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Wind loading on tilted roof-top solar arrays: The parapet effect

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ABSTRACT

Scale model wind tunnel testing was used to investigate the effect of parapets on the wind loading of a roof-top solar array with a tilt angle of 10°. Previous studies have indicated a correlation between parapet height and uplift wind loads acting on roof membranes and roof-top equipment. This relationship was reproduced in the current study for wind loads acting on roof-top solar arrays and is shown to be caused by building-induced aerodynamics, namely corner vortices. Increasing parapet height was shown to increase the peak wind loads acting on the array. These increases were found to be dependent on location on the roof, in the array, and geometry of the array itself. The parapet effect results in peak wind load increases for much of the array for typical parapet heights when all wind directions are considered.

1. Introduction

The installation of photovoltaic (PV) modules on the roofs of low-rise industrial and commercial buildings is a burgeoning industry. Researchers in the wind engineering community have been investigating the wind loading of such systems for decades (see Irwin and Gamble, 1982; Tieleman et al., 1980 or Irwin et al., 1984). These early studies focused on the determination of wind load coefficients for single rows of PV modules placed in various locations on a roof. Many proprietary studies have been completed in North America and Europe for PV racking manufacturers; it is only a recent development that results of studies investigating wind load coefficients for arrays that cover large portions of the roof have been published in the literature.

Such studies have focused on so called flat plate systems, which consist of PV modules tilted to the south (in the Northern Hemisphere), supported by a racking system which secures the PV modules, either through ballast weights, roof penetrations, or other attachments. These studies have begun to shed some light on the parameters that determine the magnitude of the wind load coefficients, which are then used to determine the required resistance of the system. Kopp et al. (2012) identified tilt angle as a key parameter, with increasing tilt angle resulting in generally higher (in magnitude) peak positive (downforce) and peak negative (uplift) coefficients.

The first organization to codify wind load coefficients is the Structural Engineering Associations California (SEAOC, 2012). The code includes many parameters to quantify wind load coefficients for a given installation, such as tilt angle, height of the system off of the roof, building (eave) height, the row-to-row spacing of the system and, if present, parapet height. Parapet height has been pointed to by others as a critical factor in wind load coefficients, with SEAOC (2012) indicating that the presence of parapets may increase loads by 50% in some areas of the array, when compared to an array on a roof with no parapet. This conclusion may seem counter-intuitive from the perspective of structural design codes since wind flows are commonly thought to be primarily horizontal and thus the parapet is often concluded to provide a sheltering effect, not an increase.

The current study investigates the changes in wind flow characteristics due to the presence of a parapet. The study is based on boundary layer wind tunnel testing, completed at a scale of 1:25. Details of the wind tunnel and data acquisition system used have been provided previously in the literature (Steckley et al., 1992).

Flow separation and corner vortices give rise to the strong uplift pressures generated on the roof surface at the corners and edges of low-rise buildings. The work of Kopp et al. (2005) and Trung et al. (2009) indicates that the strength of these vortices increases with increasing parapet height. Kopp et al. investigated the effect of parapets on a flat roof, finding that an increase in parapet height led to an increase in the magnitude of the uplift pressure coefficient acting on a flat roof surface for an averaging area similar to the size of a PV module (nominally 1–2 m^2), up to a full scale parapet height of 1.83 m. Similarly, Trung et al. found that for porous roof coverings, an increase in parapet height lead to an increase in the magnitude of the uplift pressure coefficient. Both studies indicated that the location of the peak wind load moves when parapet height is increased.

The investigation presented in the following sections attempts to explore these concepts when a low tilt (10°) flat plate PV solar array is added to a flat roof surface. It is expected that the load

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effect on solar modules which is caused by the net pressure difference across the top and bottom surfaces, both of which are exposed to mean local air flow and the fluctuating pressure effects, would be different than the roof membrane pressure which would be dominated by the local surface pressure. Wind pressure coefficients for increasing parapet heights are presented in Section 3 and an introduction to the parapet effect is presented in Section 4.

2. Wind loads on flat-plate roof-top solar arrays

2.1. Model scales for roof-top solar arrays

Boundary-layer wind tunnel research using pressure models is an effective method to ascertain the peak wind pressures over a range of averaging (or tributary) areas that characterize roof-top solar arrays (see Ho et al., 2005). However, there are many competing factors that must be balanced in order to provide the most useful data, which leads to several practical challenges and measurement uncertainties related to this kind of testing for solar arrays. Firstly, and most importantly, larger scale models are generally required to accurately reproduce geometric features specific to individual systems, and to be able to install sufficient pressure taps to obtain area averaged pressures. As a result, typical model scales range between 1:20 and 1:50 to meet the needs of specific racking geometries with respect to gaps between the modules, between the modules and the roof and ventilation openings, where included (Kopp and Banks, 2013). The photograph on the left in Fig. 1 shows a typical 1:25 scale model of a 10° (tilt) system in the wind tunnel. The photograph on the right is a close-up with the instrumented modules indicated.

