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Investigation of Wind-Induced Dynamic Effects on Rooftop Solar Arrays

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ABSTRACT: The use of photovoltaic (PV) arrays as a source of renewable energy has become increasingly popular in the USA. Despite their wide usage, rooftop PV arrays are vulnerable to damage under strong winds. This can be attributed to the underestimation of peak wind loads on these systems where dynamic effects are unaccounted for. This study consists of investigating the wind-induced dynamic effects on rooftop PV arrays based on an experimental-numerical program and field calibration. Field measurements were conducted on a rooftop PV array at Central Washington University. Finite Element Modeling was performed to design the PV array model for experimental testing such that its dynamic properties are comparable to the in-situ array. Impact hammer and wind loading tests were carried out at the NHERI Wall of Wind Experimental Facility at Florida International University. The experimental tests were calibrated and validated based on the field measurements. Significant wind-induced vibrations were observed and their effect on the structure's response was shown to increase with increasing wind speed.

KEYWORDS: Photovoltaic (PV) systems; Dynamic effects; Low-rise buildings; Large-scale testing; Field measurements.

1 INTRODUCTION

The use of PV arrays mounted on the rooftops of low-rise buildings has become widely applied across the USA over the past few years. There are currently more than 2 million rooftop PV panel installations on commercial and residential buildings (*Solar Energy Industries Association*, 2019). Rooftop appurtenances, such as PV arrays, are susceptible to damage during extreme wind events and their failure can puncture the roof surface, creating a path for water intrusion. Damage to such flexible structures could be exacerbated should the peak wind loads on the supporting structures be underestimated. Numerous wind tunnel studies (Banks, 2013; Browne et al., 2013, 2020; Cao et al., 2013; Erwin et al., 2012; Kopp, 2013; Kopp et al., 2012; Moravej et al., 2015; Naeiji et al., 2017; Stathopoulos et al., 2014) have been conducted to evaluate the wind effects on rooftop PV panels. However, major gaps in the fundamental knowledge of peak wind loads on PV arrays still exist. Specifically, the wind-induced dynamic effects on these flexible structures are neither thoroughly investigated nor accounted for in current building design standards. Previous studies showed that significant wind-induced vibrations of PV panels may occur with natural frequencies as high as 14 Hz (Estephan et al., 2022; Moravej et al., 2015; Naeiji, 2017). Moreover, these studies highlighted the well-established shortcomings of the ASCE 7-16 (2017) criterion for dynamically sensitive structures having a fundamental natural frequency ≤ 1 Hz, which was originally proposed with typical building sizes in mind and may well be misleading should it be applied to smaller structures (Estephan et al., 2022; Moravej et al., 2015; Naeiji, 2017). On the other hand, field measurements have contributed to the calibration and validation of wind tunnel techniques. So far, a limited number of field measurements on rooftop PV arrays have been undertaken to calibrate wind tunnel results (Andolsek, 2013; Harris, 2013; Plas, 2015). In-situ measurements have been conducted on a rooftop PV array located on the Hogue Technology Center (HTC) building at the Central Washington University (CWU) in Ellensburg, Washington (Bender et al., 2018; Reed et al., 2016). The findings of these studies indicated higher net pressure coefficients than those provided by the ASCE 7-16 Standard.

Based on an experimental-numerical program and field calibration, this study focuses on the investigation of wind-induced dynamic effects on rooftop PV arrays, a topic that has not been thoroughly investigated in the literature. First, field measurements were conducted on a rooftop PV array at Central Washington University (CWU). Finite Element Modeling (FEM) was then performed to design the PV array test model such that its dynamic properties are comparable to the in-situ array. Impact hammer and wind loading tests were carried out at the NHERI Wall of Wind (WOW) Experimental Facility (EF) at Florida International University (FIU) on the full-scale PV array model and the tests were calibrated and validated based on the field measurements. This research's findings can be used to inform wind load provisions in standards which will help in the design and retrofit of more resilient dynamically-sensitive building appurtenances.

