Net pressure and correlation characteristics between internal and external pressures for tall building with opening

Xu Wang¹,² | Yuanhao Qian¹ | Xianfeng Yu² | Zhuangning Xie²

¹ State Key Laboratory Breeding Base of Mountain Bridge and Tunnel Engineering, Chongqing Jiaotong University, Chongqing, China
² State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou, China

Correspondence
Xianfeng Yu, State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou 510640, China.
Email: ctxfyu@scut.edu.cn

Funding information
Key project of foundation and frontier research of Chongqing, Grant/Award Number: cstc2017jcyJAX0187; National Natural Science Foundation of China, Grant/Award Numbers: 51678544 and 51708074; State Key Laboratory of Subtropical Building Science, South China University of Technology, Grant/Award Numbers: 2018ZB27 and 2019ZB28

Summary
Net pressure and correlation characteristics between internal and external pressures for a typical high-rise building with a dominant opening are detailed investigated by a series of wind tunnel experiments on a scaled rigid model. The experimental results show that internal pressures are absolutely spatially relevant. When the dominant opening faces to approaching wind, there exists strong positive correlation between internal and external pressures of each tap on the windward wall, whereas negative correlation can be observed for each tap on the other walls. At the wind directions of 15° and 75°, the highest negative correlation coefficient occurs on the right side wall and is up to −0.6 and the mean values of area-averaged net pressure coefficient on the right side wall also reach their maximum and minimum values, respectively; meanwhile, the values of standard deviation of area-averaged net pressure coefficient are also much higher. Thus, it should be paid more attention to the wind-resistant design of side wall envelopes because they are easier to be destroyed.

KEYWORDS
correlation coefficient, dominant opening, internal pressure, net pressure, power spectrum, tall building

1 INTRODUCTION

High-rise buildings are generally wind-sensitive due to their enhanced structural flexibility, and some comprehensive investigations of wind effects on these high-rise buildings have been carried out.¹ However, the envelopes of high-rise buildings (such as curtain walls) are more vulnerable to strong wind and easier to be destroyed.² During wind-resistant design of these cladding structures, the extreme value of net pressure is always one of the control factors. It is of great significance to investigate the correlation characteristics between internal pressure and external pressure for the cladding structures. Besides, correlation characteristics are also the basis to obtain the net pressure. However, Chinese load code for the design of building structures (GB50009-2012)³ has only presented the values of shape coefficient of internal pressure in different opening areas, it fails to provide the method of obtaining the net pressure from internal and external pressures.

So far, previous studies on the correlation properties between internal and external pressures and on the net pressure mainly aimed at the roof and curtain wall of low-rise buildings with opening. However, few researches were centered on the high-rise buildings with opening. Beste and Cermark⁴ had experimentally investigated correlation characteristics between internal and the external pressure on the different positions of the roof. They pointed out that internal and area-averaged external pressures were highly correlated for separated flows over roof edges and wall corners that border a wall with a dominant opening.

Ginger and Letchford⁵,⁶ had measured the internal and external pressures on a full-scale low-rise building, and the net pressures were further investigated. The results showed that the net pressure in the nominally sealed building derived from AS1170.2⁷ was conservative. In the case of
the building with a dominant windward opening, the net pressure derived from AS1170.2\textsuperscript{[27]} was smaller compared with the measured pressures in some areas near the roof windward edge.

Based on some wind tunnel tests, net pressure and the correlation characteristics between area-averaged external pressures and internal pressure at specific region of roof for a low-rise buildings in two kinds of opening conditions were studied by Sharma and Richards\textsuperscript{[8]} and some important conclusions were drawn: (a) For the case of corner roof area with corner wall opening, the net pressure coefficient fluctuations were significantly higher than the corresponding area-averaged roof external pressure coefficient fluctuations in some wind angles. This was because of not only the large internal pressure fluctuations resulted from Helmholtz resonance but also the negative correlation between internal pressure and roof external pressures; (b) the largest mean net uplift pressure coefficient was 2.26. Fluctuating internal pressure and roof external pressure were quite significantly correlated, the largest correlation coefficient reached to -0.64.

