Final Report for Project Entitled:

Behavior of Aluminum Screen Enclosures in Strong Winds
PO Number AB3DBA

Performance Period: 10/10/2014 – 6/30/2015

Submitted on

June 15, 2015

Presented to the

Florida Building Commission
State of Florida Department of Business and Professional Regulation

by

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1. Disclaimer

This report presents the findings of research performed by the University of Florida. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the sponsors, partners and contributors. The Structural Techical Advisory Committee of the Florida Building Commission will provide a final disposition on the implications for the Florida Building Code.

2. Applicable Sections of the Code (and Referenced Documents)

- 1622.1, Florida Building Code—Building
- Chapter 20 (Aluminum), Florida Building Code—Building
- 2010 AAF Guide to Aluminum Construction in High Wind Areas

3. Executive Summary

3.1. Description of the Issues

- During the 2013-2014 research cycle, the Aluminum Association of Florida (AAF) requested a study on the comparative performance of two screen enclosure systems. The first system was based on signed and sealed, site-specific plans obtained from building code departments in NE Florida. This 'generic' system was based on conventional design practice, which is believed to represent the majority of designs outside of the HVHZ in Florida. The second system was identical to the 'generic' system except that the design conformed to requirements set forth in the 2010 AAF Guide to Aluminum Construction in High Wind Areas
- Both systems were tested in the full-scale test facility at the IBHS research center. Neither system exhibited the type of catastrophic failure observed in the 2004 hurricane season, however loss of screens, local buckling and material yielding were observed in isolated sections. AAF subsequently released a technical bulletin addressing these issues in the AAF Guide
- There are outstanding questions about the wind loading characteristics of the screen enclosure systems. Design pressure coefficients originate from a two interrelated studies performed at Clemson University and Virginia Tech (Reinhold 1999). The limited scope of the 2013-2014 testing did not allow for direct measurement of area-averaged pressures and reactions. Boundary layer wind tunnel modeling is being conducted to investigate this issue
- A companion study (Corrosion of roofing and screen enclosure fasteners) will assess the effect of corrosion on typical fastening systems used in screen enclosures systems

3.2. Major Findings and Recommendations for the Code

- Our findings are consistent with the basis study performed by Clemson University
- No change to the Code appears to be warranted
- We intend to collaborate with Dr. Reinhold to publish the combined results of these studies in a peer-reviewed journal

4. Scope of Work

- Coordinate with stakeholder groups (e.g., Aluminum Association of Florida, Insurance Institute for Business & Home Safety) to finalize the testing matrix for the boundary layer wind tunnel modeling
- Conduct boundary layer wind tunnel modeling of typical screen enclosure systems found on Florida homes to provide baseline results that can be compared with findings from the Virginia Tech and Clemson University studies performed in the early 2000s
- Interpret results, determine if the problem requires action (or not), and produce a report that explains the results and implications for the Code

5. Deliverables

- Interim report by February 15, 2015 – Interim progress report detailing the current status and progress toward completing the work described above. In addition, the Interim report will be presented to the Commission's Structural Technical Advisory Committee at a time agreed to by the Contractor and Department's Project Manager
- Final report by June 1, 2015 providing technical information on the problem background, results and implications to the Code. In addition, the final report will be presented to the Commission's Structural Technical Advisory Committee at a time agreed to by the Contractor and Department's Project Manager
- Recommendation(s) that may require revision to future edition of the FBC will be analyzed using the criteria outlined in the currently adopted code modification form

6. Detailed Project Description

The investigator convened a stakeholder meeting to finalize the project scope for the boundary layer wind tunnel (BLWT) experiments on January 20, 2015. Attending were representatives of the Aluminum Association of Florida (Tom Dowd, Mike Driscoll, Gary Hartshorn, David Johns, David Miller), JBD Code Services (Joe Belcher), the Insurance Institute for Business & Home Safety (Anne Cope, Tim Reinhold, Murray Morrison), and the Chair of the Structural TAC, Jim Schock.

The group prioritized three principal activities:

- A validation study of the Texas Tech Wind Engineering Research Field Laboratory (WERFL) low-rise building to verify similarity of experimental configurations between the University's BLWT and others around the world. WERFL has been the subject of dozens of studies since the 1990s. Data may be accessed at the NIST Aerodynamic Database (http://fris2.nist.gov/winddata/index.html)
- A validation study of the Reinhold et al. (1999) 1:24 geometric scale experiments that underpin the current load provisioning in the Code. These include quantification of wind loading on three enclosure shapes (monoslope, gable and hip), both freestanding and attached to a host structure. The experimental design employed a high-frequency force balance to measure peak base reactions, which were then normalized by a referenced velocity pressure to calculate the pressure coefficient values (GCp) that are used in the Code.

- [If time allows] Characterization panel loading using miniature load cells that affix a roof or wall panel to the 'cage.' The second thrust evaluates main wind force resisting system (MWFRS) loads (multi-axis loading of the entire structure that is resolved into base reactions, or equivalent out of plane loads that cause shear and uplift). This approach will enable quantification of component and cladding loads of individual panels, and in particular, provide new data to hone our understanding of the roof structure loads.

All deliverables were met, although the addition of the validation study precluded the component and cladding study (not included in the scope of work).

6.1. Validation Study of the WERFL Building

A validation study of the Texas Tech Wind Engineering Research Field Laboratory (WERFL) low-rise building was conducted at the University's boundary layer wind tunnel (BLWT). 216 pressure taps were installed on a 1:24 scale model of the WERFL building. Location of the pressure taps followed the configuration tested by the University of Western Ontario (UWO) as part of the NIST Aerodynamic Database (Ho et al., 2003). Pressure measurements were collected through a high speed pressure scanning system. Mean and peak pressure coefficient values were obtained and compared against measurements from the tests conducted at UWO's BLWT. Results are in good agreement, which indicates that the approach flow conditions applied to the screen enclosure models is consistent with standard practice.

6.1.1. Wind Characteristics and Measurements

The University's BLWT was configured to simulate two terrain conditions for the WERFL building test. Wind tunnel tests were performed for open and suburban exposure terrain conditions corresponding to full-scale roughness lengths of z_0 = 0.01 m (0.033 ft) and 0.087 m (0.285 ft), respectively. Roughness elements located upwind to the WERFL model were configured based on the model scale to simulate the two types of exposures. The roughness elements were set to a height of 3.5 cm (1.38 in) to simulate open exposure and 10.0 cm (3.94 in) for suburban exposure. Wind speed and turbulence intensity profiles were obtained from wind speed measurements to verify appropriate simulation of the desired terrain conditions. Cobra probe sensors manufactured by Turbulent Flow Instruments (TFI) were installed at different elevations located adjacent to the test section (as shown in Figure 2) to provide dynamic, 3-component velocity and local static pressure measurements.

6.1.2. 1:24 WERFL Building Model

A 1:24 scale acrylic model of the WERFL building was built with plan dimensions of 15.0 in x 22.5 in and a height of 6.5 in from the ground to the roof ridgeline (see Figure 3). The model was equipped with 216 pressure taps, following the tap layout of Test 7 from Ho et al., 2003. The same tap numbering scheme was used with the exception of ten additional pressure taps located along the ridgeline of the roof, as shown in Figure 4. Prior to testing, preliminary examinations were performed to ensure the model was adequately sealed ("bag test") as well as verification of proper pressure readings on all pressure taps ("puff test").