2 METHODOLOGY

The methodology adopted in this study consists of field measurements, experimental testing, and numerical analysis (Fig. 1). First, field measurements were conducted on a rooftop PV array at CWU. Second, FEM was performed to design a PV array with similar dynamic properties to the in-situ array. Finally, full-scale WOW tests were conducted on the PV array model, and the test results were validated based on the CWU field measurements.

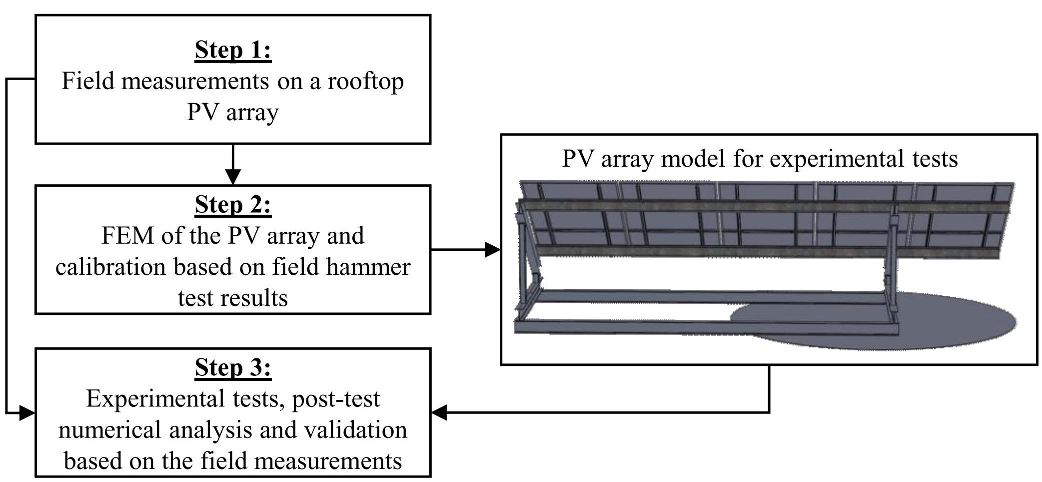

Figure 1. Experimental-numerical methodology and field measurements.

2.1 *Field measurements on the CWU rooftop PV array*

Field measurements have been conducted on a rooftop PV array located on the three-story HTC building of CWU. The enhanced field measurements help calibrate the full-scale testing of a selected PV array at the NHERI WOW EF at FIU. The overall size of the WOW flow field is 6.1 m (20 ft) wide and 4.3 m high (14 ft), whereas the size of the in-situ PV array is 53 m (173 ft) wide and 3.4 m (11 ft) high. The rather large size of the in-situ PV array and the blockage constraints of the WOW test section preclude testing the full array structure. Hence, selecting a segment having dynamic properties similar to those of the full structure is considered to be judicious. Since the PV panels located on the top array edges coincide with the strongest North-West wind direction (i.e., between 300° and 330°) and are expected to exhibit dynamic behavior, a top corner section was selected for monitoring. Pressure sensors, accelerometers, and strain gauges were installed at various locations of the array to measure the wind loads and the structure's response. Impact hammer tests were performed on the array to identify its dynamic properties. The wind speed and direction were measured using an ultrasonic anemometer located on the northern side of the array at 3 m (10 ft) height above the roof surface (Fig. 2). It should be noted that the data was recorded when the mean wind speed for two minutes was greater than 4.5 m/s (10 mph).