Actually, the curtain walls of high-rise building might also suffer much higher wind pressures during strong wind. The vortex structures on curtain wall of tall buildings are different from those on roof of low-rise buildings. Besides, the wind velocity is higher but turbulence intensity is lower for the sky lobby of high-rise buildings compared with low-rise buildings. After the windows of a sky lobby are destroyed, fluctuating internal pressure are caused by airflow flooding into, then the curtain walls will easily be further destroyed under the joint action of external and internal pressures.

The present investigation is aimed at net pressure and the correlation characteristics between internal and external pressure for a high-rise building with a dominant opening. The distributions of correlation coefficient between internal pressure and external pressure are firstly investigated. Then the variations of area-averaged net pressure in different work conditions, such as opening area, opening thickness, background leakage, and wind direction angle, were studied in detail.

2 WIND TUNNEL EXPERIMENTAL SETUP

The experimental rigid model is 150 mm × 150 mm in plan and $H = 900$ mm in height, which is made of 3-mm thick perspex. The geometric scale is 1:200, which was used to simulate a typical high-rise building with height of 180 m in prototype. A sky lobby at the height of 0.8$H$ is selected as the research object, and the height of which is 40 mm. Several kinds of dominant openings are arranged on the front wall of the sky lobby.

The mean wind velocity at the model height of 5 cm (10 m in prototype) is 8.05 m/s. The velocity scale is set to 1: 4.24, so the mean velocity at the height of 10 m in prototype is 34 m/s and the corresponding basic wind pressure is about 0.7 kPa. To correctly simulate the Helmholtz resonance frequency, the scaling requirement according to the suggestion of Holmes\textsuperscript{[9]} is

$$\nu_0 = \frac{(L_m/L_i)^3}{(U_{m}/U_{i})^2}$$

where $L$ is the characteristic length, $U_i$ is the mean wind speed at the height of 10 m, $\nu_0$ is the internal volume of structure, ”m” and ”i” stand for model and full-scale structures, respectively. To achieve the scaling requirement, internal volume of the experimental model should be increased by a factor of $(U_{10}/U_{180})^2 = 4.24^2 \approx 18$. In present study, the internal volume of the model exclude the sky lobby is used as the compensation volume. A sealed diaphragm (see Figure 1) is set at the height of 180 mm.

Twenty-seven external pressure taps (no. 1 to 27) are arranged on the outside surface of the sky lobby, also as shown in Figure 1, and three internal pressure taps (no. 28 to 30) are arranged on the internal surface of the sky lobby. In wind tunnel experiments, internal and external pressure are synchronously measured.

Generally, the porosity ($\varepsilon$: defined as the ratio of effective background leakage area to the surface area of the building) ranges from $10^{-4}$ to $10^{-3}$ according to the suggestion given by Ginger et al.\textsuperscript{[10]} In present study, the maximum background porosity is set as $\varepsilon = 5 \times 10^{-4}$, whereas total surface area of the sky lobby’s curtain walls is 24,000 mm$^2$, so 16 leakage holes with diameters of 1 mm are used to simulate the background leakage, and all of them are uniformly arranged in the back wall.

Experiments are carried out in the boundary layer wind tunnel at South China University of Technology (Figure 2). The working section of the tunnel is 5.4 m wide, 3.0 m high, and 24 m long. Exposure category B with a power law exponent of 0.15, which represents a suburban flat terrain, is simulated according to the Chinese Load code (GB50009-2012).\textsuperscript{[3]} The simulated mean wind profile, turbulence intensity distribution, and power spectrum at the height of the rooftop are shown in Figure 3. Reference wind speed ($U_r$) is 11.5 m/s at the height of the dominant opening, the sampling time is 61.8 s, and the sampling frequency is 331 Hz.

The effects of opening area, opening thickness, background leakage, and wind direction on the net pressure and correlation coefficient between internal and external pressures are investigated in detail through wind tunnel experiments. The test cases are shown in Table 1.

