Final Report for Project Entitled:

Assessing the Need to Modernize Water Penetration Resistance Test Procedures
PO Number C07078

Performance Period: 08/01/2022 – 6/30/2023

Submitted on

June 08, 2023

Presented to the

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

by

Ryan A. Catarelli, Ph.D., rcatarelli@ufl.edu, (727) 686-3901, Principal Investigator
Brian M. Phillips, Ph.D., brian.phillips@essie.ufl.edu, (352) 294-6394

Designated Project Leader: Ryan Catarelli

Engineering School of Sustainable Infrastructure & Environment

UF UNIVERSITY of FLORIDA

Table of Contents

1. Executive Summary

Existing static and cyclic water penetration test procedures for building envelope systems apply enveloped pressure and wetting conditions to simulate hurricane wind and wind-driven rain (WDR) effects. While they serve as a good first approximator for evaluating product performance, these procedures have not benefited from advances in scientific knowledge and technology that have occurred over the last several decades. In this research project, the investigator assessed the need for modernization of water penetration test procedures used for product approval by conducting experimental research using low-cost and straightforward-to-use technologies to compare "simplified" and "real-world" water penetration resistance testing.

This final report details the efforts and outcomes of all tasks listed in Section 4. The investigator began by convening an advisory group to guide the research program. With feedback from the advisory group, a test matrix was developed to study parameters that influence water ingress through generic building envelope penetrations (i.e., slot openings). The slot openings were subject to pressure sine sweeps of varying amplitude to investigate potential amplitude-dependent threshold frequencies above which applied pressure fluctuations no longer affect the water flow through the building envelope. This process is analogous to system identification procedures used in many fields of engineering to characterize dynamic systems. The application of extreme wetting rates was also studied to determine if a maximum upper bound for wetting exists. Staging and setup of the testing area was completed. Generic slot specimens and their fixtures were designed and fabricated. Round 1 testing was conducted, and summary data are presented in the report. The investigator presented the interim report for the research program to the Florida Building Commission's (FBC) Hurricane Research Advisory Committee (HRAC) by teleconference on March 23, 2023.

With feedback received during the HRAC meeting, additional advisory group members were identified and invited to provide guidance on subsequent rounds of testing. Two additional rounds of experimental testing were planned on real fenestration units with final input from the advisory group provided during the subsequent advisory group teleconference. Hurricane passage simulations were developed from available data and methodologies found in literature. The representative selection of operable windows and doors was made as a first step in understanding wind-driven rain (WDR) water ingress through building envelope systems. From the resulting analysis, guidance was developed regarding the implementation of improved standard testing procedures. A method to relate existing testing procedures to new methods of testing based on the results from the research was also explored.

2. Disclaimers

- 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 experimental hurricane test procedures presented herein is not intended (i) to be performed in accordance with any then-current or -applicable industry standards, laws, rules, regulations, building codes, or other guidelines for products of this type, or (ii) to determine whether the tested products comply with then current or -applicable industry standards, laws, rules, regulations, building codes, or other guidelines for products of this type. The testing is intended to apply UF's facilities, knowledge, research, and other information regarding unexpected hurricane and other unusual storm related conditions to various products to identify new testing procedures that do not currently exist and which may enable manufacturers to improve their products.

3. Applicable Water Penetration Test Standards/Procedures

- TAS 202-94 – Criteria for Testing Impact and Nonimpact Resistant Building Envelope Components Using Uniform Static Air Pressure Loading
- AAMA/WDMA/CSA101/I.S.2/A440-22 – Standard Specifications for Windows, Doors, and Unit Skylights

- AAMA/WDMA/101/I.S. 2/NAFS-02 – Voluntary Performance Specification for Windows, Skylights and Glass Doors
- ASTM E 331 – Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference
- ASTM E 547 – Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Cyclic Static Air Pressure Difference
- ASTM E1105 – Standard Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors and Curtain Walls by Uniform or Cyclic Static Air Pressure Difference
- ASTM E2128 – Standard Guide for Evaluating Water Leakage of Building Walls

4. Scope of Work

- Task 1 - Form a stakeholder advisory group to guide the research program
- Task 2 - Simulate hurricane-like wind pressure loading and wind-driven rain events from available data with input from the advisory group for application on selected building envelope systems, apply standard static and cyclic testing to produce a baseline for comparison, and apply pressure sine sweeps to determine the (amplitude-dependent) threshold frequency at which applied pressure fluctuations no longer affect the flow through the building envelope
- Task 3 - Analyze the data collected during the physical testing campaign at UF and proceed with data interpretation in a format that can be utilized by the FBC and industry
- Task 4 - Develop guidance regarding the implementation of improved standard testing procedures based on results from the test campaign, and develop a method to correlate existing testing procedures to new methods of testing based on the results from the research

5. Deliverables

- Interim report by February 28, 2023 – Interim report detailing progress to date on all tasks. The report will serve as a progress update that details the current state of research, preliminary results, and descriptions of any issues that may have been encountered. In addition, the interim report will be formally presented to the FBC's Hurricane Research Advisory Committee at a time agreed to by the Contractor and Department's Program Manager. The due date may be extended with the approval of the Department's Program Manager.
- Final report by June 1, 2023 containing deliverables of the four tasks discussed in Section 4. This will include summary and analysis of data acquisition, wind pressure/wetting time histories, and water infiltration and displacement time histories. In addition, the final report will be formally presented to the FBC's Hurricane Research Advisory Committee at a time agreed to by the Contractor and Department's Program Manager. The due date may be extended with the approval of the Department's Program Manager.

6. Project Overview

The project investigated the following research areas and limitations of current standard test methods:

- Steady pressure/wetting conditions are not physically realizable in a hurricane. Turbulence in the upwind flow and the flow distortion around the building cause significant spatiotemporal variation in pressure acting on the building surface. Only applying a steady "worst case" load fails to simulate the "lulls" that promote drainage – a principal design consideration for product manufacturers
- Cyclic pressure test procedures allow for lulls that promote drainage but are not representative of real-world rates of pressure fluctuation

- The origin and applicability of the wind load intensity definition (e.g., 15% or 20% of the design pressure for fenestration in water infiltration tests) remains unclear and is a major but easily addressable knowledge gap
- The basis for the current minimum wetting rate (i.e., 5.0 gph/sf) originates from trial-and-error testing to determine the threshold required to cause uniform sheeting of water on a curtain wall. It does not consider key factors such as climatology, approach wind speed, location on the building, etc.
- Defining "failure" as a single drop passing into the building interior is not a representative measure of water damage, as the unmanaged accumulation of water over an entire hurricane episode is the principal driver for damage to walls, interiors, and building contents

Task 2 (see Section 4) is broken up into the three rounds of testing. The experimental equipment used in this project is described in Section 7. For Round 1, the test matrix is shown in Section 8.1 and the test results are presented in Section 8.2. Focus areas included pressure sine sweep testing to determine the (amplitude-dependent) threshold frequency at which applied pressure fluctuations no longer affect the flow through the building envelope. The application of extreme wetting rates exceeding the industry-accepted 5 gph/sf was also studied to determine if a maximum upper bound for wetting exists. To explore these phenomena, Round 1 used a reconfigurable experimental setup with generic features to ensure that the findings are generalizable to real fenestrations in subsequent rounds of hurricane-like wind pressure testing.

Feedback from Advisory Committee: As part of Task 1, the investigator convened an advisory group formed by members of the Building Envelope Science Institute (BESI), the American Wood Council (AWC), the Insurance Institute for Business and Home Safety (IBHS), the Miami-Dade Product Control Division, and fenestration manufactures to discuss issues related to water ingress through building envelop systems. The first teleconference was held on February 02, 2023. The group agreed to proceed with the Round 1 test plan discussed herein. The group also agreed that additional standard test procedures (e.g., ASTM E331 and ASTM E547) should be performed on all fenestrations to provide a baseline for comparison—these were included in Rounds 2 and 3 of experimental testing.

After presenting the project at the HRAC meeting by teleconference on March 23, 2023, additional members were added to the advisory group including members of the Fenestration Glazing Industry Alliance (FGIA), an additional member from IBHS, and additional product manufacturers. Guidance was provided on the types of specimens and sourcing options for Rounds 2 and 3 of testing. Valuable feedback was provided on the test matrix and standard testing procedures to be conducted for baseline comparisons. For Rounds 2 and 3, the hurricane wind simulation development is shown in Section 9.1, the test matrix is shown in Section 9.2 and the test results are presented in Section 9.3. Focus areas included hurricane wind pressure and wind-driven rain loading on fenestrations. Major findings are listed in Section 10, considerations and limitations of the research project are listed in Section 11, guidance on the implementation of improved standard testing procedures are presented in Section 12, and references are listed in Section 13.

Major Activities: The major activities (conducted with the assistance of laboratory staff) included:

- Staging and setup of the testing area, including tuning of the experimental equipment's closed-loop control system to apply sinusoidal pressure fluctuations, was performed along with inspection checkouts of the individual system components
- Design of test specimens was completed with fabrication followed shortly thereafter. Detail sheets for the reconfigurable assembly can be found in **Appendix A**
- Testing of generic test specimens
- Construction of five wall units to accept a range of specimen types
- Development of hurricane passage simulations using methodologies found in literature and available data sources such as the NOAA Hurricane Research Division H*Wind surface wind field analyses, the NIST Aerodynamic Database, and Global Precipitation Climatology Project

- Testing of operable windows and doors
- Data analysis and interpretation

7. Experimental Equipment

Time-varying pressure sequences were applied to window and door specimens using the closed-loop control system of the High Airflow Pressure Loading Actuator (HAPLA) that receives feedback from an absolute pressure transducer located within the test chamber (see Figure 1). The system actuates a high-performance bi-directional valve which can produce rapid pressure changes. The face of the pressure chamber accepts each test specimen installed in a wood stud-framed wall unit (**Appendix B**). Use of this wall unit ensures that structural displacements under fluctuating wind loads, and thus impacts on specimen leakage, are similar to real-world conditions. Water was applied to the specimen surfaces using a rain rack system mounted inside the test chamber and calibrated to approximate field measurements of WDR intensities. Structural displacements were measured using a set of laser displacement sensors targeted at points of interest on each specimen (e.g., frame, glazing center points, and meeting rails). Water infiltration was measured using a high-resolution scale and water collection system to detect water quantities ranging from single droplets to gallons of flow per minute.

Figure 1. UF HAPLA experimental setup with wood stud-framed wall unit: A) Round 1 test specimen; and B) Round 2 test specimen.

8. Round 1 – Learning Phase on Generic Specimens

Round 1 of experimental testing is broken into two parts (1A and 1B). Round 1A investigates the relationships between applied sinusoidal pressure fluctuations with varying wind-driven rain intensities and horizontal opening types that represent a range of generic operable window/door configurations. This type of testing is intended to follow methods for system identification (Keesman and Keesman, 2011) common in many fields of engineering such as aerospace, automotive, chemical, electrical, and mechanical. This method is beneficial when a system is too complex to be easily modelled, and generally uses a black box input-output relationship to generate a transfer function for a given system.

8.1. Specimens & Test Matrix

This experimental setup consists of slots with fixed width (w = 48 inches) and variable height (h), a trough, and variable height risers (h_R) to contain the water flowing through the slots. Figure 2 shows a schematic view of the experimental setup with test panel geometry called out and an applied pressure sine sweep trace input depicted near the top. Applied pressure (P_{M}), wetting (R_{WDR}), and instantaneous flowrate ($Q(t)$) through the specimens were measured for each test. Only one opening type (i.e., horizontal or vertical) is tested at a time. The other opening is sealed with a blank plate. Section A-A in Figure 2 shows the path that water can take out of the test chamber. For given pressure and wetting inputs, the rate that water flows out through the system is modulated by the combination of h and h_R.