At these commonly used model scales, the size of the longitudinal turbulence eddies produced by the wind tunnel, which are most appropriate for length scales in the range of 1:300–1:500 and constrained by the size of the tunnel, are of a considerably smaller scale than that used to construct the model. This mismatch creates uncertainty in the pressure measurements, as noted by Banks (2011). Banks recommends the use of high frequency spectrum matching to address the mismatch in scales between the model and the wind flow. Banks suggests that no other corrections are required to the measurements when applying the wind tunnel pressure coefficients to a 3-s gust reference wind speed, as is used in ASCE 7. Another approach described in other research is to match the full-scale turbulence intensity, which may result in overly conservative predictions due to the exaggeration of the high frequency portion of the spectrum, which is important to elements of the size of a solar module, in compensation for the weak lower frequency portion. This issue is noted in Banks (2011).

However, in the case of roof-top solar arrays, the peak instantaneous net wind pressures (total effective pressure due to combined pressure on top and bottom surfaces) are dominated by the local aerodynamic structures generated by the building itself (body-induced, as described in Kopp et al., 2012), rather than the longitudinal turbulence in the approaching flow. More specifically, the corner vortices have been shown to be the dominant cause of peak wind loads on roof-top solar arrays (Kopp et al., 2012). Although relying on the dominance of this mechanism helps to minimize the effects of scale mismatch, it does not eliminate the uncertainties altogether as there would be an effect of scale mismatch on the production of these vortices. Further research, likely involving full-scale measurements, is required to fully evaluate the validity of any approach to dealing with the scale mismatch. For present purposes of evaluating the relative effect on peak wind loads on solar modules due to parapets, no attempt to compensate for the scale mismatch has been made. Approaching wind flow has been kept the same for all tests and the parapet effect itself is evaluated as a body-induced aerodynamic phenomenon.

With the above scaling issues in the mind, a model scale of 1:25 was selected as the basis for the research described in Section 3 of this paper. The data presented in that section were obtained using the model shown in Fig. 1, from which the most comprehensive data set was available to investigate the impact of parapets on the wind loading experienced by a roof-top solar array.

With larger models, the need to have a sufficient number of modeled rows to capture the important wind patterns over a contiguous array, leads to another practical challenge and source of uncertainty: wind tunnel blockage. ASCE 7-10 (2010) recommends a maximum limit of 8%. The blockage of the model in the wind tunnel shown in Fig. 1 ranged between 10% and 12% for the wind directions directly on a broad face, to a maximum value of 15% for 45° cornering directions. To counter the effect, the wind speed reference pitot-static tube was situated directly above the model at a model scale height of 1.525 m (5 ft), thus the effect of blockage on the measured pressure coefficients is reduced since the model and reference instrument experience similar accelerated flow across the test section. Blockage can also create a gradient in the static pressure across the test section. However, any blockage-induced variation in wind tunnel longitudinal static tunnel pressure across the test section would affect the upper and lower surfaces of each PV module equally. Since the wind load on modules is produced by instantaneous pressure difference, or net pressure, the effect of blockage as it relates to the stream-wise static pressure gradient should be negligible on net module loading.

It can also be seen that for this scale of model when the wind direction is a cornering one, or one that approaches the building at 45 degrees to the walls, the width of the model causes the lateral

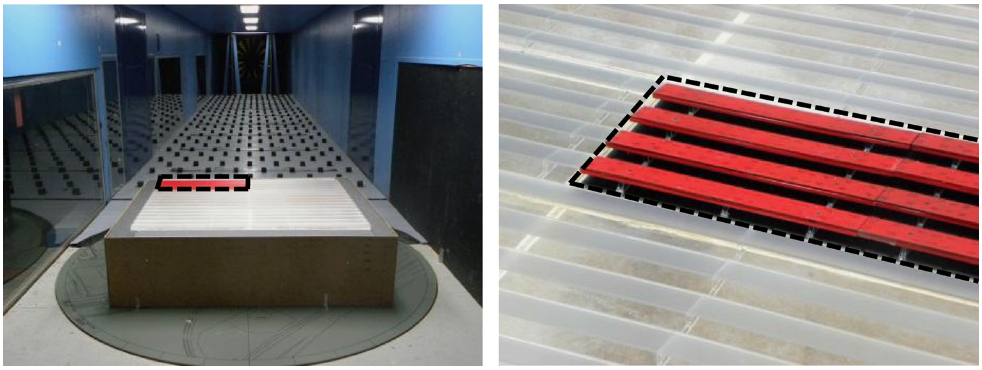

Fig. 1. Selected scale model of a 10° (tilt) system in the boundary layer wind tunnel (a) and close-up (b). Insturmented model is indicated by dashed black line.