# Comparison of wind loads on parallel roof-mounted PV system from JIS, ASCE7, and AS/NZS

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**ABSTRACT**

*The design wind force coefficients on parallel roof-mounted PV systems are compared for selected design situations with JIS C8955 (2017), ASCE 7 (2022) and AS/NZS 1170.2 (2021) design codes. The comparison was made for a one-story residential building with gable roof slopes of 10° and 20°, 2 m × 1 m modules were placed in parallel in landscape orientation.*

*It was found that there are relatively large differences in the results between Standards and the cause of such discrepancies was traced to the interpretation and nature of the studies that form the basis for each code provision. We show that the conceptual framework of ASCE 7 (consideration of tributary area, pressure equalization, combined as necessary with array-edge factors) allows the data from all the experiments to collapse reasonably well. This is limited by some of the modelling decisions made in the experimental studies, where gaps beneath (AS/NZS), or between (AS/NZS, JIS) the modules were not modelled in the wind tunnel tests.*

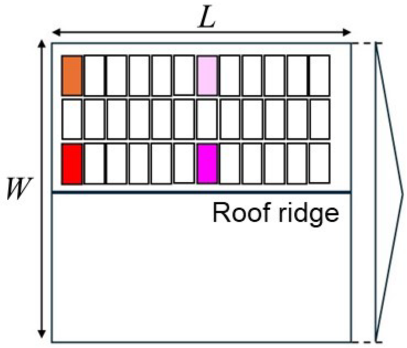
*Since the ASCE 7 provisions are based on the effect of pressure equalization (PE) through gaps around and beneath the modules, which is critical for such PV systems, they include geometric limitations related to these gaps. JIS and AS/NZS codes do not provide guidance on the impact of gaps around PV modules. This means that these provisions can be used even if PE on the target system is different to that of the tested systems used as the basis of the design codes. Although the models in these tests may have been designed to reflect the actual PV system used in Japan, Australia, and New Zealand, geometrical limitations based on the test configurations need to be specified in such codes for the appropriate use of the specified design loads.*

## INTRODUCTION

With an increase of solar photovoltaic (PV) system installation worldwide, wind design codes for such systems have been developed in several different countries. Since there are 17 parameters affecting wind loads on roof-mounted PV systems and a small variation of some parameters can change loads dramatically, it is important to specify the geometrical applicability of the design loads in codes. The current study is aimed to demonstrate this point using parallel roof-mounted PV systems.

## DESIGN PARAMETERS

Two types of residential buildings with gable roof are considered, one with a roof slope ($\theta$) of 10° and building dimension of $L = W = 15$ m, $h_{eave} = 6$ m, the other with $\theta$ of 25° and $L = W = 21$ m, $h_{eave} =$ 6 m. For both building types, modules with the dimension of 2 m (chord) × 1 m (width) are placed parallel to the roof surface with a distance ($H$) of 0.09 and 0.15 m and with gaps around modules ($G$) of 0.2 and 0.07 m, respectively. The offset from the roof edge is 0.3 m for all cases. The module locations considered are illustrated in Figure 1 with zone categories from ASCE7 and AS/NZS. JIS does not provide roof zoning for this type of solar system. Only negative (uplift) net wind force is considered for the current analysis.




| Module location | ASCE7 | AS/NZS |
|---|---|---|
| Red | Zone 3 | End |
| Orange | Zone 2 | End |
| Magenta | Zone 2 | Center |
| Pink | Zone 1 | Center |

**Figure 1. PV module locations considered on a gable roof**

## CONVERSION TO EQUIVALENT DESIGN COEFFICIENTS

The definition of basic wind speed is different among codes. Since its square is used to normalize wind pressure into a wind pressure coefficient, a correction of this effect is needed for a valid comparison of the net wind pressure coefficient, $C_f$. Basic wind speed in all codes is a function of roughness terrain, evaluating height, and gust duration. The design wind force coefficient defined in JIS C8955(2017), $C_a$, was selected to be the basis; the conversion factors were calculated for the design $C_f$ in other codes so that they can be directly compared with $C_a$. The converted design $C_f$ in other codes are denoted as $C_{a\_equiv}$.