3 DATA ANALYSIS

The history of wind pressure for tap $i$ is $P_i(t)$, so the corresponding history of nondimensional pressure coefficient $C_p(t)$ can be expressed as follows:
\[
C_{pi}(t) = \frac{P_i(t) - P_\infty}{0.5 \rho_a U_r^2}
\]  
(2)

where \(P_\infty\) is the static pressure, \(\rho_a\) is the air density, and \(U_r\) is the mean velocity at the height of dominant opening. Thus, the mean value \((\bar{C}_{pi})\) and the standard deviation \((\tilde{C}_{pi})\) of pressure coefficient history are given, respectively, by

\[
\bar{C}_{pi} = \frac{1}{N} \sum_{k=1}^{N} C_{pi,k}
\]  
(3)

\[
\tilde{C}_{pi} = \sqrt{\frac{1}{N-1} \sum_{k=1}^{N} (C_{pi,k} - \bar{C}_{pi})^2}
\]  
(4)

where \(N\) is the sampling number and is 20,480 in this test.

For the sky lobby with a dominant opening, the demonstration of pressure distribution for each wall is shown in Figure 4. The net pressure coefficients can be obtained as follows:

\[
C_{pn} = C_{pi} - C_{pe}
\]  
(5)
where $C_{pn}$, $C_{pe}$, and $C_{pi}$ are the histories of net pressure coefficient, external pressure coefficient, and internal pressure coefficient. $\rho_{ie}$ is the correlation coefficient between internal and external pressures and can be further expressed as

$$C_{pn} = C_{pi} - C_{pe}$$  \hspace{1cm} (6)

$$\tilde{C}_{pn}^2 = \tilde{C}_{pi}^2 + \tilde{C}_{pe}^2 - 2\rho_{ie}\tilde{C}_{pi}\tilde{C}_{pe}$$ \hspace{1cm} (7)
Equation 7 can intuitively show the correlation between internal and external pressures. The combination effect is weakened when \( \rho_{ie} > 0 \); oppositely, it is enhanced when \( \rho_{ie} < 0 \). Particularly, the internal and external pressures achieve their extreme values when \( |\rho_{ie}| = 1 \), and they are uncorrelated with each other when \( \rho_{ie} = 0 \).

In present study, the internal pressure and external pressures on the walls are synchronously measured, so the correlation coefficient \( \rho_{ie} \) can be directly calculated by the following formula:

\[
\rho_{ie} = \frac{\sum_{k=1}^{N} (C_{pi,k} - \bar{C}_{pi})(C_{pe,k} - \bar{C}_{pe})}{\sqrt{\sum_{k=1}^{N} (C_{pi,k} - \bar{C}_{pi})^2} \sqrt{\sum_{k=1}^{N} (C_{pe,k} - \bar{C}_{pe})^2}}
\]

\[\text{(8)}\]

\[
\rho_{ie} = \frac{C_{pi}^2 + C_{pe}^2 - C_{pn}^2}{2C_{pi}C_{pe}}.
\]

\[\text{(9)}\]
FIGURE 6  Distributions of correlation coefficients in different dominant openings

FIGURE 7  Distributions of correlation coefficients in different opening thicknesses

FIGURE 8  Distributions of correlation coefficients in different background leakages
The area-averaged external pressure coefficient and net pressure coefficient can be further defined by

\[ C_{Pe,A} = \frac{\sum A_k C_{Pe,k}}{\sum A_k} \]

\[ (10) \]
where $A_k$ is the effective area of the tap $k$.

FIGURE 10 Variations of area-averaged coefficients with wind direction angles on the front wall

\[ C_{Pn,A} = \frac{A_k}{\sum A_k} C_{Pn,k}. \]
4 | RESULTS AND DISCUSSIONS

4.1 | Spatial correlation of internal pressures

Figure 5 gives the correlation coefficients among three internal pressure taps (tap28, tap29, and tap30) for all the test cases. It shows that the correlation coefficients for all the test cases are up to 99%. In other words, the internal pressures are completely spatially relevant.

4.2 | Distribution of correlation coefficient

The distribution of correlation coefficients ($\rho_{ie}$) in different opening areas at wind direction of 0° is presented in Figure 6. It can be drawn from that (a) the values of $\rho_{ie}$ are greater than 0 on the windward wall. It is getting larger when the taps are close to dominant opening, and the maximum experimental value of $\rho_{ie}$ is 0.93. In other words, strong positive correlation between internal and external pressures is evident on the windward wall. (b) The values of $\rho_{ie}$ are less than 0 on the sidewalks and leeward wall; namely, the combination effect of internal and external pressures is enhanced. (c) The values of $\rho_{ie}$ are not evenly distributed along the sidewall, negative correlation is much stronger at the leading edge and becomes weak at the trailing edge, and the minimum negative value of $\rho_{ie}$ is −0.29 on the sidewalk. (d) The correlation coefficients are much sensitive to opening area and shape. However, they are uniformly distributed on the back wall in each opening configuration. The maximum peak negative value of $\rho_{ie}$ is −0.34 and it occurs when the opening dimension is 20 mm × 10 mm in the center of the back wall.

