were not really sudden. Another attempt was made by poking the membrane with a sharpened nail. The shortcoming of that procedure consisted in creating an undesirable overpressure inside the model at the very moment the poking was taking place. The third attempt was to burn the center of the polyethylene membrane by means of an electrically heated conducting loop having a given diameter. Despite the fact that the loop was circular, the openings were elliptically or irregularly shaped. As was mentioned previously, this is the reason a value of $\alpha = 0.875$ was used in the calculation of the effective length. A number of tests described in this paper were carried out using this last methodology but results were not totally satisfactory because of the relatively long time required to create a sudden opening and the irregularity of its shape.

The model was then modified to incorporate a mechanical device for the creation of a rectangularly-shaped sudden opening with a variable size up to 20 mm^2, i.e., 3.2 m^2 in full scale. Fig. 4(*b*) shows the experimental building model with the mechanical opening device. This device is made out of steel and contains a front plate which is a 3-mm-thick, and 57-mm-diameter disk having a 4 × 5-mm rectangular window in its center and a diametral slot guide 1 mm deep and 8 mm wide; a shutter consisting of two identical leaves mounted in the slot guide of the front plate, two adjusting screws, limiting the stroke of the leaves, and two helical springs; a rear plate, which is a 3-mm-thick, 23-mm-wide, and 51-mm-long, running-track–shaped plate; and a trigger consisting of a lever with two retaining pins, and a single cam camshaft with an under-the-floor knob.

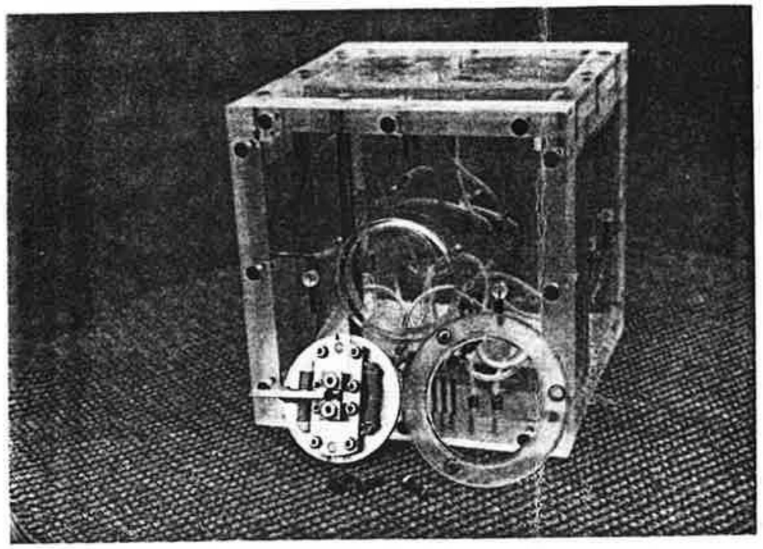


FIG. 5. Mechanical Device for Sudden Opening

The first three parts are assembled in the described order as a sandwich using eight bolts and nuts. The sandwich can be seen in its working position in the plexiglass seat in Fig. 4(*b*) as well as from its back side, outside the model, in Fig. 5. The lever of the trigger is mounted on the back side of the front plate of the sandwich, and the camshaft is vertically inserted in the plexiglass model.

Fig. 5 shows the status of the device before the test. In order to run a test the strokes of the leaves are adjusted to get the desired opening. The leaves are pressed against each other and against the springs to obturate the rectangular window of the front plate. The leaves are then locked in the closed position by pushing the trigger's lever against the sandwich, and the armed sandwich is inserted and tightened in its greased plexiglass circular seat by means of the three screws shown in Fig. 5. After rotating the knob and releasing the trigger, the device has to be reset and remounted for another test. The time required for the creation of an opening with this device was up to five times less than that required in the case of the membrane. The device was designed and fabricated in the Centre for Building Studies.

