Experimental study on vertical void for improving natural ventilation in midrise double-loaded apartments

Nikhil Kumar1*, Haruka Kitagawa2, Muhammad Nur Fajri Alfata3, Tasuku Maeda1, Daiki Nakahara1, Tetsu Kubota4*, Takashi Asawa4, Yukari Hirayama5, Andhang Rakhmat Trihamdani6

1Graduate School of Advanced Science and Engineering, Hiroshima University, Hiroshima, Japan
2Institute of Technology Center for Energy Engineering, Shimizu corporation, 3-4-17 Etchujima Koto-ku, Tokyo, 135-8530 Japan
3Division of Building Sciences, Directorate of Engineering Affairs for Human Settlements and Housing Ministry of Public Works and Housing (MPWH) Bandung 40393
4School of Environment and Society, Tokyo Institute of Technology, 4259 Nagatsuta-cho, Midori-ku, Yokohama, Kanagawa, 226-8502, Japan
5Department of Urban Design and Planning, Kogakuin University, 1-24-2 Nishishinjuku, Shinjuku, Tokyo, Japan,
6YKK AP R&D Center Indonesia, PT. YKK AP Indonesia, Tangerang 15810, Indonesia

Abstract. Affordable apartments in tropical developing countries generally have double-loaded corridors to maximise the total floor areas. Building designs with double-loaded corridors often suffer from poor environmental conditions. Passive design using a vertical void can help improve the natural ventilation in the such building design. This study investigates the effectiveness of vertical voids in enhancing the wind speed in the building. An experimental building with a vertical void, open pilotis, penthouse at rooftop and wind fin on the ground floor to help direct air to the void was constructed in Tegal, Indonesia. Five cases were considered by controlling the window openings, louver openings on the roof and change in fin size at pilotis. Wind speed and direction were recorded at one-second intervals. High wind speed was experienced in the pilotis and void when the wind direction is from the north and the wind speed in the void improved due to the wind fin being placed on the south corridor of the building. The results show the average wind speed in the void is twice as high as compared to the corridors. The building design performed best with high wind speeds in the void and corridors when all windows were kept open.

1 Introduction

Affordable housing has become a major challenge for many countries of the Global South which are experiencing massive population growth. In case of Indonesia which is projected to have a population of 331 million of which 72% people will be living in urban areas by the year 2050 [1], one of the major challenges for the Government is to provide affordable housing to its growing and urbanising population. To cater to the needs of the people for housing, Government policies have led to the construction of public housing known as Rusun (essentially means low-cost apartment buildings) apartment buildings in all the major cities of Indonesia. Rusun is classified into Rusunama apartments which are developed by private companies for sale and Rusunami developed by the central government for rental purposes (Three-year lease terms with one allowed extension).

It has been seen that design of these Rusun has double-loaded corridors aimed at maximising the usage of the area. In equatorial tropical regions like Indonesia, where both south- and north-facing facades get solar radiation all year long, solar radiation is unwelcome in tropical buildings. For this reason, the building's orientation concerning daylight is not prioritized. The design of the building is mainly concerned with accommodating the maximum number of units possible in the given land area. Poor environmental conditions, such as a lack of daylighting, thermal comfort, ventilation, and indoor air quality, frequently plague these designs [2]. The residents of these double-loaded flats who reside on the leeward side of the building may experience inadequate cross-ventilation in their residences. Particularly in low-cost affordable housing, the provision of natural ventilation can improve thermal comfort, energy efficiency, and resident health [3].

Continuous ventilation is regarded as one of the most essential comfort needs owing to the high humidity in tropical locations, which improves sweat evaporation efficiency and reduces discomfort from moisture on the skin and clothing. To increase the performance of cross-ventilation even on the leeward side of the structures, it is crucial to identify passive design techniques for double-loaded inexpensive flats.