6.1.3. Pressure Measurements

A 512 channel high speed pressure scanning Scanivalve system was used to collect pressure measurements. 39-inch long EVA tubing was used to connect all 216 pressure taps to the Scanivalve system. The tubing has an internal diameter of 0.05 inches and a wall thickness of 0.02 in. Tubing response effects were digitally filtered from raw pressure measurements following tubing response correction procedures provided by Scanivalve Co (Harthan, 2012). The setup for the tubing response test is shown in Figure 5. Results from the tubing response test are shown in Figure 6. Pressure measurements were sampled at a rate of 625 Hz for 120 seconds. Sampling rate and test duration were selected based on flow similarity laws to full-scale wind conditions. Appropriate sampling frequency was estimated using the following similarity relation:

$$\left(\frac{fL}{U}\right)_{MODEL} = \left(\frac{fL}{U}\right)_{FULL-SCALE}$$

6.1.4. Wind Tunnel Tests

1:24 scale WERFL building was tested for two terrain conditions and three wind orientations. The model was tested for parallel (0 degrees), cornered (45 degrees), and perpendicular (90 degrees) wind directions. Wind speed measurements at the eave height of the model were recorded using Cobra probe sensors to calculate velocity pressures at the eave height of the building.

Wind parameters for the WERFL building tests include:

Open Exposure Conditions (z_0 = 0.01 m):

- Mean wind speed at eave height $\overline{U}_{eave}$ = 5.5 m/s [12.3 mph]
- Roughness element height = 3.5 cm [1.38 in]
- Longitudinal turbulence intensity at eave height = 15 %

Suburban Exposure Conditions (z_0 = 0.087 m):

- Mean wind speed at eave height $\overline{U}_{eave}$ = 4.6 m/s [10.3 mph]
- Roughness element height = 10.0 cm [3.94 in]
- Longitudinal turbulence intensity at eave height = 23.5 %

Time histories of pressure measurements from the 216 taps were captured and stored using the ScanTel software provided by Scanivalve Co. After measured pressures were digitally filtered to correct for tubing response effects, mean pressure coefficients at eave height $\overline{C}_{p,eave}$ were calculated using the following equation:

$$\overline{C}_{p,eave} = \frac{\overline{P}_0 - P_{ref}}{\frac{1}{2} \cdot \rho \cdot \overline{U}_{eave}^{\,2}}$$

Here, $\overline{P}_0$ is the mean pressure of a time history from a particular tap, and P_{ref} is a reference pressure. The term ρ is the air density, which was estimated based on local air temperature and barometric pressure measurements. Figure 7-12 show mean pressure coefficient values observed in the current study (red marks). The values are compared against $\overline{C}_{p,eave}$ values from UWO.

6.1.5. Findings

Mean pressure coefficients observed in the current study appear to be in very good agreement with measured values from the UWO tests for both open and suburban exposures. Fluctuations in the pressure coefficient values, quantified by the standard deviation, also compared very well with UWO's test. This study confirms the appropriateness of the experimental similarity configuration of the University's BLWT.

6.2. Comparative Study of Wind Loads on Screen Enclosures

A comparative study of MWFRS loads on different types of screen enclosures was conducted at the University's boundary layer wind tunnel. 1:24 model scale screen enclosures were tested for four types of roof arrangements including monoslope, gable, hip, and mansard. Free-standing screen enclosure models were studied as were enclosures adjacent to a host structure. Forces at the base of the models were obtained from a sensitive high frequency force balance. The balance allowed direct measurements of mean and peak drag and uplift forces. To measure GCp values, raw data were appropriately converted for gust duration, height and exposure. Results were compared with pressure coefficient values presented in Reinhold et al. (1999).

6.2.1. 1:24 Screen Enclosure Models

Four 1:24 scale screen enclosure models were built, each corresponding to a particular roof arrangement. The models are made up of framing members which were laser cut out of basswood sheets at the University's fabrication laboratory (A^2 FabLab). The basswood framing members support a 20x20 fiberglass screen mesh which covers the entire model which can be seen in Figure 17. The models were rigidly attached to an acrylic base which was bolted to a high frequency force balance.

6.2.2. Force Measurements

Mean and peak forces at the base of the models were measured using a very sensitive high frequency force balance shown in Figure 14. The balance has a cruciform shape with a span of 18 in in the long dimension and 12 in in the short dimension. Several rows of 0.25 in holes were drilled and tapped on the balance to accommodate for attachment of different size models. An ATI Nano25 IP65 six-axis force/torque (F/T) load cell was mounted to the bottom side of the balance for force measurements (Figure 15). The load cell is calibrated for sensing ranges of 25 lbf (125 N) in the horizontal direction, 100 lbf (500 N) in the vertical direction, and 25 lbf-in (3 N-m) in moments about the two horizontal axes. Precision weights were used to ensure proper measurement of forces in the directions of interest (Figure 16).

6.2.3. Wind Tunnel Tests

A total of 24 wind tunnel tests were performed for screen enclosures with four common roof configurations. Each enclosure was tested for parallel (wind on end), cornered, and perpendicular (wind on side) wind directions. In addition, a rectangular host structure was introduced beside the screen enclosure for each case as shown in Figure 13. Load cell measurements were taken for two minute segments at a sampling rate of 100 Hz using data acquisition software (DAQ).

Mean and peak forces for base shear, uplift and overturning moments experienced by the models were obtained for each of the 24 cases. Wind speed measurements at the eave height of the enclosures were also recorded using Cobra probe sensors to calculate the velocity pressure at the enclosures' eave heights.

Wind parameters for the screen enclosure tests included:

- Mean wind speed at eave height = 6 m/s [13.4 mph]
- Roughness element height = 2.5 cm [0.98 in]. z0 = 0.005 m [0.016 ft] full-scale equivalent
- Longitudinal turbulence intensity at eave height = 13 %

All results correspond to MWFRS loads on the entire structure. Values of lateral force (drag) coefficients are based on projected solid area perpendicular to the wind direction (Belcher and Miller, 2008). Force coefficients were calculated using the following equation:

$$C_D = \frac{F_{peak}}{\frac{1}{2} \cdot \rho \cdot U_{3-\sec}{}^2 \cdot A_s}$$

F_{peak} is the peak base force directly measured by the load cell. For a 20x20 fiberglass screen mesh, the solid area is approximately 45% the gross area perpendicular to the wind direction. $U_{3-\sec}$ is the peak 3 second gust speed at eave height of the screen enclosure. Measured mean wind speeds $\overline{U}$ at eave height were adjusted to a peak 3-sec gust speed using the following equation:

$$U_{3-\sec} = \overline{U} \cdot 1.53$$

Roof lift force coefficients C_L were obtained in a similar manner using the plan solid projected area of the screen enclosures as shown in the following equation:

$$C_L = \frac{F_{peak}}{\frac{1}{2} \cdot \rho \cdot U_{3-\sec}{}^2 \cdot A_{plan}}$$

All peak coefficient values include any gust effect factor since the peaks forces were measured directly from the load cell. Table 1 compares peak drag coefficient values obtained in this study with results from Reinhold et al. (1999). Table 2 summarizes peak uplift coefficients for all cases considered.

6.2.4. Findings

Both drag and uplift coefficient values found in this study compare reasonably well with measured coefficients form the 1999 Clemson tests.

Two major findings of both studies include the following:

- The highest peak drag coefficient was observed in the free-standing monoslope screen enclosure with the wind acting parallel to the short dimension (wind angle = 0 degrees)
- The gable roof screen enclosure produced the highest peak drag coefficient when a rectangular host structure was placed adjacent to the enclosure

7. Suggestions for Future Work

C&C load characterization of roof and wall panels. The rigid models will be replicated/modified to incorporate load measurements systems for individual panels to characterize peak loads occurring on the individual panels. The priority will be to measure roof loading, particularly to better understand how air communication affects the uplift loads

8. References

- Ho, T.C.E., D. Surry and D. Morrish, 2003: NIST/TTU Cooperative Agreement – Windstorm Mitigation Initiative: Wind Tunnel Experiments on Generic Low Buildings, BLWT-SS20-2003, University of Western Ontario. Available at http://fris2.nist.gov/winddata/uwo-data/uwo-data.html
- Reinhold, T.A., J. Belcher, D. Miller and C. Everley, 1999: Wind loads on screen enclosures. Clemson University Wind Load Test Facility Report
- J. Belcher and D. Miller, 2008. Aluminum Association of Florida, Inc., South Florida Chapter, Miami Lakes, Florida.
- C. Harthan, 2012. Tubing Response Correction. Scanivalve Co., Liberty Lake, WA.