## RESULTS

Figure 2 shows the comparison of coefficients between the different codes, where the *x*-axis indicates the module location in Figure 1. We first note that the agreement between the 3 codes varies depending on the module locations.

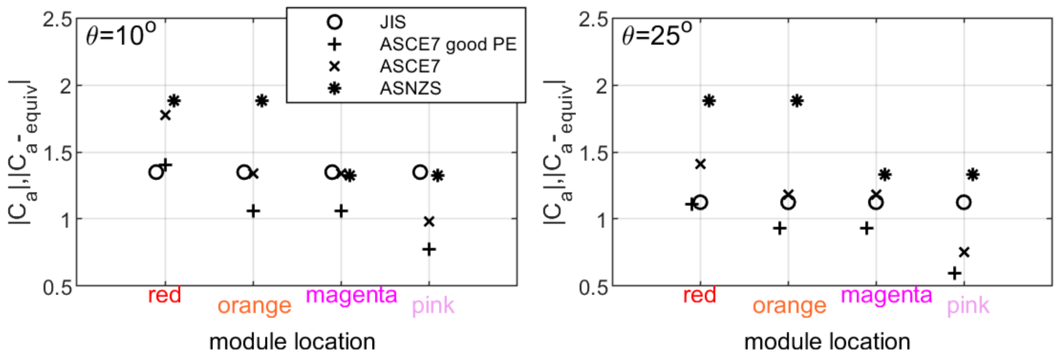



**Figure 2. Comparison of $C_{a\_equiv}$ for PVs parallel to the gable roof surface**

In the case of ASCE7, two different values are presented depending on the porosity of the PV array. Here, "ASCE7 good PE" represents the case with higher porosity, which leads to better PE. In general, for uplift (negative) pressures, 'ASCE good PE' presents the lowest magnitude, as can be seen in Figure 2. The ASCE7 recommendations are based on the work of Stenabaugh et al. (2015) who consider the effect of PE through gaps around the PV modules. As a result, lower net loads are provided when the gaps between modules are larger, and the modules are closer to the roof surface. The ASCE7 method treats roof-mounted solar like permeable building cladding. In addition to a PE factor, zones of higher loading are provided near roof edges, and loads are a function of the size of the tributary area.

The JIS method results in a single value across the entire roof, which is based on the highest coefficient observed anywhere on the roof, and so should only be expected to agree with the highest value among different module locations from the other standards. The recommendations in JIS are based on the tests by Takamori et al. (2015). In these tests, the effect of PE was not considered. Similarly with AS/NZS recommendations, which are based on tests conducted by Ginger et al. (2011), there were no gaps between PV modules, thereby limiting the amount of PE between the top and bottom surfaces of the modules.

## DISCUSSION

### Tributary area

The averaging area used in Ginger et al. (2011) and in Takamori et al. (2015) are 1.7 m² and 1 m$^2$, respectively. Since there is no gap between modules in both these tests, the 'ASCE7 good PE' results, which is PV arrays with more porosity, are excluded from the following discussion.

After adjusting the ASCE7 values to match the averaging areas used in Ginger et al. (2011) and in Takamori et al. (2015), the coefficients are compared in Figure 3, for $\theta$ of 10° and 25°. We note that the ASCE7 values are all now significantly higher than those in the JIS, other than the pink location (Figure 1). Between ASCE7 and AS/NZS, although the effect of averaging area is minor, the agreements at some module locations become better.

