Evaluation of effect of the wind pressure fluctuation for cross ventilation in the residential district

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**ABSTRACT**

In residential district, it is difficult to set appropriate wind pressure coefficient for cross ventilation design, because there are various and complex parameters that influence the wind pressure. A simpler method to identify the wind pressure coefficient is needed in general design process of the cross-ventilated space.

In this paper, wind tunnel experiment with the models in some residential district was conducted, and the difference of wind pressure coefficient ($\Delta C_p$) between two openings on the supposed flow path is analyzed to evaluate the potential for cross ventilation. And the influence of the building coverage on $\Delta C_p$ and 'effective' $\Delta C_p$ that reflect the wind pressure fluctuation are discussed.

1. INTRODUCTION

In residential district, it is difficult to set appropriate wind pressure coefficient ($C_p$) for cross ventilation design, because there are various placement of surrounding buildings that strongly influence the wind pressure. The detailed distribution of $C_p$ is obtained from the wind tunnel experiment, but the wind tunnel experiment is not usually used for design process of the cross-ventilated space because of time and effort. A simple method to identify $C_p$ value is needed for architects to design the cross-ventilated space reasonably.

In some previous studies, the wind tunnel experiment has been conducted to obtain $C_p$ of the building in built-up area, and the effect of a group of surrounding buildings has been examined. Shoda (1956) examined the relation between the gross building coverage and $C_p$ on windward and leeward surface of some rectangular building models. And Wiren (1985), and Suyama (2000) reported the wind tunnel study of the building models with ridge roof in various regular arrays. But it is necessary to accumulate more knowledge about $C_p$ in built-up area for the simple and reasonable cross ventilation design.

In this paper, wind tunnel experiment is conducted to measure the distribution of $C_p$ on the model of detached house in some residential district. And the difference of wind pressure coefficient ($\Delta C_p$) between two openings on the supposed flow path is analyzed to evaluate the potential for cross ventilation. In the analysis of this paper, there are two points in discussion; influence of the building coverage on $\Delta C_p$, and 'effective' $\Delta C_p$ that reflect the wind pressure fluctuation.

As for the first point, influence of the building coverage on $\Delta C_p$, Shoda (1956) obtained the results of the simple relation between the gross building coverage and $C_p$ on windward and leeward side from the test of some rectangular models. The result is useful as the simple method for evaluation of $C_p$ for cross ventilation design, but it has the problem in the point of the variation of wind direction, model layout and model shape. In this paper, the relation between the gross building coverage and $C_p$ is examined in the realistic residential district from the wind tunnel test changing the pitch of the building model.

As for the second point, 'effective' $\Delta C_p$ that reflect the wind pressure fluctuation, the
difference of the time-averaged value of $C_p$ is usually used for the cross ventilation design but the effect of wind pressure fluctuation is not considered in the calculation of the ventilation rate. However, it is thought that the wind pressure fluctuation has effect on cross ventilation, especially in high-density residential restrict. The second objective of this paper is that the 'effective' $\Delta C_p$ is examined to reflect the wind pressure fluctuation to the estimation of cross ventilation.

2. METHOD

2.1 Wind Tunnel Test

The wind tunnel tests are carried out in the boundary layer wind tunnel at the College of Industrial Technology in Nihon University (Maruta (2004)).

The mean velocity profile used in wind tunnel tests is the boundary layer flow simulated wind conditions over the urban terrain (Power low exponent $\alpha=0.27$, AIJ (1993)).

Pressure is measured by a CPAL (DATA INSTRUMENTS) pressure transducer (differential pressure type) by connecting a vinyl tube of 1,000 mm length to the pressure taps that could acquire the data at the same time for all ports at a sampling rate of 555.6 Hz.

2.2 Models and Layout

The model, which is used for pressure measurement, represents a Japanese two-story house in urban area (Figure 1). It set at a scale of 1/83, and has 216 pressure taps (121 points on wall, and 95 taps on roof). The layout of the pressure taps is shown in Figure 1.