Figure 7 shows the distributions of correlation coefficients ($\rho_{ie}$) in different opening thickness (wall thickness). The values of $\rho_{ie}$ on front and side walls are nearly the same in the two kinds of opening thickness. However, the negative correlation on the back wall when opening thickness $L_0 = 1$ mm is stronger than that of $L_0 = 5$ mm. The maximum peak negative correlation coefficient is −0.33 on the back wall when $L_0 = 1$ mm.

Background leakages can reduce dynamic response of internal pressure because of its damping effect.[11,12] However, it can be seen from Figure 8 that background leakages have little influence on the correlation characteristic between internal and external pressures.

Wind direction angle has a remarkable effect on the correlation characteristics between internal and external pressures. Figure 9 presents the variations of correlation coefficient $\rho_{ie}$ at different wind directions when the opening size is 20 mm × 40 mm. Some conclusions are drawn: (a) For the wall with dominant opening, the values of $\rho_{ie}$ are always greater than 0 in all wind directions, so the external pressure can be partly counteracted by the internal pressure. (b) Correlation coefficients are relatively uniformly distributed on the back wall at all the wind directions. (c) Correlation coefficients vary remarkably on the right wall at all wind directions and also vary remarkably on the left wall only at the wind directions of 0°–100°. Particularly, it reaches to its maximum peak negative value $\rho_{ie} = -0.6$ on the right wall at wind directions of 15° and 75°.

4.3 | Area-averaged net pressure and correlation coefficient

Actually, it is more valuable to investigate the area-averaged net pressure and correlation coefficient on each wall in wind engineering applications. For the front wall, the variations of internal pressures ($C_{pi}$), area-averaged external pressure coefficient ($C_{pe,A}$), net pressure coefficient ($C_{pn,A}$), and correlation coefficient ($\rho_{ie,A}$) with respect to the wind directions are given in Figure 10. The mean values of area-averaged net pressure coefficient are relatively small and fluctuate within the range of 0.25 to −0.1. The fluctuations of internal pressure are significantly bigger than that of area-averaged external pressure.
averaged external pressure at the wind directions of 60°–90°, which is induced by the Helmholtz resonance effect (see Figure 11). The fluctuations of net pressure are lower than that of internal pressure because correlation coefficients are positive at the wind directions of 0°–180°.

Figure 12 presents the variations of internal pressures ($C_{pi}$), area-averaged external pressure coefficient ($C_{pe, A}$), net pressure coefficient ($C_{pn, A}$), and correlation coefficient ($\rho_{ie, A}$) with the wind directions on the right wall. Some important conclusions are drawn: (a) The unfavorable mean and
fluctuating net pressures occur in the wind direction of 0° and 75°, so the envelope on the right wall is susceptible to be destroyed at the two wind directions. (b) At the wind directions of 0°–45° and 70°–135°, the fluctuations of net pressure remarkably greater than that of internal pressure and external pressure for negative correlation coefficients are found between internal pressure and area-averaged external pressure (see Figure 12c).
so their combination effect is enhanced. (c) At the wind directions of 70–90°, the fluctuating internal pressures significantly increase, which perhaps due to the Helmholtz resonance effect excited by gazing flow.

The variations of internal pressures ($C_{pi}$), area-averaged external pressure coefficient ($C_{pe, A}$), net pressure coefficient ($C_{pn, A}$), and correlation coefficient ($\rho_{ie, A}$) with the wind directions on the left wall are shown in Figure 13. It should be noted that both the unfavorable mean and fluctuating net pressure occur at the wind direction of 0°, so the envelope on the left wall is susceptible to be destroyed in this wind direction. In

**FIGURE 14** Variations of area-averaged coefficients with wind direction angles on the back wall
Figure 13c, negative correlation is shown between internal and external pressures at the wind directions of 0°–70°; the combination effect for them is enhanced. Particularly, $\rho_{ie, A}$ reaches its maximum peak negative value of $-0.3$ at the wind direction of 15°. On the contrary, $\rho_{ie, A} > 0$ at the wind directions of 75°–180°, which means that external pressures are counteracted by the internal pressure.