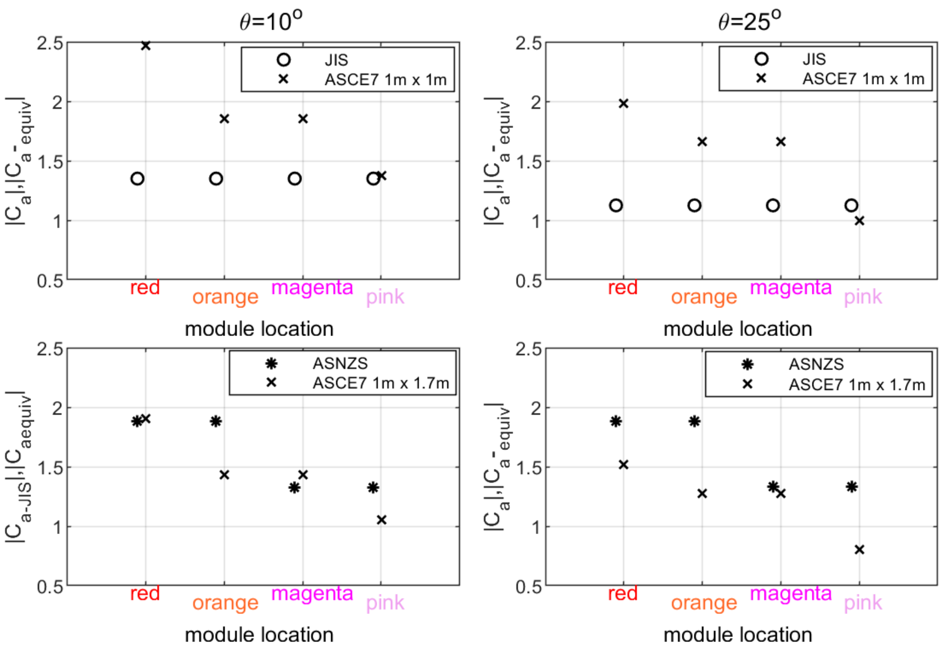



**Figure 3. Comparison of JIS $C_a$ and $C_{a\_equiv}$ after adjustment of averaging area**

### Zoning

Figure 4 (a) shows the roof zoning employed in ASCE7. JIS C8955 does not provide any zoning. ASCE7 applies the zoning for Components and Cladding (C&C) assuming that the spatial distribution of wind force coefficients acting on arrays, $C_f$, are similar to those on the external wind pressure coefficients, $Cp_e$, on bare roof. For $\theta = 10°$ and 25°, the same zoning is applied, where the largest suction pressure is provided in zone 3 and the lowest in zone 1. These zones are intended to capture the locations on the roof with the highest suction due to flow separation along the roof edges, and to scale with parameters such as the building height.

Figure 4 (b) and (c) illustrate the peak negative $C_f$, $\check{C}_f$, among all wind directions for panels/modules on gable roof with $\theta = 22.5°$ from Ginger et al. (2011) and 24.2° from Takamori et al. (2015). In the figure, $d$ is the gap between roof surface and PV modules in full scale and $C_f$ in both studies are referenced at mean roof height. Both plots do not correspond to the expected spatial variation of $Cp_e$ on a gable roof, which is the zoning employed in ASCE7 (Figure 4 (a)).

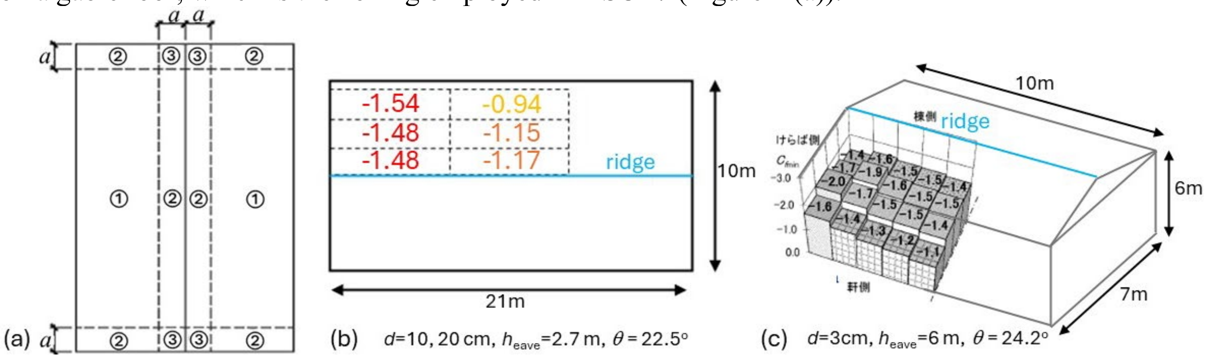



**Figure 4. (a) Roof zoning for ASCE7, $\check{C}_f$ for modules on gable roof (b) from Ginger et al. (2011) and (c) from Takamori et al. (2015)**

**Pressure Equalization**

For rooftop mounting systems, the net pressure across the PV modules is the difference between the external pressure on the module and the pressure in the cavity between the module and roof. The ASCE7 method assumes that the spatial distribution of $C_f$ is similar to $Cp_e$ on a bare roof. This assumption is valid when modules are placed so that they do not alter the flow over the roof and any local PE is the dominant factor in the net pressure (close to the roof, with regular and significant gaps). Hence ASCE7 sets its applicability limitations on the height above the roof surface to be less than 0.25 m and gap between modules to be greater than or equal to 6.4 mm.