9. Tables and Figures

Table 1. Screen Enclosure Drag Coefficients

Roof Type	Case	Wind Angle (deg)	F_{peak} Drag (N)	A_s (m^2)	$\frac{F_{peak}}{A_s}$ (Pa)	$\frac{1}{2}\rho U_{3-s}{}^2$ (Pa)	C_D	
							Current Study	Reinhold et al. (1999)
Gable	Screen Enclosure	0	1.40	0.021	66.8	49.8	1.34	1.52
		45	1.83	0.041	44.9	51.5	0.87	NA
		90	1.89	0.037	51.8	48.1	1.08	1.19
	Screen Enclosure + Host	0	1.46	0.021	69.7	51.4	1.36	1.37
		45	1.56	0.041	38.4	50.4	0.76	NA
		90	1.25	0.037	34.3	48.9	0.70	0.71
Monoslope	Screen Enclosure	0	1.37	0.019	73.7	50.1	1.47	1.64
		45	1.59	0.035	45.8	50.4	0.91	NA
		90	1.69	0.030	55.6	48.8	1.14	1.59
	Screen Enclosure + Host	0	1.05	0.019	56.5	50.8	1.11	1.18
		45	1.54	0.035	44.3	50.4	0.88	NA
		90	1.37	0.030	44.9	50.3	0.89	0.77
Hip	Screen Enclosure	0	1.32	0.021	62.7	49.6	1.27	1.35
		45	1.56	0.036	43.4	49.9	0.87	NA
		90	1.66	0.033	50.1	48.2	1.04	1.23
	Screen Enclosure + Host	0	0.93	0.021	44.1	51.3	0.86	1.02
		45	1.35	0.036	37.6	49.6	0.76	NA
		90	1.37	0.033	41.3	50.1	0.82	0.74
Mansard	Screen Enclosure	0	1.12	0.022	50.6	48.7	1.04	NA
		45	1.91	0.038	49.8	50.3	0.99	NA
		90	1.97	0.034	57.4	49.3	1.16	NA
	Screen Enclosure + Host	0	1.17	0.022	52.8	52.0	1.02	NA
		45	1.39	0.038	36.3	50.2	0.72	NA
		90	1.49	0.034	43.4	49.2	0.88	NA

Table 2. Screen Enclosure Lift Coefficients

Roof Type	Case	Wind Angle (deg)	F_{peak} Uplift (N)	A_{plan} (m^2)	$\frac{F_{peak}}{A_{plan}}$ (Pa)	$\frac{1}{2}\rho U_{3-s}{}^2$ (Pa)	C_L	
							Current Study	Reinhold et al. (1999)
Gable	Screen Enclosure	0	0.64	0.066	9.7	49.8	0.20	0.13
		45	0.72	0.066	10.9	51.5	0.21	NA
		90	0.76	0.066	11.5	48.1	0.24	0.25
	Screen Enclosure + Host	0	0.57	0.066	8.6	51.4	0.17	0.13
		45	0.31	0.066	4.7	50.4	0.09	NA
		90	0.55	0.066	8.3	48.9	0.17	0.11
Monoslope	Screen Enclosure	0	0.42	0.066	6.4	50.1	0.13	0.18
		45	0.50	0.066	7.6	50.4	0.15	NA
		90	0.73	0.066	11.1	48.8	0.23	0.23
	Screen Enclosure + Host	0	0.77	0.066	11.8	50.8	0.23	0.11
		45	0.58	0.066	8.8	50.4	0.18	NA
		90	0.64	0.066	9.7	50.3	0.19	0.18
Hip	Screen Enclosure	0	0.56	0.075	7.4	49.6	0.15	0.11
		45	0.51	0.075	6.7	49.9	0.14	NA
		90	0.85	0.075	11.3	48.2	0.24	0.17
	Screen Enclosure + Host	0	0.55	0.075	7.3	51.3	0.14	0.1
		45	0.37	0.075	4.9	49.6	0.10	NA
		90	0.71	0.075	9.4	50.1	0.19	0.18
Mansard	Screen Enclosure	0	0.63	0.088	7.2	48.7	0.15	NA
		45	0.77	0.088	8.8	50.3	0.18	NA
		90	1.04	0.088	11.9	49.3	0.24	NA
	Screen Enclosure + Host	0	1.25	0.088	14.3	52.0	0.27	NA
		45	0.86	0.088	9.8	50.2	0.19	NA
		90	0.69	0.088	7.9	49.2	0.16	NA

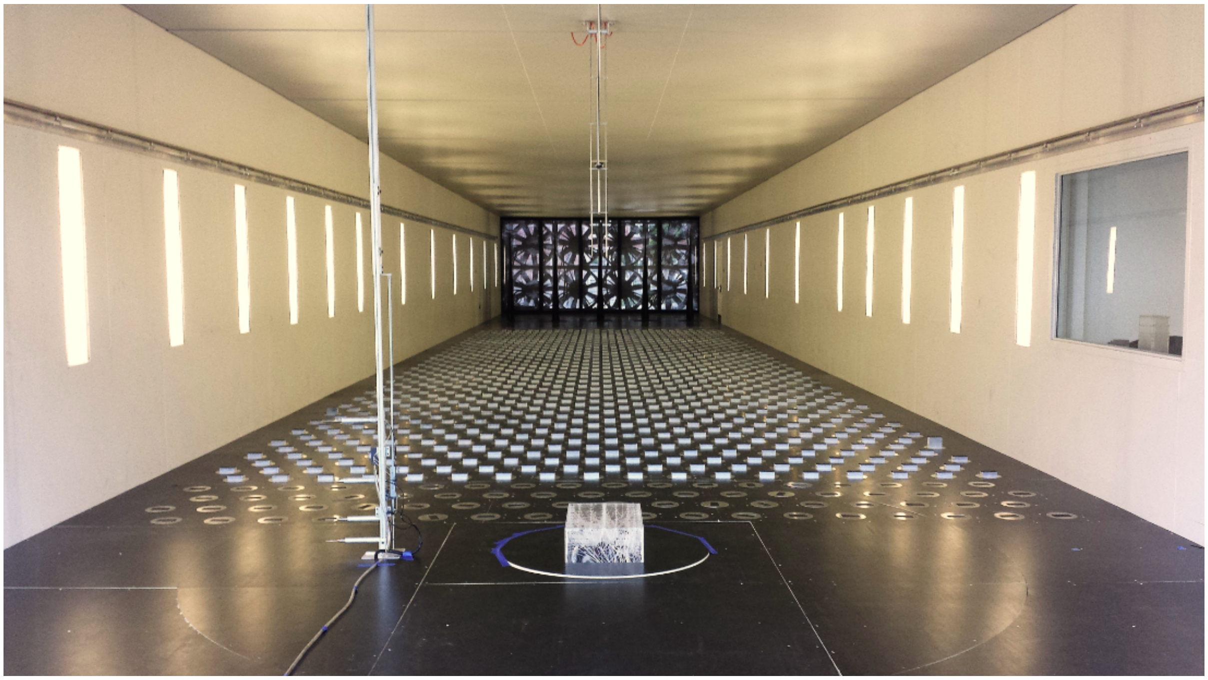

Figure 1. Wind tunnel test of 1:24 scale WERFL building in open terrain (z_0 = 0.01 m)

