



Rooftop Solar Arrays and Wind Loading

A Primer on Using Wind Tunnel Testing as a Basis
for Code Compliant Design per ASCE 7



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About the Boundary Layer Wind Tunnel Laboratory

The University of Western Ontario's Boundary Layer Wind Tunnel Laboratory (BLWTL) was one of the first wind engineering test laboratories in the world. BLWTL pioneered many of the test methods used to establish wind-induced loads and responses, and has tested many of the world's tallest buildings and longest bridges. More importantly, perhaps, is that the BLWTL performed the tests which led to the modern (and still current) form of the building code provisions for low-rise buildings in the late 1970s. Members of BLWTL were instrumental in the development of wind load provisions in building codes around the world and in the development of ASCE Manual of Practice #67, pertaining to wind tunnel test methods. BLWTL is still leading the way in modern developments with the development of the 'Three Little Pigs' Project which allows testing of full-scale structures by using pressure load actuators which can replicate any realistic pressure time history, whether measured in a wind tunnel or in a field experiment.

About the Authors

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Greg is also a Director of the University of Western Ontario's Boundary Layer Wind Tunnel Laboratory and is leading the 'Three Little Pigs' Project at UWO's Insurance Research Lab for Better Homes.

Dr. Joe Maffei, SE, PhD, LEED AP is a principal at Rutherford and Chekene, one of California's premier structural engineering firms. With the firm since 1988, Joe is an expert on implementing advanced methods of structural analysis and design, and non-prescriptive or "performance-based" design. He has experience in the seismic and wind design of a variety of structures and has directed several projects through to completion using advanced methods.

Joe has been appointed to committees writing building code provisions by the American Concrete Institute (ACI), the U.S. Building Seismic Safety Council (BSSC), the Structural Engineers Association of California (SEAOC) and the Federation International du Beton. He has been a lead investigator and author on research projects and design guidelines for organizations such as the Applied Technology Council, the Pacific Earthquake Engineering Research Center, the Portland Cement Association, the Earthquake Engineering Research Institute, SEAOC, and BSSC. He has led expert structural reviews for a number of building owners and institutions, and for the cities of Seattle, Bellevue, San Francisco, Sacramento, and San Mateo. Since 2008, in collaboration with building authorities, SunLink, and other solar companies, Joe has led the development of structural engineering design methodology and criteria for solar arrays.

Christopher Tilley, PE is CEO of SunLink Corporation, the industry leading provider of balance of system solutions to the solar industry. Chris has been in the solar industry for nearly a decade, initially as the President of a California developer and integrator and then as CEO of SunLink. In addition to being a serial entrepreneur, Chris has worked internationally as an investment banker and management consultant. He started his career as an engineer in Bechtel's R&D group.

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Design of Roof Mounted Solar Arrays Using ASCE 7 Method 3 (Wind Tunnel Testing)*

Roof-top solar arrays are increasingly being deployed on buildings across the US, as the basic economics of PV generated electricity improves. Assuring that the building structures can withstand the additional loads imposed by PV arrays on roofs has become a key issue in the deployment of these systems, and therefore a key question for structural engineers and building officials responsible for reviewing and approving such systems.

This document is intended as a primer for structural engineers and for building officials tasked with reviewing proposed tilted PV array systems on low-slope roofs.

This document focuses primarily on the issue of wind loading and on the appropriate use of wind tunnel testing as a basis for design. It also addresses the applicability of Computational Fluid Dynamics (CFD) to this issue. To assist in the review process, at the end of the document we provide a list of key issues and questions to be considered when evaluating the appropriateness of wind tunnel testing used for design of rooftop solar arrays and anchorage.