This means when PE is not expected, the spatial distribution of $C_f$ will not necessarily correspond to ASCE7 zoning, and that appears to be the case in the comparisons shown above. Figure 5 shows the scaled model employed in Takamori et al. (2015). There is no gap between modules and the plenum underneath all the modules seems to be connected. This means the inflow and outflow to the plenum are restricted to the perimeters of the PV array (which is indicated by white dot lines in Figure 5L). This design condition of $G$ (gaps between modules) = 0 in Takakamori et al. (2015) is outside of the ASCE7 geometrical applicability and this could be a main cause of discrepancy between ASCE7 and JIS in Figure 3. We would recommend limiting the geometrical applicability of JIS design values on $G$ and $H$ since these have significant effect on $C_f$ (Stenabaugh et al. (2015)).

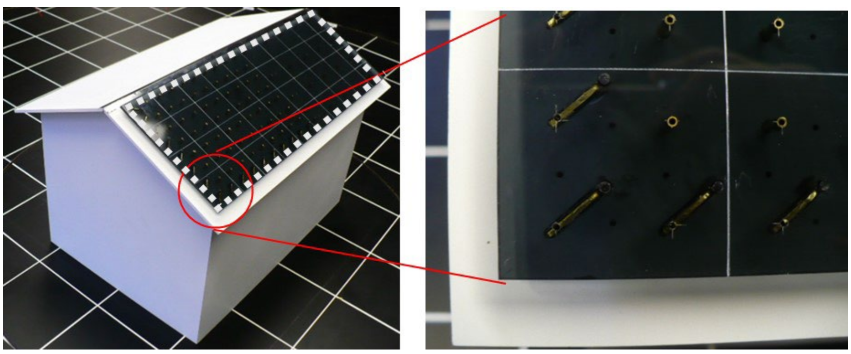


**Figure 5. Wind tunnel model used in Takamori et al.**

Since Takamori et al. (2015) provides an array setback of 0.3 m (FS) from the roof edge, the largest external negative pressure at corners may have been avoided. This also can be part of the reason behind the $C_f$ distribution being different from $Cp_e$ on bare roof as well as the magnitude of JIS value being smaller than the one for ASCE7.

The configuration is similar in the tests of Ginger et al. (2011) with the module arrangement on the roof being even more specific, representing the actual design situation in Australia/New Zealand. Figure 6 illustrates the array model employed. A 7 m × 1.7 m (= chord) array consisting of 7 modules (1 m × 1.7 m) is replicated with a continuous piece of material, meaning there is no gap between modules. In addition, its bottom side has two strips along the longer side of the model, representing rails attaching modules to roof battens or trusses. This means that the flow through the plenum is restricted along the longer side of the array (left-right direction in Figure 6L). The pressure in the plenum is therefore set entirely by the pressure at the open ends. This is evident from the results, where increasing the array size by adding an adjacent second array, as well as increasing array height off the roof, had minimal effect on the wind load on the module. This situation is different from the design situations considered in ASCE7, which allows for some PE at each module.