Figure 2. TFI Cobra Probes

Figure 3. 1:24 scale WERFL building at 0 (left), 45 (middle), and 90 (right) degree orientations

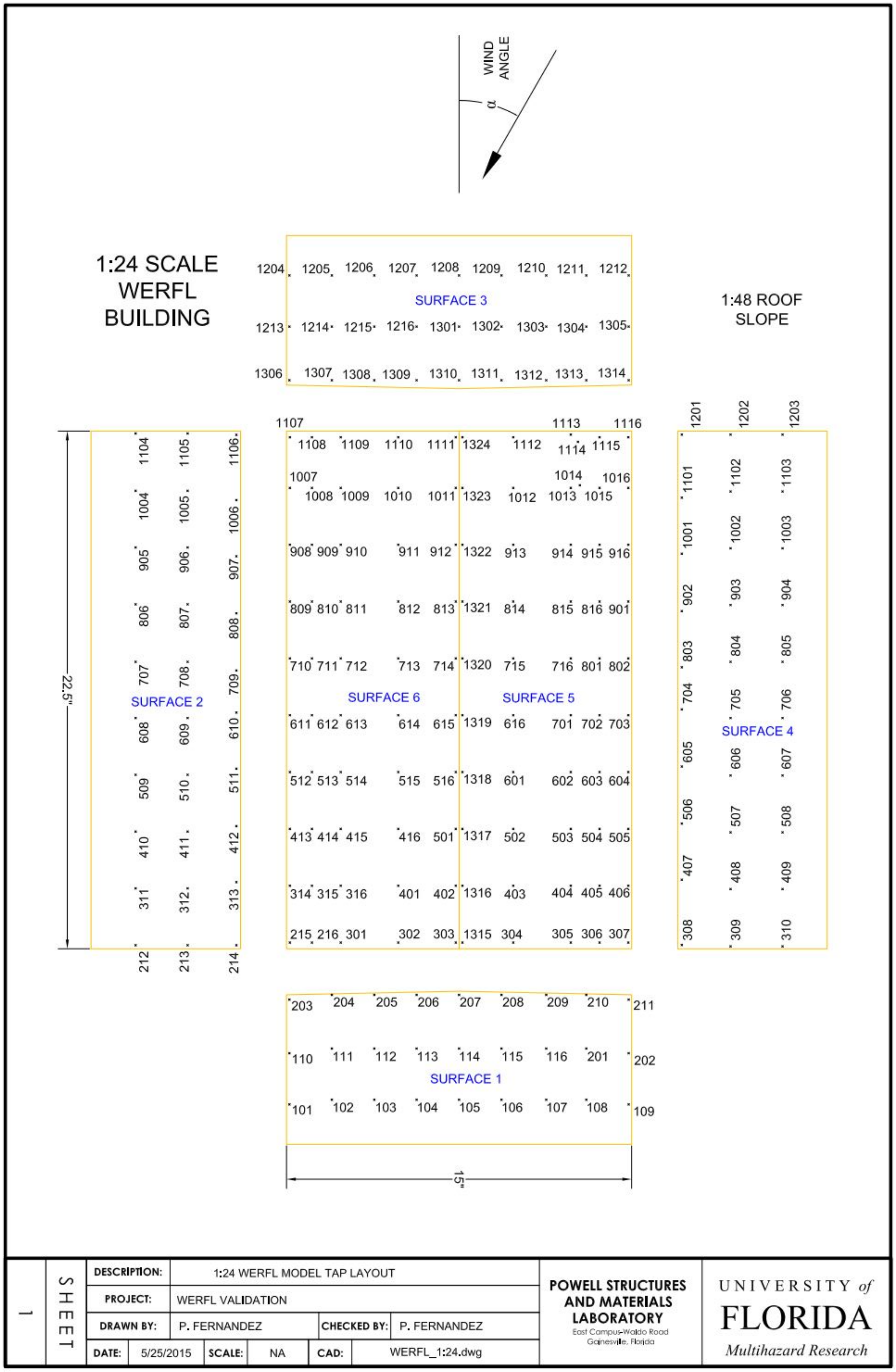

Figure 4. Pressure tap layout for 1:24 scale WERFL building model

Figure 5. Tubing frequency response correction test setup. 512-channel pressure scanning system (left) and pneumatic frequency signal source box with amplifier (right).