Surrounding models are two kinds; one is same of target model, and another is the model with the gable roof. And the surrounding models are put in around the target model on the condition in Table 1 and Figure 2. Wind tunnel tests are done in the 12 cases, changing the pitch of building of east-west orientation ($L_1$), road width on north side of the target model ($L_2$), and pitch of the site based on the most compact site ($L_3$).

And the tests are conducted for 16 wind directions, rotating the turntable form 0° to 337.5° with an interval of 22.5°. Moreover, five tests are done for each wind direction, and the mean values of the statistics of five wave of pressure at each tap are examined.

3. ESTIMATION OF WIND FLUCTUATION

3.1 Definition of $\Delta C_p$ to Estimate the Wind Fluctuation

The wind pressure coefficient $C_p$ is defined by the following equations:

$$C_p = (P_s - P_0) / \{(1/2) \rho V_H^2\}$$  \(1\)

where $P_s$ and $P_0$ are the static pressures [Pa] acting on the model surface and in the air flow at the eave height of 5.85 m, and $V_H$ are the wind speed corresponding to the height of the previous eave [m/s], and $\rho$ is the air density [kg/m$^3$].

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### Table 1: Condition of the residential district.

<table>
<thead>
<tr>
<th>Case No.</th>
<th>$L_1$</th>
<th>$L_2$</th>
<th>$L_3$</th>
<th>Gross building coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 m</td>
<td>4 m</td>
<td>6 m</td>
<td>42.5%</td>
</tr>
<tr>
<td>2</td>
<td>1 m</td>
<td>6 m</td>
<td>4 m</td>
<td>40.6%</td>
</tr>
<tr>
<td>3</td>
<td>1 m</td>
<td>7.5 m</td>
<td>4 m</td>
<td>39.7%</td>
</tr>
<tr>
<td>4</td>
<td>1 m</td>
<td>4 m</td>
<td>6 m</td>
<td>37.7%</td>
</tr>
<tr>
<td>5</td>
<td>2 m</td>
<td>4 m</td>
<td>6 m</td>
<td>39.4%</td>
</tr>
<tr>
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<td>2 m</td>
<td>4 m</td>
<td>4 m</td>
<td>33.3%</td>
</tr>
<tr>
<td>7</td>
<td>2 m</td>
<td>4 m</td>
<td>2 m</td>
<td>25.3%</td>
</tr>
<tr>
<td>8</td>
<td>2 m</td>
<td>4 m</td>
<td>0 m</td>
<td>25.3%</td>
</tr>
<tr>
<td>9</td>
<td>2 m</td>
<td>4 m</td>
<td>2 m</td>
<td>37.3%</td>
</tr>
<tr>
<td>10</td>
<td>2 m</td>
<td>4 m</td>
<td>4 m</td>
<td>31.9%</td>
</tr>
<tr>
<td>11</td>
<td>2 m</td>
<td>8 m</td>
<td>24.1%</td>
<td></td>
</tr>
</tbody>
</table>

$L_1$: Pitch of building (East-West), $L_2$: Road width.
$L_3$: Pitch of the site based on the most compact case (North-South)

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Figure 1: Residential building model and Pressure Taps.

Figure 2: Residential district setting.

Figure 3: Setting of Case 2.
For calculating the cross ventilation rate, the flow network model, which is based on the orifice equation (Eq. 2) and the mass balance, is usually used.

$$Q = \phi C_d A V_{ref} (|C_{pa} - C_{pb}|)^{0.5} \quad (2)$$

where, $Q$ is the ventilation rate [$m^3/s$] through a opening from point A to point B, $C_d$ is the discharge coefficient of a opening [-], $A$ is the opening area [$m^2$], $V_{ref}$ is the reference velocity [$m/s$], and $\phi$ is the flow direction (=1:B$\rightarrow$A, -1:A$\rightarrow$B). And normally, the time-averaged values of $C_p$ at point A and B are used as $C_{pa}$ and $C_{pb}$ to calculate $Q$ from Eq. 2, and the effect of the bidirectional flow (with relation to thermal comfort and heat exhaust) given by wind pressure fluctuation is not considered.