The basis for the recommendations and conclusions in this document stems from the long history of wind tunnel testing undertaken at the Boundary Layer Wind Tunnel Laboratory (BLWTL) at the University of Western Ontario (UWO), the contributions of the BLWTL to the various codes on wind loads (see About the BLWTL on the inside cover), and an extensive, multi-year test program undertaken at the BLWTL to determine the loads on rooftop mounted solar arrays funded by the SunLink Corporation. Insight into the how test results can be appropriately applied to specific array structures in conformance with the International Building Code is based on a multi-year analysis effort undertaken jointly by the structural engineering firm, Rutherford and Chekene, and SunLink.

Code Requirements

ASCE 7 does not provide specific guidance for the structural design of roof-top mounted solar arrays, so

engineers and building officials typically look to the ASCE 7 requirements for components and cladding. ASCE 7 provides three different methods for determining the design wind loads on buildings and components and cladding. These methods, and their applicability to design of roof-top mounted solar arrays, are discussed below.

Method 1 and Method 2

ASCE 7 Method 1 (Simplified Procedure) and Method 2 (Analytical Procedure) provide prescriptive approaches for determining design wind pressures. These methods do not require experimental testing of the specific system being designed. The design pressures resulting from these methods are based on past experience and testing of certain types of roof components and cladding which are not similar in size, shape, or configuration to solar arrays.

Based on our testing and research, using Method 2 with arrays treated as components and cladding on a mono-slope roof provides a safe and generally conservative estimation of the actual loads on an array, particularly when one considers the loads over larger areas. However, when smaller tributary areas are considered, the code values appear to be less conservative and may, in certain cases, be unconservative.

An alternative approach for determining wind design loads is provided in ASCE 7 under Method 3.

*Section 6.6 Method 3 in ASCE 7-05 is now presented as Chapter 31 in ASCE 7-10. While this paper refers to the language and headings in the ASCE 7-05, it is equally applicable to ASCE 7-10.

Method 3 Approach

Method 3 permits the use of wind tunnel testing as the basis for design if the testing meets specified requirements. ASCE 7-05 Section 6.6.2 requires that tests meet all of the following conditions:

1. **The atmospheric boundary layer has been modeled to account for the variation of wind speed with regard to height.**
2. **The relevant integral and micro length scales for the longitudinal component of atmospheric turbulence are modeled to approximately the same scale as that used to model the building or structure.**
3. **The modeled building and surrounding structures and topography are geometrically similar to their full scale counterparts, except that, for low rise buildings meeting the requirements of Section 6.5.1, tests shall be permitted for the modeled building in a single exposure site as defined in Section 6.5.6.3.**
4. **The projected area of the modeled building or other structure and surroundings is less than 8 percent of the test section cross-sectional area.**
5. **The longitudinal pressure gradient in the wind tunnel test section is accounted for.**
6. **Reynolds number effects on pressures and forces are minimized.**
7. **Response characteristics of the wind tunnel instrumentation are consistent with the required measurements.**

Boundary Layer Wind Tunnels

The requirements listed above for Method 3 are, in fact, difficult to meet, and are only met at a few facilities in North America. These specially designed facilities, called Boundary Layer Wind Tunnels (BLWT's) are expensive to design, build, calibrate and maintain. They are extensively used for the design of high-rise buildings, long-span bridges and other complex structures where wind loading is a critical concern. While there are other types of wind tunnels in operation that provide useful information on virtually anything that moves through the air, they are

not appropriate for determining design wind loads on buildings and other structures unless they satisfy the detailed requirements above.

The expertise needed to properly design and run experiments in these facilities is similarly specialized and limited. Proper BLWT modeling and testing must be done carefully, following the requirements as listed above, as well as those in ASCE Manuals and Reports on Engineering Practice No. 67, "Wind Tunnel Studies of Buildings and Structures."



Figure 1: Boundary Layer Tunnel with building and rooftop solar array at UWO facility

The Challenge of Scale

One of the key challenges in designing wind tunnel testing for rooftop solar arrays is addressing the issue of scale. Because of the complexity of the flow field on a building rooftop, simply estimating or approximating this flow field is inappropriate for the purpose of determining design loads. In order to create the appropriate flow field, the building must be part of the model and included in the testing. Per requirement 4 above, the building must be relatively small so as to not block more than 8% of the wind tunnel test section cross-sectional area. Because the modules are in turn small compared to the building, the actual array model on which measurements need to be taken is typically quite small (e.g. 1:30). Working at this scale presents a variety of challenges, discussed in subsequent sections of this paper, which differ depending on the test method and design.