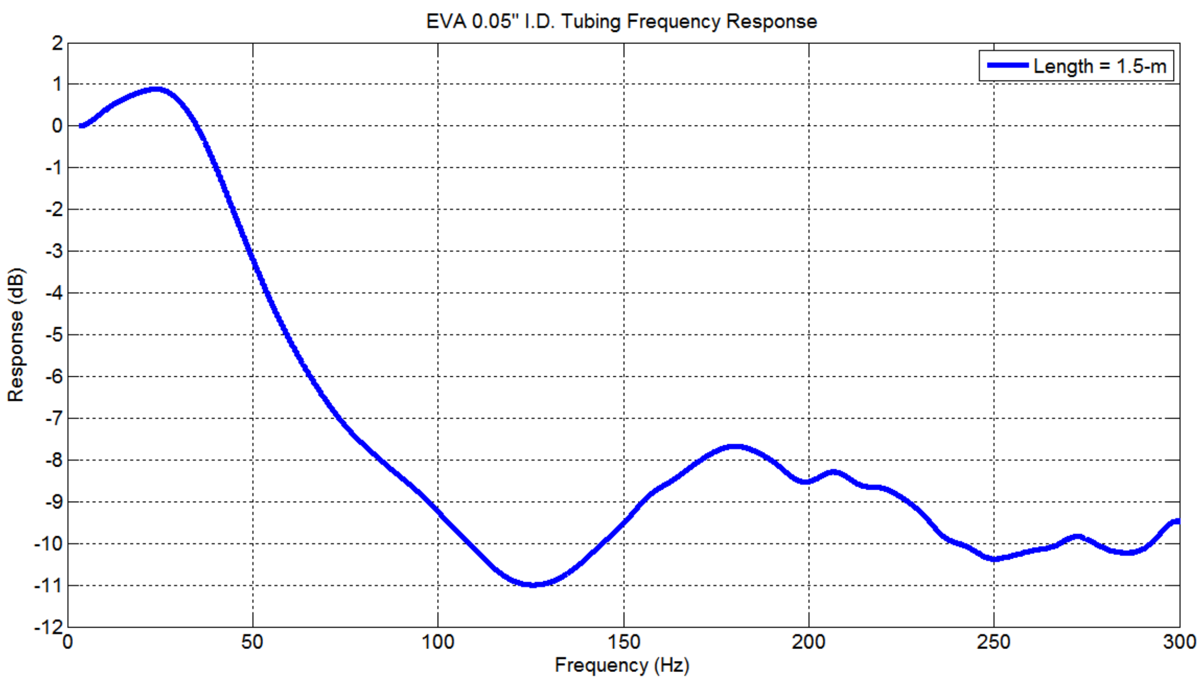

Figure 6. Response of 0.05” inner diameter EVA tubing

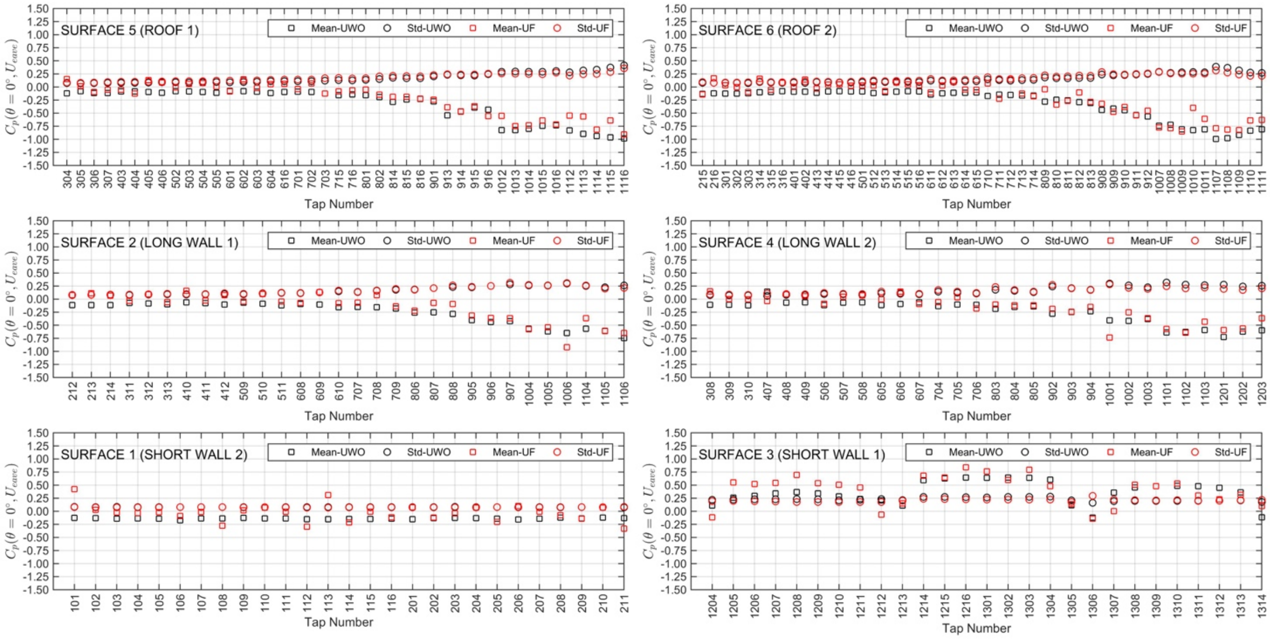

Figure 7. WERFL 1:24 Cp values for open exposure (z0 = 0.01 m) and wind direction parallel to roof ridgeline (0 degrees)

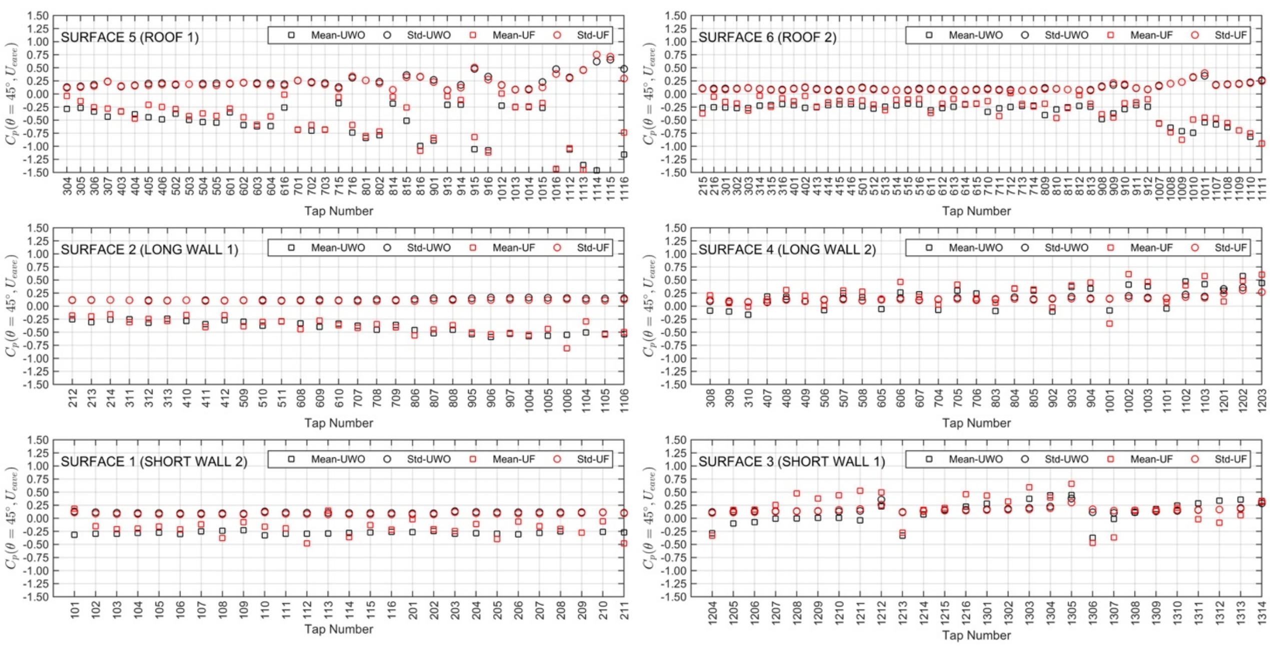

Figure 8. WERFL 1:24 Cp values for open exposure (z0 = 0.01 m) and cornered wind direction (45 degrees)

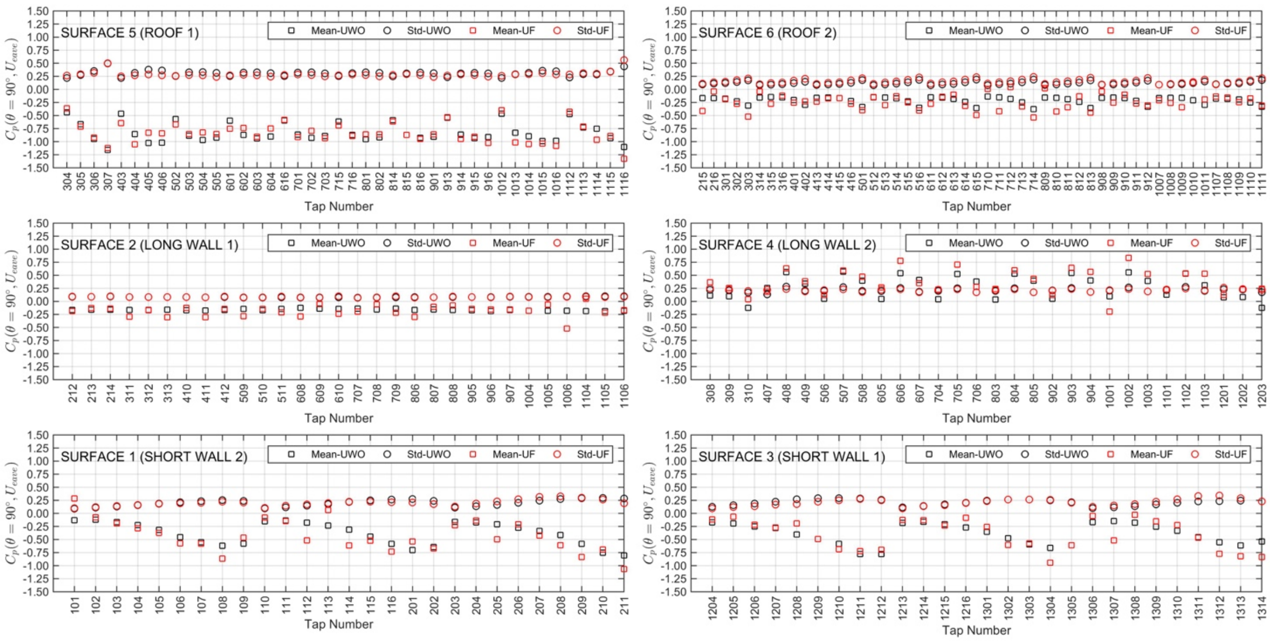

Figure 9. WERFL 1:24 Cp values for open exposure (z0 = 0.01 m) and wind direction perpendicular to roof ridgeline (90 degrees)

