Effects of closed vertical void on natural ventilation in double-loaded apartment building

Tetsu Kubota*[1], Hayato Shima[1], Hanief Sani[1], Nikhil Kumar[1], Haruka Kitagawa[2], Takashi Asawa[3], Muhammad Nur Fajri Alfata[4]

1 Graduate School of Advanced Science and Engineering, Hiroshima University
1-5-1 Kagamiyama, Higashi-Hiroshima, 739-8529, Japan
**Corresponding author: tetsu@hiroshima-u.ac.jp*

2 Institute of Technology, Shimizu Cooperation
3-4-17 Etchujima, Koto-ku, Tokyo, 135-8530, Japan

3 School of Environment and Society, Tokyo Institute of Technology, 4259 Nagatsuta-cho, Midori-ku, Yokohama, Kanagawa, 226-8502, Japan

4 Directorate for Settlements and Housing Engineering Development, Ministry of Public Works and Housing, Indonesia
Jl. Panyawungan, Cileunyi Wetan, Kabupaten, Bandung 40393, Indonesia

ABSTRACT

We proposed a new design of an affordable apartment with a closed-vertical void to improve the indoor natural ventilation especially for the leeward side of the building and constructed a full-scale experimental house in Indonesia in 2020. This paper analyses the effects of the proposed ventilation system through field measurements in the experimental house. In the experimental house, the vertical-closed void with a width of 2.85 m was designed between the two rows of units. A pilotis was provided on the ground floor and a wind fin was attached to the bottom of the vertical void. The rooftop of the void was basically closed. First, vertical and horizontal distributions of wind velocities were measured at 125 points placed inside and outside the void with various window/door-opening conditions in 2022. Second, the volumetric flow rates (VFRs) for the void space as well as leeward units were measured through a tracer gas decay method and based on the measured inlet wind velocities respectively in 2023. The average wind velocity ratio, $\overline{WVR}$ at the inlet of the pilotis was approximately 2.4 times higher than that in front of the building at the same height (reference point) due to the venturi effect. However, the increased winds did not reach the upper floor of the leeward units sufficiently even when the fin size was increased. Opening conditions of windows/doors significantly affected the wind velocity distribution in and around the void. Sufficient levels of VFR were obtained even in the upper floor of leeward units due to the increased static pressure inside the closed void. The proposed ventilation system would be able to provide sufficient cross ventilation to the double-loaded apartment buildings entirely with the increase in static pressure even for a mid-rise building.

KEYWORDS

Natural ventilation, Void, Field measurement, Tracer gas method, Hot-humid climate

1 INTRODUCTION

Affordable housing is highly demanded in the Global South in respond to the rapid rise of middle-class in urban areas. Meanwhile, these countries are also required to meet low-carbon targets such as the Paris Agreement. To date, most affordable apartments in the Global South are constructed with a double-loaded corridor system because south-facing orientation is not necessarily a strong design requirement unlike those in the northern hemisphere (Prasetya et al., 2023). In the case of double-loaded apartments, rows of occupied units are located on both sides of the building from the single central corridor, and therefore poor environmental conditions, such as daylighting and natural ventilation, often take place (Bardhan et al., 2018; Lueker et al., 2020).

One of the natural ventilation strategies to cope with the above-mentioned environmental issues is to incorporate an internal void within such a double-loaded apartment—

Abbreviations

ACH	Air changes per hour
CFD	Computer fluid dynamics
VRF	Volumatic flow rate
WVR	Wind velocity ratio