The Challenge of Generalization

Another key issue that needs to be addressed is site specificity. Many engineers are familiar with the use

of wind tunnel testing to capture unique characteristics of a specific building or site. If a specific building, with specific architectural features and surroundings, is accurately modeled and tested in a boundary layer wind tunnel, the test measurements can be used in a direct manner to determine design loads. This is typical of testing performed under Method 3 of the Code for design of tall buildings. In the typical case, a new high-rise building is modeled, with the surrounding buildings and tested in the wind tunnel. The measurements (e.g., force-balance readings at the base, pressure readings on the surfaces) are then used in a fairly straightforward manner to design the foundation, structure, and cladding for that building.

However, designing a test program which yields design load values that can be applied to a variety of buildings, rooftops and surroundings that are different than those tested is substantially more complex. An accepted methodology for achieving this goal can be found in the testing approach used to develop the design values prescribed in ASCE 7 Method 2 for rooftops.

Figure 2 illustrates how site specific effects are separated from the aerodynamic characteristics of rooftops in the ASCE 7 formulation.

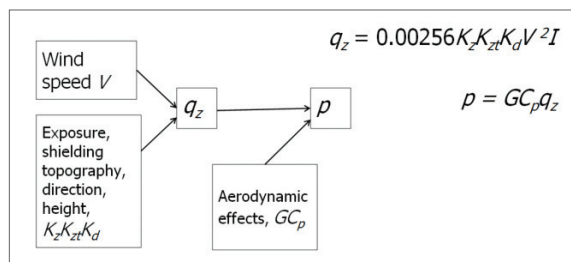


Figure 2: ASCE 7 design wind pressure p , depends on site and building conditions (q_z) and on aerodynamic effects ($G C_p$). Wind tunnel analyses for a specific site, for example a tall building, establish exposure (K_z), shielding, topography (K_{zt}), and direction factors (K_d), as well as establishing aerodynamic effects ($G C_p$). Other test programs may be designed to focus on different properties, for example aerodynamic effects ($G C_p$).

The $G C_p$ curves (relationships of $G C_p$ to tributary area) provided in Method 2 for the different types of roof structures were derived from a wind tunnel test program that included a large, but inevitably limited number of building shapes, sizes, heights etc. (much of which was done at the Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario). The curves that were developed from this program, however, are prescribed by the code to be applied

to buildings with different shapes, sizes and heights than were modeled in the test program. The key to this methodology is to generalize the results sufficiently so that the worst case scenarios are captured and enveloped.

The testing and methodology used to generate bounding $G C_p$ curves in ASCE 7 for various types of roofs (e.g., roof slope, roof shape, building height, etc.) therefore provides a good starting point and framework for generating design values for rooftop solar arrays that can be applied across a wide spectrum of building types and shapes.

Unlike in the case of rooftops, rooftop solar arrays do not necessarily span the length and width of the building. As a result, the geometry and layout of the array as well as its location on the roof needs to be addressed. These factors are in fact critical characteristics that influence the array/rooftop aerodynamics and therefore the loading on the array and roof. Generalizing how these factors affect the loading for specific arrays on specific roofs is difficult and requires a great deal of testing and/or analysis to be able bound the worst aerodynamics cases.

Wind Tunnel Models and Approaches

With the goal of general applicability in mind, there are basically three possible test approaches that might be used to generate design values for solar arrays on rooftops. These approaches are distinguished by the type of models and instrumentation used, and include, aeroelastic fly-away models, force-balance models, and pressure tapped models. Table 1 summarizes the three approaches, and each is described below in more detail. As noted above, in all cases these models must be tested in an appropriately scaled atmospheric boundary layer, if the results are to be used for design.

