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In situ measurement of wind pressure loadings on pedestal style rooftop photovoltaic panels

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ABSTRACT

The installation of rooftop photovoltaic (PV) arrays is increasing throughout the US. Until recently, pedestal type PV framing systems for rooftops were basically designed using procedures from the ASCE7-10 Components and Cladding Standard for rooftop equipment. The 2011 Japanese Standard Load design guide on structures for photovoltaic arrays was useful in characterizing the pressure coefficients on rooftops, but the Standard employs different wind speed and importance factors, making its use in the US quite limited. Even the updated 2017 version is written for a different audience. Because rooftop pressure loadings are high due to flow separation, SEAOC and other organizations contracted boundary layer wind tunnel tests of panels attached to rooftops to ascertain if the ASCE7-10 equipment loadings were appropriate. The investigations resulted in new standards for pedestal-style arrays that appear in Chapter 29 of ASCE7-16. However, the new standards are limited to simple geometries and orientations, and the dynamics of the simply-supported thin PV plates do not appear to be considered. Questions regarding the ability of the boundary tunnels to simulate accurately the turbulence at the scale required for the attached panels have been raised. In response, very limited full-scale investigations in large-scale tunnels and in situ have been undertaken to calibrate the tunnel results. The results of this paper represent one of these calibration investigations. Specifically, in situ full-scale net wind pressure loadings on a rooftop PV array in a pedestal-style framing system located on the three story Hogue Technology Building of Central Washington University (CWU) in Ellensburg, Washington were measured. The CWU campus has a rural setting in a region with steady winds: Ellensburg is located in the Kittitas Breezeway portion of the Northwest wind power region. Indeed, the Wild Horse Wind and Solar Farm is located on the outskirts of town. The data described here were collected from April through August 2014. The measured net pressure coefficient time series were similar to those for rooftop pressure loadings for low-rise buildings described in the literature such as the Wind Engineering Research Field Laboratory at Texas Tech University (Ham and Bienkiewicz, 1998 [1]; Levitan and Mehta, 1992 [2]). The analysis of the net pressure time series data included an examination of the minimum, maximum, mean, and RMS values. Preliminary results suggest that the range of the values is larger than assumed in the ASCE7 Standard, and that the magnitude of the loadings vary considerably spatially over the multiple panel array. The pressure loading measurements are ongoing.

1. Introduction

1.1. Wind loads on rooftop PV panels

Rooftop PV panels have become more prevalent in the US in recent years as renewable energy has become more popular e.g. [3,4]. It is noted that the terms solar "cells", "modules" and "panels" are used in different ways in the technical literature, e.g. [5–9]. According to the manufacturing literature, "cells" are assembled into "modules", which are the "building blocks" of photovoltaic (PV) systems e.g. [5]. One or more modules are used to create a panel, and two or more panels are used to create an array. Technical specifications in the solar industry often use the term "module" to connote what civil engineers describe as a "panel" e.g. [10,11]. In the context of this paper, the term "panel" is used in the structural engineering sense, as a thin rectangular plate comprised of several modules e.g. [8,9]. Each panel is assumed to be supported along two or more of its edges as in a framing system, or attached at points, via brackets, in the structural engineering sense. A set of panels attached in this manner is called an "array" in this paper. Numerous wind tunnel studies e.g. [12–19,7,20] and full-scale investigations e.g. [21–23] have been undertaken to analyze the pressure loadings on rooftop panels. Although many panels are attached directly

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to a sloped building roof using brackets or other connectors, this paper does not examine this type of connection but rather focuses on pedestal style arrays.

PV panels in landscape format placed on commercial buildings in North America are typically arranged in arrays supported by elevated steel or aluminum frames at an angle between twenty and forty degrees with respect to the horizontal plane of a flat roof, e.g. [24], rather than the closed triangular framing system advocated in Europe e.g. [16,25]. It is well known that the edges of flat roofs incur the largest wind loadings, e.g. [1,2] and that the effects of pedestals and parapets can significantly affect the flow separation phenomena that result in high suctions e.g. [9]. Failures of panel systems during strong winds illustrate the importance of proper connectivity to the roof e.g. [26]. In this paper, panels mounted in pedestal style framing systems that are attached to the roof are investigated. These systems are popular in the western US primarily because the connections of the framing systems are not as intrusive to roofing as racking-style systems.

One of the challenges in boundary layer testing of these panel arrays is accurate simulation and matching of the turbulence scales as discussed in [27]. In 2016, Mooneghi et al. [27] cited difficulties with obtaining large enough turbulence scales required for simulating wind loadings on small-scale appurtenances located on buildings. Because “it is not normally possible to fully simulate the low frequency end of the turbulence spectrum”, the “partial turbulence simulation” (PTS) method was introduced [27]. Investigations into the use of PTS for wind loadings on appurtenances are currently underway at the Florida International University Wall of Wind.

Many in-place PV array systems rely on ballasts or other means to anchor the pedestal legs due to the reluctance of owners to drill directly into roofing systems for frame attachment. The pedestal style is challenging to scale in the wind tunnel; and for this reason, the in situ measurements are especially important. Loading provisions for rooftop PV panels have been incorporated recently into the ASCE 7-16 Standard based on the tunnel tests, but unfortunately the framing geometries considered are limited. The 2017 Japanese Standard [25] is similar to the ASCE7-16 Standard, but it is challenging to implement because of the differences in the estimation of the velocity pressures.