The purpose of the current study is to parametrically evaluate the wind flow in the vertical void with changes in apertures and fin size in the structure. Three objectives of the study are: First, to understand and validate the wind flow patterns in the open pilotis and the void area of the double-loaded residential structures, considering the wind direction perpendicular to the building façade. Second, it is to determine how window
openings affect the variations in wind velocity in the vertical void. Thirdly, it is to check the impact of the fin on the wind flow in the pilotis and void region. From this study, we would be able to offer decisive evidence towards passive design architectural principles of a closed-vertical void which can be used into double-loaded apartment complexes for future affordable housing.

The performance of natural ventilation is examined in this study using experimental measurements of wind speed and wind direction in response to changes in factors including (i) door and window openings, (ii) an open or closed penthouse, and (iii) wind fin size. The wind speed is then normalised using data from measurements of 2D ultrasonic anemometer placed at a distance of 6 m from the building.

The study will give a brief idea about improving natural ventilation with the help of passive design elements. Chapter 2 will explain the building design features which help increase natural ventilation, the measurement plan and the cases to test the effectiveness of the void have also been described. Chapter 3 compares the results from the measurements concerning the different sections of the building. Furthermore, a wind velocity ratio has been used to compare the cases. Finally, the study is concluded in Chapter 4 providing the future works and limitations of the study.

2 Building design, measurement setup and case design.

The present authors in their previous works have proposed an alternative design solution for such double-loaded apartments for an effective ventilation system [4,5]. As shown in Fig. 1a. The design consists of a closed vertical void between the two sides of the corridor. separating the building into two sections, open pilotis and wind fin at the bottom floor. The vertical void with a close-end roof will further provide a superior ventilation rate. The closed-vertical void dispersed wind pressure to the leeward side of the building and would induce natural ventilation inside the units. Additionally, the ground floor's vertical wind fin was built to channel wind upward and into the void. Fig. 1b. shows the areil view of the building and its surroundings there is a toilet of 3m height on the left and a water tank of 3m height on the right. Fig. 1c. shows the wind direction and wind speed recorded in the weather station placed at the rooftop. Fig. 1d gives the outdoor air temperature and humidity during the measurement period.

In this study, we further focus on testing the proposed design in an actual experimental building to further advance the result to a real scenario. Fig. 1b. shows the experimental building. The experimental building in Tegal, Central Java, Indonesia. The building was designed based on passive design approaches to maintain thermal comfort for the residents. Among them, we are focusing on the impacts of passive design features in the building which help increase natural ventilation. As shown in Fig. 2a. there is a vertical void of 2.85 m width separating the two building sides. Fig 2b. shows the pilotis area which has a height of 4 m and is kept open for better natural ventilation. There is a wind fin of 12 m in length and 4 m in height in the pilotis area to direct the wind toward the vertical void. Fig 2c. shows the penthouse at the roof level of the building with dimensions of 3.05 m X 12.05 m and a height of 2.4 m.

Reinforced concrete was used to create the experimental building's main structure, while autoclaved aerated concrete (AAC) brick was used mostly for the outside walls. As shown in Fig. 3 the loft units (ceiling height of 5.1 m) have a gross floor area (GFA) of 47.6 m2, whilst the standard units (ceiling height of 3 m) had a GFA of 43.2 m2. Both unit types include a full balcony with a 1.5 m width that faces the

Fig. 1. (a)Concept of ventilation for the building design [6] (b) experimental building at Tegal, Indonesia, (c) measured wind speed and direction at rooftop (d) measured air temperature (e) measured relative humidity.

2.1 Building design

The existing experimental building is located in a tropical climate condition in the city of Tegal, Central Java, Indonesia. The building was designed based on passive design approaches to maintain thermal comfort for the residents. Among them, we are focusing on the impacts of passive design features in the building which help increase natural ventilation. As shown in Fig. 2a. there is a vertical void of 2.85 m width separating the two building sides. Fig 2b. shows the pilotis area which has a height of 4 m and is kept open for better natural ventilation. There is a wind fin of 12 m in length and 4 m in height in the pilotis area to direct the wind toward the vertical void. Fig 2c. shows the penthouse at the roof level of the building with dimensions of 3.05 m X 12.05 m and a height of 2.4 m.