Fly-away testing of aeroelastic models

Fly-away testing of aeroelastic models is not only a well-established methodology for testing but also one that is intuitively easy to explain. In this type of test, the solar array model is placed on the model building in the tunnel and the wind speed is increased until the array moves. (The term “fly-away” is misleading in many cases as the point at which the model first moves is typically below the point at which the model “flies” – indeed structural failures are not always associated with “flight” as pointed out by Kopp in his work on windborne debris). With the mass of the

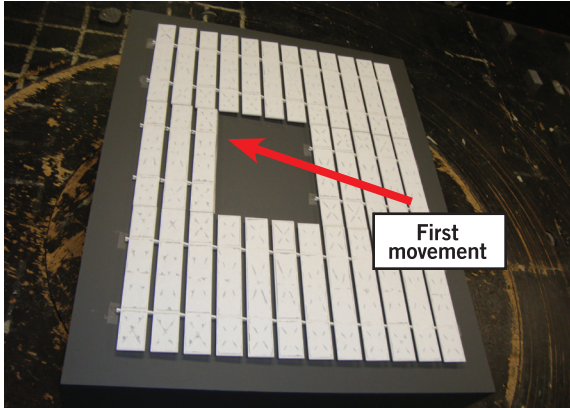


Figure 3: Fly-away testing of rooftop solar array in a Boundary Layer Wind Tunnel showing array at “failure” wind speed (notice the very slight displacement). One disadvantage of fly-away testing is that it does not record downward forces.

array, component stiffness properties, and the coefficient of friction between the array contact points with the roof surface known and accurately modeled, the wind speed required to move the array can be measured.

While this method of testing is intuitive and straightforward, there are a variety of challenges inherent in the process. The first of these challenges is simply the number of experiments needed to obtain reliable results. Given the complexity of mechanisms involved and the stochastic nature of wind, tens of test runs may be needed for each experiment to establish confidence levels around the wind speed at which movement occurs. Given that experiments need to be run for all practical wind angles and for the various types of roof/array orientations, and array configurations, the number of tests to obtain results for generalized use in design can quickly make this type of testing prohibitive.

The second and perhaps most daunting challenge relating to fly-away testing is the construction of appropriate aeroelastic models. To achieve accurate results, the model weight and stiffness must be modeled accurately and at the appropriate scale. This is extremely difficult to do with a small (e.g., 1:30) model of a solar array. The stiffness of the structural members and joints must be accurately modeled at this scale or the results may not be representative. The stiffness of these components and joints can be quite complex to obtain via analysis or measurement at full scale, but this is required as a starting point prior to even attempting to build a representative model.

Because stiffness of the model is both critical to the results and difficult to model at 1:30 scale, it needs to be looked at carefully. The sensitivity of the test results to stiffness diminishes as the stiffness of the array structure increases. Assuming a fully rigid structure therefore simplifies the analysis and is something that one might be able to justify for very small sections of an array – i.e. 1 PV module, but for array structures larger than this, the assumption of rigidity will lead to an underestimation of the design loads.

A third challenge related to fly-away testing of aeroelastic models is the difficulty of generalizing results to arrays of different sizes and shapes from that which is tested. For example, if an accurate aeroelastic model is created for a six module by six module array, the results will provide guidance for a six module by six module array with the same weight distribution and stiffness as the model. It will not however provide accurate guidance for a 3 module by 2 module array, other smaller array structures, arrays with different shapes, or even a six by six array with different weight distributions or component stiffnesses. Many combinations of array sizes, shapes and ballast configurations would therefore need to be properly modeled and tested (on different locations on the roof, and with different wind approach angles) to produce design values that are appropriate for array layouts of various shapes and sizes. Given the complexity and cost of producing representative aeroelastic models and the issue of having to run multiple tests for each data point, the cost of modeling and testing can quickly become prohibitive using this method. (See *Table 1 on page 7*).