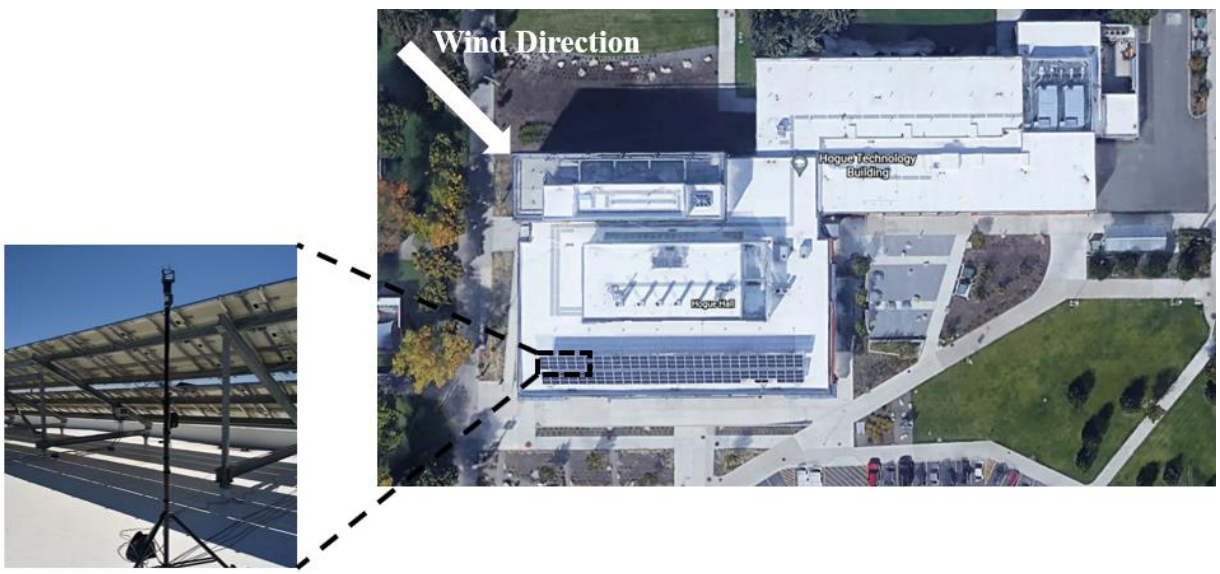

Figure 2. Rooftop PV array at CWU and location of the ultrasonic anemometer.

2.2 *Finite Element Modeling of the PV array*

An essential first step of this research was to design the PV array for the full-scale WOW testing such that its dynamic properties are comparable to the in-situ CWU array. For this purpose, the selected top corner section for WOW tests (i.e., Configuration 1) and the full CWU array (i.e., Configuration 2) were modeled using the FEM Software SAP2000® (Fig. 3). The frame elements (e.g., I-beams, C-channels, columns, and aluminum rails) and solar panels were modeled with material and geometric properties similar to those of the in-situ array. The bolted connections between the different elements were modeled as rigid links, and the array supports were assigned as fixed joints. A modal analysis was performed to identify the natural frequencies of the different modes of vibration of both systems.