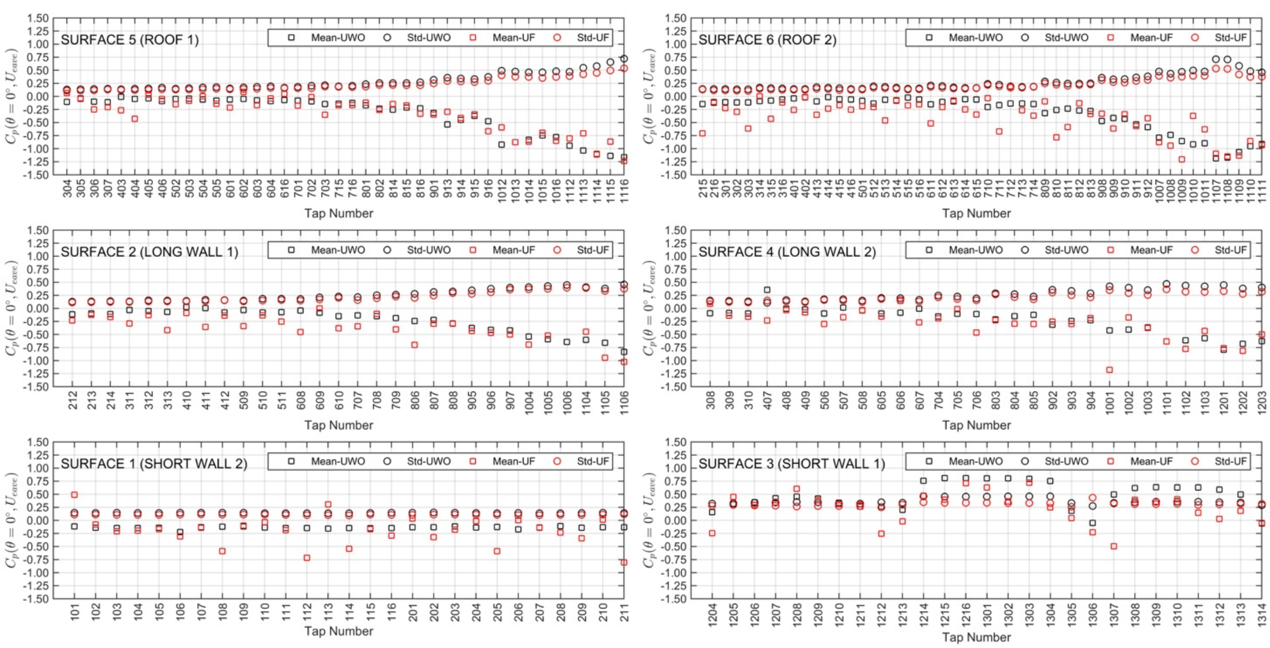

Figure 10. WERFL 1:24 Cp values for suburban exposure (z0 = 0.087 m) and wind direction parallel to roof ridgeline (0 degrees)

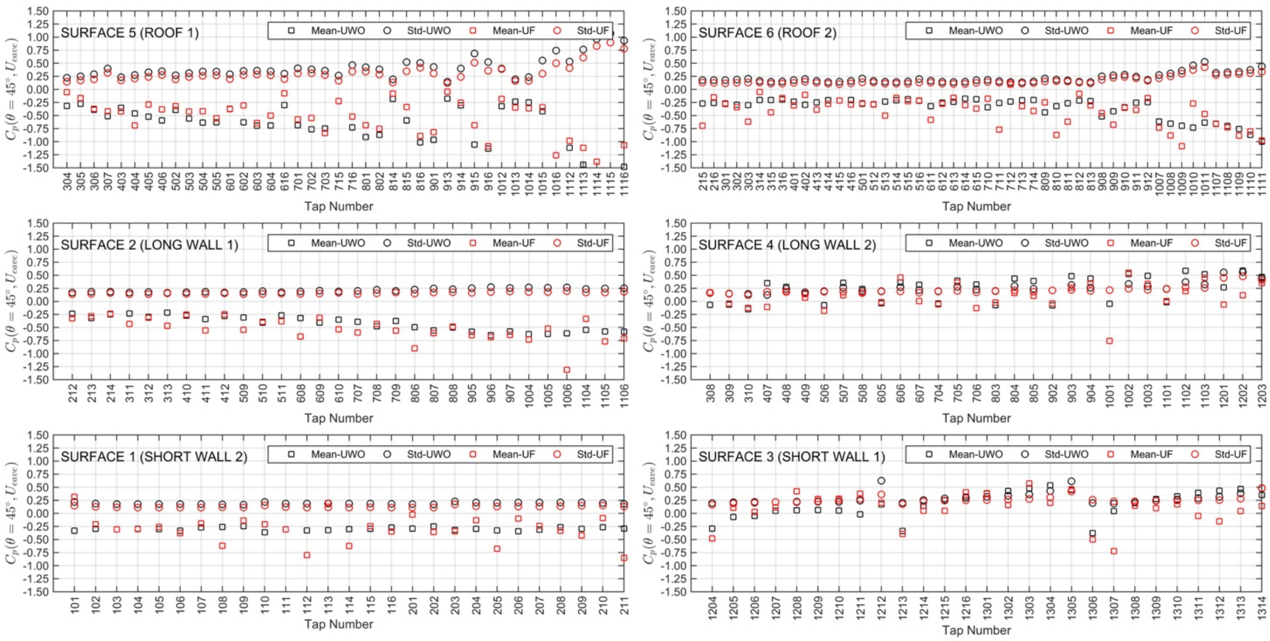

Figure 11. WERFL 1:24 Cp values for suburban exposure (z0 = 0.087 m) and cornered wind direction (45 degrees)

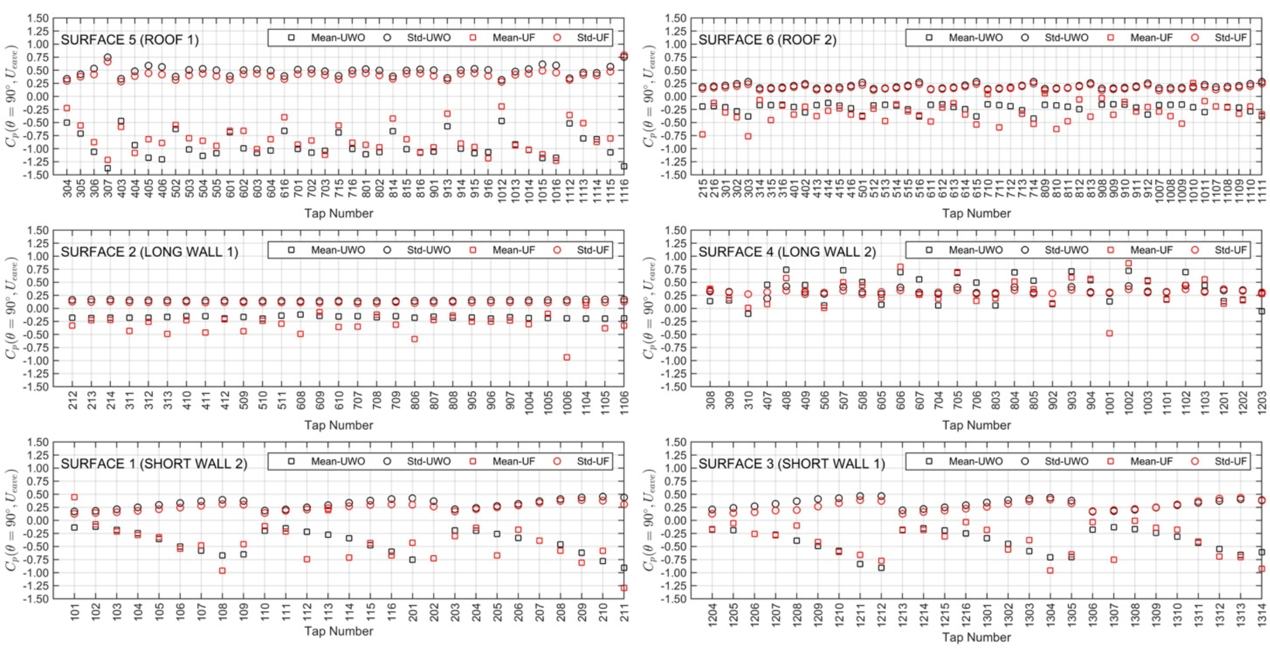

Figure 12. WERFL 1:24 Cp values for suburban exposure (z0 = 0.01 m) and wind direction perpendicular to roof ridgeline (90 degrees)