this will divide the single central corridor into two single-loaded corridor systems. In fact, approximately 34% of the existing public apartments in Indonesia were equipped with vertical voids, although the percentage of those with voids tends to decline in recent years (Prasetya et al., 2023). All of the above-mentioned internal voids were opened-vertical voids where the rooftop of the voids is opened to the sky. These opened voids may create upward winds inside the voids caused by the negative pressure created on the rooftop due to the separated winds. These upward winds would improve cross ventilation from the outdoors to the indoor units for both sides of the building. On the other hand, we proposed a new alternative design of affordable apartments with a closed-vertical void to improve the indoor natural ventilation especially for the leeward side of the building (Kumar et al., 2021, 2022). Kumar et al. (2021) proved that the new closed-vertical void apartment design may be prior to that of the conventional opened-void apartment, at least for the natural ventilation performance on the leeward side of the building. Fig. 1 illustrates the ventilation concept of the proposed alternative building design that incorporates a closed-vertical void. The proposed design has a pilotis on the ground floor and a closed-vertical void with a slit-shaped wind fin attached to the vertical void's edge on the leeward side. The idea of the proposed design was to create a positive pressure region inside the closed-vertical void by combining the venturi effect and wind fin. To analyse the resultant ventilation performance, we then constructed a full-scale experimental house in the city of Tegal, Indonesia in 2020. This paper analyses the effects of the proposed ventilation system through field measurements in the experimental house.

2 METHODS

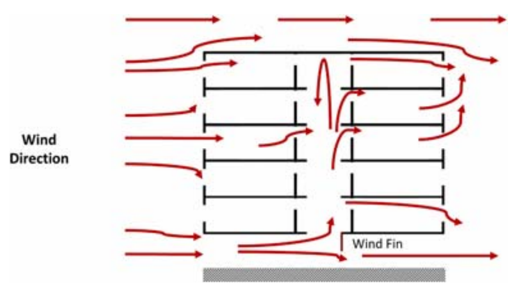


Fig. 1. Natural ventilation concept of the proposed apartment building with a closed-vertical void (Kumar et al., 2022).

Fig. 2. Experimental house in Tegal, Indonesia.

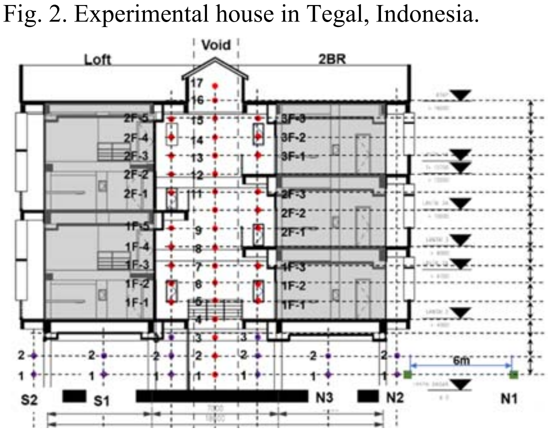


Fig. 3. Measuring positions of anemometers.

Table 1. Measurement cases for the 1st experiment.

Case	Window and door	Penthouse window	Fin size
1.1	✓	✓	Large
1.2	-	✓	Large
1.3	✓	-	Large
1.4	-	-	Large
1.5	-	-	Small

✓: Open, -: Close

2.1 Full-scale experimental house in Tegal

The experimental house is an apartment building with a total floor area of approximately 2,000 m^2 (Fig. 2). The northern side consists of six standard units (3 stories, 52.4 m^2/unit) with a floor-to-ceiling height of 3.05 m, whereas the southern side is composed of six loft units (2 stories, 63.2 m^2/unit) with a larger height (5.15 m). The vertical-closed void with a width of 2.85 m is located between the two rows of units. The size (height) of the wind fin is manually changeable. On the rooftop of the vertical void, there is a penthouse to secure natural lighting. Louver windows are designed for the penthouse to exhaust the excessive heat. The experimental house is located approximately 800 m south from the northern costal line of the Java island (6.86°S, 109.12°E), and therefore a sea breeze prevails from the north during the afternoon on sunny days. The design and construction of this experimental house are detailed in Alfata et al. (2023).

2.2 Wind velocity distributions

The 1st field experiment was conducted during the dry season from June to July 2022. Outdoor air temperature ranged from 22.5-33.2□ with an average of 27.5□, whereas relative humidity ranged from 36-98%. Outdoor wind velocity at 1 m above ground was averaged at 1.21 m/s (up to 7.6 m/s) during daytime and at 0.69 m/s (up to 8.7 m/s) during night-time. Vertical and horizontal distributions of wind velocities were measured at multiple points shown in Fig. 3. A total of 122 anemometers (KOA Windgraphy (hot-wire anemometer); Kamomax Model 6333 and 0976-03 (thermal anemometer)) were placed in and around the vertical void, whereas three 2D ultrasonic anemometers (YOUNG Model 86000) were placed inside and outside the pilotis. A weather station was placed on the rooftop (21 m above the ground level). The experiment was conducted in five cases with changing window/door opening conditions and size of the wind fin (Table 1). The measured wind velocities were normalized to wind velocity ratio (WVR) by Eq. 1.

$$WVR = V_m / U_o \qquad (1)$$

Table 2. Measurement cases for the 2nd experiment.