Reinforced concrete was used to create the experimental building's main structure, while autoclaved aerated concrete (AAC) brick was used mostly for the outside walls. As shown in Fig. 3 the loft units (ceiling height of 5.1 m) have a gross floor area (GFA) of 47.6 m2, whilst the standard units (ceiling height of 3 m) had a GFA of 43.2 m2. Both unit types include a full balcony with a 1.5 m width that faces the
outside and serves as a shade structure. Both north and south-facing facades in the tropical tropics, like Indonesia, get solar radiation all year round. To further shield the experimental units from thermal impacts, high insulation materials (such as rock wool, which has a thermal conductivity of around 0.035 W/mK) were put on the west- and east-facing external walls.

Fig. 2. Experimental building at Tegal, Indonesia with passive design features. (a) Vertical void (b) Open pilotis and wind fin (c) Penthouse over the vertical void.

Semi-open and next to the vertical void space, the corridor in the experimental building was created. To reduce the interior air temperature through natural ventilation, it is crucial to maintain a lower air temperature in the neighboring corridor spaces. The windows and doors were specifically designed to maximize the ventilation performance in the units in addition to the ventilation strategies used in the building layout and configuration, including the use of operable insect screens, security grills, and small ventilation windows, among other things.

Fig. 3a. shows the plan of the building and Fig. 3b shows the section of the building. The size of the building is 18.4 m x 21.6 m with a roof height of 16 m. The building is a double-loaded corridor with six residential units on both sides. There are two different unit designs used for the residential units. One side has the standard unit design with two bedrooms with the bedroom size being 2.9 m x 3 m each, one combined toilet and bathroom of 1.4 m x 2.4 m, living area and dining area are combined with a size of 6 m x 2.6 m there are an open kitchen on the side with 3.5 m x 1.5 m dimensions. The floor-to-ceiling height of the unit is 4 m. There are two standard units per floor with a total of three floors. The living area of each unit is 41.6 m² with an additional balcony area of 10.75 m².

The other side of the building has loft units with a floor-to-ceiling height of 5.1 m. There is a loft floor at a height of 2.6 m which is accessible with the help of stairs in the unit. The loft floor-to-ceiling is 2.5 m. The unit has one living area of 6 m x 3.2 m, a dining area and an open kitchen of size 3.4 m x 3 m, one combined toilet and bathroom at 2.5 m x 1.8 m, and two bedrooms located in the loft area. The size of the master bedroom located on the external wall is 3.2 m x 2.8 m and the second bedroom is 2.3 m x 3m. The total floor area of the unit is 35.5 m² with an additional loft area of 18.5 m² and a balcony size of 9.2 m².

2.2 Measurement setup

A total of three 2D sonic anemometers, (YOUNG Model 86000 Ultrasonic Anemometer) were used for the measurements. 122 Hot wire anemometers were used to record the wind speed in the vertical void and the pilotis area of which 108 windgraphy (Wind speed sensors from KOA Corporation) and 14 Kanomax (Airflow Transducer model 6333 and sensor model 0976-03) sensors were used.

Fig. 3a. shows the measurement setup for the study. The sensors were placed in three planes perpendicular to the building façade West (W), Middle (M) and East (E). A total of 8 planes starting from the north N1, N2, N3, Standard (Std.), Void, Loft, S1 and S2 were made parallel to the building façade. Sensors for wind speed and wind direction are placed on the intersection of these planes at various heights as shown in Fig. 3b. N1 being 6 m north of the building has two 2D ultrasonic anemometers placed at 1 m height from the ground at N1W and N1M. N2M has a 2D ultrasonic anemometer at 1 m with two hotwire anemometers at 1 m and 2 m respectively.

