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Wind tunnel study of wind loading on rectangular louvered panels

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Abstract. Drag forces on a rectangular louvered panel, both as a free-standing structure and as a component in a generic low-rise building model, were obtained in a wind tunnel study. When tested in a building model, the porosity ratio of the wall opposite the louvered panel was varied to investigate its effect on the loading of the louvered panel. Both mean and pseudo-steady drag coefficients were obtained. Comparisons with the provisions for porous walls in contemporary loading standards indicate that for some opposite wall porosity ratios, the standards specify significantly different wind loads (larger and smaller) than obtained from this wind tunnel study.

Keywords: louver; porosity; wind loading; drag coefficients.

1. Introduction

Louvered panels/screens are often used as components and claddings for buildings and other structures or as free-standing sign boards, such as highway signs (Hajj and Mesrobian 2008). Fig. 1 shows a building wall with louvered panels as an example. However, the design of louvered panels currently lacks specific guidance and relies on provisions that were developed for other types of structural components. In particular, the design of louvered panels as building components are guided in practice by specifications which were primarily developed to assess wind loading on walls that are not louvered in nature (Davenport *et al*. 1977, Davenport *et al*. 1978). For example, in "Minimum Design Loads for Buildings and Other Structures", version 7-05, published by American Society of Civil Engineers (ASCE 2005), which will be subsequently referred to as ASCE 7-05, the net drag force acting on a wall of a low-rise building is determined based on specified external and internal pressure coefficients, which depend on categorization of the buildings as open, partially enclosed or enclosed, based on the porosity of the wall receiving positive pressure and that of the remainder of the building envelope. The effect of the exact porosities of the wall of interest and of the other surfaces of the building on the pressure coefficients is not considered. Nor are the effect of the shape and distribution of the openings in the walls of interest. These provisions can potentially be questionable when used in the design of louvered panels, because these panels are essentially "quasi-porous", meaning that they have a solid surface area when projected onto a plane normal to

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Fig. 1 A building wall with built in louvered panels

horizontal wind, yet provide significant openings for through air-flow. The applicability of such provisions in the design of louvered panels can be further questioned because the openings in louvered panels can be purposely shaped and distributed as opposed to those formed by, for example, windows, or those created by wind-born debris in wind storms. In addition, some standards, such as ASCE 7-05, do not have specific provisions for wind loading of free-standing structures with quasi-porous panels, such as louvered sign boards. Consequently, designers often have to design louvered sign boards utilizing solid board data. Even when a standard, such as the Australian/New Zealand Standard (AS/NZS 1170.2:2002) (Standard Australia 2002), specifies pressure coefficients for porous panels, these pressure coefficients are again based on tests of porous panels which differ from louvered panels. Due to these considerations, a series of exploratory tests were conducted in a wind tunnel to directly measure and assess the wind force acting on a louvered panel both as part of a generic low-rise building model and as a free-standing porous board. The drag coefficients obtained from these tests are compared with those specified by ASCE 7-05 and AS/NZS 1170.2, which would have been used in practice for the design of these structural components. To facilitate this comparison, the pertinent provisions in these standards are first briefly reviewed.

2. Provisions of contemporary standards

2.1 ASCE 7-05

ASCE 7-05 specifies that the design wind pressure on component and cladding elements of low-rise buildings shall be determined using the equation

$$p = q_h[(GC_p) - (GC_i)] \tag{1}$$

where q_h is the velocity pressure, GC_p and GC_i and are the external and internal pressure coefficients, respectively. The velocity pressure is determined following the equation

$$q_h = 0.613 K_z K_{zt} K_d V^2 I \tag{2}$$

in which K_z is velocity pressure exposure coefficient, K_{zt} the topographic factor, K_d the directionality factor, and V the 3 – s gust wind speed at 10 m above ground in Exposure category C specified by the standard. Equations and collectively can be equivalently expressed as

$$p = \frac{1}{2}(C_D)_{\text{ASCE}}\rho V^2 \tag{3}$$

where ρ is air density, and

$$(C_D)_{\text{ASCE}} = K_z K_{zt} K_d I\,[(GC_p) - (GC_i)] \tag{4}$$

can be treated as an equivalent drag coefficient according to the provisions of ASCE 7-05. The external pressure coefficient, GC_p, is specified as a function of the effective wind area (ASCE 7-05, Fig. 6-11) defined as the span length of the component or cladding element multiplied by its width. This approach attempts to account for the effect due to a lack of correlation in the gustiness of the wind. The effect of the roof slope is represented by a 10% reduction factor on the external pressure if the slope is less than 10°. The internal pressure coefficient, GC_{pi}, is specified in accordance with the openness of the building, specifically, according to whether the building can be categorized as open, partially enclosed or enclosed based on the porosity of the walls and roof within its envelop. ASCE 7-05 specifies discrete internal pressure coefficients for these three categories of buildings. It requires that both positive and negative internal pressure coefficients be used to determine the critical load conditions.