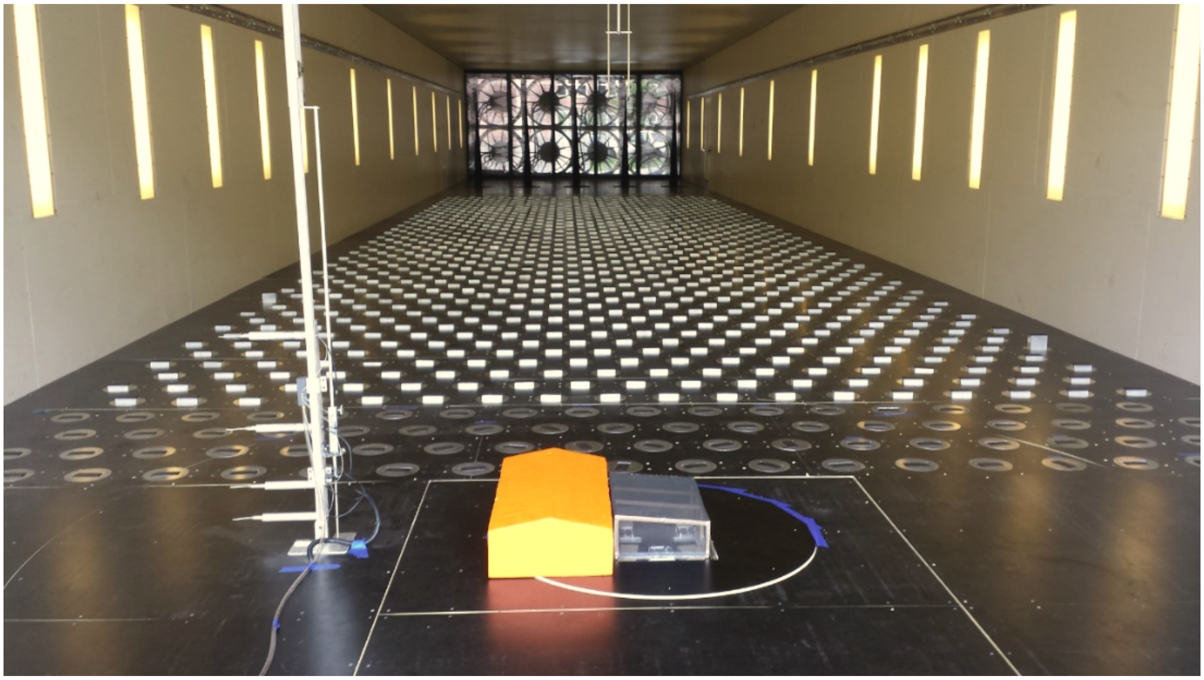

Figure 13. Wind tunnel test of 1:24 scale monoslope roof screen enclosure with host structure with wind direction parallel to the ridgeline