Case	Standard units (windward)		Loft units (leeward)		
	1N1 2N1 3N1	1N2 2N2 3N2	1S1 2S1	1S2 2S2	1S3 2S3
2.1	✓	✓	✓	✓	✓
2.2	✓	-	-	✓	-
2.3	-	-	-	✓	-
2.4	-	-	-	✓2S2	-
2.5	-	-	-	✓1S2	-

✓: Open, - : Close

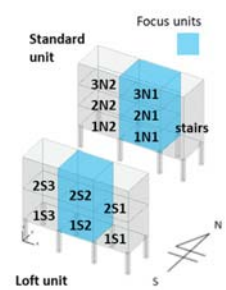


Fig. 4. Measuring positions of dust meters and anemometers.

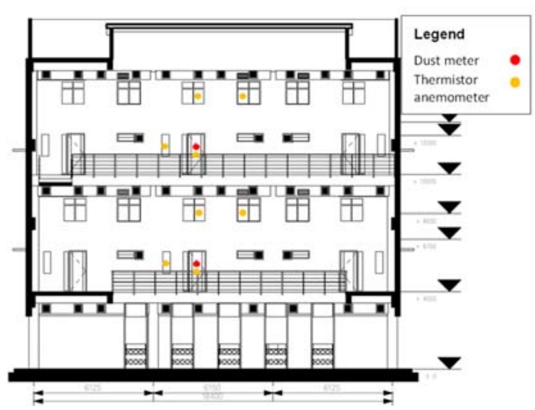


Fig. 5. Measuring positions of anemometers: North section of the leeward loft units.

Where V_m is the measured wind velocities (m/s) and U_o is the wind velocities recorded at the 2D ultrasonic anemometer (at 1 m above the ground) at 6 m north from the building (m/s) (N1 in Fig. 3).

$\overline{WVR}$ represents the temporal average value of WVR. We analysed the $WVRs$ under the daytime prevailing wind direction of NNE, allowing 30° deviations on each side, with a wind velocity of more than 1 m/s at the above-mentioned reference anemometer. The wind velocities at the middle section were analysed in this paper.

2.3 Flow rate measurement

The 2nd field experiment was conducted during the dry season in September 2023. Outdoor air temperature ranged from 22.5-33.7□ with an average of 26.9□, whereas relative humidity was averaged at 63.9%. Outdoor wind velocity at 1.5 m above ground was averaged at 1.37 m/s during daytime and at 0.88 m/s during night-time. As before, we analysed wind velocities under the daytime prevailing wind direction of NNE ±30° with a wind velocity of more than 1 m/s at the reference point. Here, the volumetric flow rate (VFR) for the vertical void space was measured through a tracer gas decay method using a fog machine (ANTARI Z-1000 II), where propylene glycol gas was used. The concentration of smoke was measured using a digital dust meter (Shibata LD-5R) in a corridor space at 1.5 m above the floor in front of the leeward units (Fig. 4). The measurement was carried out in five cases with various opening conditions during the daytime prevailing wind directions, i.e., north winds (Table 2). The louver windows on the penthouse were opened throughout this measurement. During the measurement, the opening of the void was closed with a cover, while the fog machine filled the void with smoke. Once the concentration was equal between the 1st and 2nd floors of the leeward side, the cover was opened and the decay of smoke concentration was recorded until it became the normal level. The measured values were calibrated by comparing them with those measured by the CO_2 decay method afterward.

