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 (ΔC_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 ΔC_p, and 'effective' ΔC_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 (ΔC_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 ΔC_p, and 'effective' ΔC_p that reflect the wind pressure fluctuation.

As for the first point, influence of the building coverage on ΔC_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' ΔC_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' ΔC_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 α=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 ΔC_p to Estimate the Wind Fluctuation

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

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

where P'_s and P_s 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 ρ is the air density [kg/m^3].

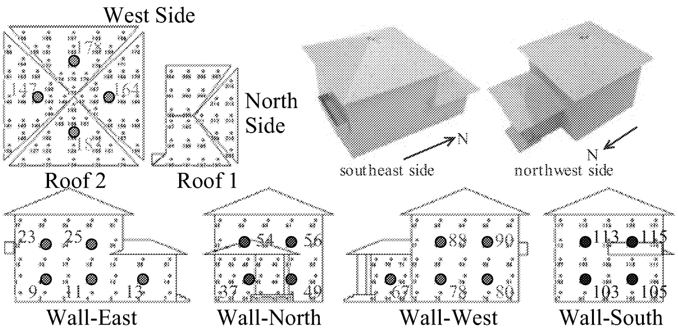


Figure 1: Residential building model and Pressure Taps.

Table 1: Condition of the residential district.

Case No.	L_1	L_2	L_3	Gross building coverage
1	—	—	—	(3.6%)
2	1 m	4 m	0 m	42.5%
3		6 m		41.0%
4		7.5 m		39.2%
5		4 m	4 m	40.6%
6		6 m	6 m	37.7%
7	2 m	4 m	0 m	39.4%
8	4 m			33.3%
9	8 m			25.3%
10	2 m		4 m	37.3%
11	4 m			31.9%
12	8 m			24.1%

*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)

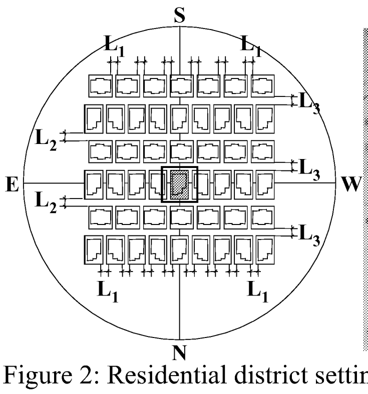


Figure 2: Residential district setting.

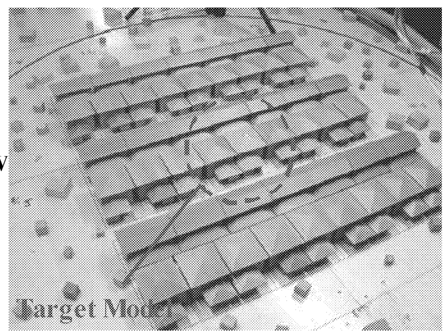


Figure 3: Setting of Case 2.

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.

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

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 ϕ is the flow direction (=1:B→A, -1:A→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 ΔC_p are defined as follows, to examine the effect of the wind pressure fluctuation (Figure 4).

ΔC_{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.

