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A new approach to wind load estimation of photovoltaic panels mounted parallel to sloped roofs

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SUMMARY:

Wind loads on photovoltaic (PV) panels mounted on a hip roof are investigated based on a numerical simulation using the unsteady Bernoulli equation and the time histories of wind pressure coefficients on the bare roof which were measured in a turbulent boundary layer. The results indicate that PV panels installed near the roof edges (eaves and ridges) are subjected to large uplift forces. Then, we propose to install PV panels with small gaps between them along the short edges, which will reduce the wind loads on the PV panels as well as on the roof significantly due to pressure equalization. The optimum gap width is discussed from the viewpoint of load reduction.

Keywords: Photovoltaic panel, wind load, hip roof, gap between panels, numerical simulation

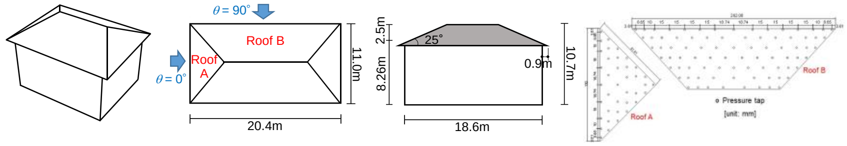
1. INTRODUCTION

Hip roofs are often used for residential houses in Japan. Recently, many houses are equipped with photovoltaic (PV) panels on the roofs. Wind loads on structures are usually estimated by wind tunnel experiments. However, it is difficult to make wind tunnel models of PV panels with the same geometric scale as that for the building, because the thickness (t_{panel}) of PV panels and the clearance (H_{panel}) between PV panels and roof are both as small as several centi-meters. Hence, we proposed a numerical simulation using the unsteady Bernoulli equation and the time histories of wind pressure coefficients on the bare roof obtained from a wind tunnel experiment in order to evaluate the pressures in the space between PV panels and roof (Uematsu et al., 2022). In this paper, we apply this method to the wind load estimation of PV panels mounted on a hip roof. We propose to install PV panels with small gaps between them along the short edges, which will reduce the wind loads on the PV panels as well as on the roof significantly.

2. WIND TUNNEL EXPERIMENT

2.1. Experimental model and procedure

The building considered here is a residential house with hip roof. The roof pitch β is 25° (Fig. 1a - 1c). The geometric scale of wind tunnel model is 1/100. The PV panels are not reproduced in the model. Many pressure taps are installed on the roof (Fig. 1d). The wind tunnel flow is a turbulent boundary layer with a power-law exponent of about 0.27. The wind velocity U_H at the mean roof height is 8 m/s. The velocity scale of the wind tunnel flow is assumed 1/3.5. Wind pressures at all pressure taps are measured simultaneously at a sampling rate of 800 Hz for a sampling duration of 21 s (600 s at full scale). A low-pass filter with a cut-off frequency of 300 Hz is used to eliminate high-frequency noise from the signals. The wind direction θ (see Fig. 1b) is changed from 0° to 355° at an increment of 5°. The measurements are repeated 10 times for each case. The statistical values of wind pressures, such as the minimum pressures, are obtained by applying ensemble averaging to the results of the consecutive 10 runs. The measured wind pressures are normalized by the velocity pressure q_H at the mean roof height to calculate the wind pressure coefficients C_{pe}.

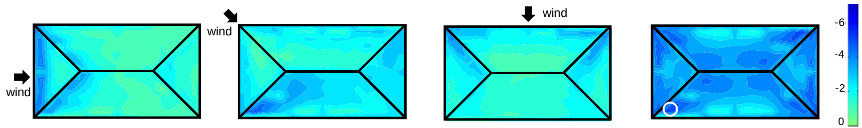


(a) General view (b) Roof plan (c) Elevation (d) Arrangement of pressure taps

Figure 1. Investigated building and pressure tap arrangement on the roof of wind tunnel model.

2.2. Experimental results on wind pressure distributions

The distributions of the minimum peak pressure coefficients $\check{C}_{pe}$ at $\theta = 0°$, 45° and 90° are shown in Figs. 2a – 2c. When the wind direction is normal to a wall (i.e., $\theta = 0°$, 90°), large peak suctions occur near the windward eaves and corner (declining) ridges. On the other hand, in a diagonal wind (i.e., $\theta = 45°$), larger suctions occur near the leeward corner ridge. The distribution of the most critical minimum peak pressure coefficients $\check{C}_{pe,\mathrm{cr}}$ irrespective of wind direction is shown in Fig. 2d. Large suctions are generated near the eaves and ridges (both corner and main ridges), which are generated by flow separation at the roof edges. These results are consistent with previous experimental results. The minimum value of $\check{C}_{pe,\mathrm{cr}}$ among all pressure taps is –5.08, observed at a point marked by a white circle in Fig. 2d when $\theta = 35°$.