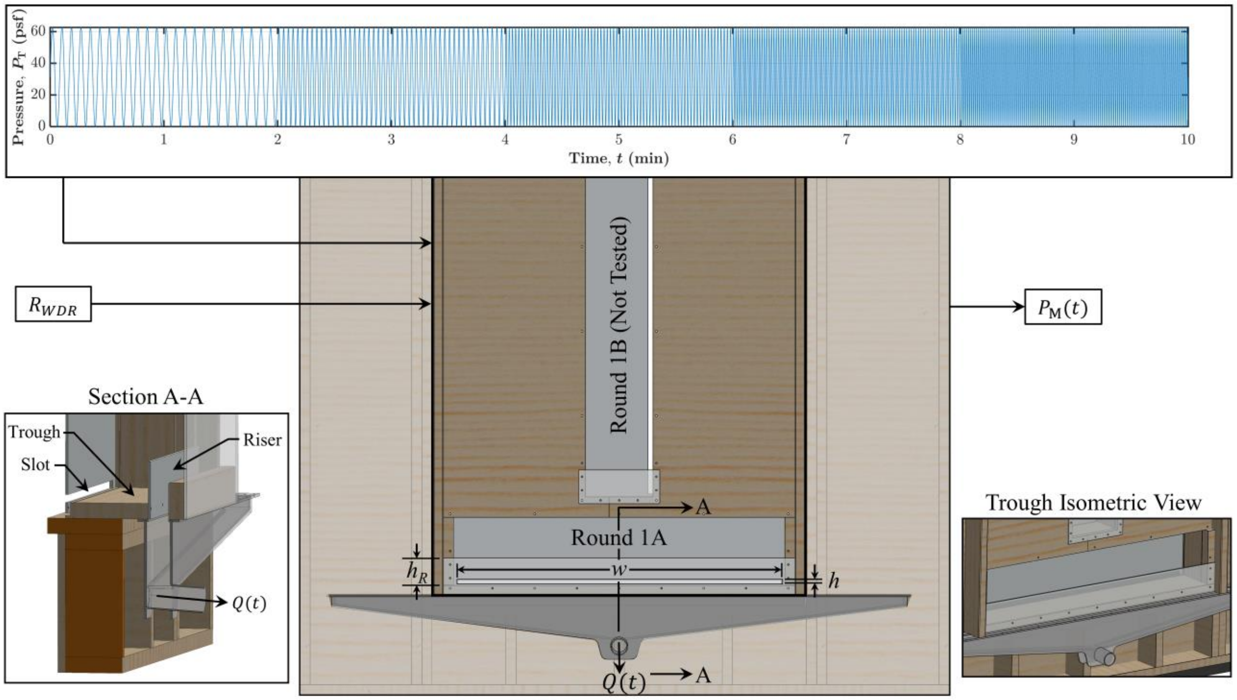


Figure 2. Schematic diagram of Round 1 experimental setup.

Table 1 shows the relevant test variables. In Round 1A, three (3) horizontal opening specimens of varying slot height h were evaluated under various pressure, wetting, and riser conditions. Each test was 10 minutes in duration and swept through five (5) frequencies of pressure from low to high for two (2) minutes at each frequency. For each specimen, three (3) pressure amplitudes were tested at each of three (3) wetting rates for a total of nine (9) tests. Additionally, each specimen was tested with four (4) riser conditions resulting in a total of 36 tests per specimen.

The total set of tests run was 108 for a total of approximately 20 test hours (not including reconfiguration time). Time permitting, additional horizontal opening specimens will be added to Round 1A. Round 1B will follow the Round 1A test matrix for a vertical opening and will be completed shortly after submission of the interim report.

Table 1. Round 1 configurations and experimental parameters.

	Sine Sweep Frequencies	Pressure Amplitudes	Wetting Rates	Slot Heights	Openings	Riser Heights
Nomenclature	f	A	R_{WDR}	h	N/A	h_R
Units	Hz	psf	gph/sf	inch	N/A	inch
Quantity	5	3	3	3	2	4
Variable	0.2,0.4,0.6, 0.8,1.0	5.22,15.67,31.34	5.2,15.7,31.3	1/16,1/8,1/4	Horizontal, Vertical	0.5,1.0,2.0,4.0

8.2. Results & Discussion

In accordance with Task 3, data analysis from Round 1A of testing is presented in Figures 3-6. An example of one sine sweep segment is shown in Figure 3 to illustrate the sine sweep process, which occurs as follows: a sinusoidal pressure trace is input into the control system; the proportional integral derivative (PID) controller follows the trace; and the resulting applied pressure and flow out of the system is measured. The three subplots in the figure show the target pressure (P_{T}) and measured pressure (P_{M}) fluctuations produced by the closed-loop HAPLA control system, the measured water ingress (W_{IN}) using the high-resolution scale, and the flow rate (Q) calculated by the taking the time derivative of the scale measurement. The observed water ingress behavior is complex, but in general the behavior of the system to catch water and permit drainage during lulls in the pressure is observed as expected. This can be observed in Figure 3C, where the flowrate increases and decreases in response to the applied pressure (with phase lag caused by the travel time from the trough to the scale).

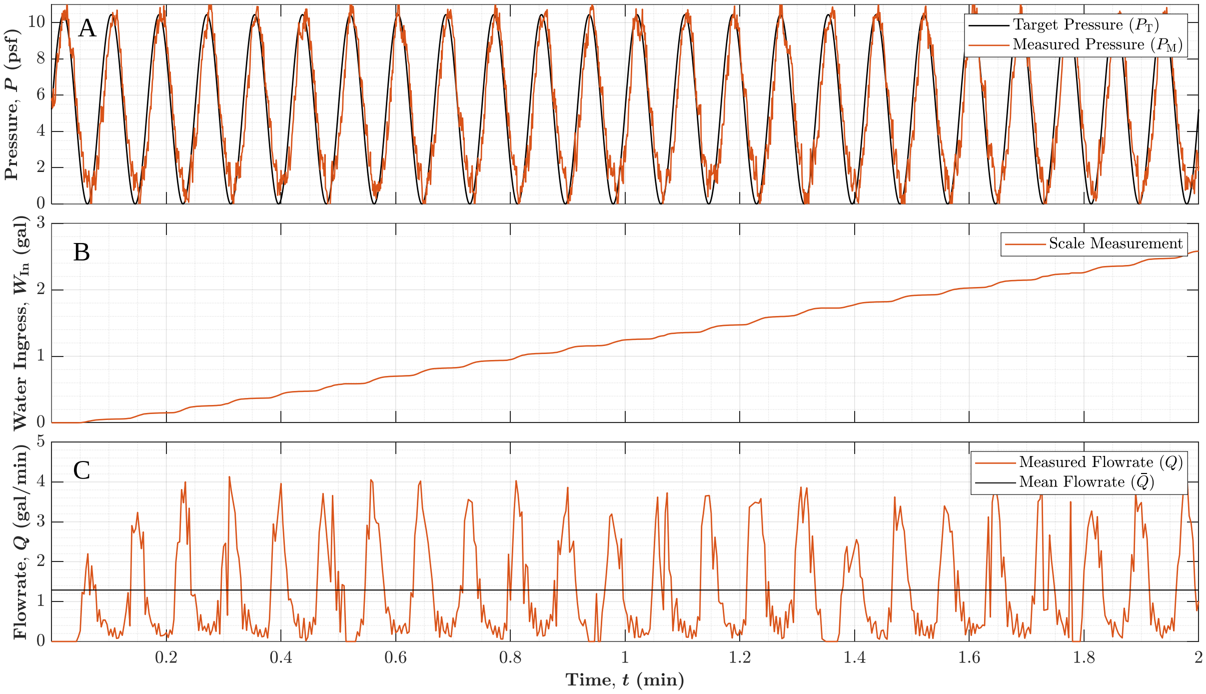


Figure 3. Example application of a two-minute 0.2 Hz pressure trace to h = 1/8 inch slot specimen with a peak pressure of 10.44 psf, a 0.5 inch riser height, and a 7.5 gph/sf wetting rate: A) applied pressure trace; B) water ingress from scale measurement; and C) calculated flowrate.

Results from each experimental configuration (see Table 1) are plotted in Figures 4-6. Each figure contains 12 subplots, one for each combination of riser heights (4) and applied peak pressures (3). Within each subplot, the three wetting rates (3) are shown. An individual subplot shows the frequency-dependent average flowrate ($\bar{Q}$) for a given test configuration. The results from Round 1A indicate that a threshold wetting rate has not been reached since all tests for which there is significant water ingress show increases in ingress as wetting increases even beyond 5 gph/sf. The results also indicate that a threshold (maximum) frequency has not yet been reached and in some cases the water ingress begins to increase at the maximum applied frequency. This indicates that frequencies higher than 1 Hz may need to be included in the hurricane wind pressure simulation traces. One clear trend is the effectiveness of risers in reducing average flowrate ($\bar{Q}$) regardless of the other test parameters. Also, riser effectiveness reduces as pressure increases (i.e., counteracting the backpressure created by the riser).

Data from the h = 1/16 inch slot opening is shown in Figure 4. The general trend for this slot opening is for water ingress to increase as frequency increases, which is counterintuitive since the overall system hydraulic/pneumatic impedance should increase as frequency increases. Data from the slot opening h = 1/8 inch is shown in Figure 5. In general, as riser height increases, flow through the system decreases as expected, and as peak pressure increases, flowrate through the system increases. In some cases, water ingress reaches a minimum at 0.8 Hz before increasing again. Data from the slot opening h = 1/4 inch is shown in Figure 6. In these tests, the riser is an effective strategy for preventing water ingress for all slot openings. Data from these tests will be shared with the advisory group.

In lieu of Round 2B testing, which was decided to be of limited additional value, the trends discussed above were investigated in supplemental Round 1A testing conducted to further explore the relationships between wetting rates and fluctuation frequency. The results of these tests can be found in Figure 7, where an additional slot opening was tested with increased upper limit on frequency and increased wetting rates were also tested.

Figure 7 shows how the combination of thin slot (h = 1/32 inch) and large riser (h_R = 4 inch) nearly eliminates flow through the generic specimen at all input levels of pressure and wetting. This is an ideal result, and if a real specimen is able achieve this level of performance, it is likely to perform well in a real extreme wind environment. Additional increased wetting rates were also tested since the initial Round 1A testing did not show a plateauing of water ingress through the systems.

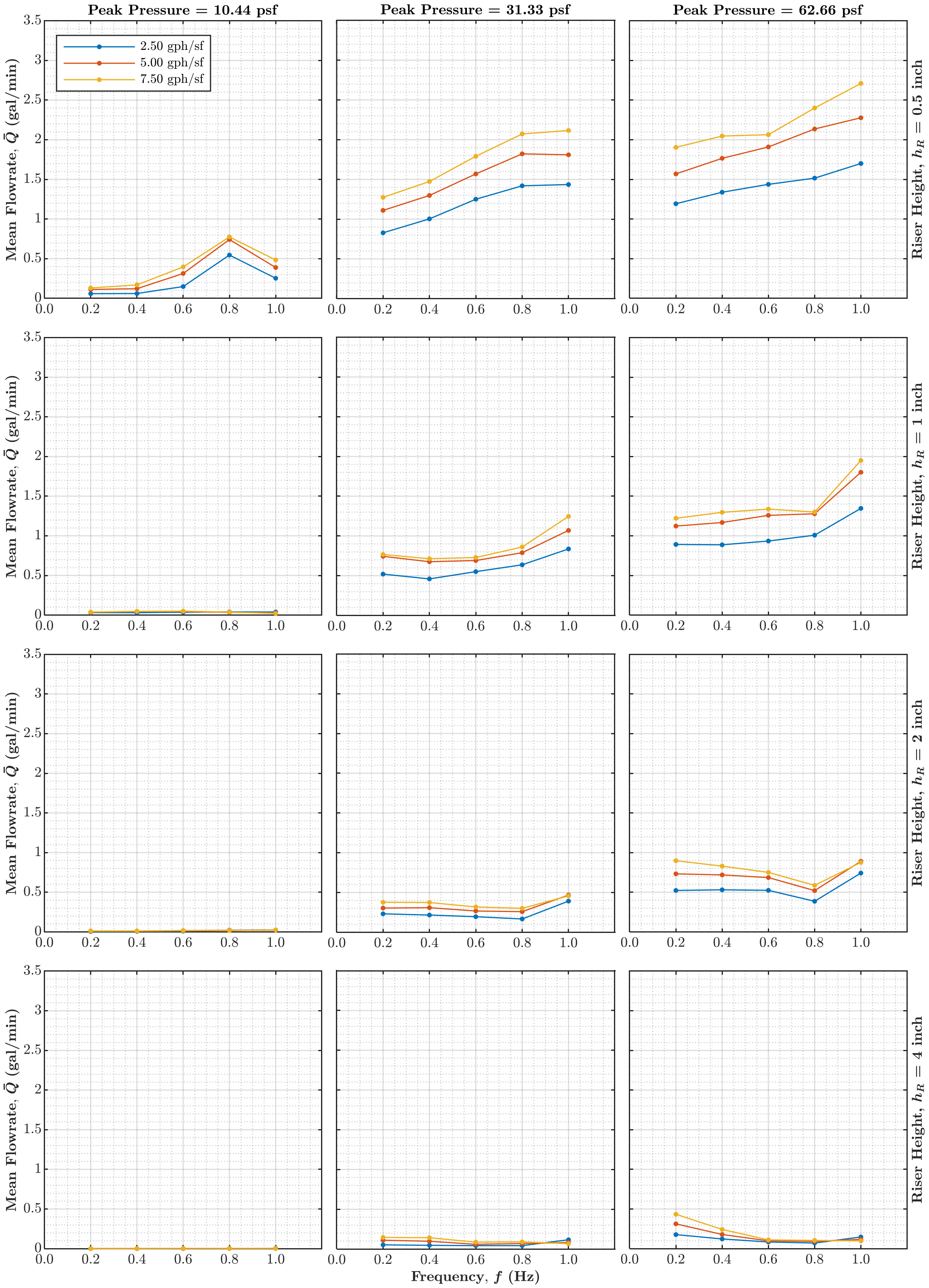


Figure 4. Slot opening (h = 1/16 inch) pressure sine sweeps. Each subplot shows three wetting rates for each test configuration of peak pressure amplitude and riser height.