Wind velocities were measured at the centres of every opening (windows and doors) of the selected leeward units (1S2 and 2S2) (Kamomax Model 6333 and 0976-03), whereas wind velocities and directions were measured in the corridor and void spaces (Fig. 5). The reference values were obtained 6 m north of the building (YOUNG Model 86000). The VFR_{unit} for the leeward units (1S2 and 2S2) was calculated based on the measured wind velocities at the inlet openings. All the VFR_{unit} values were normalized as VFR_0 based on the reference value, VFR_{ref} as follows:

$$VFR_0 = VFR_{unit}/VFR_{ref} \quad (2)$$
$$VFR_{ref} = A_{void}\, V_{ref} \quad (3)$$

Where A_{void} is the cross-sectional area of the inlet of the vertical void (m^2) and V_{ref} is the temporal average wind velocity measured at the reference point during the measurement (m/s).

3 RESULTS AND DISCUSSION

3.1 Wind velocity distributions

Fig. 6 shows the results of comparisons between open windows/doors (Cases 1.1 and 1.3) and closed windows/doors (Cases 1.2 and 1.4), respectively. The conditions of penthouse windows were different between Cases 1.1 & 1.2 (opened) and Cases 1.3 & 1.4 (closed). In all cases, it can be seen that the wind velocities were increased at the inlet of the pilotis due to the venturi effect. $\overline{WVR}$ at the inlet (N2) was approximately 2.4 times higher than the reference point in most cases. In the pilotis, $\overline{WVR}$ ranges from 1.2-2.4 on the windward side, while those on the leeward side range from 0.2-1.8. When the windows and doors were opened, the wind velocities were increased not only on the windward side of the building, but also on the leeward side. The increase in $\overline{WVR}$ can be seen in the vertical void, particularly at the internal corridor spaces of the leeward units. $\overline{WVR}$s in the void in Cases 1.1 and 1.3 are approximately 1.6 times higher than those in Cases 1.2 and 1.4.

When the windows/doors are opened, the volume of inflows to the indoor spaces will be largely increased. The increased inflows are provided from the windward units as well as pilotis to the vertical void and then to the leeward units. This increased inflows simply improved

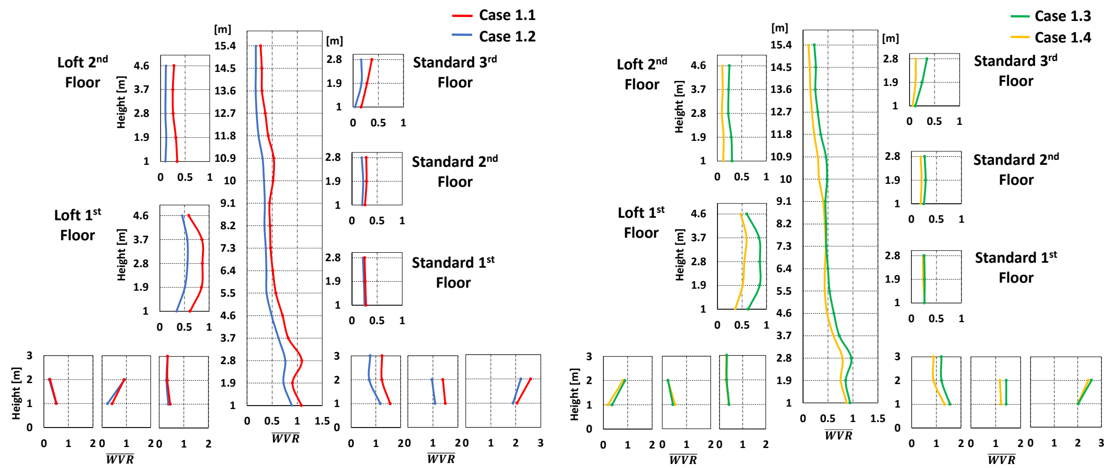


Fig. 6. $\overline{WVR}$ with changes in window/door opening conditions; (a) with penthouse open, (b) with penthouse closed.