ASCE 7-05 does not provide provisions for porous boards, such as louvered panels as free-standing structures.

2.2 AS/NZS 1170.2

According to AS/NZS 1170.2 the design wind pressure on components and cladding elements of low-rise buildings shall be determined following the equation

$$p = 0.5\rho[V_{des.\theta}]^2 C_{fig} C_{dyn} \tag{5}$$

In this equation, ρ is air density; $V_{des.\theta}$ is the design wind speed orthogonal to the face of the components and cladding elements, which is determined based on the site wind speed and the factors accounting for the directionality, terrain/height, shielding and topographic effects (M_d, $M_{z,cat}$, M_s and M_t respectively, defined in the standard), and $^2C_{\text{fig}}$ and C_{dyn} are the aerodynamic shape factor and the dynamic response factor, respectively. For external pressures

$$C_{\text{fig}} = C_{\text{p,e}} K_{\text{a}} K_{\text{c}} K_l K_{\text{p}} \tag{6}$$

For internal pressures,

$$C_{fig} = C_{p,i} K_C \tag{7}$$

In these two equations for C_{fig}, $C_{p,e}$ and $C_{p,i}$ are the external pressure coefficient and the internal pressure coefficient, respectively, and K_a, K_c, K_l and K_p are the area reduction, combination, local pressure and porous cladding reduction factors, respectively, specified by the standard. Eqs (5), (6) and (7) collectively can be expressed equivalently as

$$p = \frac{1}{2}(C_D)_{\mathrm{AS/NZS}}\rho V^2 \tag{8}$$

in which $(C_D)_{\mathrm{AS/NZS}}$ can be treated as an equivalent drag coefficient according to provisions of AS/NZS 1170.2

$$(C_D)_{\mathrm{AS/NZS}} = (M_d M_{z,cat} M_s M_t)^2 (C_{p,e} K_a K_c K_l K_p - C_{p,i} K_c) C_{dyn} \tag{9}$$

The external pressure coefficient, $C_{p,e}$, is determined based on the depth to width ratio of the building and the slope of the roof. For windward walls, external pressure coefficients also depend on the height of the building and whether the building is elevated or on the ground. Values of internal pressure coefficient, $C_{p,i}$, are given for permeable walls without dominant openings and for walls with dominant openings on one surface, respectively. In particular, in this standard, "a surface is considered to contain dominant openings if the sum of all openings in that surface exceeds the sum of openings in each of the other surfaces considered one at a time". Apparently, louvered walls can often be categorized as constituting a dominant opening. For this type of wall, the internal pressure coefficient is specified based on "the ratio of dominant opening to total open area of other walls and roof surfaces" and the location of the dominant openings (i.e., windward, leeward, side walls or roof). It is apparent that AS/NZS 1170.2 specifies the internal pressure coefficient in a quite different manner from that in which ASCE 7-05 does. As will be seen subsequently, this difference will result in significantly different wind loading provisions by these two standards when applied to the design of louvered walls.

AS/NZS 1170.2 has provisions for free standing walls which account for wall aspect ratio, panel elevation above ground, panel porosity and wind direction. Net pressure coefficients are determined along with notional centers of pressure for moment calculations.

3. Experimental configuration

The experiments were conducted in the Texas Tech University boundary-layer wind tunnel, which can generate wind speeds of up to 45 m/s. The boundary-layer test section of this wind tunnel has a cross section of 1.84 m wide and 1.26 m high, and an upstream fetch of 17 m for generation of the desired boundary layer. The model studied is a plastic louvered panel: 254 mm wide, 193 mm high and 28 mm deep. It has 6 blades of 3 mm thickness, inclined at an angle of 45°. Figs. 2 and 3 show the front and side views of the louvered panel model. This panel is nominally a 1 to 25 scale model of a full-scale louvered panel. Due to the quasi-porous nature of louvered panels, the conventional concept of porous ratio cannot be used to assess their openness. As a result, in a typical design situation, the openness of a louvered panel is often characterized by the so-called free area ratio, which is defined as the ratio of the area formed by the intersection of the plane normal to the flow and the open ducts between the louver blades and the walls to the area of the panel projected to the plane normal to the flow (AMCA, 2009). For example, the free area ratio of the panel subjected to testing can be determined as