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

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

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

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

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

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

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

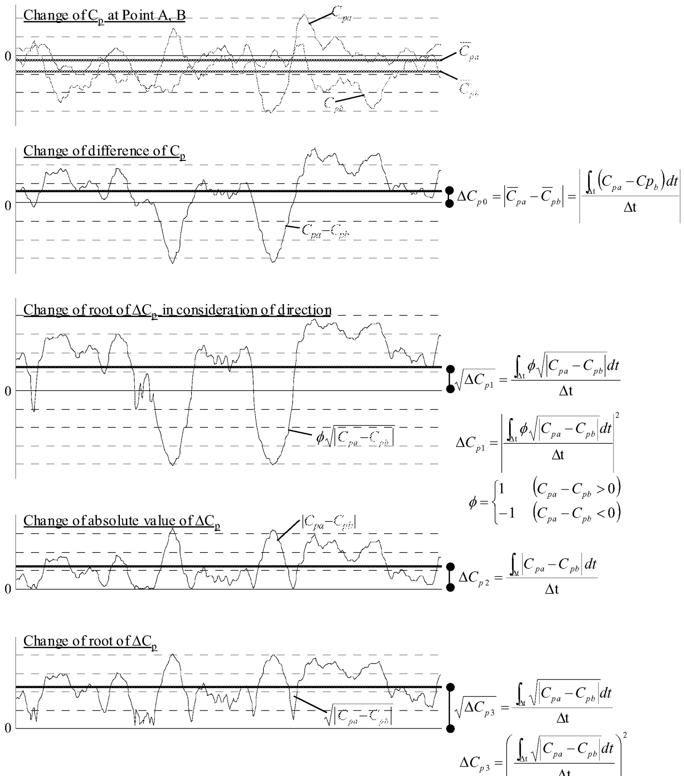


Figure 4: Definition of ΔC_ps.

$$\Delta C_{p2} = \int_{\Delta t} \left| C_{pa} - C_{pb} \right| dt / \Delta t \qquad (6)$$

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

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

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

The ventilation rate flowing into a room from both openings is able to be evaluated, when ΔC_{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 (ΔC_{p0}, ΔC_{p1}, ΔC_{p2}, ΔC_{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 ΔC_{p1}, ΔC_{p2} and ΔC_{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.

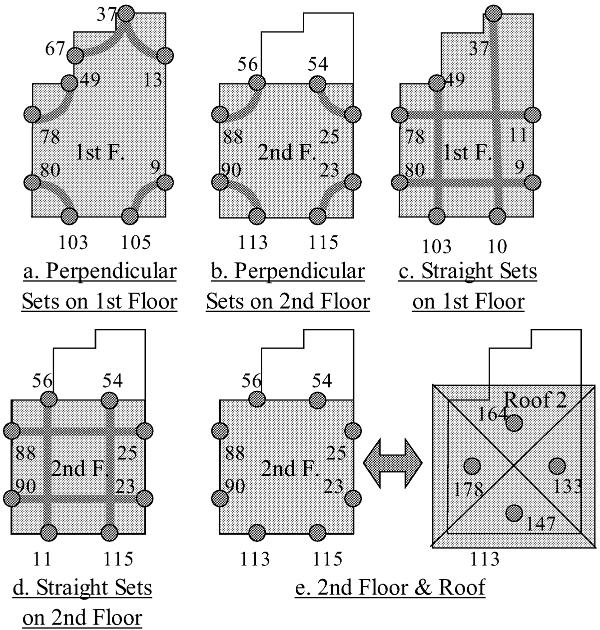


Figure 5: Opening sets to examine the pressure fluctuation.

4. RESULTS AND DISCUSSIONS

4.1 Relation between ΔC_ps

Figure 6 shows the relation between the normal ΔC_p (ΔC_{p0}) and other ΔC_p (ΔC_{p1}, ΔC_{p2}, ΔC_{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).

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

ΔC_{p2} and ΔC_{p3}, which are introduced to examine the effect of pressure fluctuation as Eq. 6 and 7, have larger value when ΔC_{p0} is about 0; The minimum value of ΔC_{p3} is about 0.03 in the opening layout of group A (Figure 6a, c). And the minimum value of ΔC_{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 ΔC_{p0} because of the wind pressure fluctuation. And it is necessary to use ΔC_{p3} to