The pilotis have hot wire anemometers from Kanomax whereas the vertical void has windgraphy sensors from KOA corporates. The windgraphy sensors are placed in the corridors of the standard and loft units and the centre of the void. A total of 9 windgraphy sensors is placed at each intersection of StdW, StdM, StdE. Whereas 17 windgraphy sensors are placed in the intersection in the void. The first sensor is put at a height of 1m after that the distance between the two windgraphy sensors is 0.9 m. Kanomax sensors were placed only on the M plane at N2, N3, Std, Loft, S1 and S2.

Calibration was done for all 108 windgraphy sensors used for measurements with the help of a small wind tunnel at the Laboratory of Building Sciences, Ministry of Public Works and Housing. The 2D sonic anemometer and Kanomax sensors used were industry calibrated.

Fig. 4. Shows the sensor placement in and around the building. the building (a) windgraphy sensors placed in the corridors and the void, (b) Kanomax sensor placed in the pilotis along the middle of the void (c) 2D sonic anemometers placed outside the building toward the windward side.
2.3 Case design

To compare the passive design elements and study their impacts a total of five cases were created by opening windows, opening penthouse windows and changing the fin size. The data were collected during the dry season when the days are sunny with minimal rainfall. Data collection for each case was done for five to six days in starting from 26th June 2022 to 28th July 2022. Table 1 explains the details of all the settings for the cases. The cases were designed in a way to figure out the impacts of the passive design elements used in the building design. Case 1 has all windows of units and penthouse open with a large size fin to direct air into the vertical void. Case 2 has closed windows to compare with Case 1 to know the impact of open windows in the units. Case 3 has the penthouse windows closed and compared to Case 1 will show the impact of a penthouse on the wind speed. Case 4 has a closed window, a penthouse and a large fin Case 5 has the same conditions as case 4 except the fin size is small to understand the impact of the fin size.

Table 1. Detail building design conditions from Case 1 to Case 5.

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Window and door</th>
<th>Penthouse window</th>
<th>Fin size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Open</td>
<td>Open</td>
<td>Large</td>
</tr>
<tr>
<td>Case 2</td>
<td>Close</td>
<td>Open</td>
<td>Large</td>
</tr>
<tr>
<td>Case 3</td>
<td>Open</td>
<td>Close</td>
<td>Large</td>
</tr>
<tr>
<td>Case 4</td>
<td>Close</td>
<td>Close</td>
<td>Large</td>
</tr>
<tr>
<td>Case 5</td>
<td>Close</td>
<td>Close</td>
<td>Small</td>
</tr>
</tbody>
</table>

3 Results

A parametric study was conducted to understand the natural ventilation flow in the vertical void of the building. The wind speed measurements were normalized to wind velocity ratio (WVR) by Eq. 1.

\[
WVR = \frac{V_M}{U_0} \tag{1}
\]

where \(V_M\) is the measured velocity magnitude and \(U_0\) is the velocity magnitude recorded at the 2D sonic anemometer at a height of 1 m and distance of 6 m from the building. \(WVR\) represents the average value of wind velocity ratio.

For this study, we have considered the data which has wind speed above 1 m/s and a wind angle perpendicular to the façade has been considered allowing for 30° change in direction on each side. This was decided from the previous study by the authors in which it was proved that a wind angle of 30° from the perpendicular to the windward side can provide a similar level of wind pressure in the void [5]. The building is at an angel of 22.5° to the North, hence a wind angle between 352.5° and 52.5° (60°) was considered for the study. Rest of the data was discarded for this study.
3.1 Comparison of section planes of the building

Fig. 5. shows the $WVR$ in the vertical void from Case 1 to Case 5 at the three sections West (W), Middle (M) and East (E) as presented in Fig. 3a. The $WVR$ in the pilotis was between 0.8 to 1.4. As the height of the building increases the $WVR$ in the vertical void decreases. The $WVR$ on the East section of the building was higher than the West and Middle sections. It was due to the surrounding buildings. There is a small obstruction on the Northwest side of the building which reduces the airflow into the vertical void for the West and Middle sections. At the same time, there is an obstruction on the South East side of the building which acts as an extra wind director towards the vertical void helping improve the $WVR$ for the ‘E’ plane. In Case 2 the $WVR$ for Section, E was much higher than Sections W and M. Post the pilotis area the $WVR$ in the vertical void for all three sections (W, M and E) shows a similar pattern for all other floors.