Finally, a fourth challenge of this method relates to understanding the various load paths between components. Without some idea of the load sharing required between modules, the designer cannot analyze if the array structure is strong enough to withstand the highly concentrated, local loads. This is an important issue for wind design as local loads (e.g., 10 ft²) can be many times higher than what would be expected by simply extrapolating from measurements taken on larger areas (e.g., 200 ft²).

An alternative approach to using fly away testing that avoids many of the issues pertaining to aeroelastic models outlined above, involves testing a single, disconnected module unit at all locations across the roof (and all wind directions) while measuring the wind speed required to move that single module. This could then be followed with another set of tests using

Table 1: Wind tunnel testing methods & applicability to rooftop solar arrays

TYPE OF MODEL	AEROELASTIC FLY-AWAY	FORCE-BALANCE	PRESSURE TAP
Description	Wind speed is increased until model moves (e.g., slides or lifts).	Strain gauges or load cells measure reaction forces at connections to the roof.	A grid of pressure taps measures wind pressure on each surface (e.g., module faces).
Results obtained	Wind speed at which model overcomes friction and/or gravitational force.	Reaction force coefficients for a range of wind speeds.	Local and overall design pressure coefficients for a range of wind speeds and module areas.
Measurement of local pressure peaks	“Local” defined as area of model that can move independently. Therefore not typically measured at the module level or smaller.	“Local” defined as area of the model that can be shown to contribute to load on a given load cell. Therefore not typically measured at the module level or smaller.	“Local” defined as area attributable to a given pressure tap. Measurement at module and sub-module level is therefore possible.
Measures downward forces on array or roof?	No	Yes	Yes
Data points gathered per wind tunnel run:	1	~1 x 10 ⁵ to 1 x 10 ⁶	~1 x 10 ⁷
Key Challenges / Drawbacks	<ul style="list-style-type: none"> • Large numbers of experiments required to generate reliable data set. • Fidelity of scaled model (geometry, weight, stiffness) is critical to accuracy of results and difficult to attain. • Cannot be easily applied to arrays of different sizes or shapes. 	<ul style="list-style-type: none"> • Large data sets to manipulate and analyze. • Instrumentation is difficult at small model scales. • Extensive computational and analytic capability required to apply results to arrays of different sizes, shapes and ballast configurations. 	<ul style="list-style-type: none"> • Large data sets to manipulate and analyze. • Instrumentation required to accurately measure pressures on all appropriate surfaces is challenging. • Extensive computational and analytic capability required to apply results to arrays of different sizes, shapes and ballast configurations.
Feasibility	Scale of testing required for reliable and applicable results can be cost prohibitive. Sufficiently accurate model may be beyond state of the art depending on scale and complexity of structure.	Currently difficult to instrument at scale needed.	Is the most common method of testing to determine design requirements for wind loads on low-rise buildings and building components.

a multi-module array that allows any individual module in the array to move independently of the others.

A similar set of tests could then be run (i.e., with the array at various locations on the roof and with different wind approach angles) with each module disconnected from the others and the wind speed at which any module moves recorded. The maximum force calculated for any module in this series of tests could then be used as the load value for all modules in the array with some confidence that it would provide a sufficient basis for design (at least for uplift).

Even with such an extensive fly-away test program, one key design value cannot be determined with this approach, the downward load imparted to the roof by the array. This is a critical shortcoming. Based on our testing and research, this load can be an important consideration in design of some components and in analyzing roof deck loads.

Force-balance models

Another approach to determining the wind forces on arrays is to create a similar test program to what is described above, but instead of using fly-away models, use array models that are attached to the roof and which have strain gauges or load cells attached to these connection points. If each module is instrumented appropriately, a good picture of the forces on the modules could be obtained. The primary difficulty with this methodology is the instrumentation. Creating a model at the scale needed (e.g., 1:30) with strain gauges across the array and on connection points, that could each be accurately calibrated and read at the required frequency is at the boundary of the state of the art. Setting up and creating appropriate models for the large number of experiments (i.e., multiple array sizes and shapes and locations on the building rooftop) needed would be a very large and expensive undertaking.