Figure 14 presents the variations of internal pressures ($C_{pi}$), area-averaged external pressure coefficient ($C_{pe, A}$), net pressure coefficient ($C_{pn, A}$), and correlation coefficient ($\rho_{ie, A}$) with the wind directions on the back wall. It can be seen from Figure 14a,b that the mean net pressures at the wind directions of 0° and 180° are much higher, but their fluctuations are much less. Besides, at the wind directions of 80°–100°, although the fluctuations of net pressure are bigger, their mean values are much less. Thus, the envelope of the back wall at these wind directions could not be easily destroyed. Furthermore, as illustrated from Figure 14b, the fluctuations of net pressure are much larger than those of internal and external pressures at the wind directions of 0°–40°, 80°–100°, and 120°–180°. That is because negative correlation coefficients are shown in those wind directions, external pressures are counteracted by the internal pressure. It is worth noting that the maximum peak negative correlation coefficient is $-0.37$ and occurs at the wind direction of 90°. At this time, the standard deviation of net pressure coefficient also reaches to its peak value of 0.43 that is induced by strong Helmholtz resonance effect, which can be seen from the power spectra densities of area-averaged net and external pressure coefficients (see Figure 15).

5 CONCLUSIONS

(1) Internal pressures are completely spatially relevant in the sky lobby of high-rise building with dominant opening.

(2) When the dominant opening faces to approaching wind, a strong positive correlation between internal and external pressures can be founded on the front wall, and the maximum positive correlation coefficient is 0.93, whereas negative correlation can be found from the other walls; that is, external pressures are counteracted by the internal pressure.

(3) The opening thickness has little influence on the correlation between internal and external pressure of the front and side walls. However, the negative correlation coefficient when the opening thickness $L_0 = 1$ mm is bigger than that of $L_0 = 5$ mm. Besides, the effect of background leakages on the distribution of correlation coefficient can be omitted.

(4) In the wind direction angles of 15° and 75°, the negative correlation coefficient between internal and external pressures on the right wall reaches its minimum value of $-0.6$. Actually, the mean values of area-averaged net pressure are also the highest in the two wind directions, and the fluctuating area-averaged net pressures are larger too. Thus, it should be paid more attention to the wind-resistant design of side wall envelopes because they are easier to be destroyed.

(5) For the envelope of the back wall, the probability of damage is much less in all wind direction angles.

ACKNOWLEDGMENTS

This research is fully supported by the State Key Laboratory of Subtropical Building Science, South China University of Technology (Grants 2019ZB28 and 2018ZB27), the National Natural Science Foundation of China (Grants 51708074 and 51678544), and the Key project of foundation and frontier research of Chongqing (Grant cstc2017jcyjAX0187). The financial supports are gratefully acknowledged.
ORCID

Xianfeng Yu  https://orcid.org/0000-0002-3047-4886

REFERENCES


AUTHOR BIOGRAPHIES

Xu Wang is an associate professor in the State Key Laboratory Breeding Base of Mountain Bridge and Tunnel Engineering at Chongqing Jiaotong University. His research interests include the antiseismic performance of long-span bridges and vibration control of long-span bridge and high-rise structures.

Yuanhao Qian is a master candidate in the State Key Laboratory Breeding Base of Mountain Bridge and Tunnel Engineering at Chongqing Jiaotong University. His research interests focus on antiseismic performance of long-span bridges.

Xianfeng Yu is a lecturer in State Key Laboratory of Subtropical Building Science at South China University of Technology. His research interests focus on structural wind engineering.

Zhuangning Xie is a professor in State Key Laboratory of Subtropical Building Science at South China University of Technology. His research interests focus on structural wind engineering.

How to cite this article: Wang X, Qian Y, Yu X, Xie Z. Net pressure and correlation characteristics between internal and external pressures for tall building with opening. Struct Design Tall Spec Build. 2019;28:e1607. https://doi.org/10.1002/tal.1607