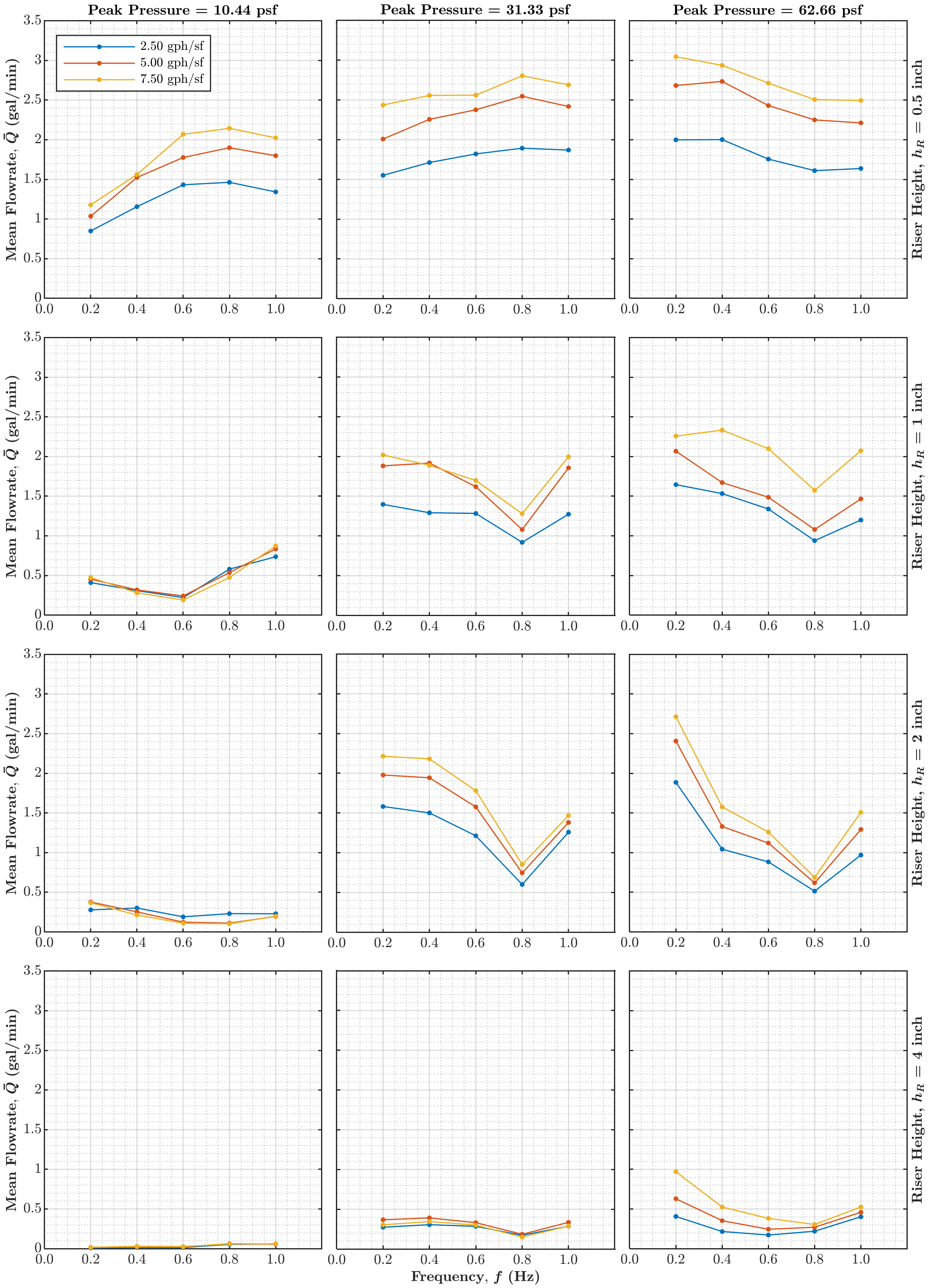


Figure 5. Slot opening (h = 1/8 inch) pressure sine sweeps. Each subplot shows three wetting rates for each test configuration of peak pressure amplitude and riser height.

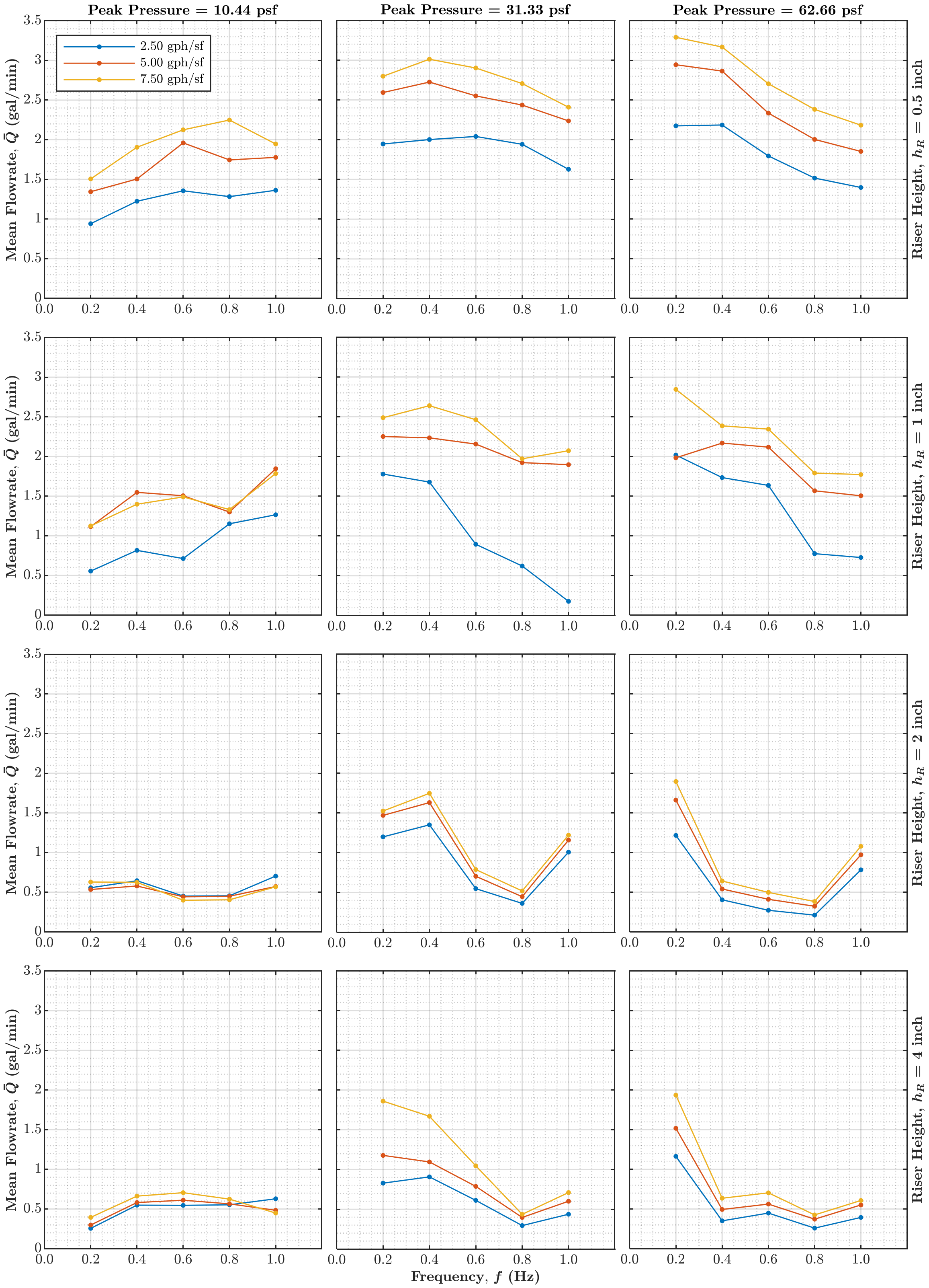


Figure 6. Slot opening (h = 1/4 inch) pressure sine sweeps. Each subplot shows three wetting rates for each test configuration of peak pressure amplitude and riser height.

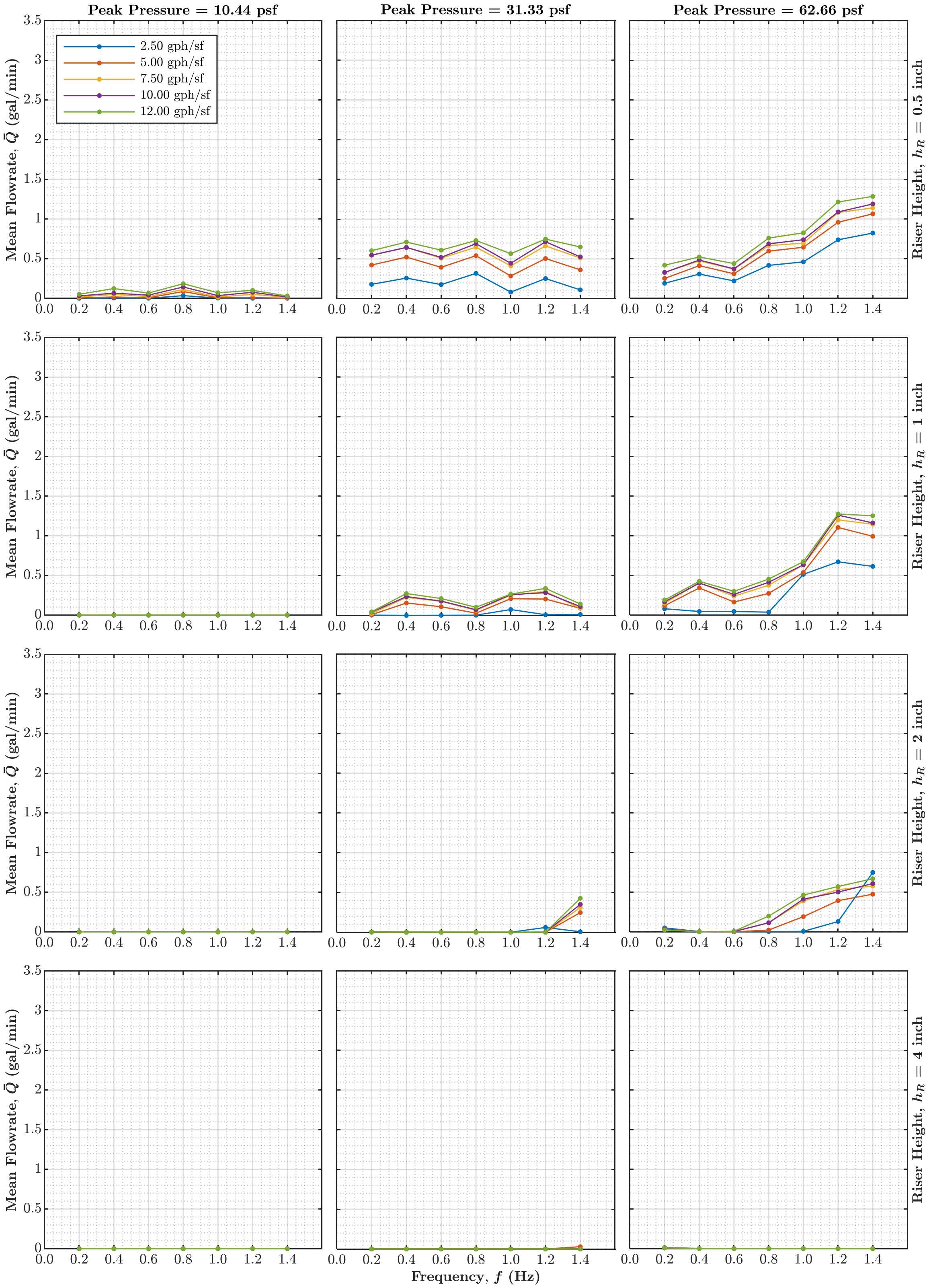


Figure 7. Slot opening (h = 1/32 inch) pressure sine sweeps with an increased range up to 1.4 Hz. Each subplot shows five wetting rates for each test configuration of peak pressure amplitude and riser height.