EXPERIMENTAL RESULTS AND INTERPRETATIONS

The results of two typical wind-tunnel tests, using the membrane technique, are presented in Figs. 6(*a*) and 6(*b*), which show the internal pressure traces—measured in inches of water—before, during and after the sudden opening. The variation of stagnation pressure is also shown at the top diagram of each figure. Fig. 6(*a*) corresponds to a wind velocity equal to 9 m/s and a nominal area of opening equal to about 3.5 mm^2. The internal pressure coefficient measured at the transient response was found equal to 1.47, using the recorder, and 1.57, using the data acquisition system. Fig. 6(*b*)

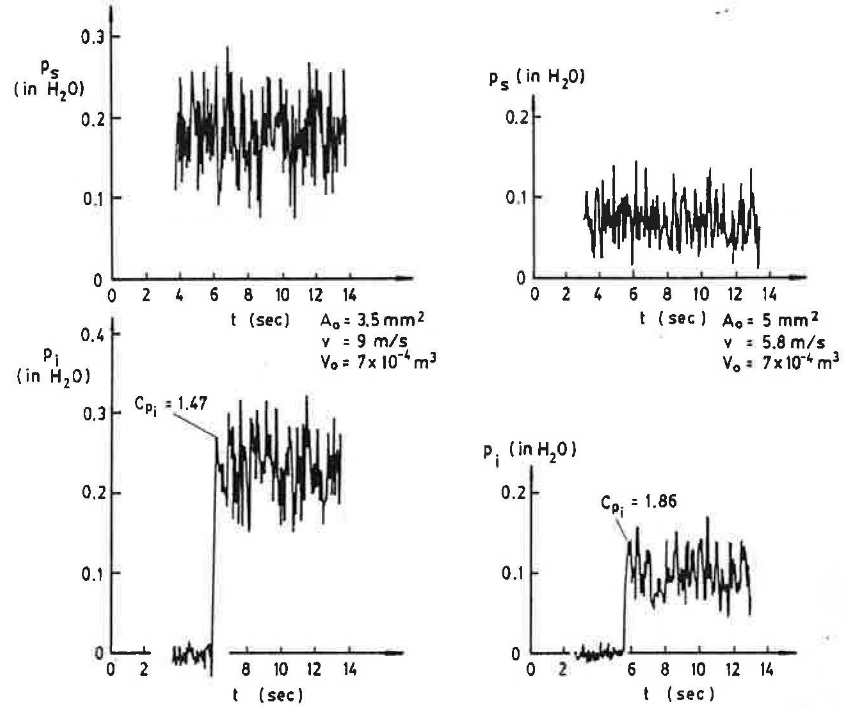


FIG. 6. Fluctuations of Dynamic Velocity Pressure and Transient Response to Sudden Opening: (*a*) v = 9 m/s; (*b*) v = 5.8 m/s

corresponds to a wind velocity equal to 5.8 m/s and a nominal area of opening equal to about 5 mm^2. The internal pressure coefficient at the transient response recorded in the pressure trace and by the data acquisition system was equal to 1.86. In both cases it was apparent that the transient response overshooting of internal pressure was not as high as the subsequent steady-state peak fluctuations. This was also found in measurements through the MACSYM2 and it has always been the case in a series of eight additional tests with different parameters. Also, the results were not affected by the location of the internal pressure tap used.

By using the parameters of the wind-tunnel tests (i.e., the internal volume of the model tested), velocities ranging between 4 and 11 m/s, and windward wall opening areas varying between 2 and 30 mm^2, Eq. 1 has been numerically solved for 128 cases. The results are presented in Fig. 7 in a format similar to that of Fig. 2. The experimental data obtained from previous tests have also been included in the figure. The comparison between experimentally determined and analytically evaluated transient-response, internal-pressure coefficients is very good for these cases.

Regarding the time response, however, results using the membrane technique are not as satisfactory. In the case of the test shown in Fig. 6(*a*), the data acquisition system displays a time-response value of 0.225 s, while the theoretical value is around 0.028 s (eight times smaller). In the case of the