In this paper, four kind of $\Delta C_p$ are defined as follows, to examine the effect of the wind pressure fluctuation (Figure 4).

$\Delta C_{p0}$ between point A and B is the normal difference of the time-averaged values of $C_p$ as above stated. It is defined as Eq. 3.

$$\Delta C_{p0} = \left| \int_{\Delta t} (C_{pa} - C_{pb}) dt \right| / \Delta t = \left| C_{pa} - \bar{C}_{pa} \right| \quad (3)$$

where, $C_{pa}$, $C_{pb}$ is the instantaneous value of the wind pressure coefficient at point A, B, and $\bar{C}_{pa}$, $\bar{C}_{pb}$ is the time-averaged values of $C_p$ at two points.

$\Delta C_{p1}$ is defined to correctly calculate the mean value of cross ventilation rate ($Q$) from point A to B. $Q$ is expressed in Eq. 4.

$$\bar{Q} = \int_{\Delta t} Q \, dt / \Delta t = C_d V_{ref} \int_{\Delta t} \phi |C_{pa} - C_{pb}|^{0.5} \, dt / \Delta t \quad (4)$$

And to consider the instant change of cross ventilation rate in Eq. 2, another $\Delta C_p$, $\Delta C_{p1}$, is able to be defined as Eq. 5. $\Delta C_{p1}$ is different from the normal difference $\Delta C_{p0}$ in the point that the mean value of the cross ventilation rate $Q$ is correctly calculated.

$$\Delta C_{p1} = \left( \int_{\Delta t} \phi |C_{pa} - C_{pb}|^{0.5} \, dt / \Delta t \right)^2 \quad (5)$$

$\Delta C_{p2}$ is defined as Eq. 6 to reflect the wind pressure fluctuation between point A and B.

$$\Delta C_{p2} = \left( \int_{\Delta t} \phi |C_{pa} - C_{pb}|^{0.5} \, dt / \Delta t \right)^2 \quad (6)$$

When the normal wind pressure coefficient $\Delta C_{p0}$ is equal to 0, $\Delta C_{p2}$ is estimated at larger value reflecting the effect of pressure fluctuation.

$\Delta C_{p3}$ is defined to evaluate the cross ventilation rate included in the two-way flow caused by pressure fluctuation. $\Delta C_{p3}$ is a power mean of the instantaneous difference of $C_p$ with power = 0.5, and it is defined as Eq. 7.

$$\Delta C_{p3} = \left( \int_{\Delta t} |C_{pa} - C_{pb}|^{0.5} \, dt / \Delta t \right)^2 \quad (7)$$

The ventilation rate flowing into a room from both openings is able to be evaluated, when $\Delta C_{p3}$ is used in the orifice equation.

### 3.2 Opening Layouts in Consideration of Cross Ventilation Path

To evaluate the effect of wind pressure fluctuation on cross ventilation, four kind of difference of wind pressure coefficient above-mentioned ($\Delta C_{p0}$, $\Delta C_{p1}$, $\Delta C_{p2}$, $\Delta C_{p3}$) are examined at 5 groups of opening layout (Figure 5). As shown in Eq. 5, 6 and 7, the position of
two openings are needed to calculate $\Delta C_{p1}$, $\Delta C_{p2}$ and $\Delta C_{p3}$, and 5 groups of opening layout are set in consideration of cross ventilation path. Group A and B are set for the room with two openings on the right-angled path. And group C and D are set for a large room with two opposed openings or some rooms connected by indoor openings on the straight path. And group E is set for the airflow path through a skylight opening.