9. Rounds 2 & 3 – Operable Window & Door System Water Ingress Testing

9.1. Development

To expand on Task 2 with “real-world” loading conditions, the investigator completed development of methodologies built on prior work (Walker et al., 1988; Jancauskas et al., 1994; Kopp et al., 2010; Lopez et al., 2011) to simulate hurricane-like wind pressure loading events for application on building envelope systems in Rounds 2 and 3 of testing. Fluctuating applied pressure sequences and WDR rates were synthesized from available data in the following steps.

Wind Speed Records: A hurricane passage time history was derived empirically from historical hurricane track and intensity records from the front right quadrant of intense hurricanes representative of a design-level event. These records can be found in the NOAA Hurricane Research Division H*Wind surface wind field analyses. Many severe storms including Hurricanes Andrew, Charley, Dennis, Ike, and Ivan were considered. From these data, a three-second gust wind speed (V_g) envelope ranging from 78-190 mph over the span of three hours at a height z = 33 ft in open terrain (i.e., Exposure C; z_0 = 0.03 m full-scale) was identified as a worst-case hurricane passage. The hurricane passage time history in Figure 8 was then developed following Walker et al., 1988, where a translating intense tropical cyclone’s wind intensity and direction are calculated with respect to a stationary reference location of interest—in this case the windward face of a low-rise building. As the cyclone approaches the location of interest, the combination of translational and rotational wind velocities generate wind direction changes and intensities at an increasing rate up to the point of eye wall passage, at which point the simulation concludes. The point at which the wind direction is at 45 degrees or greater is when the positive surface pressure fluctuations will be significant. Thus, the last hour of the simulation is critical and has been divided into 10 stationary ergodic segments of incrementally increasing wind angle.

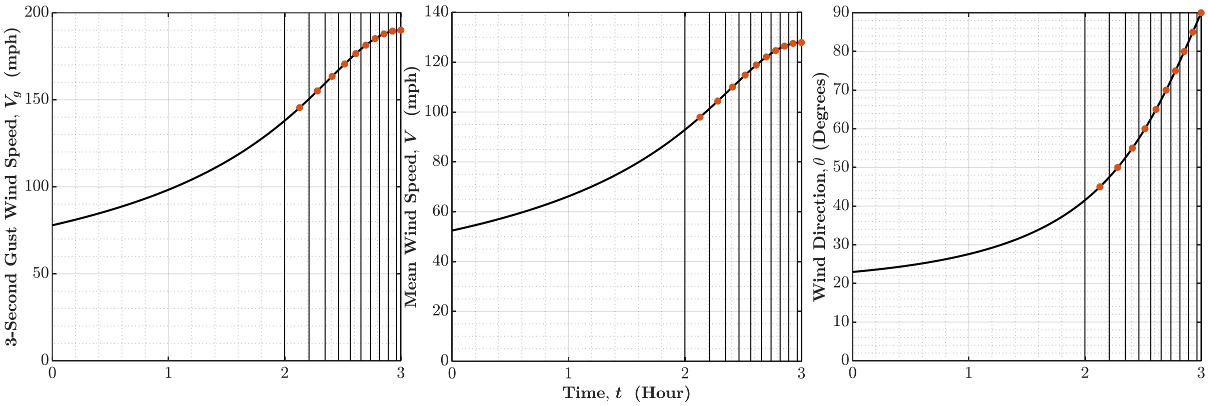


Figure 8. Hurricane passage simulation referenced to z = 33 ft in Exposure C. Black lines indicate the continuous functions for each parameter and the red dots indicate the values used for each segment in the last hour of the passage simulation when wind angle is greater than 45 degrees.

Fluctuating Surface Pressure Coefficient Records: Fluctuating surface pressure records were extracted from model configuration jp1 found in the NIST Aerodynamic Database, which is a data repository for a large number of boundary layer wind tunnel experiments on bluff bodies representing simplified low-rise structures. Many wind directions were considered to determine a representative worst-case mean pressure time history tap location for a worst-case open terrain condition (Exposure C). These records and tap locations can be found in **Appendix C**. The model-scale pressure coefficient (C_p) records were converted to an equivalent full-scale dynamic pressure in the following steps. Scaling of the non-dimensional C_p records is achieved using the reduced frequency relationship

$$\left(\frac{fL}{V}\right)_{\text{Model-scale}} = \left(\frac{fL}{V}\right)_{\text{Full-scale}} \tag{1}$$

where f is the sampling rate (i.e., frequency) of the pressure sensor, L is a characteristic geometric length dimension of the subject building, and V is the velocity referenced at a specified and height and over a specified duration. The C_p values are defined by the following

$$C_p = \frac{p - p_{ref}}{\frac{1}{2}\rho_{air} V_{ref}^2} \tag{2}$$

where p is pressure measured on the model surface, p_{ref} is the reference static pressure and V_{ref} is the reference mean velocity—usually taken at upper level of wind tunnel or mean roof height (averaging duration must be specified at roof height)—and ρ_{air} is the mass density of air. To convert wind tunnel data to full-scale data, Eq. (2) is rearranged and the non-dimensional C_p records are converted to full-scale surface pressures using

$$p = \frac{1}{2}\rho_{air} V_{ref}^2 C_p \tag{3}$$

The experiment selected for this project (jp1) is a 1:100 scale WERFL-like model with an eave height of 40 ft full-scale (FS) tested in open country (Exposure C; z_0 = 0.03 m FS) approach flow conditions. When strung together sequentially, the fluctuating pressure segments simulate the passage of a hurricane including changes in wind speed, direction, and precipitation. Two taps were selected near the upper corner of the windward wall (**Appendix C**): the first tap selected (211) is where the average mean pressure coefficient ($\bar{C}_P$) values for the wind direction range of 45-90 degrees (angle relative to wall surface) were found to be a maximum and the tap height is z = 25 ft full-scale; and the second tap (304) was selected with the maximum average $\hat{C}_P$ and maximum average RMS C_P values of all the model wall taps (**Appendix D**). After the datasets were scaled, a third-order lowpass Butterworth filter was applied to the data with a corner frequency of f_c = 2 Hz (informed by sine sweep testing). The timing of the passages and tap locations on the building were selected to nominally create increasingly severe conditions with each new segment. The wind angle range of 45-90 degrees, where 45 degrees is a quartering wind and 90 degrees is perpendicular to the wall of interest, was selected because wind angles less than 45 degrees were found to be predominantly in suction. These angles are not expected to significantly contribute to water ingress due to the net negative pressure on the specimen surface.

Wind-drive Rain Simulation: Velocity-dependent wetting rates (R_{WDR}) were derived using the following equation from Blocken and Carmeliet (2004):

$$R_{\mathrm{WDR}} = W \alpha V R_h \cos(\theta) \tag{4}$$

where W = 0.5 is the wall factor (i.e., the fraction of WDR rain droplets impacting the wall), α = 0.0671 sec/ft is the WDR coefficient (inverse of raindrop terminal velocity), V is mean wind speed (see Figure 8), R_h is the horizontal rainfall intensity (i.e., raining falling vertically through a horizontal plane), and θ is the angle between the wind direction and the line normal to the wall. The linearly varying R_h range chosen for this project was 1-2 in/hr, which approximates rainfall rates for intense tropical cyclones and is based on data from the Global Precipitation Climatology Project (Krajewski et al., 2000).

Complete Wind Passage Simulation: Figure 9 shows the complete simulation for the maximum $\bar{C}_P$ record strung together sequentially in 10 segments (Test 4; see Table 6). The variation of V_g, V, θ, $\bar{C}_P$, $\hat{C}_p$, and R_{WDR} are all shown for the most intense one-hour period of the hurricane passage. The instantaneous wind pressure fluctuations, as well as the 10-minute and 1-minute moving average pressure fluctuations are also shown. Probability densities and power spectra are also shown to reveal the changing distribution of pressures as wind direction and intensity change. Figure 10 shows the same characteristics for the complete simulation of the maximum $\hat{C}_p$ strung together sequentially in 10 segments (Test 5; see Table 7).

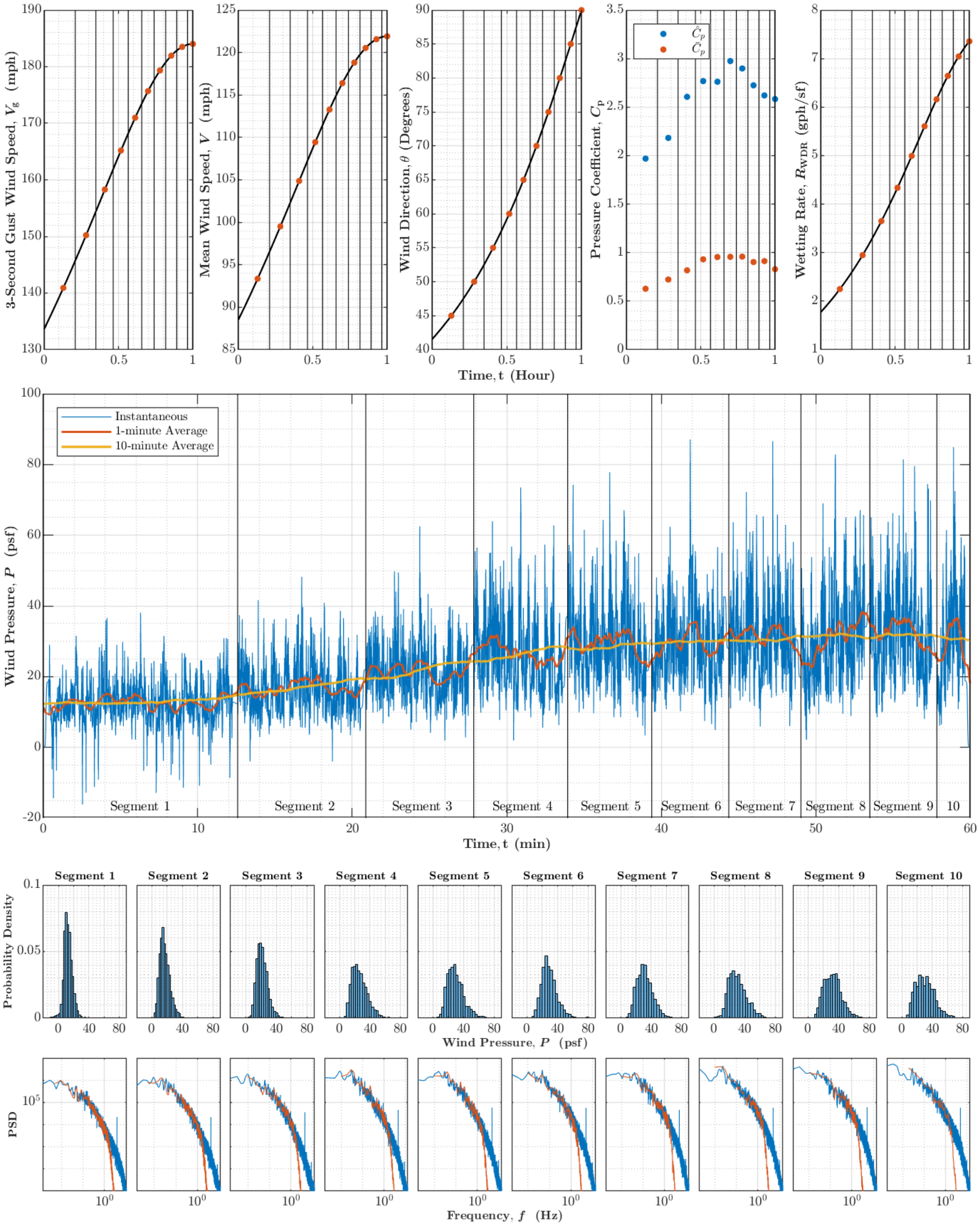


Figure 9. Maximum average $\bar{C}_P$ hurricane simulation. The top row of subplots shows hurricane passage variations of V_g, V, θ, C_p, and R_{WDR}. The middle subplot shows the complete 60-minute wind pressure record. The bottom set of subplots show the distributions and power spectra of surface pressures.