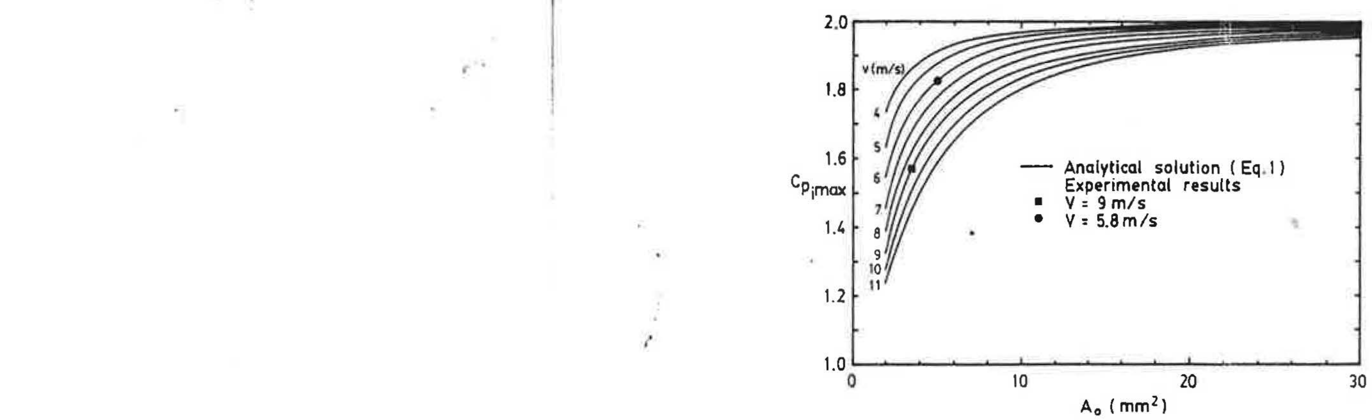


FIG. 7. Maximum Internal Pressure Coefficients at Time of Sudden Change (Experimental Data for Membrane Case)

second test [Fig. 6(*b*)], the measured value is 0.190 s while the theory predicts 0.025 s. This indicates that the membrane technique for creating a sudden opening is not fast enough. A quicker method is mandatory for more accurate measurements.

All subsequent tests were thus carried out with the model equipped with the mechanical device that provides a much faster creation of the sudden opening. All other test parameters were kept the same with the exception of the sampling rate which was increased to 1,024 samples/s for improvement of accuracy. A typical example of the measured internal pressure in the model building is presented in Fig. 8. Digitized data plotted for the second, in which the sudden opening occurs, are characteristic of the transient behavior of wind-induced internal pressure. The short time achieved for the realization of the sudden opening is apparent, as is the magnitude of overshooting, which is lower than the level of the subsequent instantaneous peak values. This has consistently been the case regardless of the method used for creating the sudden opening.

Fig. 9 compares the transient internal pressure coefficients measured using the mechanical device for the sudden opening with those calculated analytically for the same wall opening and wind velocity. Considering the flow differences between theory and experiments, and the difficulties involved in this type of experimental measurement, the agreement found between theory and experiment is encouraging. Furthermore, the duration of overshooting, using the model with the mechanical device, has been compared with the theoretical value for a number of wind velocities and differently sized openings. The duration of overshooting, t_o, was calculated from the computer data, as previously indicated in Fig. 8. Since t_o varies drastically (even between tests of nominally identical configurations), the range of measured t_o in four identical experiments has been used for comparative purposes in each test configuration. Fig. 10 shows the results of these comparisons for three different wind velocities. Note that the agreement is much better than in the case of the membrane technique, but the experimental values are still generally higher than their theoretical counterparts, particularly for higher wind

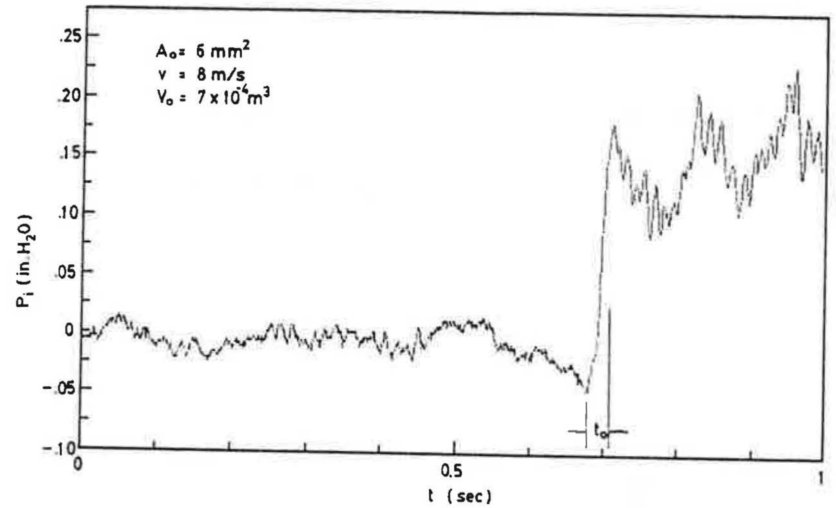


FIG. 8. Reproduction of Internal Pressure Fluctuations Registered by Data-Acquisition System at Time of Sudden Change (Through Mechanical Device)