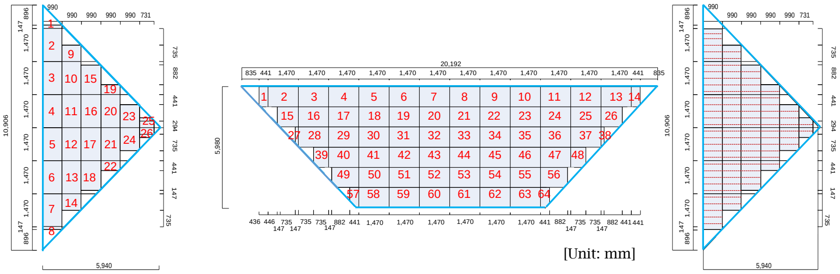
(a) $\theta = 0°$ (b) $\theta = 45°$ (c) $\theta = 90°$ (d) All wind directions

Figure 2. Distributions of the minimum peak pressure coefficients $\check{C}_{pe}$.

3. NUMERICAL SIMULATION

3.1. Method of simulation

The simulation method employed here is the same as that we used in our previous studies (Uematsu et al., 2021, 2022). The arrangements of PV panels on Roofs A and B are shown in Figs. 3a and 3b, respectively. The size of PV panels is 1.47 m (length) × 0.99 m (width), which is often used in Japan. Some small rectangular panels are arranged near the corner ridges. When PV panels are installed with gaps between them along the short edges, the length of PV panels is shortened by the gap width G. It is assumed that t_{panel} = 30 mm and H_{panel} = 70 mm. The value of G is set to 5 mm as a default except in **3.4** where the effects of G on the wind loads of PV panels and roof are discussed. The space under PV panels is divided into many sub-spaces, called 'Rooms', as shown in Fig. 3c. The size of Room is basically 294 mm (width) × 990 mm (length) × 70 mm (thickness). The pressure in each Room is called 'layer pressure' in this paper. The unsteady Bernoulli equation is applied to the cavity flows between Rooms as well as to the gap flows between the external space and Rooms. The driving forces of the gap and cavity flows are the pressure differences between Rooms or between the external space and Room. The layer pressure is determined from the balance of the mass of air flowing into and out of the Room assuming the weak compressibility of the air and an adiabatic condition. The wind force coefficient C_f on a PV panel is provided by the difference between the external pressure coefficient C_{pe} obtained from the wind tunnel experiment and the layer pressure coefficient C_{pl} obtained from the numerical simulation. The area-averaged value of C_f over each PV panel ($C_{f,\mathrm{panel}}$) is computed. Because the resolution of pressure taps on the wind tunnel model is relatively course (see Fig. 1d), a spatial interpolation using the cubic spline function is applied to the measured C_{pe} values at pressure taps in order to obtain the value at the center of each Room.



(a) Panel arrangement (Roof A) (b) Panel arrangement (Roof B) (c) Rooms (Roof A)

Figure 3. Panel arrangement and division of the space under PV panels into ‘Rooms’.

3.2. Wind loads on PV panels

Fig. 4 shows the minimum peak values of $C_{f,\mathrm{panel}}$, represented by $\check{C}_{f,\mathrm{panel}}$, of the panels mounted on Roof A when $\theta = 0°$, 45° and 90°. The panel numbers are shown in Fig. 3a. The largest value of $|\check{C}_{f,\mathrm{panel}}|$ occurred on Panel 1 when $\theta = 0°$. However, because the area of this panel is small, the net wind load on this panel is not so large. Except for this panel, the values of $|\check{C}_{f,\mathrm{panel}}|$ are smaller than 2.5. Larger values of $|\check{C}_{f,\mathrm{panel}}|$ occur on the panels located along the windward eaves when $\theta = 0°$. Similar features were observed for the PV panels mounted on Roof B.

In Japan PV systems are generally designed based on JIS C 8955 (2017), which provides positive and negative wind force coefficients C_a on PV panels as a function of β. When $\beta = 25°$, the negative value of wind force coefficient is specified as −1.13 for regular modules and -1.48 for end modules. The dynamic load effect is considered by a gust effect factor G_f. The value of G_f for Terrain Category III (suburban exposure) is specified as 2.5. The value of $C_{f,\mathrm{panel}}$ obtained above should be compared with $C_a \times \check{G_f}$ (= −2.8 for regular module and -3.7 for end modules). The values of $C_{f,\mathrm{panel}}$ obtained above are generally smaller in magnitude than that of $C_a \times G_f$. The standard does not specify the wind force coefficients for PV panels installed in the edge zones up to 0.3 m from the edges, because panels located in the edge zones are subjected to large uplift forces. However, the present results imply that the specification can be applied to such panels too. This may be because the panels are installed with gaps of G = 5 mm in this study, as will be described in **3.4**.