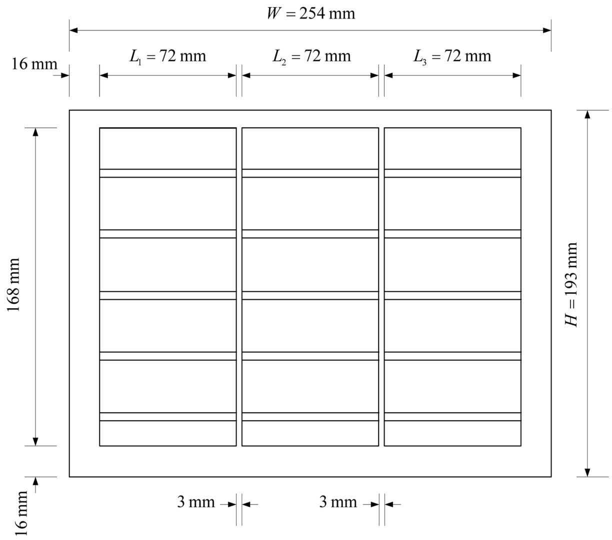

Fig. 2 Front dimension of the louvered panel tested in the wind tunnel

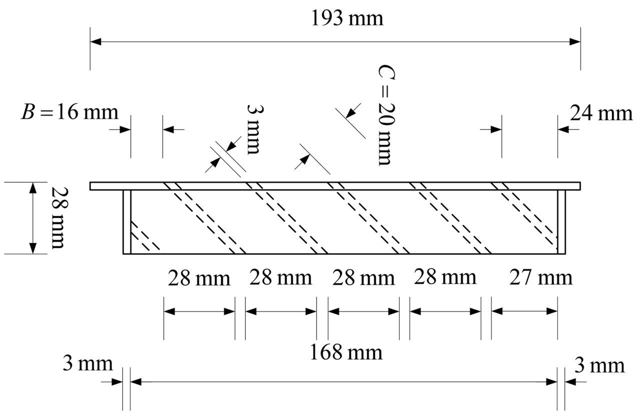

Fig. 3 Side dimension of the louvered panel tested in the wind tunnel

$$\text{free area ratio} = \frac{(L_1 + L_2 + L_3)(4 \times C + B)}{W \times H} \tag{10}$$

in which the dimensions (L_1, L_2, L_3, B, C, W and H) are shown in and Figs. 2 and 3. The free area ratio of this particular panel is 42%.

The Openness of the panel can also be characterized by the pressure loss coefficient, which is defined as

$$K = \frac{P_u - P_d}{\rho U_f^2/2} \tag{11}$$

where P_u and P_d are the static pressure upstream and downstream of the quasi-porous panel, ρ is air density, and U_f is the mean velocity of the approaching wind. According to Eq. (11), this coefficient represents the static pressure drop normalized by the mean dynamic pressure of the approaching wind. It is a measure of the porosity of the panel as well as the effects of the shape and distribution of the openings on the resistance to the flow by the panel. In the present study, the pressure loss across the louvered panel shown in Fig. 2 was measured in a small wind tunnel with its test section slightly modified so that its cross-section is completely covered by the louvered panel model. The dynamic and static pressure on either side of the louvered panel model was measured by pitot tubes aligned along the centerline of the test section and each being 5 cm from the panel model. Based on the measurements, the pressure loss coefficient of this panel is estimated to be 11.8. For comparison purposes, a full-scale louvered panel used in practice with the same free area ratio but slightly different louver blade configuration was also tested for pressure drop across the panel. The pressure loss coefficient for this full-scale panel is estimated to be 10.3. These values compare favorably with pressure loss coefficients for other porous materials (e.g., Letchford *et al*. 2000).

In wind loading standards and recently published results (e.g., Holmes 1994, Krishna 1995, Stathopoulos 1995, Ginger *et al*. 1997, Surry 1999, Stathopoulos 2003, Ho *et al.* 2005 and Oh *et al.* 2007), wind loading on the walls of low-rise buildings are assessed based on pressure measurements on the surface of these walls. For louvered panels, such pressure measurements are challenging and may become impractical, since it is difficult to install pressure taps in the thin blades of louvered panels at model scale and also difficult to route the tubing system. Due to this consideration, a six-component load cell (ATI Industrial Automation, Inc. Gamma series, calibration SI-32-2.5) was used to directly measure wind loading on the louvered panel model. For all tests conducted to measure the net drag coefficients on the louvered panel as a component of a building, two dummy panels with the same blade configuration and of the same height but half the width of the panel model shown in Fig. 2 were installed on each side of the center panel model, which was completely supported by the load cell. These two dummy panels were not instrumented. They were fixed to the rest of the building model, which was in turn fixed to the wind tunnel floor. The three panels formed a complete wall, nominally 12.7 m wide, 4.83 m high and 7.5 m deep at full-scale, of a generic building model or a story of a building model. Fig. 4 shows the wall of a generic building model formed by the two fixed (side) louvered panels and the third instrumented (center) panel.