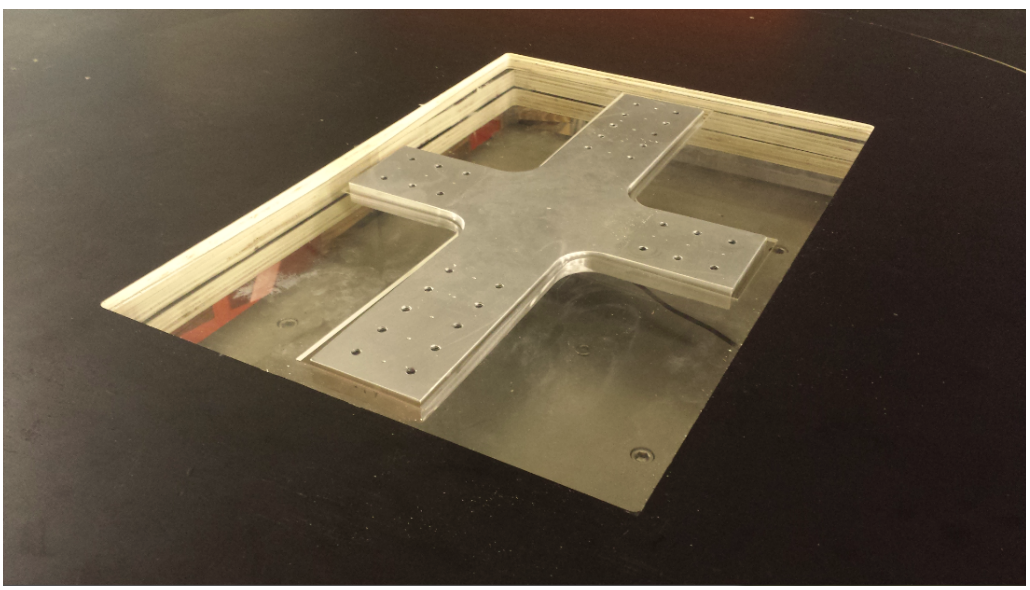

Figure 14. High-frequency force balance mounted on wind tunnel test section

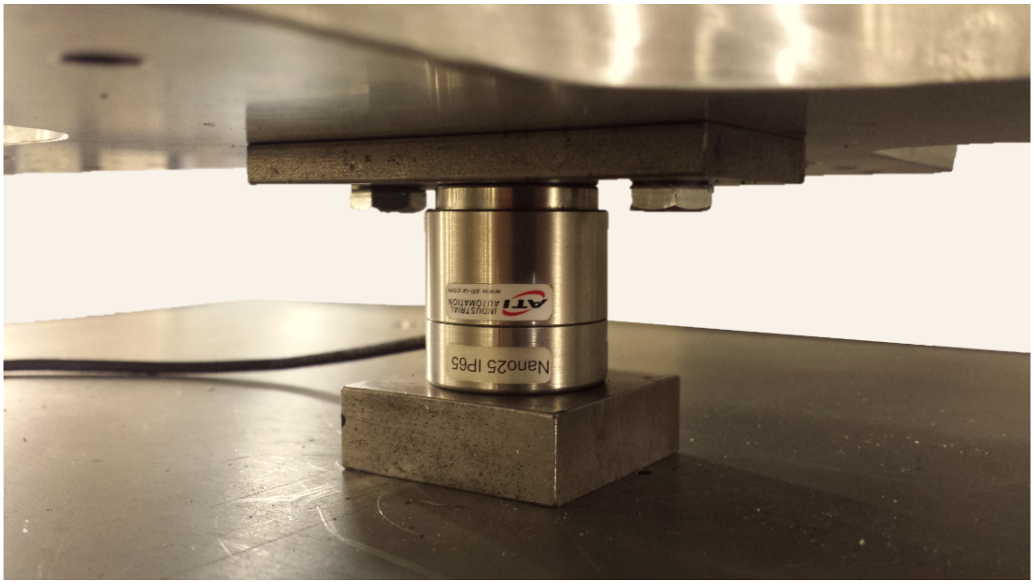

Figure 15. ATI Nano25 IP65 six-axis Force/Torque (F/T) sensor

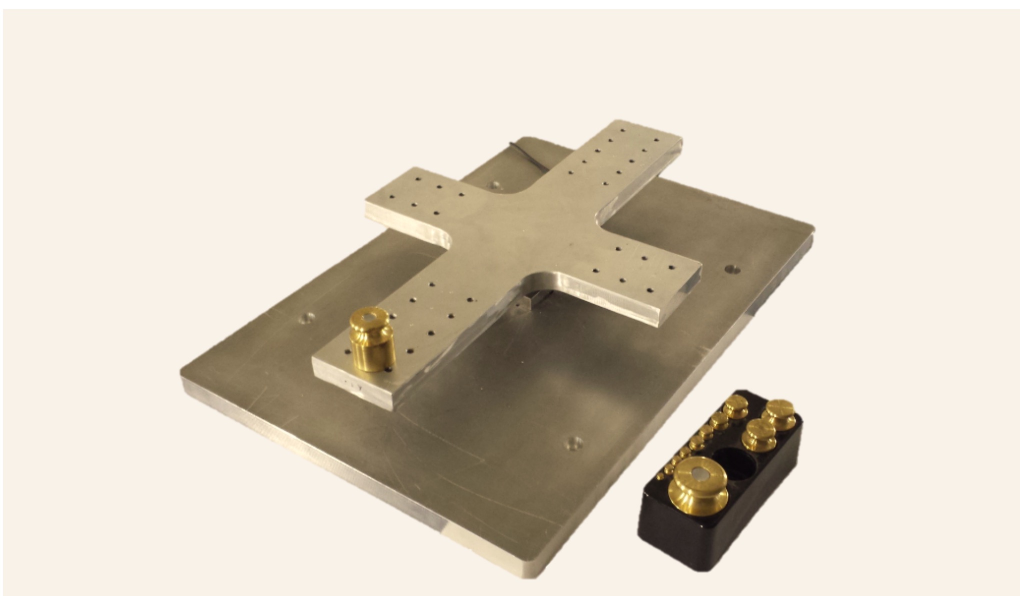

Figure 16. Calibration of high-frequency force balance

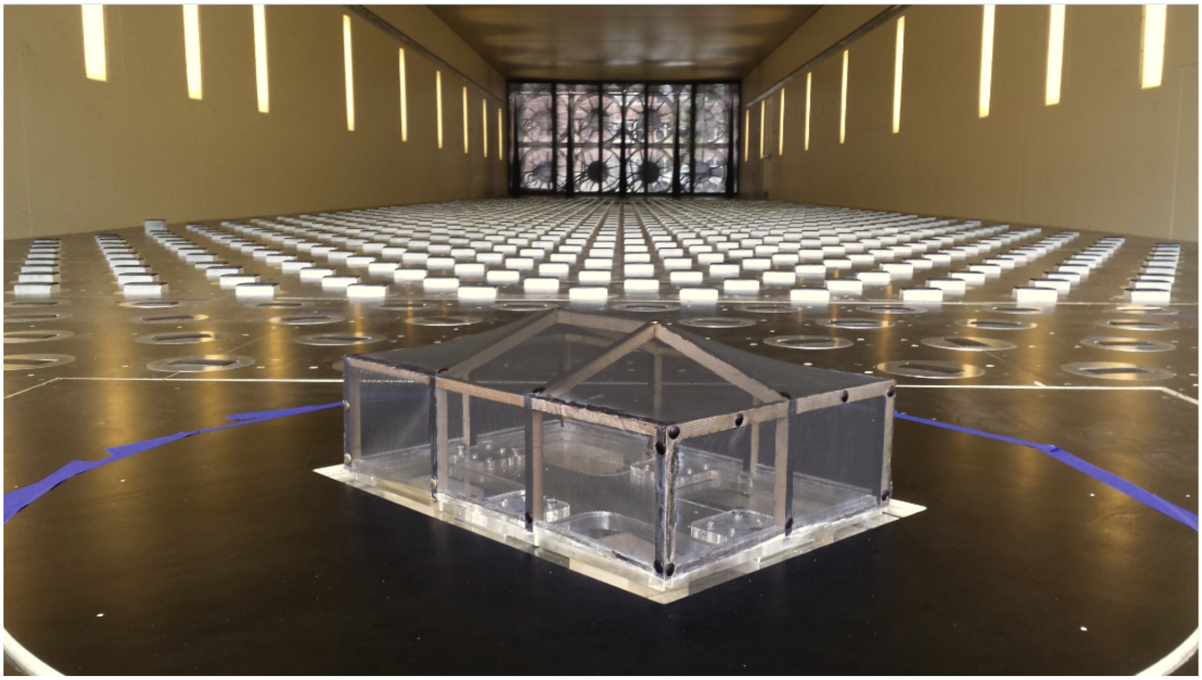

Figure 17. Wind tunnel test of 1:24 free-standing hip roof screen enclosure at a 45 degree wind angle

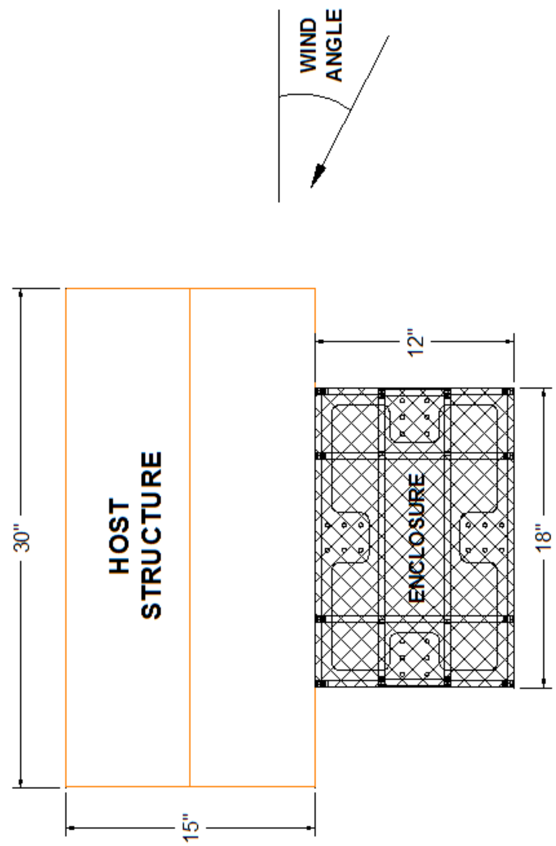

Figure 18. Plan view of 1:24 scale screen enclosure model and host structure

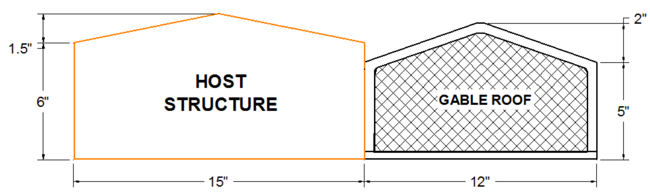

Figure 19. Elevation view of 1:24 scale gable roof enclosure with host structure

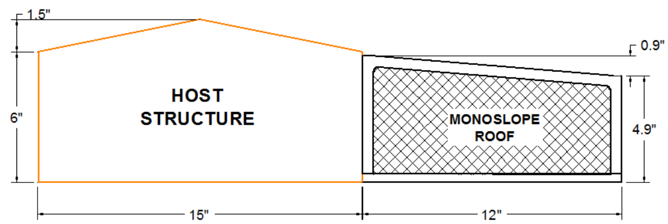

Figure 20. Elevation view of 1:24 scale monoslope roof enclosure with host structure