Harris, Dowds, Andolsek and others have undertaken testing of in situ full-scale panels located on a rooftop at the University of Colorado at Denver e.g. [21–23]. In their investigations, plywood panels were employed as “faux” or artificial PV panels on the rooftop of an exposed campus building at the University of Colorado at Denver. Strain gauges attached to the framing system in conjunction with local anemometers were used to estimate the wind loadings on an instrumented single panel or two panels. The panels were located 1.2 m [4 ft] away from the edge of the (flat) roof on a 9.1 m [30 ft] high building. The resulting calculated force coefficients, with wind velocities in the range of 2.2–15.6 m/s [5–35 mph], were found to be in the range of 0.1–18.7 for 3-s rolling averages. The range of the force coefficients was much higher than expected even though the loadings were for adverse conditions, i.e. out of the northwest quadrant. The pressure loadings were not determined directly, but derived through the strain gauge and anemometer readings. The University of Colorado at Denver studies were not conclusive, but brought up questions about the full-scale rooftop conditions to which pedestal panel arrays are subject. One of the motivations of this study was to follow through on the Denver investigations. Specifically, measurements taken on the edge of a large pedestal style rooftop array are presented. Preliminary results are provided and implications for future work are discussed. Before the measurements are described, the wind conditions of the site are discussed.

1.2. Wind conditions at the measurement site in Ellensburg, Washington

The Central Washington University (CWU) campus is located in Ellensburg, Washington, on the “inland” eastern side of the Cascade Range. The Cascades extend from southern British Columbia, Canada to Northern California in the US. Persistent wind exists over the inland Northwest in the region known as the “Kittitas Breezeway” with conditions conducive to Class 3–5 wind energy generation [28,29]. Ellensburg typically experiences higher wind speeds in the spring and summer than in the winter months. Winter storms along the western region of the Pacific Northwest can produce strong westerly flows that cross through Stampede Gap in the Cascades and along the Kittitas Breezeway, but they tend to remain aloft due to the cold, stable air in the eastern region [28]. For this reason, wind farms such as Wild Horse [30] are located about 21 km [13 miles] outside of Ellensburg at higher elevations along Whiskey Dick Mountain with a peak elevation of 1179 m [3871 ft] in order to benefit from strong wind speeds year round.

The closest weather station at the Bowers Field airport, National Weather Service designation *KELN*, is approximately 2 km north of the Hogue Center at CWU. Using Local Climatological Data (LCD) hourly mean wind speed V and the corresponding direction data for Bowers Field from 2007 to 2016 [31], a wind rose analysis was undertaken [32]. The results are shown in Fig. 1 for sixteen directions. From Figs. 1 and 2, it can be seen that the dominant directions specifically are out of the North (30.5%) and Northwest (21.8%). The hourly mean wind speeds are greater than 10 m/s [22 mph] on average 7.4% of the time; and, between 8 [17.9 mph] and 10 m/s [22 mph], 7.9% of the time as shown in Fig. 3. Structural engineers are interested in the larger magnitude velocities and their direction since they will influence the extreme loadings on the array. In this case, the Northwest quadrant is important, especially as the panel array is aligned almost exactly in a North-South direction, with the front of the array facing south. According to the Applied Technology Council website [33], the ASCE7-10 standard 3-s peak gust wind speeds for Ellensburg are 32 m/s [72 mph] for a 10-year MRI (serviceability) and 40.7 m/s [91 mph] for a 100-year MRI (strength). These wind speed values are provided for structural engineering context, not as a design recommendation. Other climate challenges to panel durability may be summer weather as temperatures in the summer may reach 40 °C [104 °F].

In summary, Ellensburg, Washington is located in the Kittitas Breezeway. It experiences persistent hourly mean wind speeds primarily out of the Northwest quadrant. Because the wind speeds are steady throughout the year, the rural area surrounding the CWU campus is home to many wind turbines. According to the National Renewable Energy Laboratory [NREL], it is also an area that supports a

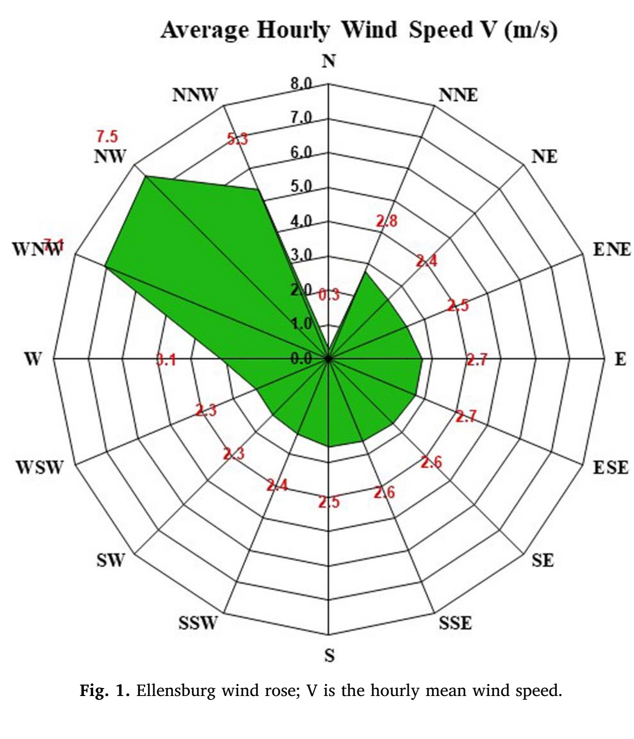

Fig. 1. Ellensburg wind rose; V is the hourly mean wind speed.