Fig. 5 illustrates all four test configurations with the louvered panel being a component of a building wall at the ground level and as *q* second-story wall of a two-story building. At each level,

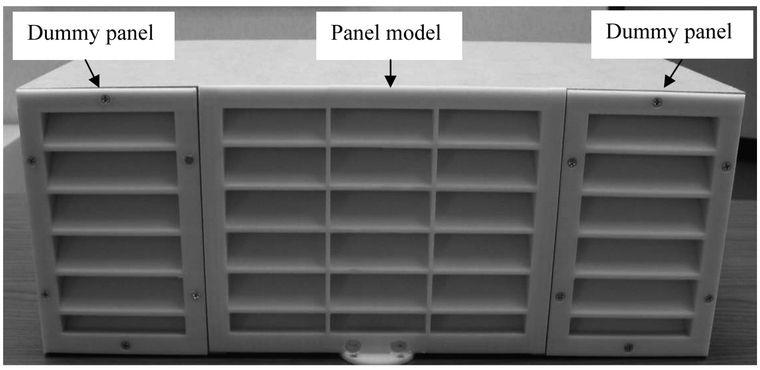

Fig. 4 A wall of the generic building model composed of louvered panels

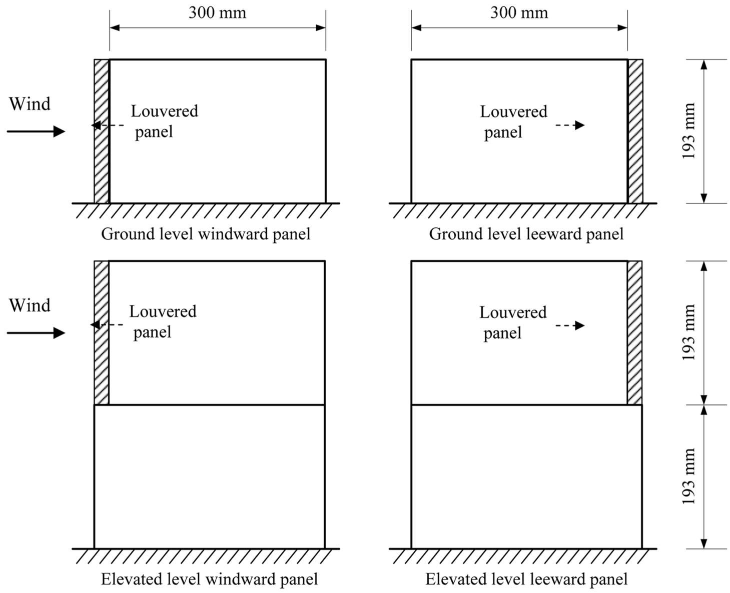

Fig. 5 Tested louvered panel configurations (Porosity of the wall opposite the louvered panel varied)

the louvered panel was tested both on the windward side and the leeward side of the building models. For each louver model configuration, the porosity of the wall opposite the louvered panel was varied, ranging from completely open to fully closed with various wall porosities in between. This allowed an investigation into the effect of the opposite wall porosity on louvered wall loads. The openings in the walls opposite the louvered panel were formed by circular holes that are mostly evenly spaced. The openness of these walls is subsequently characterized by the porosity ratio, which is defined as the ratio of the total area of the holes to that of the whole wall. A shortcoming for these experimental configurations is their incorrect scaling of the internal volume of the buildings, which can affect the fluctuating loading on the panel models. Since the buildings being modeled are small, however, the effect of this shortcoming can be neglected (Holmes 1979).

For tests of free-standing louvered panels, only the center front wall section of the model was in place. These free-standing panels were tested both at the wind tunnel floor level and at an elevated level at the same height as when they are in the building models. At both levels, one set of tests were conducted with the front face of the panel on the wind ward side and the other set with the front face on the leeward side.

For all tests conducted, the wind was normal to the louvered panels. The wind speeds were measured by a Cobra probe (Turbulent Flow Instrumentation, series 100) located at the same height as the top of the building model, away from its direct influence.

Given the size of the models and the cross-sectional dimensions of the wind tunnel, the maximum blockage ratio was 8.5% for the configurations with the louvered panel at an elevated level in a generic building. For blockage ratios over 5%, corrections should be applied (Cermak *et al.* 1999). Making such correction for porous or quasi-porous walls (such as louvers) in a building, however, requires extensive study, which to the knowledge of the authors has not been done. As a result, the correction for blockage effect for the elevated louvered panels were undertaken approximately using Eq. (12) proposed by Barlow *et al.* (1999).

$$(C_D)_{\text{corrected}} = \frac{(C_D)_{\text{measured}}}{\left[1 + 0.25\left(\frac{A_m}{A_t}\right)\right]^2} \tag{12}$$

where C_D is drag coefficient, A_m is the area of the model face normal to the flow, and A_t is the cross-sectional area of the wind tunnel test section. While this type of correction is not precise, it does approximately account for the blockage effect.

For the free-standing panels and for the configurations with the louvered panels located on the wind tunnel floor as a component of a building model, the blockage ratios were less than 5%, and no blockage corrections were made.