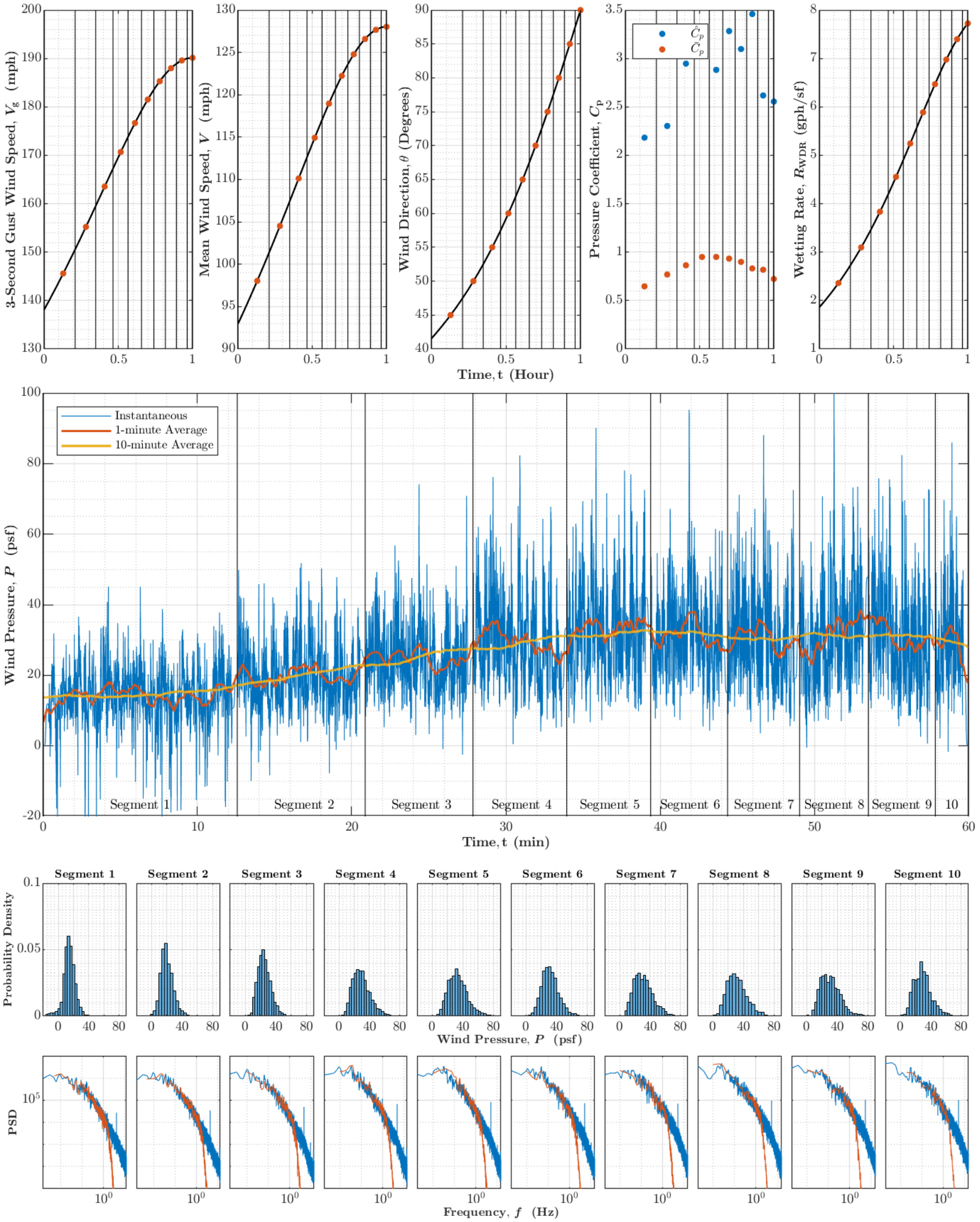


Figure 10. Maximum average $\hat{C}_p$ Hurricane Simulation. The top row of subplots shows hurricane passage variations of V_g, V, θ, C_p, and R_{WDR}. The middle subplot shows the complete 60-minute wind pressure record. The bottom set of subplots show the distributions and power spectra of surface pressures.

9.2. Specimens & Test Matrix

The following two (2) rounds of experimental testing were planned with final input from the advisory group provided during the third advisory group teleconference. Key aspects of hurricane-like wind pressure loading simulation for application on building envelope systems were discussed with the knowledge gained during Round 1 informing decisions regarding maximum wetting rates and applied cutoff frequencies.

Round 2. A total of five (5) operable window systems were identified, acquired, and tested. The specimens were selected to be representative of available off-the-shelf products within the market and all had Florida product approvals for water ingress. The final number of window specimens tested was limited by time and product availability. Baseline ASTM standard tests were performed to verify that specimens were undamaged and properly installed prior to sine sweep testing and hurricane passage simulations.

Round 3. A total of three (3) operable door systems were identified, acquired, and two (2) were tested. The specimens were selected to be representative of the available products within the market. The final number of door specimens tested was limited by time and product availability. Baseline ASTM standard tests were performed to verify that specimens were undamaged and properly installed prior to sine sweep testing and hurricane passage simulations.

Rounds 2 and 3 of experimental testing investigated the relationships between applied pressure fluctuations, varying WDR intensities, and the performance of commercially available operable window/door systems tested using existing standard water penetration test procedures. The experimental design was intended to investigate the ability of existing test procedures to predict the likely real-world performance of operable window and door systems during the passage of a fast-moving intense compact tropical cyclone similar to those previously experienced in the State of Florida (e.g., Hurricane Andrew). Figure 11 shows a schematic view of the experimental setup with applied pressure trace input depicted near the top. Measured pressure (P_{M}), wetting (R_{WDR}), and instantaneous flowrate ($Q(t)$) through the specimens were measured for each test. The specimens and test matrix are described in the tables below.

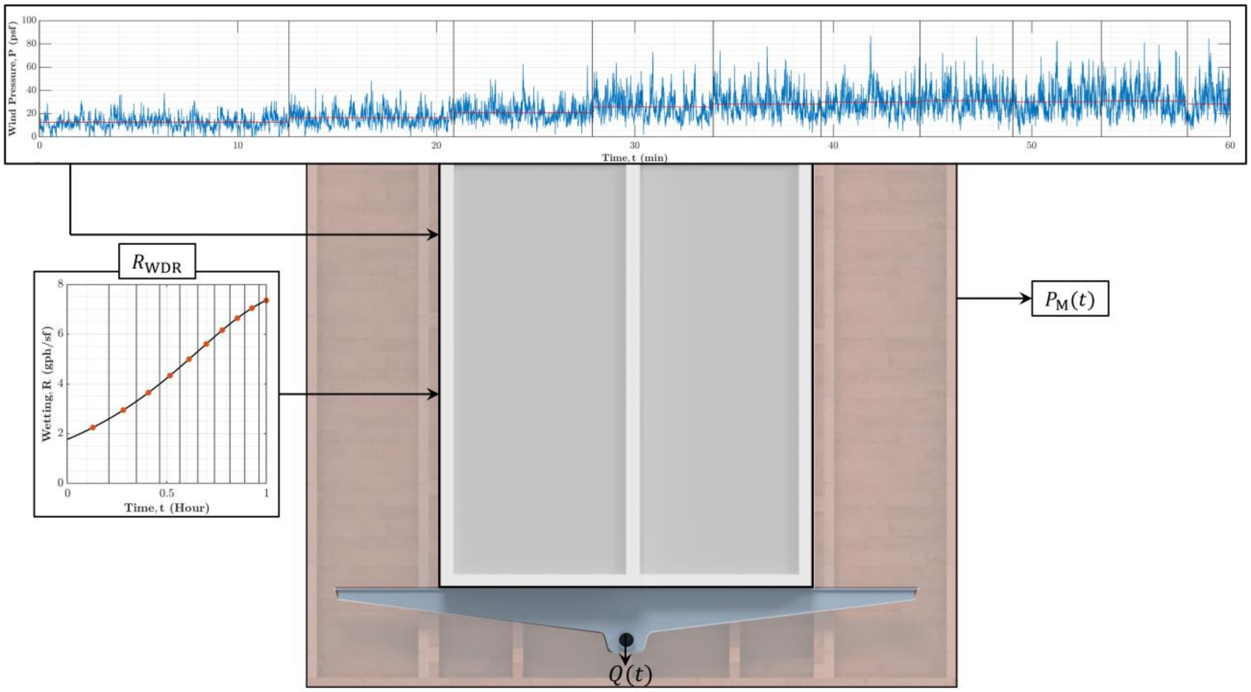


Figure 11. Schematic diagram of Rounds 2 and 3 experimental setup.

Table 2 lists the specimens tested during Rounds 2 and 3 of the project. Operator types, design pressure (DP) ratings, unit dimensions, and test standards indicated by the manufacturer are also listed for each specimen. Specimens are anonymized to omit manufacturer name and Florida product approval number.

Table 2. Specimens tested for water penetration resistance.

Round	No.	Operator Type	DP (psf)	Unit Size (in)		Test Standards	ASTM
				W	H		
2	1	Single-hung Window	+65/-70	35.5	47.5	TAS 201 202 203	E331-00
	2	Double-hung Window	+50/-50	33.75	48.75	AAMA/WDMA/CSA 101/I.S.2/A440-11	E547-00
	3	Twin Casement Window	+70/-90	52	62	TAS 201 202 203	E331-00
	4	Twin Awning Window	+70/-90	52	62	TAS 201 202 203	E331-00
	5	Horizontal Slider Window	+50/-55	51.875	37.125	TAS 201 202 203	E331-00
3	6	Gliding Patio Door	+50/-50	71.25	79.5	AAMA/NWWDA 101/I.S.2/NAFS-02	E547-00
	7	Single Outswing Door	+70/-70	36	80	TAS 201 202 203	E331-00
	8	Single Outswing Door	+65/-65	35.5312	79.3125	TAS 201 202 203	E331-00

Table 3 lists the tests performed on each specimen in chronological order. For the specimens that use TAS test standards (see Table 1), a pressure-only preload was applied (Test 0) prior to being subjected to water infiltration testing (Test 1 and 2). This pressure-only preload test applied 50% of the positive pressure test load (50% x 1.5 x DP rating) for 30 seconds followed by 1 minute of rest at no load. Then the full design load (DP rating) was applied for 30 seconds followed by a 1 minute of rest at no load.

Table 3. Tests performed on each specimen.

No.	Test Type
0	TAS Pressure-only Preloading (TAS Specimens Only)
1	ASTM E331-00 (2016) Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference
2	ASTM E547-00 (2016) Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Cyclic Static Air Pressure Difference
3	Round 1 Sine Sweep Extended Test Procedure
4	Maximum Average $\bar{C}_P$ One-Hour Hurricane Wind Pressure and WDR Simulation
5	Maximum Average $\hat{C}_P$ One-Hour Hurricane Wind Pressure and WDR Simulation

Table 4 lists the parameters used for the ASTM standard tests conducted. These parameters include chamber pressure, wetting rate, test duration, cycles, and pass/fail criteria. Each specimen was fully drained after Test 1 prior to being subjected to Test 2. Full positive test loads, negative loads, and air infiltration were not tested for this project.

Table 4. ASTM E331 and ASTM E547 standard tests conducted for each specimen.

Test Parameter	ASTM E331	ASTM E547
Test Number	1	2
Chamber Pressure (psf)	15% of positive DP Rating	15% of positive DP Rating
Wetting Rate (gph/sf)	5	5
Cycles	1	4
Cycle Duration (min)	15	1 min off / 5 min on
Full Duration (min)	15	24
Pass/Fail Criterion	One drop past the plane	One drop past the plane

If any specimen failed Test 1 or 2 (ASTM standard tests), the failure was noted and the specimen and/or installation was considered defective. In this situation, the unit was inspected, necessary adjustments were made, and the standard tests were run again. If issues with the unit could not be resolved, the unit was omitted from final analysis. Upon completion of Tests 1 and 2, the specimen was subjected to the sine sweep tests conducted during Round 1 for later comparison to the generic specimen test results.