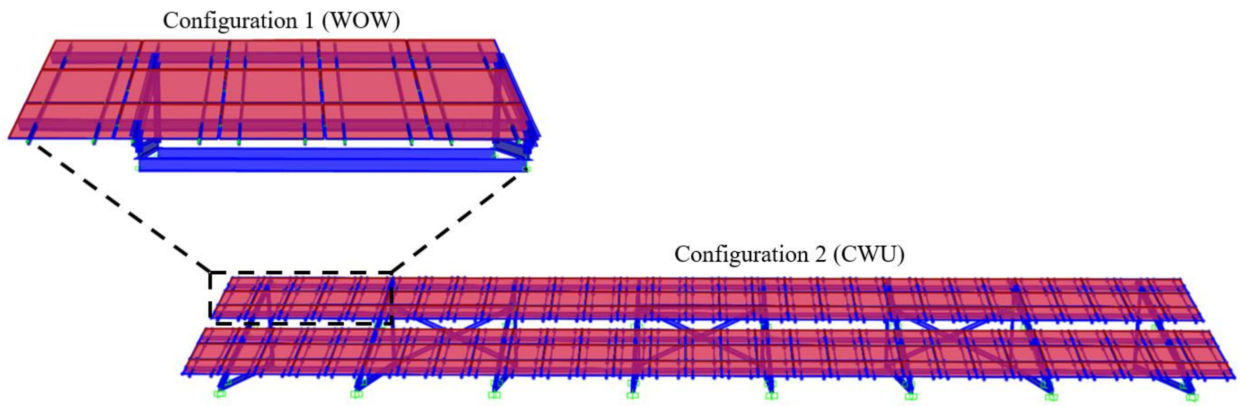

Figure 3. FEM PV array models: Configuration 1 (WOW) and Configuration 2 (CWU).

2.3 *Full-scale WOW experimental testing of the PV array model*

The 12-fan WOW is a full- and large-scale testing facility capable of generating wind speeds and turbulence characteristics similar to those recorded in Category 5 hurricanes (Chowdhury et al., 2017, 2018). Impact hammer and wind loading tests were performed at WOW on the full-scale PV array model, and acceleration time histories were recorded using five accelerometers installed on the panels' bottom surface, at similar locations to those installed on the CWU array (Fig.4). The in-situ array is located in the flow reattachment region of the roof where the effect of flow separation and conical vortices is minimal. For this reason, a ground-based WOW testing of the PV array is considered to be representative of the in-situ condition. Suburban terrain wind flows with similar turbulence parameters to those recorded at the CWU site were simulated at WOW. Hammer tests were first performed on the PV array with the absence of wind. The model was then subjected to wind speeds ranging between 7 m/s and 30 m/s at the array's mean height of 1.5 m (5 ft) and wind directions θ ranging between 180° and 360° for a two-minute duration each. Peak accelerations were estimated for a one-hour full-scale storm duration based on Extreme Value Analysis Type I with a 78% probability of non-exceedance.

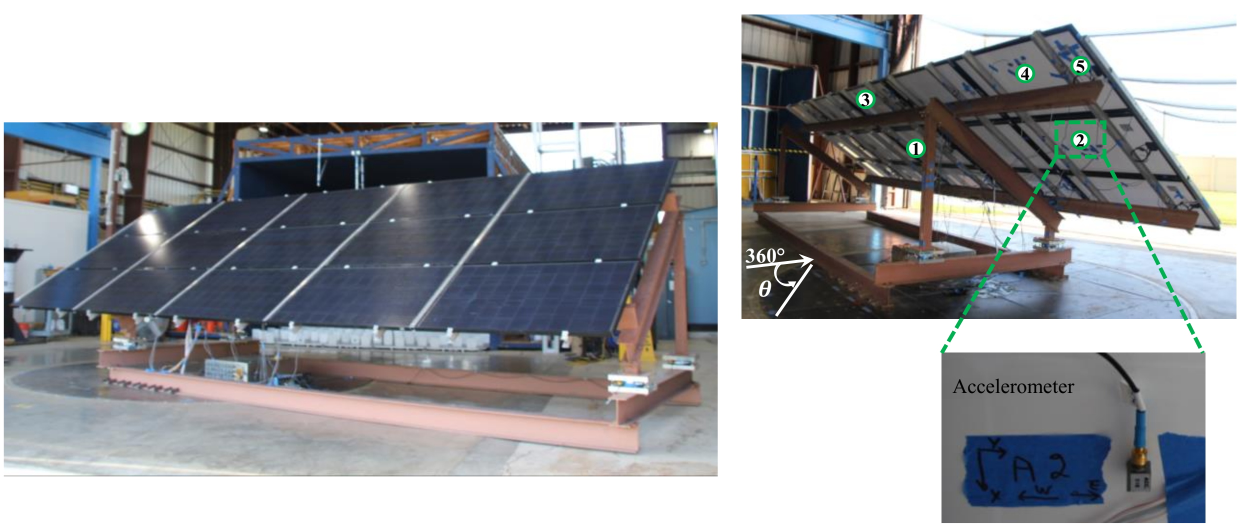

Figure 4. Full-scale PV array model and location of accelerometers at WOW EF.