The test wind speed was approximately 10 m/s at 0.4 m height, which was taken as equivalent to a wind speed of 40 m/s at 10 m height at full scale. For each test run, all the instrumented channels were sampled for 96 seconds at 250 Hz, which correspond to 10 minutes and 40 Hz at full scale.

4. Test results

The tests were conducted in boundary layer flow simulated to represent Exposure Category C specified by ASCE 7-05 and Terrain Category 2 specified by AS/NZS 1170.2. Fig. 6 shows the profiles of the mean wind speed and the along-wind turbulence intensity. In the profile of mean wind speed, the measured wind speeds were normalized by the wind speed at a height of 0.4 m above the wind tunnel floor. A least-squares fit of the height against mean wind speed assuming that the profile is logarithmic in nature yields a roughness length value of z_0 = 0.039 m, which is equivalent to a full-scale roughness length of z_0 = 0.039 m at a 1 : 25 scale. For reference, a typical exposure C mean-wind-speed profile with a full-scale roughness length of z_0 = 0.02 m is also shown in this graph. Fig. 7 shows the power spectrum of the along-wind component of the simulated flow at a height of 0.4 m above the wind tunnel floor, together with the Kaimal spectrum at this height. In this figure, S_u is the power spectrum density function, σ_u^2 is the variance of the along-wind turbulence, z is the height above ground, and n is frequency. It can be seen that the

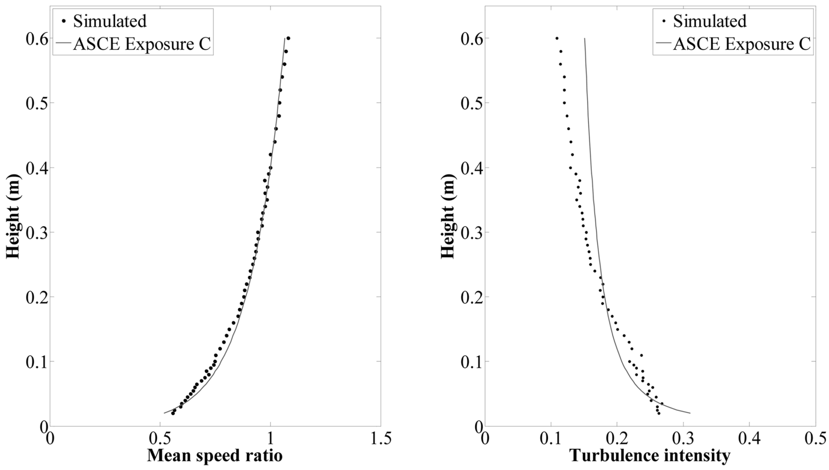

Fig. 6 Mean wind speed and turbulence profile of simulated boundary-layer flow

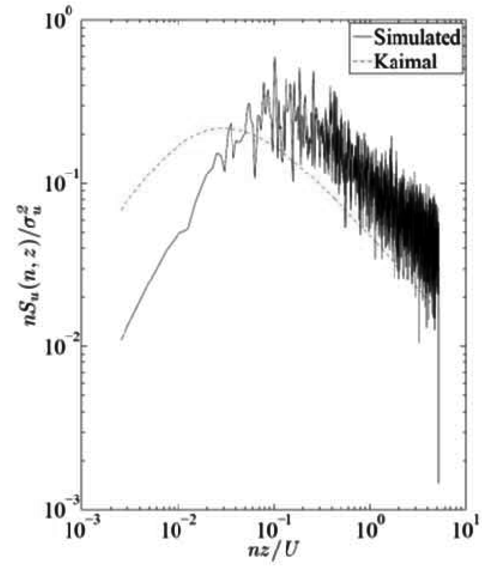

Fig. 7 Power spectrum of along-wind flow at 0.4 m height in the simulated boundary layer

simulated flow has higher energy content in the high frequency range (i.e., at smaller turbulence scales) than would be expected at full scale. This is considered a fairly typical shortcoming for the length scale (1 : 25) used in the current study.

Both mean- and pseudo-steady drag coefficients were estimated based on the tests. For this purpose, each configuration was tested 10 times. A drag coefficient time history was computed based on the following equation

$$C_D(t) = \frac{F_D(t)}{\frac{1}{2}\rho U^2 A} \tag{13}$$

where F_D is the drag force, t is time, U is the mean wind speed at the height of the top of the building model, and A is the area of the panel model face. This experimentally estimated drag coefficient can be directly compared to the equivalent drag coefficients defined by equation according to ASCE 7-05 and equation according to AS/NZS 1170.2.

For the drag coefficient time history derived from each test run, the mean value was computed, and the average of the 10 mean values for each test configuration was taken as the mean drag coefficient, $\overline{C}_D$.