The $WVR$ for the first floor from 4.6 m to 9.1 m after the pilotis area are between 0.75 to 0.5. The $WVR$ further reduces as the height of the building increases and was less than 0.5 after 10 m height. The overall $WVR$ for Case 1 and Case 3 was much higher as the windows and doors of units are kept open and there was airflow from the units. When comparing Case 1 to Case 2 there was an approximate difference of 0.2 $WVR$ due to the wind flow in the units. Comparing Case 2 and Case 4 we can see that opening the penthouse window increase the $WVR$ in the vertical void at various heights. Whereas the $WVR$ in Case 4 was constantly decreasing with the increase of height. Comparing Case 4 and Case 5 we can see the impact of fin size as the fin size in Case 5 was small a drastic decrease in $WVR$ can be seen as the unit floors start.

Fig. 6. Shows the boxplot of $WVR$ at the M plane for Case 1 with open windows, open penthouse and large fin size. The results of $WVR$ in the corridors of the loft unit show major differences as the $WVR$ on the first floor of the loft unit was minimum at 1 m from 0.5 to 0.7, the maximum $WVR$ was recorded at 2.8 m which was the approx. centre of the loft corridor at 0.54 to 1.12. Whereas for the second floor the minimum $WVR$ was 0.19 to 0.3 at 4.7 m and the maximum $WVR$ was 0.27 to 0.4 at 1 m height from the loft second-floor corridor.

Overall the recorded $WVR$ on the first floor was almost two times the $WVR$ on the second floor. The wind speed was not maintained from the first floor to the second floor due to the presence of the corridor. Whereas in the case of standard units the overall $WVR$ was around 0.2 to 0.35 for all placed sensors except for the 2.8 m on the third floor which has a $WVR$ of 0.1 to 0.2. The void area receives the best $WVR$ for Case 1 where the overall $WVR$ was more than 0.5 except beyond 12.7 m where the $WVR$ drops to a minimum of 0.3 for the next four sensor positions. As shown in Fig. 5. Case 1 was the best-performing case in terms of wind speed. Boxplots of all the sections and cases show a similar trend with varying values hence the results were further analysed using the average wind velocity ratio ($WVR$) for the W, M and E planes and the cases. Comparisons between cases were done to figure out the importance of passive design elements in the building. The middle plane was the least impacted by the surrounding buildings hereafter it has been considered the representation plane for graphs of each case. The $x$-axis of the graph shows the $WVR$ whereas the $y$-axis shows the height of the sensor in their respective locations.
3.2 Window openings and their impact

Fig. 7. Shows the variations in WVR for cases with windows open and closed, other parameters were kept the same details in Table 1. In Case 1 and Case 3, all the windows in the building are open whereas in Case 2 and Case 4 they are closed. The WVR of Case 1 and Case 3 show similar trends for the open window condition whereas Case 2 and Case 4 show similar trends for the WVR.

Fig 7a. shows the comparison of WVR of Case 1 and Case 2 with open and closed windows respectively. The WVR in the windward side of pilotis for Case 1, was 2.3, 1.4 and 1.3 at points N2, N3 and standard respectively. For Case 2 the average WVR on the windward side were 0.4 less than Case 1. The leeward side WVR for Case 1 and Case 2 were approximately the same with 0.3, 0.3 and 0.5 at loft, S1 and S2 respectively. The WVR in the corridors of standard units for Case 1 are similar with an average WVR 0.26 on all the floors, whereas for Case 2 the WVR was 0.18 which was 0.08 less than Case 1. In Case 1 the WVR on the leeward side loft units corridor on the first floor were 0.6, 0.8, 0.8, 0.8 and 0.5 for 1 m, 1.9 m, 2.8 m, 3.7 m and 4.6 m respectively and for the second floor, it reduced to 0.3, 0.3, 0.2, 0.2 and 0.21 m, 1.9 m, 2.8 m, 3.7 m and 4.6 m respectively. The average WVR for the first and second floors are 0.75 and 0.28 respectively. In Case 2 the WVR on the loft side, corridors are further reduced to an average of 0.48 and 0.1 on the first and second floors respectively. The overall reduction in WVR between Case 1 and Case 2 was 0.15. The WVR in the vertical void for Case 1 was 0.57. The WVR in the vertical void slowly decreases from the bottom to the top of the void. The WVR in the vertical void for Case 2 is 0.4 which is 0.17 less than that of Case 1.