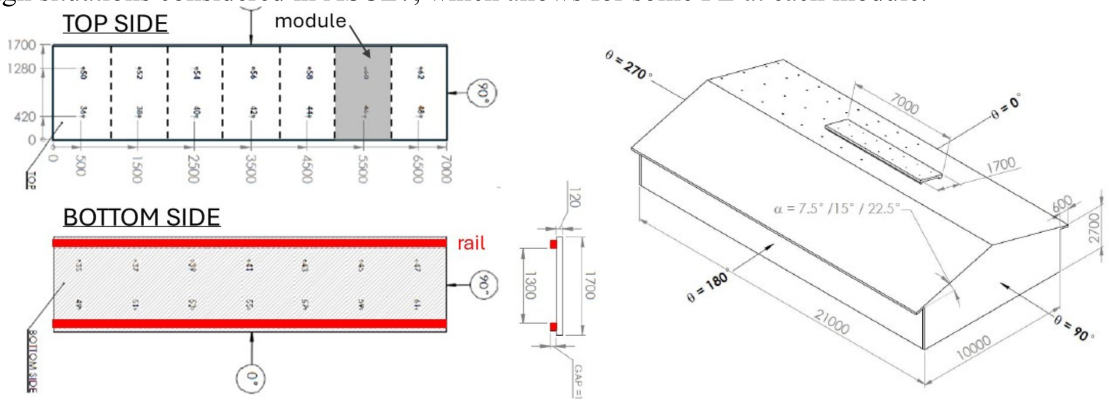



**Figure 6. PV array model from Ginger et al. (2011)**

## Array edge factor

Furthermore, in Ginger et al. (2011) an isolated instrumented array was tested. Measurements were carried out at each roof location by changing the location of the instrumented array. This means that regardless of the location of the instrumented array on the roof, most tests experienced an 'array edge effect' where the attached flow travelling along the roof surface separates from the discontinuity at the edge of the array, creating larger local suction pressures. Figure 7 provides information on the tap location and wind direction when the worst negative wind pressure is measured (it is expressed in the format of nett pressure coefficient), and the dotted rectangle drawn on the roof indicates the location of the instrumented array model. Regardless of the location of the instrumented array, peak negative pressure coefficeitnts were measured at the windward edge modules, which can be attributed to the array edge effect. If the roof was completely covered by multiple array models, the array in the interior of the roof would not have experienced such large negative $C_{\text{fig}}$. This means that the results from Ginger et al. (2011) cannot provide sufficient information for roof-mounted PVs, since they did not necessarily capture the effect of flow separation at the roof edge. Instead, the zoning in AS/NZS is created based on these results which include the array edge effect, and therefore, which is different from that used in ASCE7, which uses the spatial variation of $Cp_e$ on bare roof. Note that ASCE7 considers both the effect of flow separation at the roof edge (by providing roof zones) and the effect of array edge effect (with array edge factors) although the array edge factors have room for improvement (SEAOC 2017).

In addition, the rails beneath the array are closer to the long array edges Both underside pressure taps are between the rails, and the array overhang is negligible and not instrumented in the model. Because of the array edge effect, higher net pressure would be expected on the overhang (between the rails and the array edge) had these been measured. Similar to the recommendations for JIS, it would be recommended that AS/NZS should limit the geometric applicability of design values, and these values can be used only for similar building dimensions and PV modules configurations to Ginger's test. This would require the sum of the gap areas between adjacent panels, between the panel and rails, and between the rails and the roof to be inconsequential compared to the 100 mm gap at the array ends.

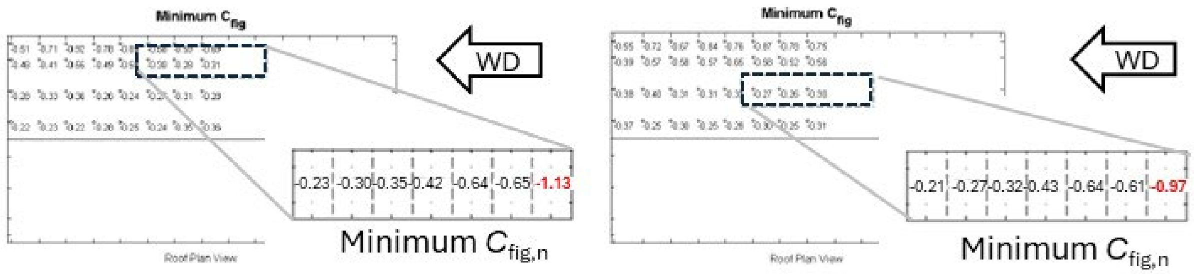



**Figure 7. $C_{\mathrm{fig}}$ for modules on building with $\theta$=7.5° from Ginger et al. (2011)**

## SUMMARY

The design wind force coefficients on parallel roof mounted PV systems among 3 different codes were compared and the causes of their disagreement were examined based on available literature. Differences in some details of the scaled models are found to have caused some discrepancies in the comparisons. In the case when such details affect wind loads acting on modules, they should be clearly specified in codes as applicable geometrical limitations.

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