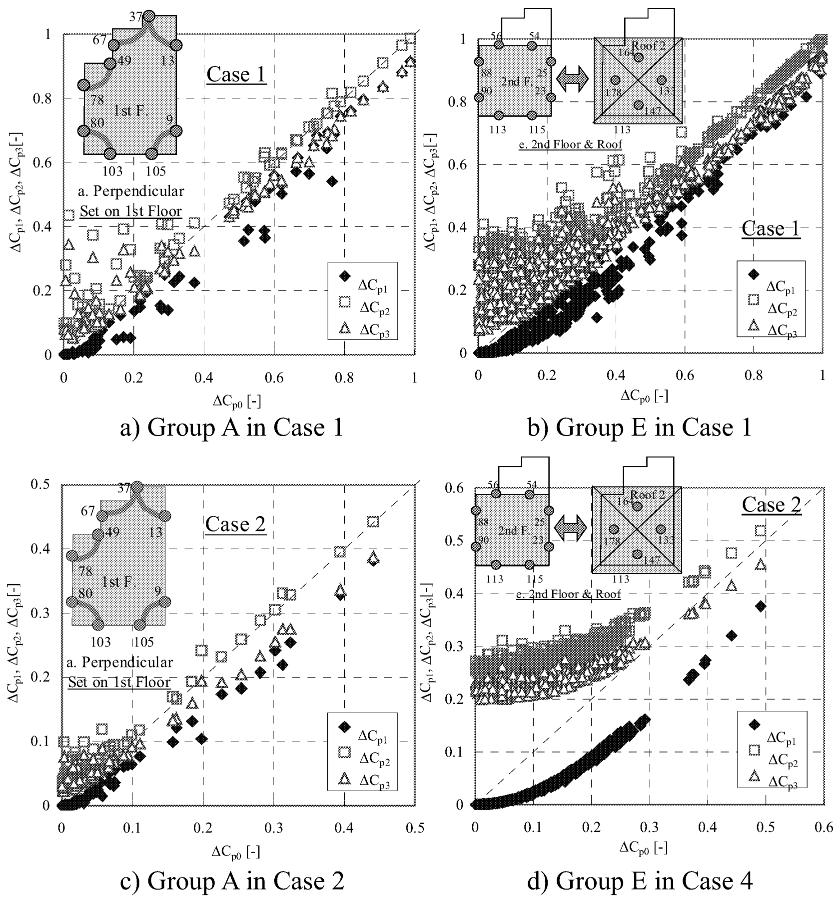


Figure 6: Relation between ΔC_{p0} and ΔC_{p1}, ΔC_{p2}, ΔC_{p3}.

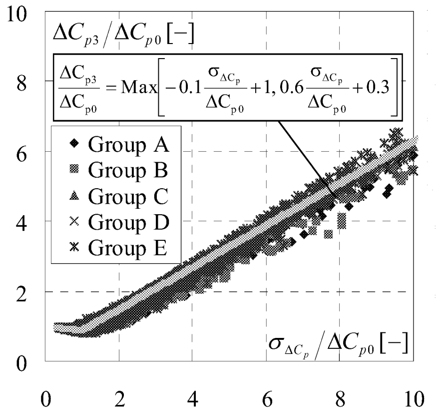


Figure 7: $\sigma_{\Delta Cp}/\Delta C_{p0}$ and $\Delta C_{p3}/\Delta C_{p0}$.

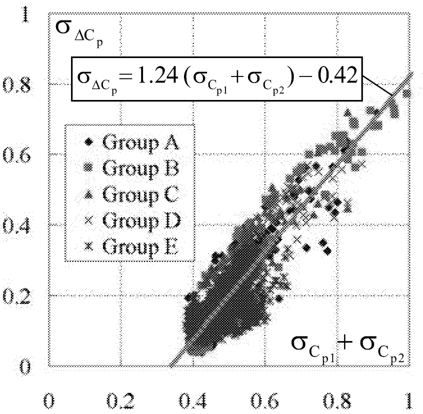


Figure 8: σ_{Cp} and $\sigma_{\Delta Cp}$.

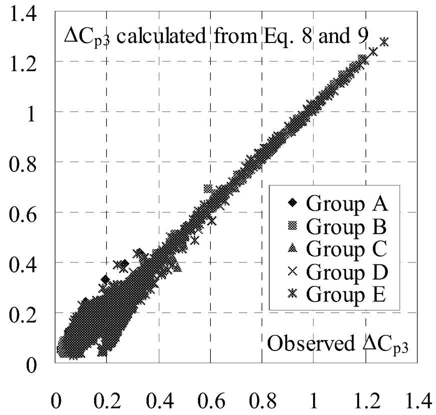


Figure 9: ΔC_{p3} calculated from Eq.8 and 9.