Fig. 7b. compares the WVR of Case 3 and Case 4. Case 3 has open windows with a closed penthouse and large fin whereas Case 4 has closed windows with a closed penthouse and large fin. The WVR on the windward side, pilotis were 2.2, 1.4 and 1.3 for N2, N3 and standard planes for Case 3 respectively. Case 1 also had the same values. The WVR on the windward side pilotis were 2.2, 1.9 and 1 for Case 4 which was 0.1 higher than Case 2. The leeward WVR for Case 3 and Case 4 are similar with 0.3, 0.3 and 0.5 for loft, S1 and S2 planes. The WVR in the standard corridor units for Case 3 are 0.25, 0.26 and 0.23 which was approximately 0.15 higher than that of Case 4. The WVR in the corridor of loft units for Case 3 are 0.75 and 0.25 for the first and second floor respectively. In Case 4 the WVR in the loft units corridor were 0.49 and 0.11 for the first and second floors respectively. The WVR in the vertical void for Case 3 was 0.52 and that for Case 4 was 0.41, overall a decrease of 0.11.

Overall the WVR is higher in the vertical void and pilotis when the windows are open. The corridors in the building experience higher WVR by 0.15 approx. due to the window openings in all cases. The windward side pilotis were impacted by the opening of the windows and the WVR recorded is higher in Case 1 and Case 3. Though the leeward side pilotis were not impacted by window openings. The higher WVR at the N2 plane was due to the building façade directing the air downward into the pilotis increasing the volume of air similar to the venturi effect.

3.3 Penthouse and its impact

Fig 8. Shows the WVR comparison of cases with variation in penthouse opening while the other parameters are the same. Fig. 8a shows the WVR of Case 1 with an open penthouse and Case 3 with a closed penthouse, the other parameters are the same open windows and large fin. The WVR both cases are similar in the pilotis area with a maximum of 2.5 at the N2 plane and a minimum of 0.4 at the S2 plain. The WVR in the vertical void was higher in Case 1 by 0.1 at most points in the vertical void. WVR in the corridors of the
standard units was the same for both cases on all three floors. The \( WVR \) in the standard third floor is the highest at 0.4. The average \( WVR \) in the corridors of the standard unit was 0.27. In the loft units the \( WVR \) in Case 1 was higher than Case 3 by 0.01.

Fig. 8b. shows the comparison of \( WVR \) of Case 2 and Case 4 with closed and open penthouse respectively. For the pilotis level the \( WVR \) was similar for both the cases in the vertical void Case 4 performs much better with a minor 0.1 increase in the \( WVR \) than Case 2. In case of the corridors of standard units the \( WVR \) was almost the same in both the cases, the loft units also show similar values of \( WVR \) in both cases.

Overall the \( WVR \) the pilotis were not affected by the opening and closing of pilotis window. At the same time the \( WVR \) in the corridors of the windward side standard units are also not affected by the presence of the penthouse. A minor impact in the \( WVR \) on the corridor of leeward loft units can be seen with a minor increase of 0.05 when the penthouse was open. The \( WVR \) in the vertical void increased by 0.1 due to the penthouse opening this directly means the flow of wind from the pilotis to the outside was improved cause of the penthouse opening. Hence penthouse should be opened when the flow is to be taken outside the building and can be kept closed in case the flow is to be directed toward the units.