Table 5 shows the relevant test variables for the sine sweep tests conducted on each specimen. Each test was 14 minutes in duration and swept through seven (7) frequencies from low to high. For each specimen, three (3) pressure amplitudes were tested at each of five (5) wetting rates for a total of 15 sine sweep tests. Once Tests 1, 2, and 3 were completed, two (2) one-hour duration hurricane simulations were run for each specimen (Tests 4 and 5).

Table 5. Sine sweep conditions tested for each specimen in Test 3.

	Sine Sweep Frequencies	Pressure Amplitudes	Wetting Rates
Nomenclature	f	A	R_{WDR}
Units	Hz	psf	gph/sf
Quantity	7	3	5
Variable	0.2,0.4,0.6,0.8,1.0,1.2,1.4	5.2,15.7,31.3	2.5,5.0,7.5,10.0,12.0

The one-hour hurricane passage tests (Tests 4 and 5) were each broken into 10 stationary ergodic fluctuating surface pressure segments. Table 6 shows relevant statistics for Test 4—the first hurricane wind pressure simulation (see Figure 9). The table shows segment number, segment duration, wind angle, mean wind speed, 3-second gust wind speed, $\bar{C}_P$, $\hat{C}_P$, mean pressure, peak pressure, RMS pressure, and wetting rate.

Table 6. Maximum Average $\bar{C}_P$ One-Hour Hurricane Wind Pressure and WDR Simulation Statistics.

Test 4: Hurricane Simulation No. 1										
Segment No.	1	2	3	4	5	6	7	8	9	10
Duration (min)	12.58	8.29	6.99	6.08	5.44	4.99	4.67	4.46	4.34	2.15
Wind Angle (degrees)	45	50	55	60	65	70	75	80	85	90
Mean Wind Speed (mph)	93.36	99.52	104.87	109.44	113.28	116.4	118.82	120.54	121.57	121.91
3-sec Gust Speed (mph)	140.91	150.22	158.29	165.19	170.98	175.69	179.34	181.94	183.5	184.02
$\bar{C}_P$	0.63	0.72	0.82	0.93	0.95	0.96	0.96	0.9	0.91	0.83
$\hat{C}_P$	1.97	2.18	2.61	2.77	2.76	2.97	2.9	2.72	2.62	2.58
Mean Pressure (psf)	12.56	16.92	21.5	26.43	29.58	29.32	31.71	30.73	32.31	30.71
Peak Pressure (psf)	38.08	48.21	62.51	73.51	77.78	87.07	86.57	82.82	81.44	84.89
RMS Pressure (psf)	13.82	18.2	22.76	28.39	31.46	31.11	33.46	32.99	34.33	33.15
Wetting Rate (gph/sf)	2.25	2.95	3.65	4.34	4.99	5.61	6.16	6.64	7.05	7.36

Table 7 shows relevant statistics for the 10 stationary ergodic segments of the second one-hour hurricane wind pressure simulation (see Figure 10), The table shows segment number, segment duration, wind angle, mean wind speed, 3-second gust wind speed, $\bar{C}_P$, $\hat{C}_P$, mean pressure, peak pressure, RMS pressure, and wetting rate.

Table 7. Maximum Average $\hat{C}_P$ One-Hour Hurricane Wind Pressure and WDR Simulation Statistics.

Test 5: Hurricane Simulation No. 2										
Segment No.	1	2	3	4	5	6	7	8	9	10
Duration (min)	12.58	8.29	6.99	6.08	5.44	4.99	4.67	4.46	4.34	2.15
Wind Angle (degrees)	45	50	55	60	65	70	75	80	85	90
Mean Wind Speed (mph)	98.04	104.51	110.13	114.93	118.96	122.24	124.77	126.58	127.67	128.03
3-sec Gust Speed (mph)	145.59	155.21	163.55	170.68	176.66	181.53	185.3	187.99	189.59	190.13
$\bar{C}_P$	0.65	0.77	0.86	0.95	0.95	0.93	0.9	0.83	0.82	0.72
$\hat{C}_P$	2.18	2.3	2.95	3.04	2.88	3.28	3.1	3.46	2.62	2.56
Mean Pressure (psf)	14.17	19.79	24.91	29.77	33.62	31.88	31.31	31.57	30.66	29.37

Peak Pressure (psf)	45.16	51.74	74.14	82.28	90.13	95.28	88.03	100.79	82.37	85.94
RMS Pressure (psf)	16.27	21.48	26.42	32.03	35.88	33.88	33.79	34.23	33.17	31.69
Wetting Rate (gph/sf)	2.36	3.1	3.83	4.55	5.24	5.89	6.47	6.98	7.4	7.73

Each specimen was subjected to Test 1 for 15 minutes and Test 2 for 24 minutes (unless repeat runs were required), Test 3 for 210 minutes, Test 4 for 60 minutes, and Test 5 for 60 minutes for a total specimen test time of 369 minutes. The total test time for Rounds 2 and 3 was approximately 43 hours not including setup and breakdown time. The setup and breakdown time roughly doubled the testing time.

9.3. Results & Discussion

In accordance with Task 3, testing outcomes (see Table 8), types of data collected, results and data analyses (Figures 12-17), and observational notes from each specimen in Rounds 2 and 3 are described in this section. The HAPLA operator noted observed issues with testing and listed the issues in the test matrix. Those observations are detailed below.

Table 8. Testing outcomes for each specimen in Rounds 2 and 3.

Specimen	Test Type				
	Test 1: ASTM E331	Test 2: ASTM E547	Test 3: Sine Sweeps	Test 4: Hurricane Simulation No. 1	Test 5: Hurricane Simulation No. 2
1	Pass	Pass	Complete	Complete	Complete
2	Fail	Fail	Not Run	Not Run	Not Run
3	Pass	Pass	Complete	Complete	Complete
4	Pass	Pass	Complete	Complete	Complete
5	Pass	Pass	Complete	Complete	Complete
6	Fail	Fail	Not Run	Not Run	Not Run
7	Fail	Fail	Not Run	Not Run	Not Run
8	Not Tested	Not Tested	Not Tested	Not Tested	Not Tested

Specimen 1 – Single-hung Window: After the successful preload of the specimen, ASTM E331 was initiated. A perimeter sealant failure was observed occurring between the frame and buck, crossing the interior plane. The frame was re-sealed to the buck and the test was run a second time. Another sealant failure was observed and subsequently corrected. After another re-run, the perimeter frame seal leaks were no longer observed, ASTM E331 was completed, and the subsequent ASTM E547 test experienced no issues. After completion of the two ASTM tests, the specimen was cleared for subsequent testing. Sine sweep testing was then conducted. During testing, a small pinhole leak through perimeter seal formed. As pressure levels increased, water began flowing over corners of the sill dam. Additional pinhole leaks in frame perimeter sealant developed, and water flowing over corners of sill dam increased. After sine sweep testing was completed, the system was drained and Hurricane Simulation No. 1 was conducted successfully. Hurricane Simulation No. 2 was also completed successfully.

Specimen 2 – Double-hung Window: During the first attempt at running the ASTM tests, leaks from around the glazing at the bottom of the upper sash resulting in the specimen failing based on the stated testing criterion. After inspecting and adjusting the specimen, the ASTM E331 test was re-run. Additional leaks around the glazing were observed and the unit was determined to be unsuitable for further testing and test sequence was terminated.

Specimen 3 – Twin Casement Window: After the successful preload of the specimen, ASTM E331 testing was initiated. It was completed with no observed issues. ASTM E547 also experienced no issues. However, after completion of the ASTM tests, the perimeter sealant began to leak as the sine sweep testing began. The perimeter was re-sealed and retested with no further leaking reported. Pool from leak expanded slightly, but did not flow to scale. Leak continued Noticed at 4 mins water bubbling through bottom left corner of interior vent. By end of test leaking to step below. moderate leaking at lower left corner of left panel. 10 mins, moderate leaking at lower left corner of right panel, increases at 13 mins. 13 mins, sealant starts leaking at lower right corner of specimen. 20 mins, whole lower left jam of right panel is leaking moderately.

22 mins, top corners of left panel begin leaking lightly. 13mins, bottom corners of right panel begin to leak. At 21 mins, bottom left corner of right panel and right seem of median leak heavier. After sine sweep testing was completed, the system was drained and Hurricane Simulation No. 1 was conducted successfully. Hurricane Simulation No. 2 was also completed successfully.

Specimen 4 – Twin Awning Window: After the successful preload of the specimen, ASTM E331 testing was initiated. It was completed with no observed issues. ASTM E547 also experienced no issues. After initiation of sine sweep testing, a minor leak on left side mullion joint formed. Minor leaking continued through the duration of sine sweep testing. After sine sweep testing was completed, the system was drained and Hurricane Simulation No. 1 was initiated. Leakage was concentrated at the bottom left corner, in the channel, which filled over time before pouring over. There was also a slight leak at the bottom right corner, in the channel, that was filling up much more slowly, but also very slightly leaking out of the channel. Water would occasionally leak more profusely through the center-right handle/lock during high pressure spikes. Additionally, during these spikes, water would pour through the far right lock. The simulation was completed successfully. Hurricane Simulation No. 2 was also completed successfully with similar leakage and observations described in hurricane 1 trace.

Specimen 5 – Horizontal Slider Window: After ASTM E331 was initiated, water began collecting in the sill dam as expected. The water level stabilized and the unit passed. For ASTM E547, water successfully filled and drained in the sill dam and also passed. Sine sweep testing was then initiated. At lower frequencies, the filling and draining of the dam was regular and adequately contained the water. As frequency increased and the entire window began to bend and flex more rapidly, water spillage increased significantly, and the dam did not have time to drain. Water eventually began leaking through the fixed lite glazing at both corners. Increased water coming from corners of left pane, water also splashing out from right corner of right pane. After sine sweep testing was completed, the system was drained and Hurricane Simulation No. 1 was conducted successfully. Hurricane Simulation No. 2 was also completed successfully.

Specimen 6 – Gliding Patio Door: During the first attempt at running the ASTM tests, leaks from around the glazing and glide rail brush seals flowed into the track and overtopped the track riser within the first minute of testing. The test was paused, the system was inspected for missing components and damage, and the ASTM tests were re-run. However, the continued leaking from the same locations and the unit failed ASTM testing. At that point the unit was determined to be unsuitable for further testing and test sequence was terminated.

Specimen 7 – Single Outswing Door: During the first attempt at running the ASTM tests, leaks from around the bottom corners of the door, flowing past the perimeter seal through a ¼ inch gap in the seals on both sides. The test was paused, the seals were adjusted, and the ASTM tests were re-run. However, the specimen began leaking from other locations along the perimeter seal and after less than 5 minutes, the unit failed ASTM testing. At that point the unit was determined to be unsuitable for further testing and test sequence was terminated.

Specimen 8: Shipping delayed. Not tested.

Sine Sweep Testing: Sine sweep data from all successfully tested specimens are shown in Figure 12. Each row of three subplots shows applied peak pressures (3) on an individual specimen. Within each subplot, the five wetting rates (5) are shown for the frequency-dependent average flowrate ($\bar{Q}$) of a given test configuration normalized by specimen surface area (see dimensions in Table 2). The frequency response of Specimens 1, 3, and 4 are essentially flat (i.e., weak frequency dependence). However, Specimen 5 shows a strong frequency dependence with a maximum response occurring at ~1 Hz for the higher wetting rates. This difference is likely due to the operator type and the water storage mechanisms utilized. The performance of these specimens in Figure 12 are highly correlated with their performance in the hurricane simulations (Figures 14-17).