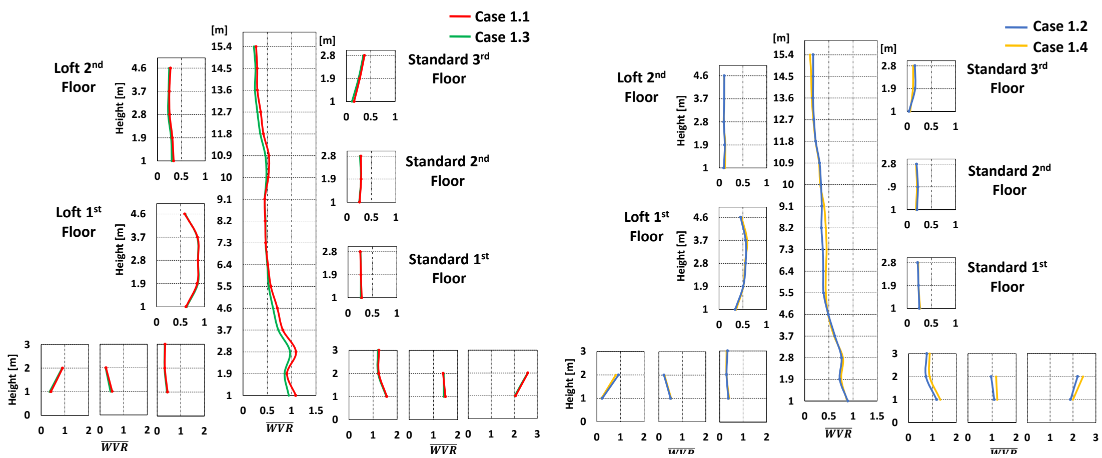


Fig. 7. $\overline{WVR}$ with changes in penthouse window-opening conditions; (a) with windows/doors open, (b) with windows/doors closed.

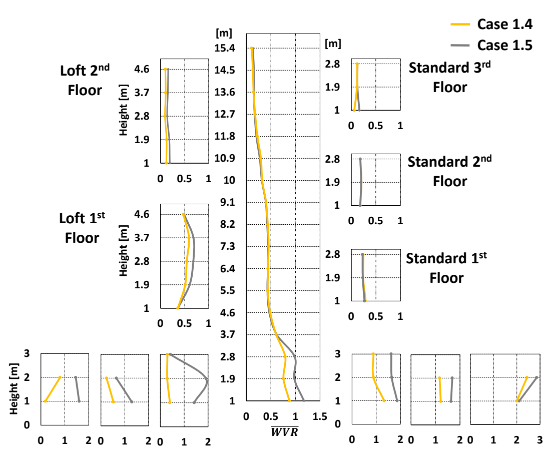
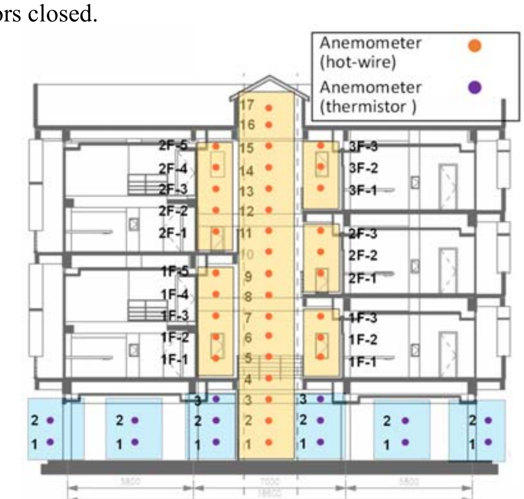


Fig. 8. $\overline{WVR}$ with changes in fin size.



the wind velocities inside the building. However, the increased inflows from the pilotis did not reach the upper floor and therefore the wind velocities inside the void significantly decreased with height regardless of the window opening conditions. The internal corridor also obstructed the wind flow towards the 2nd floor of the loft units.

Fig. 7 depicts the results of comparisons between open and closed louver windows of the penthouse. The conditions of windows and doors were different between Cases 1.1 & 1.3 (opened) and Cases 1.2 & 1.4 (closed). Overall, the increase in $\overline{WVRs}$ is not observed except for a lower part (at 1.0-4.6 m) and upper part (at 10.9-13.6 m) of the void in Case 1.1. This is mainly because the wind-forced ventilation is dominant in the present natural ventilation system rather than those based on the temperature difference, and the increase in inflow volume did not reach the upper part of the building sufficiently as discussed before.