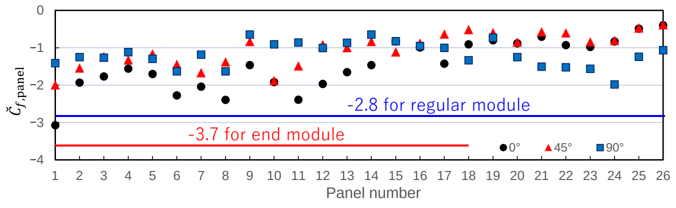
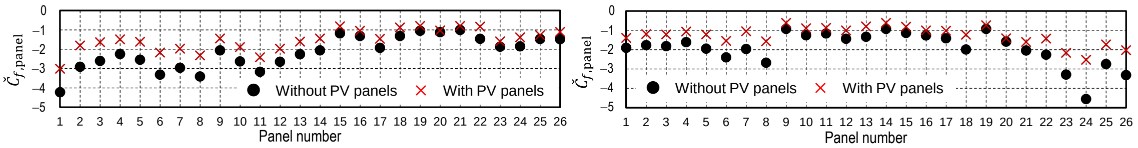


Figure 4. Minimum peak panel force coefficients $\check{C}_{f,\mathrm{panel}}$ at $\theta = 0°$, 45° and 90° (Roof A).

3.3. Effect of PV panels on the roof pressures

Fig. 5 shows the effect of PV panels on the roof pressures when $\theta = 0°$ and 90°, in which the minimum peak pressure coefficients $\check{C}_{pe}$ on the roof at the location of panel centers in two cases with and without PV panels are plotted. It is clear that the magnitude of peak suctions near the windward eaves at $\theta = 0°$ is significantly reduced by installing PV panels on the roof. Similarly, the peak suctions near the roof top at $\theta = 90°$ are also suppressed significantly. This implies that PV panels can be used as a device for reducing wind pressures on the roofing.



(a) $\theta = 0°$ (b) $\theta = 90°$

Figure 5. Minimum peak pressure coefficients $\check{C}_{pe}$ at the location of panel centers on the roof (Roof A).

3.4. Effect of gap width on the wind loads of PV panels

Fig. 6 shows the effect of gap width G on the minimum peak panel force coefficients $\check{C}_{f,\mathrm{panel}}$ at $\theta = 0°$, in which G is varied from 0 to 5 mm. It is found that the values of $|\check{C}_{pe}|$ generally decrease with an increase in G. The results for G = 10 mm, not shown here, were found to be almost the same as those for G = 5 mm. Therefore, it can be said that G = 5 – 10 mm is the optimum value from the viewpoint of wind load reduction within the limits of the present analysis.

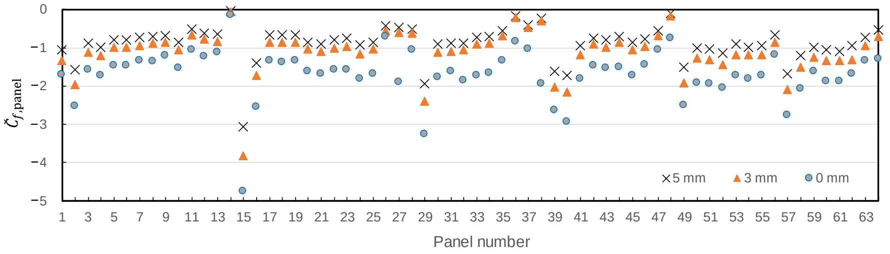


Figure 6. Effect of gap width G on the minimum peak panel force coefficients $\check{C}_{f,\mathrm{panel}}$ at $\theta = 0°$ (Roof B).

4. CONCLUDING REMARKS

Wind loads on PV panels mounted parallel to the hip roof with a pitch of 25° were investigated numerically, in which the unsteady Bernoulli equation was applied to the gap and cavity flows. The layer pressures (pressures between PV panels and roof) were simulated using the time histories of wind pressure coefficients on the bare roof obtained from a wind tunnel experiment. We proposed to install PV panels with small gaps between them along the short edges. The optimum gap width D_e was found to be 5 – 10 mm within the limits of the present analysis.

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