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Effect of wind-induced internal pressure on local frame forces of low-rise buildings

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ABSTRACT

Given the significant role of internal pressures in the wind-induced loading of low-rise buildings, their correct estimation is critical for the accurate determination of the net (external plus internal) wind effects. This paper presents results of an investigation conducted to study the effect of wind-induced internal pressures on structural frame forces on low-rise buildings with single or multiple dominant openings. Models from the National Institute of Standards and Technology (NIST) aerodynamic database with internal pressure measurements were used. Large-scale experiments were also conducted in the Wall of Wind (WOW) facility at Florida International University (FIU) using a model with multiple openings. Calculations of frame forces were performed using the Database-Assisted Design (DAD) methodology. It was found that internal pressure significantly increases the forces induced by wind with the most unfavorable direction on the frames located close to the openings. However, its effect on the frames located away from the openings was smaller. Effects of internal pressure also varied between different cross-sectional locations of the same frame, depending upon the correlation between forces induced by external and internal pressures. For the highest net frame forces, the reduction factor applied to the response induced by internal pressures, that accounts for the imperfect correlation between the external and internal pressures, was found to be approximately 0.85. Comparison between frame forces calculated using experimentally measured internal pressures and their counterparts evaluated by using ASCE 7–10 provisions for internal pressures showed that the latter result in unconservative estimates of frame forces in both enclosed and partially enclosed buildings. An additional significant result is that the ASCE 7 classification of buildings with equally sized windward and leeward openings as enclosed buildings can lead to the underestimation of net frame responses. It is therefore proposed that this classification be changed to reflect the appropriate internal pressure effects.

1. Introduction

The design of buildings for wind should account for the possible increase of the wind loading due to failures of unprotected windows and/or doors. The characteristics of wind-induced internal pressures are affected by the size, geometry and location of the openings, the volume, shape and envelope flexibility of the building structure, and the characteristics of the external wind pressure. An opening on the windward side can induce high positive internal pressures, which when combined with negative external pressures on the roof might produce high net pressures that can lead to building failures. This is a particularly common scenario in severe events such as tropical cyclones, during which openings can be breached by windborne debris or by direct wind loading [1]. The importance of understanding the effects of wind-induced internal pressures on low-rise buildings is widely recognized and has been the subject of extensive research. However, difficulties associated with model scaling requirements needed for the correct measurement of internal pressures in wind tunnels have limited the amount of reliable experimental data available.

Most previous research on internal pressure has dealt with understanding the characteristics of internal pressures under various opening configurations. However, in design, it is not only the internal pressures themselves that are important; what matters from a design viewpoint is the net loading induced by the combination of internal and external pressures. Net fluctuating pressures/responses are highly affected by the correlation between the fluctuating internal and external pressures, and between the

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respective responses they induce: higher correlation coefficients entail higher net pressure peaks.

Internal pressure loading may contribute a high proportion of the total wind loading for both major structural elements and for cladding of low-rise buildings [2]. Some researchers ([3–6]) have studied the nature of net wind-induced loads on cladding of low-rise buildings for which high correlations between external and internal pressures were observed. Wind loads on cladding are determined by the pressure distribution within a relatively small surface area. However, wind-induced forces on structural systems, for example frames, are affected by the correlation of the external and internal pressures in the entire area tributary to the system.

The scope of the few available studies of the internal pressure effects on low-rise building Main Wind Force Resisting Systems (MWFRS) is limited. This paper therefore presents results of a comprehensive study of this topic. According to Holmes and Ginger [1], if the size of an opening is greater than approximately twice the total background leakage area, the opening can be considered as dominant. Typically, the single dominant opening on the windward side is the case usually considered critical in design. However, the accurate evaluation of internal pressures in buildings with single or multiple openings can be warranted as well ([7,8]). Hence, this study also included multiple opening cases.

The structures considered in this study are low-rise industrial buildings characterized by rectangular shapes, gable roofs with no overhangs, no ceilings or wall partitions, and a structural system composed of equally spaced moment resisting steel frames. Data on internal pressures available in the National Institute of Standards and Technology (NIST) aerodynamic database (www.nist.gov/wind) were used to represent models with single dominant openings. In addition, large-scale testing was conducted at the Florida International University's (FIU) Wall of Wind (WOW) facility to measure wind-induced internal and external pressure on a low-rise building model with multiple dominant openings. Time histories of wind-induced frame forces were evaluated from time-histories of experimentally recorded pressures using Database-Assisted Design (DAD) methodology [9]. DAD is a computer-intensive, user-friendly automated design procedure that can be used for evaluating the time-histories of frame responses from time-histories of internal, external and net wind pressures recorded on large number of pressure taps.