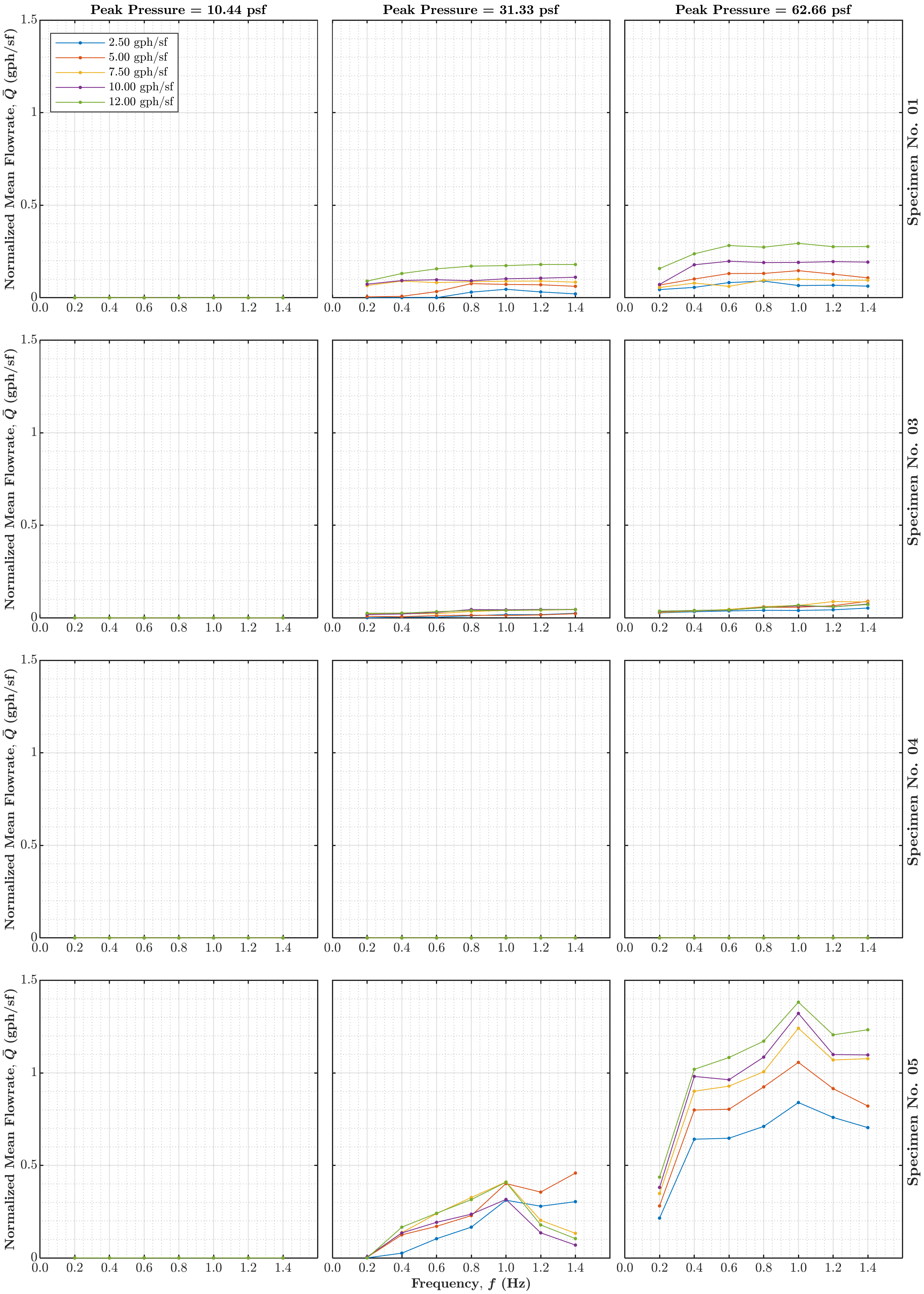


Figure 12. Rounds 2 and 3 pressure sine sweeps. Each row of subplots shows five (5) wetting rates and three (3) pressure amplitudes applied to a given specimen.

Hurricane Passage Testing: An example segment of the second one-hour hurricane passage segment is shown in Figure 13 to illustrate the hurricane passage process, which occurs as follows: a fluctuating hurricane surface pressure trace is input into the control system; the PID controller follows the trace; and the resulting applied pressure and flow out of the system is measured. The three subplots in the figure show P_{T} and P_{M} fluctuations produced by the closed-loop HAPLA control system, the measured W_{IN} using the high-resolution scale, and Q calculated by the taking the time derivative of the scale measurement. The observed water ingress behavior is complex, but in general the behavior of the system to catch water and permit drainage during lulls in the pressure is observed as expected. This can be observed in Figure 13C, where the flowrate increases and decreases in response to the applied pressure (with phase lag caused by the travel time from the trough to the scale). These behaviors are similar to those seen during sine sweep testing.

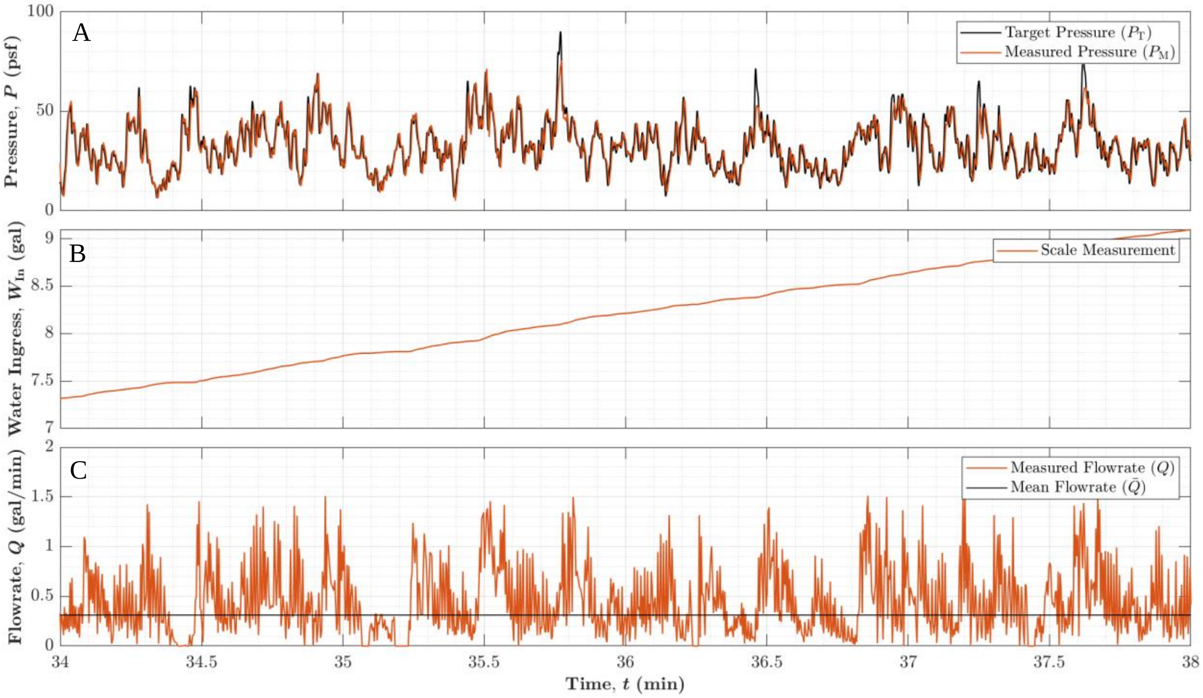


Figure 13. Example application of Test 5 pressure and wetting to Specimen 5 over a span of four minutes: A) applied pressure trace; B) water ingress from scale measurement; and C) calculated flowrate.

Figures 14-17 show hurricane simulation results for the four (4) successfully tested specimens in Rounds 2 and 3. The left column of each figure shows Hurricane Simulation 1 and the right column shows Hurricane Simulation 2 for side-by-side comparison. The top row of each figure shows instantaneous, 1-minute moving average, and 10-minute moving average pressure applied to the specimens as well as ASTM and design pressure levels. The second row shows instantaneous, 1-minute moving average, and 10-minute moving average applied wetting rates and ASTM wetting levels. The third row shows instantaneous, 1-minute moving average, and 10-minute moving average flowrate through the specimen normalized by specimen surface area (see dimensions in Table 2) to remove the differences in flowrate between specimens caused by specimen size differences. The bottom row compares the two hurricane simulations cumulative water ingress normalized by specimen surface area. None of the specimens exhibited any visible signs of structural failure during testing, and none of the measurements suggest that any discontinuities in specimen performance occurred.

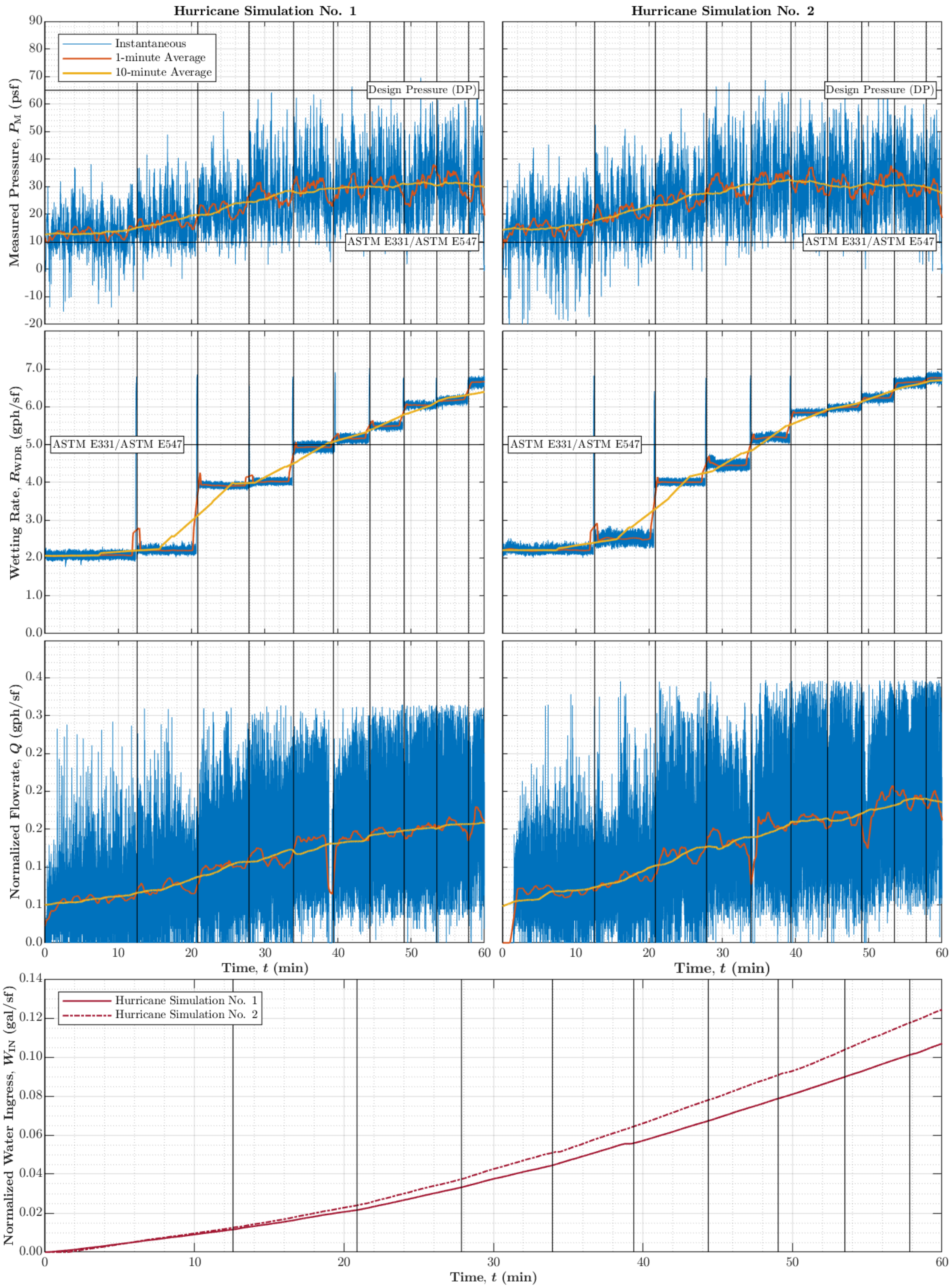


Figure 14. Specimen 1 – Single-hung window hurricane simulations 1 and 2. Measured chamber pressure, wetting rate, normalized flowrate, and normalized cumulative water ingress are shown.