The system's dynamic properties (i.e., natural frequency f_n, structural ζ_s and aerodynamic ζ_a damping ratios) were computed from the acceleration time histories using two system identification (SID) techniques: the Iterative Least Squares (ILS) (Chowdhury & Sarkar, 2003, 2004) and Random Decrement (RD) (Jeary, 1992; Tamura & Suganuma, 1996). The acceleration data were first converted into displacement time histories using the Newmark Integration Method and were used as inputs for the SID techniques.

3 RESULTS AND DISCUSSION

3.1 *FEM and CWU hammer test results*

Results of the FEM provide an insight into the modal behavior of the in-situ PV array and the corresponding WOW model. A comparison was made between the natural frequencies of the first three modes of vibration of Configurations 1 and 2 of the FEM and those obtained from the in-situ hammer tests (Fig. 5a). It was observed that the natural frequencies of both systems are in reasonable agreement, with differences smaller than 8%. The natural frequencies of the first three vibration modes were about 11, 14, and 19 Hz, respectively. As shown in Figure 5b, the first mode shape of the WOW model consisted of vertical oscillations while torsional oscillations were dominant for the second mode shape. Based on the comparison results, it was concluded that Configuration 1 can be considered as an appropriate model for the WOW tests given the similarity between its dynamic properties and those of the full in-situ array.

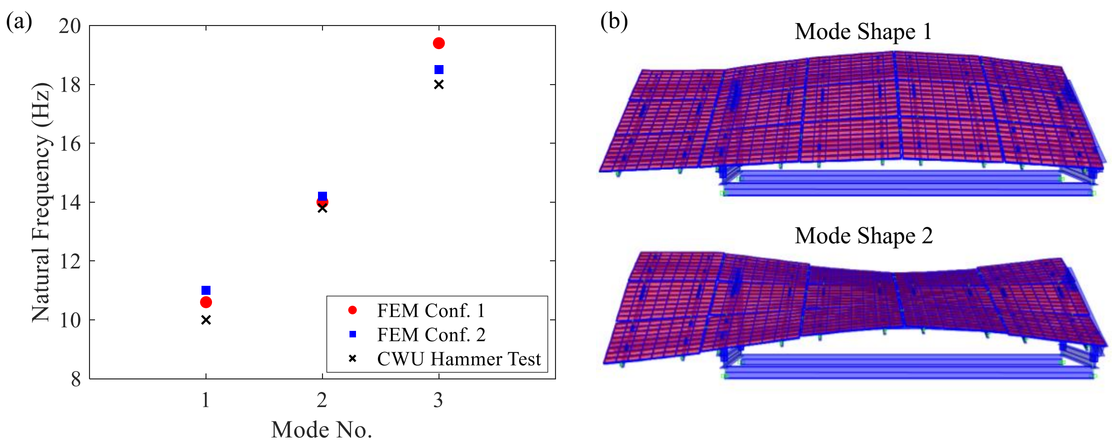

Figure 5. (a) Natural frequencies of the first three modes of vibration; (b) Mode shapes of the WOW model.