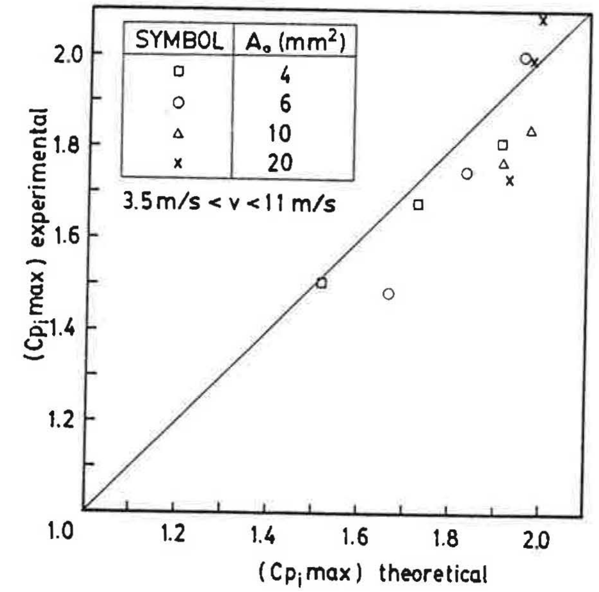


FIG. 9. Comparison of Transient Internal Pressure Coefficients Measured and Predicted—Sudden Opening Through Mechanical Device

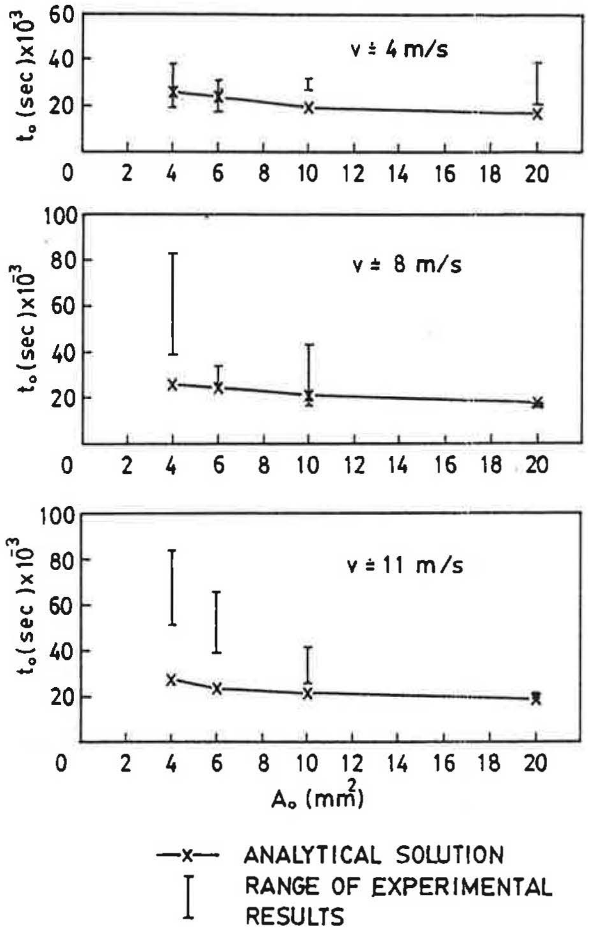


FIG. 10. Comparison of Measured and Predicted Transient Overshooting Time—Sudden Opening Through Mechanical Device

speeds. However, the reduction of t_o by increasing the size of the opening is clear both analytically and experimentally.

In spite of the difficulties involved, the experimental data have been useful in indicating that the sudden-change, peak internal pressure is not higher than the steady-state peak fluctuations. Note that the experimental data were obtained from a rigid model which was absolutely tight so that air could not leak out from any point. In reality, buildings always have some inherent porosity (cracks, joints, etc.) that would tend to alleviate, even more, the transient peaks of the internal pressure. Flexibility of the building envelope is an additional factor that has not been considered in the present study. It is expected that transient overshooting will be further reduced in a real building. In view of the preceding, there does not appear to be a need to take the case of sudden opening into account in the structural design of buildings,

against wind, provided that the steady-state peak values of internal pressure coefficients are utilized. Unfortunately, this is not always the case with present wind standards and codes of practice.