Pressure tapped models

While fly-away and force-balance models monitor behavior at the interface between the array and the roof, pressure tapped models measure wind pressures directly on the surface of each module. Pressure tapped models have small holes (pressure taps) across the surfaces of the models to be tested. These holes are actually the open end of air-tight tubes that are connected to equipment that can measure pressure in the tubes. The pressures on the model surfaces are measured such that net forces on each

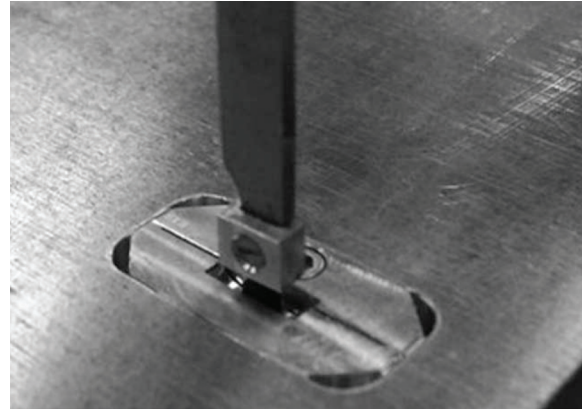


Figure 4: A small load cell used for measuring attachment forces in a wind tunnel.

of the surfaces can be obtained from these measurements. These forces can then be summed to provide the load on individual sections of the array or the entire array.

There are many advantages to this type of testing which will be discussed below, but it also has significant challenges. The key challenge is creating models at the scale needed and setting up instrumentation that can accurately measure the pressures in each tube at the frequency needed.

Fortunately, this type of testing has the benefit of being extremely well developed, as it is the standard methodology used for wind tunnel testing of buildings. In fact, pressure tapped models were used as the basis for developing the rooftop load curves (GC_p curves) used in ASCE 7 for low-rise buildings in the late 1970s. In these tests, model buildings were created with hundreds of taps across the roof surface. Pressure readings were taken at each tap, hundreds of times per second, for all wind approach angles. This data set was then analyzed to determine the highest load generated for different sized areas (the measurements from nearby taps were combined to create a load for each area). The worst case pressure calculated for each area size was used as the basis for design. The GC_p curves given in the code for roofs are the result of these experiments and analysis. As can be seen from the curves, the GC_p values are much higher for smaller areas. They also provide values for both upward and downward wind force as they occur.

In order to measure the forces on an array using this methodology, an array model needs to be created with pressure taps across the various surfaces of the model, including, for example taps on both the upper

and lower surfaces of the modules. These models then need to be placed on a model building rooftop and measurements made for all wind approach angles and with the array in different locations on the roof.

The data from these experiments can then be used to determine net forces on any expanse of array desired at any instant in time. The peak pressures at any given instant in time (considering all of the time history) for any array area can then be calculated. If one calculates the peak net forces over all relevant area combinations (e.g. 1 module areas, 2 module areas, 3 module areas, etc.) for experiments covering all wind angles and appropriate setbacks, a curve similar to the G_{Cp} curve provided in the code for rooftops can be created, but in this case for areas of the solar array.

As in the case of the code, a curve constructed in this manner will provide a bounding case on the magnitude of loads for various areas of array, provided of course that the array geometry (e.g. tilt angle, spacing between rows, clearance off the roof) is consistent with what was tested. Unlike the fly-away model approach, this method provides information on both upward and downward loads on the array.

While the peak values determined by this methodology are appropriate for design, the key challenge is determining how to appropriately apply the various area-specific peak values to the array to check for strength of the array and the connections between the array and the roof. Any solution to this challenge is computationally demanding as it requires calculations on the components of the array for every array design and for multiple area-specific load cases applied to different areas within the array.