3.2 *Experimental test results and comparison with field measurements*

The wind flow at WOW was simulated with turbulence characteristics similar to their in-situ counterparts for a suburban terrain exposure ($z_0 = 0.25$m). Figure 6a shows the power spectral density (PSD) of the WOW longitudinal velocity fluctuations and the corresponding CWU spectrum at a height of 3 m (10 ft) above the roof surface. It can be seen that the high-frequency component of the turbulence spectrum was fully simulated at WOW, whereas the low-frequency part was missing compared to its full-scale counterpart. This is due to the size limitations imposed by the wind tunnel test section. The effects of the missing low-frequency turbulence on the peak wind loads are analytically incorporated in the post-test numerical analysis using the Partial Turbulence Simulation (PTS) approach (Estephan et al., 2022; Mooneghi et al., 2016; Moravej, 2018). Figure 6b shows the acceleration PSD recorded on the WOW model by accelerometer 4 for a 30 m/s wind speed at the mean array height. Dynamic resonant vibrations were detected in the spectrum in the form of spectral peaks at the natural frequencies of 11.7, 14.7, and 17.9 Hz. This agrees well with the natural frequencies obtained from the FEM and CWU hammer tests. In addition, the structural damping ratio computed using the ILS and RD techniques based on the hammer test's acceleration data was found to be 3.6% and 3.7%, respectively. The aerodynamic damping showed an increasing trend with ratios ranging between 0.4% and 1.2% for the simulated wind speeds of 7 m/s to 30 m/s, respectively.

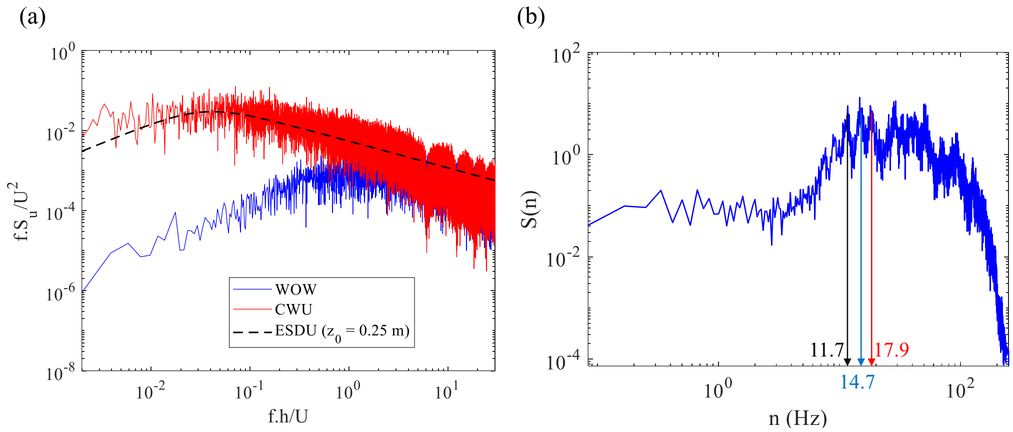

Figure 6. (a) PSD of the wind velocity fluctuations; (b) PSD of the acceleration for accelerometer 4 at 30 m/s.

Peak accelerations recorded on the WOW array for accelerometer 4 are presented in Figure 7a as a function of the reduced velocity U_{3s}/nB for wind directions of 300°, 315°, and 330° that are predominant at CWU. The full-scale 3-sec gust wind speeds U_{3s} ranged from 17 m/s (38 mph) to 72 m/s (161 mph), the natural frequency n was 11.7 Hz, and the width B of the panels located in the wind flow field was 5 m (16.4 ft). It was observed that the peak accelerations for the three considered wind directions increase with increasing wind speeds. Specifically, the peak accelerations ranged between -7 to -120 m/s^2 as the reduced velocity increased from 0.3 to 1.3. The highest U_{3s} recorded near the CWU array was 17 m/s. Hence, the WOW peak accelerations ranging between -7 to -8 m/s^2 were compared to the corresponding CWU value of -8.8 m/s^2 for $U_{3s}/nB = 0.3$, and a reasonable agreement was observed.