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

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

$$\begin{aligned}\Delta C_{p1} &= \mathrm{Min}[1.22\Delta C_{p0}\exp(-0.5\sigma_{\Delta Cp}/\Delta C_{p0}), \Delta C_{p0}]\\ \Delta C_{p2} &= \mathrm{Max}[0.2\Delta C_{p0} + 0.7\sigma_{\Delta Cp}, \Delta C_{p0}]\\ \Delta C_{p3} &= \mathrm{Max}[\Delta C_{p0} - 0.1\sigma_{\Delta Cp}, 0.3\Delta C_{p0} + 0.6\sigma_{\Delta Cp}] \end{aligned} \quad (8)$$

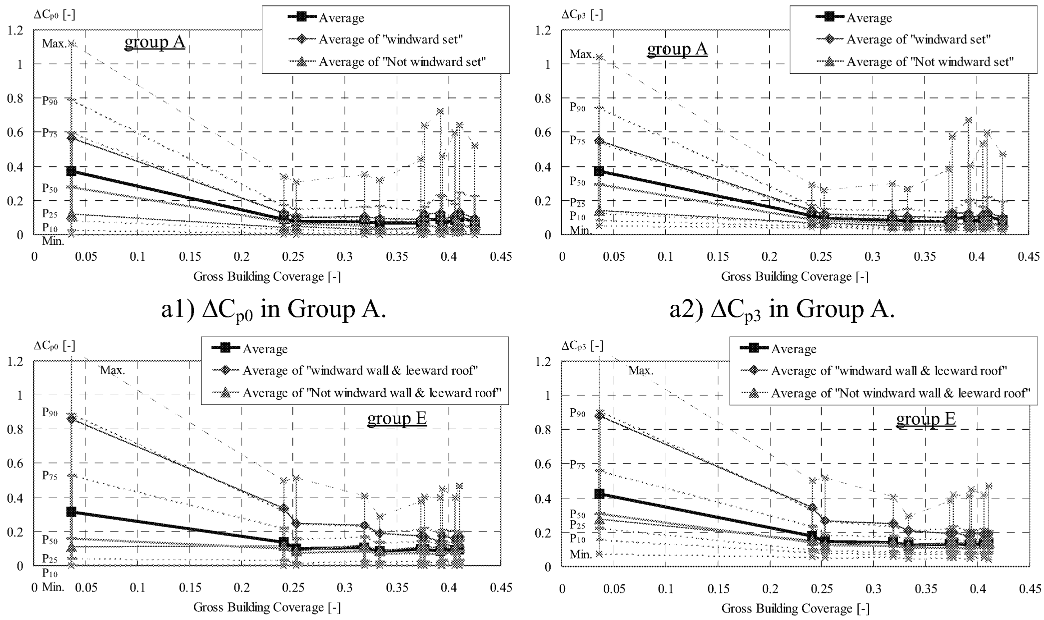
Data of the wind pressure coefficient is arranged as the mean value of each point, and as the standard deviation of C_p (σ_{Cp}) of each point at most. Therefore it is generally difficult to directly estimate $\sigma_{\Delta Cp}$ because there are millions of opening sets. However it is confirmed that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

$$\sigma_{\Delta Cp} = 1.24\,(\sigma_{Cp1} + \sigma_{Cp2}) - 0.42 \quad (9)$$

4.2 Gross Building Coverage and ΔC_{p3}

For cross ventilation design, ΔC_p between two (and more) openings is needed as the information about wind pressure. But it is difficult to accurately predict ΔC_p in consideration of wind direction and surrounding buildings. So, in this study, ΔC_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 ΔC_{p0} and ΔC_{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 ΔC_{p0} and ΔC_{p3} in relation to the gross building coverage; ΔC_{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 ΔC_{p0} and ΔC_{p3}; the minimum of ΔC_{p3} is evaluated at more than 0 (about 0.3 to 0.5) while the minimum of ΔC_{p0} is almost 0. This means the potential for cross ventilation is not appropriately evaluated in low ΔC_p range when the wind fluctuation is not considered.



a1) ΔC_{p0} in Group A. a2) ΔC_{p3} in Group A.

e1) ΔC_{p0} in Group E. e2) ΔC_{p3} in Group E.

Figure 10: Gross Building Coverage and ΔC_p.

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 ΔC_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 ΔC_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 ΔC_p (ΔC_{p0}, ΔC_{p1}, ΔC_{p2}, ΔC_{p3}) are introduced and examined at 5 groups of opening layout. And it is confirmed that ΔC_{p3}, in which is reflected the correct ventilation rate including two-way flow caused by pressure fluctuation, is related to the normal ΔC_p (ΔC_{p0}) and the intensity of the wind pressure fluctuation.

The relation between the gross building coverage and ΔC_{p3} on the supposed flow path is examined, and it is confirmed the potential for cross ventilation is not appropriately evaluated in low ΔC_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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