Summary

While there is no specific guidance provided in ASCE 7 for determining appropriate design loads for rooftop solar arrays, typical practice has been to use Method 2 with arrays treated as a roof surface (e.g. using components and cladding coefficients for mono-slope roof coefficients). There is no real engineering basis for this approach, given that the aerodynamics of roof surfaces are typically very different than those of typical solar arrays. However, based on our research, this approach appears to lead to conservative estimation of the design loads for various array geometries. Wind tunnel testing per Method 3 provides an alternative for determining design loads for solar arrays. However, appropriately applying Method 3 to this situation is much more complex

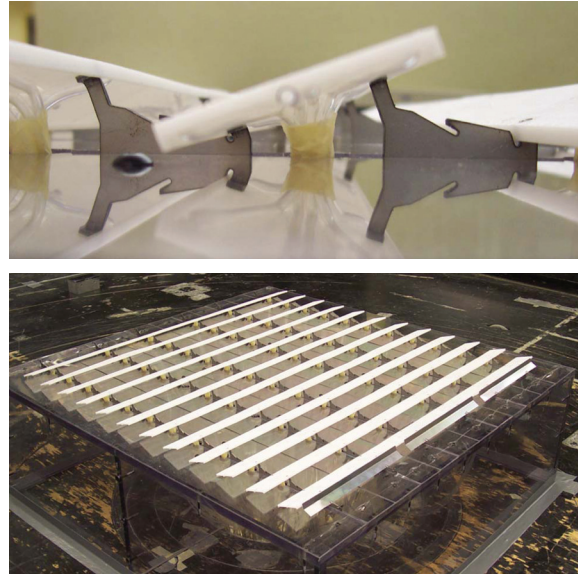


Figure 5: Pressure tapped models of solar array on rooftop in UWO tunnel. This type of model parallels the testing approach that is used to derive wind coefficients for cladding in the building code.

than might be assumed for two reasons.

First, the testing needs to be done in a facility and with experts that can reliably meet the minimum requirements set out in Method 3. There are very few facilities in North America that can meet this requirement.

Secondly, testing per Method 3 contemplates using a model that is representative of a specific array on a specific building, on a specific site. Because the cost, time and effort required to perform this type of testing for each specific PV project would be prohibitive, the challenge is to develop a set of test data that can be used to provide design loads for a wide variety of different buildings, sites and array shapes. This type of generalization is possible with the appropriate test program, but is a complex and challenging undertaking.

The nature of challenges faced in such an undertaking depends upon the type of model and instrumentation used in the wind tunnel. Of the three types of testing approaches typically used in boundary layer wind tunnels, fly-away testing of aeroelastic models, force-balance models and pressure tapped models, only the force-balance and pressure tapped models can provide all the critical information needed for such a program.

Fly-away testing of aeroelastic models cannot provide downward forces on the array that are transmitted to the roof structure. They also do not provide a

clear idea of load distributions across the array and therefore make it very difficult to determine what the demands are on the various array components.

On the other hand, pressure tapped models and force-balance models directly measure the loads on the array over time. This time history along with the spatial distribution of loads can be used to determine the appropriate set of design loads for the array and array components.

Given the current state of technology and the constraints imposed on the testing by Method 3, the force-balance model approach may not be practical at the scale required. Pressure tapped models are therefore the best single approach for this type of program. However, because each of the three modeling and testing approach offers a slightly different perspective on array performance, there is value to looking at each.

In conclusion, wind tunnel testing can provide an appropriate basis for design of rooftop solar arrays per the code if the testing is done properly and the results of these tests are appropriately applied. The enclosed "Quick Reference" provides a list of key questions that can help to qualify the appropriateness of the testing and methodology used.

What about Computational Fluid Dynamics?