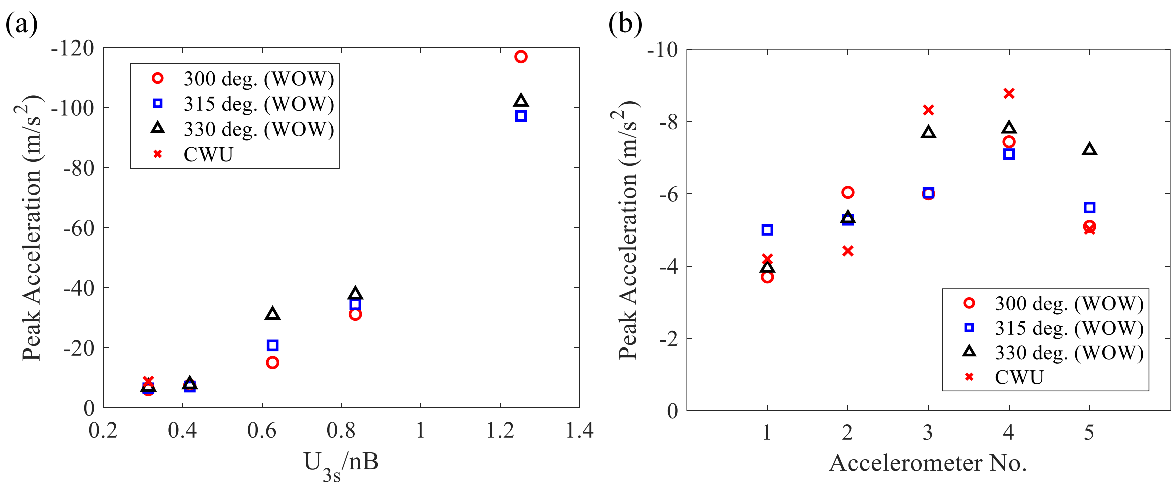

Figure 7. (a) Peak acceleration as a function of reduced velocity; (b) Spatial distribution of peak accelerations.

Moreover, the peak accelerations computed at U_{3s} = 17 m/s for the five accelerometers are displayed in Figure 7b for the three considered wind directions. A reasonable agreement was observed between the experimentally computed peak accelerations and those obtained from the field measurements. The highest WOW peak acceleration of -8 m/s^2 was detected for accelerometer 4 and for a wind direction of 330°, which agrees well with the highest CWU value of -8.8 m/s^2 detected at the same accelerometer location. This can be due to the location of accelerometer 4 on the top corner panel which coincides with the strongest wind direction.

4 CONCLUSION

This study investigated the wind-induced dynamic effects on rooftop PV arrays based on an experimental-numerical program and field calibration. Field measurements were conducted on a rooftop PV array at CWU. The PV array full-scale model was designed for WOW tests using FEM and was calibrated and validated based on field hammer test results. Hammer and wind loading tests were carried out on the full-scale PV array model at WOW and acceleration time histories were recorded. Results of the FEM and hammer tests were well comparable, meaning that the selected model for WOW testing is dynamically representative of the full in-situ array. Peak accelerations were computed for various wind directions and speeds. Results showed that significant panel vibrations occurred based on the increase in peak accelerations as the wind speed increased. The highest peak acceleration was detected at an accelerometer location coinciding with the strongest winds at CWU. The comparison of the experimental results with those obtained from the field measurements showed a reasonable agreement. As part of the ongoing work, the proposed methodology will be enhanced by analytically incorporating the dynamic effects into the measured wind loads on full- and large-scale PV array models. The compensated wind loads for dynamic effects will be compared with net reaction forces from load cells mounted on the array's supports. The interference effects from surrounding structures on the wind flow and loading characteristics will be also investigated based on large-scale rigid model testing. The experimental-numerical methodology will be further calibrated and validated based on collected pressure, acceleration, and strain gauge data at CWU. The obtained dynamic properties from this study will be used as inputs for the post-test numerical analysis to incorporate dynamic effects in the wind loads on rooftop PV arrays. Compensated wind loads for dynamic effects can help inform provisions in wind load standards. In addition, the measured acceleration data can provide early indications of potential failures which can be used by PV panel manufacturers to predict its field performance and lifetime.

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