4. RESULTS AND DISCUSSIONS

4.1 Relation between $\Delta C_p$s

Figure 6 shows the relation between the normal $\Delta C_p$ ($\Delta C_{p0}$) and other $\Delta C_p$ ($\Delta C_{p1}$, $\Delta C_{p2}$, $\Delta C_{p3}$). Figure 6a shows the relation of group A in Case 1 (Isolated setting) for all wind direction, and Figure 6b shows the relation of group E. And Figure 6c and 6d show the relation of group A and E in Case 2 (Most compact layout).

$\Delta C_{p1}$, which is introduced to correctly calculate the mean value of cross ventilation rate using the orifice equation, consistently has smaller value than $\Delta C_{p0}$. This means the cross ventilation rate, as one-way flow rate, is overestimated when it is calculated from the normal difference $\Delta C_{p0}$. The decrease of $\Delta C_{p1}$ is especially prominent in the range of small value of $\Delta C_{p0}$ and the case that has large pressure fluctuation (e.g. Case 2).

$\Delta C_{p2}$ and $\Delta C_{p3}$, which are introduced to examine the effect of pressure fluctuation as Eq. 6 and 7, have larger value when $\Delta C_{p0}$ is about 0; The minimum value of $\Delta C_{p3}$ is about 0.03 in the opening layout of group A (Figure 6a, c). And the minimum value of $\Delta C_{p3}$ is about 0.2 in group E of Case 2 (Figure 6d). This means there is obviously the range in which the ventilation rate flowing into a room from both openings is larger than the cross ventilation rate calculated from the normal difference $\Delta C_{p0}$ because of the wind pressure fluctuation. And it is necessary to use $\Delta C_{p3}$ to

Figure 5: Opening sets to examine the pressure fluctuation.

Figure 6: Relation between $\Delta C_{p0}$ and $\Delta C_{p1}$, $\Delta C_{p2}$, $\Delta C_{p3}$. 

evaluate the cross ventilation rate including bidirectional rate. $\Delta C_{p3}$ approaches asymptotically to $\Delta C_{p1}$ and is below the normal difference $\Delta C_{p0}$ in the range of large $\Delta C_{p0}$. Therefore, the cross ventilation rate including bidirectional rate calculated from $\Delta C_{p3}$ is larger than the normal ventilation rate calculated from $\Delta C_{p0}$ in the range of small $\Delta C_{p0}$, and smaller in the range of large $\Delta C_{p0}$.

It is possible that $\Delta C_{p1}$, $\Delta C_{p2}$ and $\Delta C_{p3}$ are related to $\Delta C_{p0}$ and the intensity of the wind pressure fluctuation. Figure 7 shows the relation between $\sigma_{\Delta C_{p}}/\Delta C_{p0}$ and $\Delta C_{p3}/\Delta C_{p0}$ of 5 groups, all wind directions, all cases. $\sigma_{\Delta C_{p}}$ is the standard deviation of the instantaneous difference of $C_{p}$ between two points. $\Delta C_{p3}/\Delta C_{p0}$ has obvious relation to the intensity of the wind pressure fluctuation $\sigma_{\Delta C_{p}}/\Delta C_{p0}$. And $\Delta C_{p2}$ and $\Delta C_{p3}$ are able to be approximately expressed in Eqs. 8.

$$\Delta C_{p1} = \text{Min}[1.22\Delta C_{p0} \exp(-0.5\sigma_{\Delta C_{p}}/\Delta C_{p0}), \Delta C_{p0}]$$
$$\Delta C_{p2} = \text{Max}[0.2\Delta C_{p0} + 0.7\sigma_{\Delta C_{p}}, \Delta C_{p0}]$$
$$\Delta C_{p3} = \text{Max}[\Delta C_{p0} - 0.1\sigma_{\Delta C_{p}}, 0.3\Delta C_{p0} + 0.6\sigma_{\Delta C_{p}}]$$