![Fig. 8 Average Wind velocity ratio recorded with changes in penthouse openings (a) Case 1 penthouse open Case 3 penthouse closed with windows open and large fin size (b) Case 2 penthouse open Case 4 penthouse closed with windows closed and large fin size.](image1)

### 3.4 Effect of Fin size

Fig. 9 shows the comparison of \( WVR \) in the middle plain for Case 4 and Case 5. In Case 4 the fin size was large whereas Case 5 has a smaller fin size rest of the parameters are the same in both cases with closed windows in the units and penthouse. The \( WVR \) on the windward side of the pilotis for Case 5 was the highest at N2 (2.85) slowly decreasing towards N3 (1.6) and standard (1.6) which was higher than Case 4 by 0.4 in all the cases. The \( WVR \) on the leeward side of the pilotis was again higher in Case 5 as the smaller wind fin allowed higher volumes of air to pass through. The \( WVR \) on the leeward sides for Case 5 are 1.2 at the loft, reducing to 0.9 at S1 and S2 whereas Case 4 has an average \( WVR \) of 0.3 which was almost 0.8 times less than Case 5. Case 5 recorded a higher \( WVR \) in the pilotis area. In the vertical void Case 5 and Case 4 show similar trends after the first floor starts. In the case of standard corridors, both cases show similar trends and values of \( WVR \) are similar for all three corridors between 0.1 to 0.3. The loft corridors show a similar trend for the second loft floor with the \( WVR \) between 0.1 to 0.2. In the case of the first-floor loft corridor the \( WVR \) was higher in Case 5. This explains that the smaller fin size allows better flow of air in the pilotis as well as allows a better direction of flow into the void. In the case of a large wind fin, the incoming air volume gets completely stopped by the larger fin and was forced to move in the void area thereby reducing the wind speed by backflow after hitting the large fin.

![Fig. 9 Average Wind velocity ratio recorded with windows and penthouse closed for Case 4 large fin size and Case 5 small fin size.](image2)
4 Conclusion

The study intended to do an experimental measurement to facilitate natural ventilation in the vertical void with the help of a wind fin at pilotis level. The passive design elements to increase natural ventilation were parametrically assessed in the building. A total of 5 cases were studied by opening and closing the windows, doors and changing the fin size. The minimum wind speed for analysis was assumed at 1 m/s and wind direction at 352.5° and 52.5°. The following are the key conclusions that can be drawn:

- The WVR in the void when the doors and windows are open is approximately 0.15 higher than when the doors and windows are closed.
- The large fin size directs more air into the vertical void but higher WVR are recorded in Case 5 with a small fin size compared to Case 4 where the fin size is bigger though the rest of the conditions are kept the same.
- The impact of the penthouse opening can be seen in the vertical void area with a minor increase in the WVR.
- The WVR in the corridors is much less than that in the vertical void, Overall the corridors act as an interruption to the wind flow.
- The first-floor loft receives the highest WVR as the wind fin at pilotis level directs all the wind towards leeward units when the wind is perpendicular to the windward façade.
- The WVR at the pilotis level is almost 1.5 times the outside natural ventilation due to the venturi effect.
- The leeward side pilotis area is not impacted by the opening and closing of windows.

These findings can be further advanced by adding more environmental factors for measurements like air temperature, humidity, etc. There is a need to further study the wind pattern and thermal comfort inside the units too.

There is a need to further discuss the location of the corridor in the building design. There is a need to study the airflow patterns in the case of an external corridor which can further enhance the wind environment and can add more privacy to the residents. Overall the results can help ascertain whether the vertical void and wind fin help improve the natural ventilation in affordable housing.

Acknowledgments

This research was partially supported by the Science and Technology Research Partnership for Sustainable Development (SATREPS) in collaboration with Japan Science and Technology Agency (JST, JPMJSA1904) and Japan International Cooperation Agency (JICA). We also highly acknowledge the support from the YKK AP Inc. and the Asahi Glass Foundation. The field measurement was also funded by the Indonesia National Budget (APBN) of the Ministry of Public Works and Housing.

References