Also, for each drag coefficient time history, a maximum value was identified. The mean extreme drag coefficient, $\hat{C}_D$, was obtained from the 10-minute mode and dispersion estimated by fitting a type I Fisher-Tippett extreme value distribution to the 10 maximum values. This means that the hourly mean extreme drag coefficients can be estimated using equation (Letchford 2001)

$$\hat{C}_D = \text{mode}_{10\text{minute}} + [0.577 + \ln(6)] \times \text{dispersion}_{10\text{minute}} \tag{14}$$

The pseudo-steady drag coefficients were estimated using the following equation

$$\tilde{C}_D = \frac{\hat{C}_D}{G^2} \tag{15}$$

where G is the gust factor defined as

$$G = 1 + 3.7I_U$$

in which I_U is the turbulence intensity of the flow at the height of the top of the building model.

Figs. 8 to 11 show the drag coefficients of the louvered panel in the building model for all the configurations tested. It can be seen that for all configurations, when the porosity ratio of the wall opposite the panel is greater than 50%, the mean and pseudo-steady drag coefficients were close. This result is similar to findings of previous studies on wind loading of rectangular panels (Letchford 2001). When the porosity of the opposite wall was below 50%, however, the two force

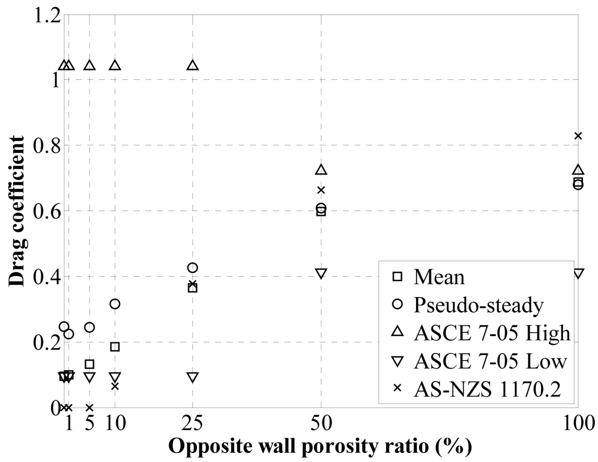

Fig. 8 Drag coefficients for windward louvered panel at wind tunnel floor level in a building model

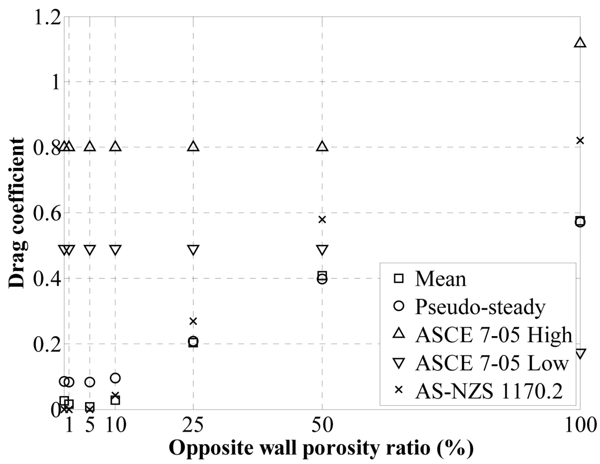

Fig. 9 Drag coefficients for leeward louvered panel at wind tunnel floor level in a building model

coefficients differ significantly for each test configuration, which is not unusual for situations where the mean coefficient tends to zero. In any case, the pseudo-steady drag coefficients are preferable for design purposes because they account for building induced turbulent loads. It is also worth noting that when the porosity ratio of the opposite wall was small, i.e., less than 25%, the drag coefficients of the louvered panel for all test configurations were very small. This is due to the high internal pressure created inside the cubic housing in these situations.

Although the experimentally estimated drag coefficients are only for wind normal to the louvered panels, since they would be close to the maximum drag coefficient values for all wind directions, it is reasonable to compare these coefficients with those that can be determined based on interpretation of design standards. Figs. 8 and 9 include a comparison between the experimental results and the equivalent drag coefficients determined based on ASCE 7-05 and AS/NZS 1170.2 provisions [Eqs. (4) and (9), respectively] for full-scale prototype of the tested configurations with the louvered panels on the wind tunnel floor. Only the drag coefficients for these two configurations are used for comparison because the experimentally obtained values did not require correction. Since no topographical and directional effects were considered in the wind tunnel tests, in determining $(C_D)_{\mathrm{ASCE}}$ based on ASCE 7-05, the factors K_{zt} and K_d in Eq. (2) were both set to be unity. The importance factor, I, was also set to be unity for a generic building, and K_z was determined according to ASCE 7-05 to be 0.86. Since ASCE 7-05 specifies both positive and negative internal pressure coefficients for every design situation except when a building is open, Figs. 8 and 9 present two sets of drag coefficients ("ASCE 7-05 high" and "ASCE 7-05 low") determined based on combination of the specified external pressure coefficients and the internal pressure coefficients of opposite signs to facilitate comparison with the experimental results, although for any given opposite wall porosity ratio, only the larger drag coefficient would be used in design according to the provisions of ASCE 7-05. For the design situation simulated by the configurations in the wind tunnel tests, when determining $(C_D)_{\mathrm{AS/NZS}}$ according to AS/NZS 1170.2, the wind direction, shielding and the topographical multipliers (M_d, M_s and M_t), as well as the combination, local pressure permeable cladding reduction, and the dynamic effect factors (K_c, K_l, K_p and C_{dyn}) are determined based on AS/NZS 1170.2 to be unity; the terrain/height multiplier ($M_{z,\mathrm{cat}}$) is determined to be 0.91 and the area reduction factor (K_a) was determined to be unity.