Data of the wind pressure coefficient is arranged as the mean value of each point, and as the standard deviation of $C_{p}$ ($\sigma_{C_{p}}$) of each point at most. Therefore it is generally difficult to directly estimate $\sigma_{\Delta C_{p}}$ because there are millions of opening sets. However it is confirmed that the relation between $\sigma_{\Delta C_{p}}$ and $\sigma_{C_{p}}$ at each point is approximately expressed in Eq. 9 (Figure 8), and $\Delta C_{p1}$, $\Delta C_{p2}$ and $\Delta C_{p3}$ are able to be estimated from Eqs. 8 and 9 (Figure 9).

$$\sigma_{\Delta C_{p}} = 1.24(\sigma_{C_{p1}} + \sigma_{C_{p2}}) - 0.42$$

4.2 Gross Building Coverage and $\Delta C_{p3}$

For cross ventilation design, $\Delta C_{p}$ between two (and more) openings is needed as the information about wind pressure. But it is difficult to accurately predict $\Delta C_{p}$ in consideration of wind direction and surrounding buildings. So, in this study, $\Delta C_{p}$ is organized in Figure 10, in relation to the gross building coverage and the group of the supposed flow path as one of the simplest information about wind pressure coefficient. Figure 10 shows the average, percentile (P10 is 10 percentile in figures), etc. of $\Delta C_{p0}$ and $\Delta C_{p3}$ including the results of all wind direction in group A and E. In figure, two 'average' lines are added besides the average of all data; Average of 'windward set' in Figure 10a means the average value of the opening sets including the opening which faces 'windward side', and 'windward side' fills the angle between the wind direction and the wall direction is 45 or lower degree. And 'Not windward set' means not including 'windward' opening in the sets. And in Figure 10e, "windward wall & leeward roof" means the combination of 'windward' opening on 2nd floor and the skylight opening on 'leeward' roof.

There is little difference between $\Delta C_{p0}$ and $\Delta C_{p3}$ in relation to the gross building coverage; $\Delta C_{p3}$ tends to be smaller when the gross building coverage has larger value, in any group of opening layout. But there is one different point between $\Delta C_{p0}$ and $\Delta C_{p3}$; the minimum of $\Delta C_{p3}$ is evaluated at more than 0 (about 0.3 to 0.5) while the minimum of $\Delta C_{p0}$ is almost 0. This means the potential for cross ventilation is not appropriately evaluated in low $\Delta C_{p}$ range when the wind fluctuation is not considered.
And it is confirmed that the influence of the wind direction on cross ventilation potential is not too large in the residential district; Even if the opening is simply set on 'windward side', it is difficult to take large $\Delta C_p$ in the normal residential district, especially on 1st floor. There is not all that much difference between the average of 'windward set' and 'Not windward set', and it is not too effective to employ the usual design method for cross ventilation in consideration of the prevailing wind direction in the normal residential district.

5. CONCLUSIONS

In this paper, the wind tunnel experiment is conducted to measure $C_p$ on the model of detached house in some residential district. And $\Delta C_p$ between two openings on the supposed flow path is analyzed to evaluate the potential for cross ventilation.

To evaluate the effect of wind pressure fluctuation on cross ventilation, four kind of $\Delta C_p$ ($\Delta C_{p0}$, $\Delta C_{r1}$, $\Delta C_{p2}$, $\Delta C_{p3}$) are introduced and examined at 5 groups of opening layout. And it is confirmed that $\Delta C_{p3}$, in which is reflected the correct ventilation rate including two-way flow caused by pressure fluctuation, is related to the normal $\Delta C_p$ ($\Delta C_{p0}$) and the intensity of the wind pressure fluctuation.

The relation between the gross building coverage and $\Delta C_{p0}$ on the supposed flow path is examined, and it is confirmed the potential for cross ventilation is not appropriately evaluated in low $\Delta C_p$ range when the wind fluctuation is not considered. And it is not too effective to employ the usual design method for cross ventilation in consideration of the prevailing wind direction in the normal residential district.

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