CFD is an emerging discipline in wind engineering, and there has been substantial progress in the past number of years. However, CFD is not currently in a state where it can be used reliably to estimate peak pressures on low-rise building roofs, let alone solar arrays on such buildings, and should not be used as a basis for design at this point in time. ASCE 7 does not currently allow it to be used as a design basis and it would appear that CFD-based studies are a long way from being used to modify code formulations for Component & Cladding loads. The primary challenge is that peak pressures and peak loads at the component scale are not well estimated by this method. This is unsurprising, given the fact that turbulence models (such as Reynolds-Averaged Navier Stokes, RANS, models) have been developed to estimate the mean flow field. When the ratio of mean load to mean wind speed squared is the same as peak load to peak wind speed squared (i.e., the quasi-steady theory is valid), then CFD should work well if one interprets the results via quasi-steady theory. However, our experience with uplift on roof-mounted, and to a lesser extent for ground-mounted, solar systems is that QST does not hold well.

References

ASCE 7-05, *Minimum Design Loads for Buildings and Other Structures*, American Society of Civil Engineers, Reston, Virginia, 2006.

Kopp, G. A., Galsworthy, J. K., Oh, J. H., 2010 "Horizontal Wind Loads on Open-Frame, Low-Rise Buildings." *Journal of Structural Engineering*, Vol. 136, No. 1, 98-105.

Kordi, B., Kopp, G. A., 2011 "Effects of initial conditions on the flight of windborne plate debris." *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 99, No. 5, 601-614.

ASCE 7-10, *Minimum Design Loads for Buildings and Other Structures*, American Society of Civil Engineers, Reston, Virginia, 2010.

ASCE Manuals and Reports on Engineering Practice No. 67, *Wind Tunnel Studies of Buildings and Structures*, American Society of Civil Engineers, Reston, Virginia, 1999.

For More Information

To be included on the distribution list for future publications, webinars and workshops addressing the structural design and analysis of solar arrays, visit www.sunlink.com/pvstructuralpubs.

Quick Reference

Key issues and questions to be considered when evaluating the appropriateness of wind tunnel testing used for design of rooftop solar arrays and anchorage.

For all types of models and approaches:

- Is there an expert in this type of testing that will attest that the tests meet each of the 7 requirements listed under Method 3 in ASCE 7?
- What level of quality control existed for these tests?
- Was a model of the specific array and building tested or are the design values being proposed derived from another series of tests?
- If a model of the specific building and array layout was not tested, what supports the generalization of the test data to the project at hand?
- Is the array geometry (tilt angle, spacing between rows) the same as what was tested?

If fly-away testing is the basis for the design values being presented:

- What are the characteristics of the aeroelastic model used in the tests?
 - » Has the stiffness and strength of all members and joints in the structure been measured and incorporated appropriately in the scale model? Has this been verified by testing?
- Has an array of the same shape and ballast configuration (or roof connector locations) been tested in the same location on the roof as being proposed?
 - » If not, where are the load design values coming from? Has there been a testing program that covers a wide variety of array shapes and sizes, including an array consisting of single module tested on various parts of the roof and from all wind angles? Are the highest value for a single module being used?
- If a non-uniform ballast or connector configuration is being proposed, is the structure strong enough to transfer loading through the structure to the connection or the ballast? How is this being calculated?
- How are the downward forces on the array being calculated?
- How was the coefficient of friction between the array model and the building model measured?

If force-balance measurements form the basis for design parameters:

Was this done at the appropriate scale to meet the requirements outlined in the code?

- How was the instrumentation calibrated and verified?
- Is the segment of the array being measured by each load cell small enough to be treated as rigid body (e.g. 1 module area)?
- Has an array of the same configuration and same place on the roof been tested?

If pressure measurements are the basis for design parameters:

- Were there sufficient taps on the model to determine loads on the surfaces ?
- Were the response characteristics in the acceptable range per ASCE Manual of Practice No. 67?
- Was the same array layout and location on the roof tested as that which is being designed ?
 - » If not, how are the loads for the specific array being determined ?
 - » If area-averaged pressure coefficients being used, how are area loads being applied to the specific array being considered ?
- Is strength of the array being checked ?