This study also presents a thorough comparison between wind forces computed using experimentally measured internal pressures on the one hand and based on Minimum Design Loads for Building and Other Structures [10] provisions on the other. Furthermore, instead of comparing the experimentally recorded internal pressures to those recommended by ASCE 7–10, as was done in most previous studies, this work focuses on the effective influence of internal pressures on the net wind-induced force. The results of this research can assist in developing improved code provisions on wind-induced internal pressures.

Section 2 provides a brief description of the experimental data used in this study. In Section 3, the effect of internal pressures on net frame forces is investigated. Section 4 presents a comprehensive comparison of frame forces computed using experimentally recorded internal pressures to those estimated using ASCE 7–10 provisions. Finally, conclusions are provided in Section 5.

2. Experimental data

This study used data from the NIST public aerodynamic database, and from experiments conducted at FIU's WOW facility. Two models from the NIST database (referred to as the NIST model 1 and NIST model 2) were used to study the effects of internal pressures on frame forces in low-rise buildings with single dominant openings. Since internal pressure measurements in the NIST database are limited to models with single dominant opening, a large-scale experimental testing was conducted at the WOW using a model with multiple dominant openings (referred to as the WOW Model). A third model from the NIST database (referred to as the NIST Model 3), with full-scale dimensions identical to the WOW model, was used to compare results computed using the NIST database with those evaluated experimentally at the WOW, for a no-opening case. Table 1 provides summary of the experimental data used for the different analyses.

The following subsections provide descriptions of the NIST and WOW experimental data.

2.1. NIST dataset

The NIST public aerodynamic database covers building configurations characterized by rectangular shape in plan, gable roof, and no overhang. The total number of buildings with distinct dimensions and roof slopes covered by the database is 37, and all the models were tested in both open and suburban terrain for 39 wind directions at 5 deg increments. However, of those 37 models, internal pressure measurements were conducted on only two models, both of which have a dominant opening.

NIST models 1 and 2 that include internal pressure measurements have identical dimensions except for their eave heights. The models have equivalent full-scale width $W = 24.4$ m and length $L = 38.1$ m, with a roof slope $\theta = 1{:}12$. The first model, henceforth referred to as NIST Model 1 has eave height $H = 12.2$ m, and the second model, henceforth referred to as NIST Model 2 has eave height $H = 4.9$ m. These models, which were tested at the University of Western Ontario (UWO) [7], were constructed of acrylic glass at a scale of 1:100. Each model had a large opening representing 3.3% of the wall area (rectangular opening in Fig. 1), small openings (circular opening in Fig. 1), and uniform background leakage (provided by eighty holes of 1.6 mm diameter at model scale). In this study, only the large openings were used, and during testing, the openings for the background leakage remained open [7].

Wind-induced pressure measurements were conducted at the UWO boundary layer wind tunnel for equivalent full scale time duration of 3600 s, at a velocity scaling of 1:4. During experimental investigations of internal pressure fluctuations in a micro-meteorological laboratory (wind tunnel or open jet facility), if a scaled down wind velocity is used, which is true in most cases, additional volume should be incorporated into the building model ([11,12]). This is required in order to scale correctly the frequencies of the internal pressure fluctuations to those associated with the external pressures. To satisfy this requirement additional volume was added underneath the UWO wind tunnel [13]. Internal pressures were measured simultaneously at two locations within the model (using 30-inch long tubing systems to connect the pressure taps to solid state high speed pressure scanners, at a sampling frequency of 500 Hz for a period of 100 s. Detailed information on the test models, UWO wind tunnel characteristics, and test protocols can be found in Ho et al. ([13,14]).

NIST model 3 had no building openings and was used to compare results computed using the NIST database with those evaluated experimentally at the WOW.

2.2. Wall of Wind (WOW) test data

The WOW (Fig. 2) is an open jet facility capable of producing hurricane strength wind speeds. It has 12 electric fans arranged in a two row by six-column pattern, which produces a wind field 6 m wide and 4.3 m high, allowing aerodynamic testing of large-scale models or full-scale portions of small buildings.