Fig. 8 shows the results of comparison between the large size of the wind fin (Case 1.4) and that of the small size (Case 1.5). The wind fin was 4 m by 12 m for the large size and approximately 2.4 m by 12 m for the small size (see Fig. 2). As shown in Fig. 8, $\overline{WVRs}$ in pilotis are higher in most measuring points when the fin size was small. This is because the cross section of the pilotis was increased with the small size of the fin. The volume of inflows to the void was reduced as the size of the fin reduced and thus the wind pressure (i.e. static pressure) inside the void should be decreased accordingly. However, the increase in fin size did not result in the increase in wind velocity. Instead, $\overline{WVRs}$ were increased by up to 0.12 in Case 1.5 (small fin) at the internal corridor of the 1st floor loft unit (leeward side) because of the increased wind velocities of the inflow from the pilotis.

3.2 Flow rate measurement

Fig. 9 depicts the vertical distributions of averaged wind velocities measured at the openings at four different levels on the corridor side of the leeward units. It should be noted that the wind velocities at the lower level of the 1st floor loft unit received stronger winds than the outdoor reference values especially when the window/doors were opened (Cases 2.1-2.3, 2.5). Similarly, the wind velocities at the 2nd floor units were almost equal but slightly increased in Case 2.2 compared with Case 2.3 when the windows/doors of the windward units were opened. As seen

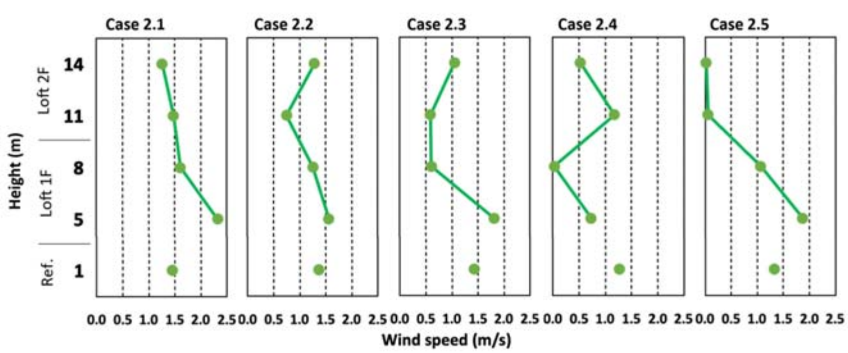


Fig. 9. Vertical distributions of wind velocities on the corridor side of the leeward units.

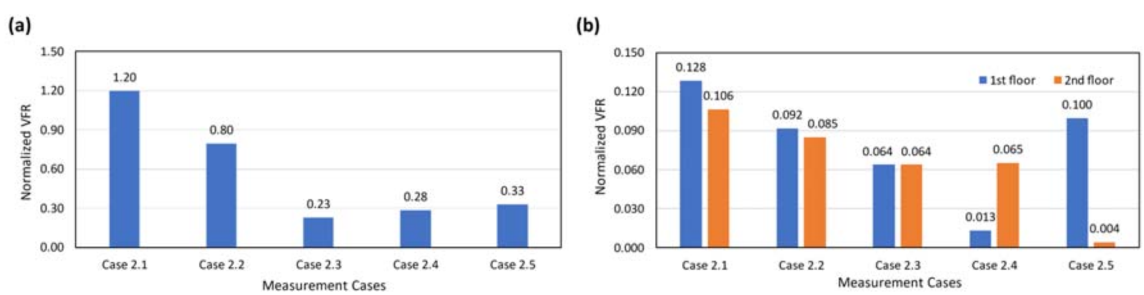


Fig. 10. Normalized volumetric flow rates in (a) vertical void and (b) leeward loft units.

in the above-mentioned measurement, window/door-opening increased the wind velocities for most spaces in and around the void (see Fig. 6).