Conclusion

This paper examines the transient response of wind-induced internal pressures in buildings. The present work applies the theory based on the unsteady isentropic Bernoulli equation to a large number of cases yielding to a parametric study. This shows the increase of the transient internal pressure peaks when increasing the windward wall opening area and decreasing the building internal volume and/or wind speed.

Furthermore, experimental measurements carried out in a boundary layer wind tunnel compare satisfactorily with the analytically evaluated data regarding transient internal pressure peaks. The use of a specially designed mechanical device for the sudden opening provided better estimates of the time response values for overshooting internal pressures.

Internal pressure peaks measured under steady-state conditions have always been found higher than the transient peaks detected in the present study. Therefore, it can be concluded that no extra care should be taken to include sudden opening changes in the design if the instantaneous peak values of internal pressures are utilized.

Acknowledgments

The research presented in this paper was supported by the Natural Sciences and Engineering Research Council of Canada and the Fonds pour la Formation de Chercheurs et l'Aide à la Recherche of the province of Quebec. The contribution of Hans Obermeir to the fabrication of the model and its mechanical opening device, and his assistance in collecting experimental measurements are gratefully acknowledged.

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Appendix II. Notation

The following symbols are used in this paper:

A_e = effective area of single windward opening;
A_o = nominal area of opening;
Cp_i = internal pressure coefficient;
k = polytropic exponent;
L = wall thickness;
L_e = effective length of air slug;
l = length;
m = index for model;
n = constant defined in Eq. 2c;
p = index for prototype;
p_a = initial internal pressure (ambient pressure);
p_e = total external pressure;
p_s = stagnation pressure [$p_s = p_e - p_a = (1/2)\rho_a v^2$];
t = time;
t_o = duration of overshooting;
V_o = internal volume of building;
v = wind velocity (at opening's height);
x = substitution for time;
y = substitution for internal pressure;
z = derivative of internal pressure with respect to time;
α = empirical jet-related coefficient; and
ρ_a = air density.

Eigenproperties of Classically Damped MDOF Composite Systems[a]

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Abstract: A perturbation technique is employed to determine the eigenproperties of structural systems composed of multi-degree-of-freedom (MDOF) primary and MDOF secondary systems. The eigenproperties of the individual subsystems are used to estimate those of the combined system. Gerschgorin's discs are introduced to establish an accurate criterion to distinguish between tuned and detuned modes. The effects of tuning and interaction between the subsystems are considered in the analysis. For the tuned case, the solution of a small special eigenvalue problem related to the tuned modes and a similarity transformation of the original tuned system results in a new detuned system. High-order perturbations of the mode shapes and frequencies are developed, and numerical results can be obtained to any order of accuracy by evaluating the higher-order terms. Gerschgorin's theorem provides an efficient means of evaluating the error in the estimated eigenvalues. The proposed technique appears to be more efficient and accurate than existing methods.

Introduction

In many structures light secondary systems, such as piping and equipment, are often attached to a primary structure. Piping in industrial structures, drilling and exploration equipment on offshore platforms, and communication and control devices on space vehicles are examples of such systems. The dynamic analysis of the combined primary-secondary system is prone to numerical problems, because of the combination of the mass and stiffness matrices of the primary structure, which contains large elements, with the matrices corresponding to the secondary system, which contains much smaller elements. The increase in the size of the problem due to the addition of the secondary system is also undesirable in practice. Since the eigenproperties of the combined system are expected to deviate only slightly from those of the individual subsystems, the problem is well suited for perturbation techniques. Perturbation methods that overcome the aforementioned hurdles have recently been proposed.

Sackman and Kelly (1979) first introduced perturbation techniques to analyze the eigenproperties of primary-secondary systems. Igusa and Der Kiureghian (1985) studied quite general composite systems and derived closed-form solutions for their eigenproperties. These, however, were extensions of results derived for two-degree-of-freedom (2-DOF) systems and have some shortcomings (Harichandran and Zhang 1989). Suarez and Singh (1987) in-

[a]Presented at the May 23–25, 1988, ASCE/EMD Specialty Conference held at Blacksburg, VA.

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Note. Discussion open until December 1, 1989. Separate discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on May 3, 1988. This paper is part of the ***Journal of Engineering Mechanics***, Vol. 115, No. 7, July, 1989. ©ASCE, ISSN 0733-9399/89/0007-1515/$1.00 + $.15 per page. Paper No. 23682.