According to Figs. 8 and 9, when the louvered panel is on the floor level, except for the case in which the panel is on the windward side of the building and the opposite wall is fully open, the equivalent design drag coefficients determined based on ASCE 7-05 (the set of larger values, denoted "ASCE 7-05 high") are significantly higher than those estimated based on the wind tunnel tests. This is especially true for the configurations with small opposite wall porosity ratios. The graphs also suggest that, for the windward floor level panel, the set of lower drag coefficients (denoted "ASCE 7-05 low") determined based on ASCE 7-05, which are not to be used in design, are quite close to the experimental results for opposite wall porosity ratios of up to 10%, while for the leeward floor level panel, the set of lower-valued drag coefficients are significantly different from the experimentally estimated drag coefficients except when the opposite wall porosity ratio is 50%. The large difference between the design drag coefficients specified by ASCE 7-05 and the experimentally estimated drag coefficients are believed to be due to the questionable manner in which low-rise buildings are categorized and, on this basis, the internal pressure coefficients are specified in this standard. For example, according to this standard, the full-scale prototype of the one story building model with windward louvered panel should be categorized as enclosed when the wall opposite the louvered panel is complete open and as partially enclosed when the opposite wall

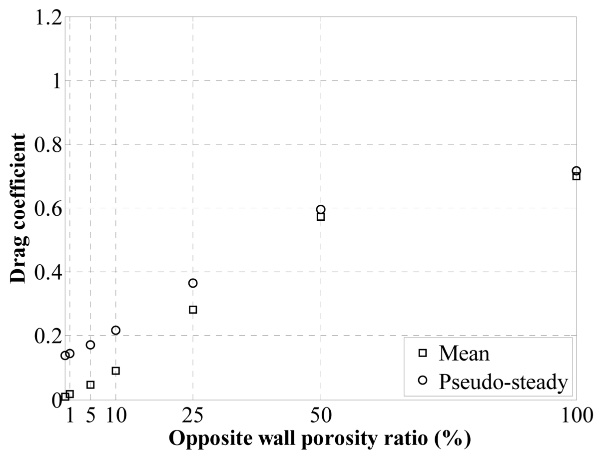

Fig. 10 Drag coefficients for windward elevated louvered panel in a building model

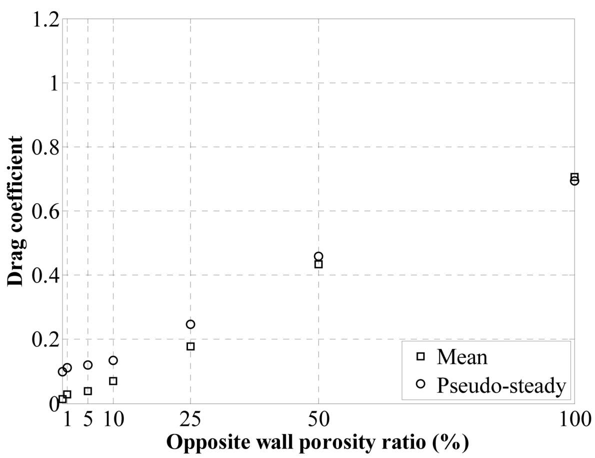

Fig. 11 Drag coefficients for leeward elevated louvered panel in a building model

is completely closed. This results in the former having a specified internal pressure coefficient of ±0.18, and the latter having a specified internal pressure coefficient of ±0.55 (Figs. 6-5, ASCE 7-05). This leads to larger design forces for the louvered panel with the opposite wall completely closed than with the opposite wall fully open, since the code also requires that both negative and positive internal pressure coefficients should be combined with the specified external pressure coefficient to "determine the critical load requirements" (Figs. 6-5, ASCE 7-05). This approach contradicts fundamental fluid behavior and is certainly directly opposite the outcome from the wind tunnel tests. Furthermore, the requirement by ASCE 7-05 that both the negative and positive internal pressure coefficients be used for the same building configuration to determine the critical loading scenario is, in itself, questionable and can lead to overly conservative designs. For example, for all the test configurations with the wall opposite the louvered panel being open, it is impossible for the louvered panel to be subjected to positive mean internal pressure when it is on the windward side of the building, and impossible for the panel to be subjected to negative mean internal pressure when it is on the leeward side of the building. This particular provision in ASCE 7-05 also manifests itself in Fig. 8 as the fact that, for the windward panel with small opposite wall porosity ratios (i.e., less than 25%), the set of large drag coefficient values determined based on the standard, which would be used in design, are much larger than the coefficients estimated based on the wind tunnel tests, while the set of smaller drag coefficients determined based on the standard for these opposite wall porosity ratios, which are not to be used in design, are much closer than the experimentally estimated coefficients.