Fig. 10 presents the results of *VFR* measurements. As shown in Fig. 10a, the *VFR* for the void was maximized (1.20) when all the windows/doors were opened in Case 2.1, which is equivalent to approximately 193 ACH (times/h). As expected, the opening conditions of the windward units affected the *VFR* of the void. However, even when the windows/doors were closed on the windward side, sufficient *VFRs* of approximately 0.23-0.33 were obtained through the inflows from the pilotis (Cases 2.3-2.5), which are approximately 36.6-48.2 ACH. As indicated in Fig. 10b, *VFRs* of the leeward units were largest in Case 2.1 (all windows/doors opened), followed by Case 2.2 (windward units were opened) and Case 2.3 (windward units were closed). It can be seen that among Cases 2.1-2.3, *VFRs* for the 1st floor leeward unit received larger values than those for the 2nd floor unit, but similar levels of *VFRs* were obtained even on the upper floor of the leeward units unlike the wind velocity distributions. It can be seen that approximately 11% of *VFR* of the void entered the 1st floor loft unit, whereas approximately 8.8% went to the 2nd floor loft unit in Case 2.1. This means that about 81% of *VFR* went to other spaces in this case. Similarly, in Case 2.2, approximately 12% went to the 1st floor loft unit and about 11% went to the 2nd floor unit. When the windows and doors of the windward units were closed in Case 2.3, approximately 28% of *VFRs* of the void entered the respective units (1st floor and 2nd floor), while the rest, approximately 44% or less might go back to the pilotis and a small amount passed through the penthouse's louver windows.

Similar results were obtained in the previous CFD simulation studies (Kumar et al., 2021, 2022). Kumar (2022) conducted a parametric study for a similar type of apartment building with a closed-vertical void. The results showed that the mass flow rates were slightly larger for the 1st floor leeward unit compared to the upper floors except for the top floor. An isolated vortex was created inside the closed void space and streamlines went back to the pilotis. The increase in wind speed was also observed near the corridor-side external wall of the lower leeward units in the CFD simulation results as seen in Figs. 6-8. Overall, it can be said that the results of the previous CFD simulations (Kumar et al., 2021, 2022) well replicate the present measurement results.

4 CONCLUSIONS

The venturi effect was clearly observed at the pilotis. However, the increased winds did not reach the upper floor of the leeward units sufficiently even when the fin size was increased. Opening conditions of windows and doors significantly affected the wind velocity distribution in and around the void, though those of penthouse were negligible. Sufficient levels of *VFR* can be obtained even in the upper floor of leeward units due to the increased static pressure inside the closed void. Furthermore, the *VFR* of the lower floor of leeward units received slightly larger *VFRs* not only due to the increase in the overall static pressure but also in the wind velocities (i.e., dynamic pressure) for the specific areas. The proposed ventilation system would be able to provide sufficient cross ventilation to the double-loaded apartment buildings entirely with the increase in static pressure even for a mid-rise building. Moreover, the previous CFD simulation results well replicated the present measurement results.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

Alfata, M.N.F., Trihamdhani, A.R., Kubota, T., Asawa, T. (2023) Development of Low-Carbon Affordable Apartments in the Hot and Humid Climate of Indonesia: Construction of a Full-Scale Experimental House, Environmental Science and Engineering, 2537-2546.

Bardhan, R., Debnath, R., Malik, J., Sarkar, A. (2018) Low-income housing layouts under socio-architectural complexities: a parametric study for sustainable slum rehabilitation, *Sustain. Cities Soc.* 41 (2018) 126–138.

Kumar, N., Bardhan, R., Kubota, T., Tominaga, Y., Shirzadi, M. (2022) Parametric study on vertical void configurations for improving ventilation performance in the mid-rise apartment building, *Build. Environ.* 215, 108969.

Kumar, N., Kubota, T., Tominaga, Y., Shirzadi, M., Bardhan, R. (2021) CFD simulations of wind-induced ventilation in apartment buildings with vertical voids: effects of pilotis and wind fin on ventilation performance, *Build. Environ.* 194, 107666.

Lueker, J., Bardhan, R., Sarkar, A., Norford, L. (2020) Indoor air quality among Mumbai's resettled populations: comparing Dharavi slum to nearby rehabilitation sites, *Build. Environ.* 167 (2020) 106419.

Prasetya, A., Ho, A.D., Kubota, T. (2023) Analysis of typical layout of apartment buildings in Indonesia, *Buildings*, 13(6), 1387.