By contrast, according to Figs. 8 and 9, the equivalent drag coefficients obtained according to AS/NZS 1170.2 for large opposite-wall porosity ratios (i.e., greater than 10%) are generally closer to the experimentally determined values than those based on ASCE 7-05. This is primarily due to two reasons. Firstly, AS/NZS 1170.2 specifies the internal pressure coefficients based on the location of the dominant openings in the building, which enables the code to clearly specify the sign of these pressure coefficients. Secondly, AS/NZS 1170.2 varies the internal pressure coefficients based on the porosity of the wall containing the dominant opening relative to the porosity of the rest of the building envelope, instead of the porosity of the wall receiving positive pressure relative to the rest of the building envelope, as is the case in ASCE 7-05. It also can be seen in Figs 8 and 9, however, that AS/NZS 1170.2 underestimates the net pressure acting on the louvered panel when the porosity ratio of the opposite wall is small (i.e., less than 25%), this is believed to be due to the high internal pressure values specified by this standard, which is based on study of buildings with openings different from those in louvered panels. For example, for opposite wall porosity ratio of less than 10%, the internal pressure specified by AS/NZS 1170.2 is the same as the external pressure. Also, when the porosity ratio of the opposite wall is small (i.e., greater than 25%), AS/NZS 1170.2 over estimates the net pressure acting on the louvered panel. This is believed to be largely due to the fact that the shape of the openings of louvered panels is not considered by this standard.

Table 1 Drag coefficients of free-standing louvered panel and of panels in generic buildings with 100% opposite wall porosity lists the experimentally estimated drag coefficients of free-standing louvered panel with its front face on the windward side and the leeward side, together with the drag coefficients for the same panel when it is part of the generic building tested. For comparison with the code, the equivalent drag coefficients that can be determined according to AS/NZS 1170.2 (essentially $[M_d M_{z,cat} M_s M_t]^2 C_{fig} C_{dyn}$) for a louvered hoarding of the same size, porosity ratio and clearance ratio are also included in the table. It can be seen that the experimentally determined drag coefficients are quite different for opposite wind directions. This is believed to be due to the

Table 1 Drag coefficients of free-standing louvered panel and of panels in generic buildings with 100% opposite wall porosity

Configuration		Drag coefficients		
		Free-standing panel		Panel in generic building with 100% opposite wall porosity
		Test result	AS/NZS 1170.2 Provisions	Test result
Ground	Front wind	1.09	.81	0.68
	Back wind	0.66	.81	0.57
Elevated	Front wind	1.16	n/a	0.72
	Back wind	0.81	n/a	0.70

presence of the solid panel areas around the louvered part of the face of the panel. Because of these solid areas, the flow will be different when wind approaches from the front and the back side of the free-standing panel ("front wind" and "back wind" in Table 1). This can also be use can also be used to explain the difference between the drag coefficients of the louvered panel when it is free-standing and when it is part of a wall of the low-rise building wall. This is also part of the reason why the experimentally determined drag coefficients are different from the coefficients determined according to AS/NZS 1170.2, since the coefficients defined in the standard are for hoardings.

5. Conclusions

A series of wind tunnel tests were conducted to study wind loading on louvered panels making up walls of buildings and boards of free-standing signs. Several configurations were tested with various arrangements of building porosity. Both mean and pseudo-steady drag coefficients were estimated based on direct force measurements using a load cell. The outcome of the study suggests that the wind loading on louvered panels can be significantly different from both ASCE 7-05 and AS/NZS 1170.2 provisions. The difference between the experimental results and AS/NZS 1170.2 provisions is likely due to the fact that louvered panels are quasi-porous and that openings in these panels are fundamentally different from those considered by the standard. The same reason can also partly account for the difference between the experimental results and the provisions of ASCE 7-05. This void in the standards can be filled by introducing a factor based on more extensive study to reflect the configuration of the openings in the structural components. The drastic difference between the experimentally estimated drag coefficients and the drag coefficients determined based on interpretation of ASCE 7-05, however, is due to the ambiguous manner in which the internal pressure coefficients are specified in ASCE 7-05. In particular, the requirement by ASCE 7-05 that both positive and negative internal pressure coefficients of the same magnitude be used to determine the critical wind loading can result in overly conservative design loads across the louvered panel. It is clear that this shortcoming of ASCE 7-05 is not limited to the design of louvered panels. It can also over conservatively affect the design of other porous structural components in low-rise buildings.

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