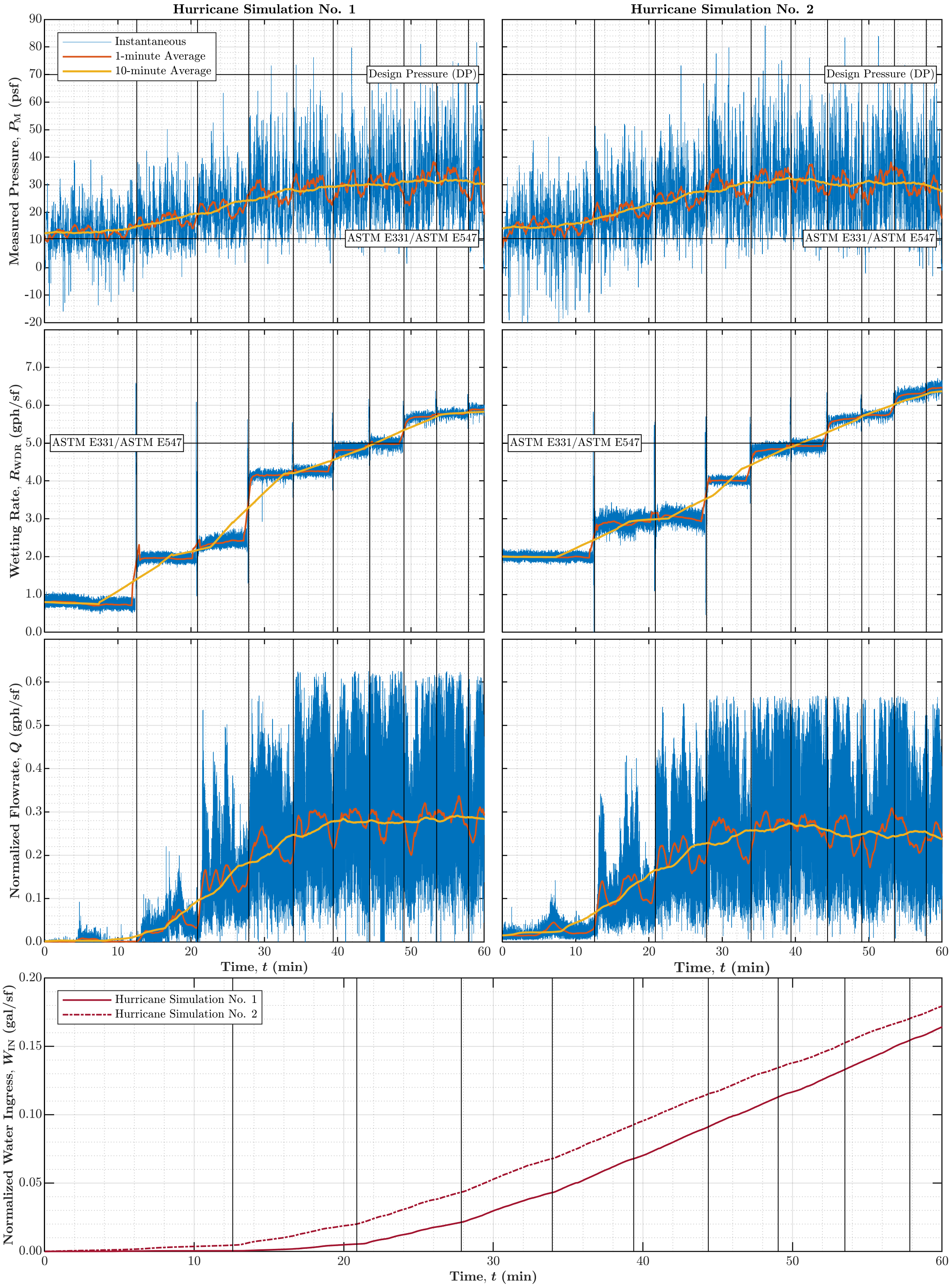


Figure 15. Specimen 3 – Twin casement window hurricane simulations 1 and 2. Measured chamber pressure, wetting rate, normalized flowrate, and normalized cumulative water ingress are shown.

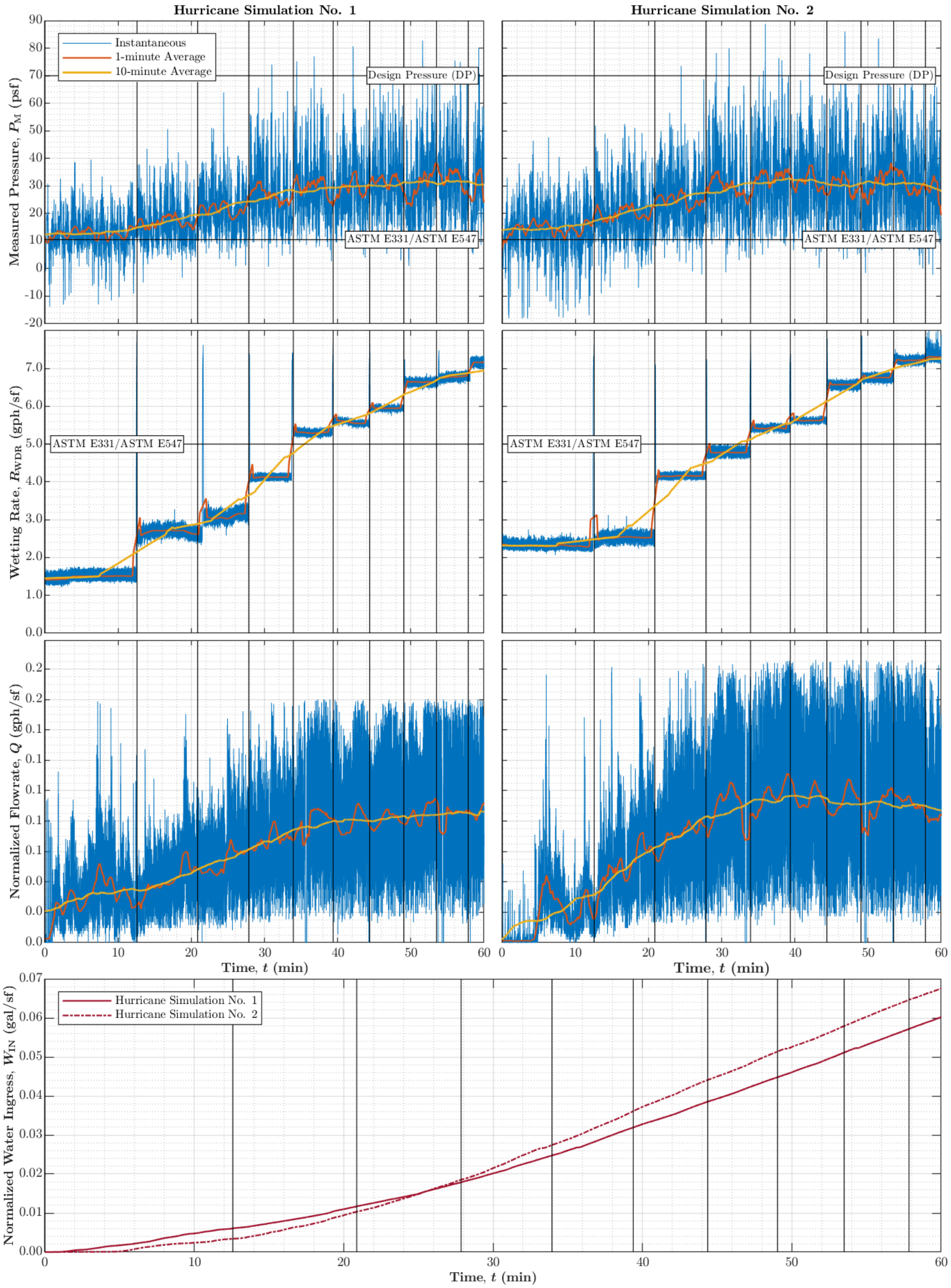


Figure 16. Specimen 4 – Twin awning window hurricane simulations 1 and 2. Measured chamber pressure, wetting rate, normalized flowrate, and normalized cumulative water ingress are shown.

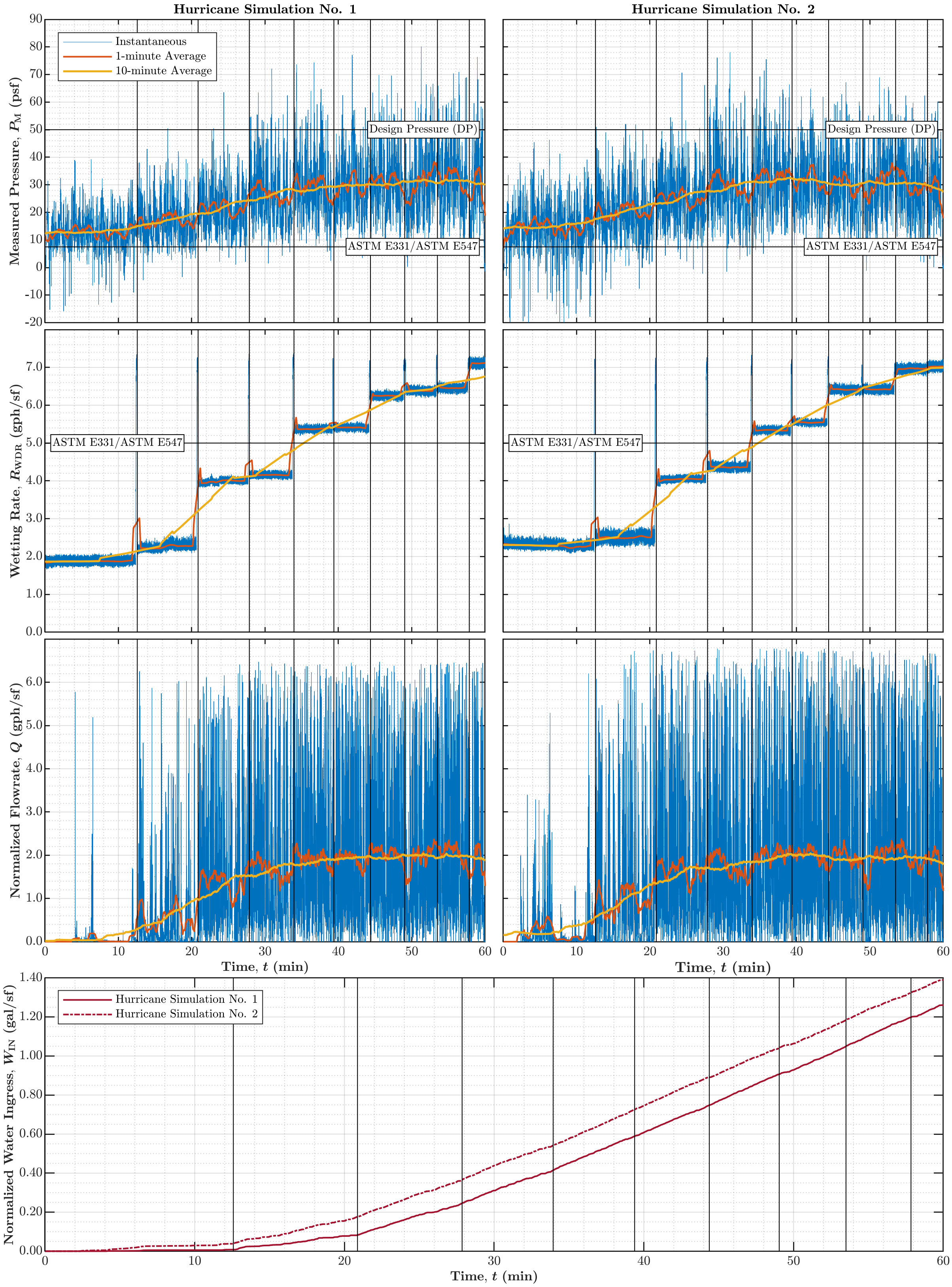


Figure 17. Specimen 5 – Horizontal slider window hurricane simulations 1 and 2. Measured chamber pressure, wetting rate, normalized flowrate, and normalized cumulative water ingress are shown.

10. Major Findings

1. All specimens to pass both ASTM E331 and ASTM E547 (15% DP rating; see specimen DP ratings in Table 2) experienced some amount of water ingress during sine sweep and/or hurricane passage simulations. Furthermore, ingress rates varied widely without immediate indication of a cause. This indicates that performance of a system in ASTM testing at water testing below 10 psf may not fully predict behavior during an extreme wind event such as an intense tropical cyclone. These findings may be related to the research areas listed below:
    - Turbulence in the upwind flow and the flow distortion around the building cause significant spatiotemporal variation in pressure acting on the building surface
    - Cyclic pressure test procedures allow for lulls that promote drainage but are not representative of real-world pressure fluctuation frequencies (e.g., f = 0.1-1.0 Hz)
    - The origin and applicability of the wind load intensity definition (e.g., 15% or 20% of the design pressure for fenestration in water infiltration tests) remains unclear and is a major but easily addressable knowledge gap that will strongly influence existing pass/fail performance
    - The basis for the current minimum wetting rate (i.e., 5.0 gph/sf) originates from trial-and-error testing to determine the threshold required to cause uniform sheeting of water on a curtain wall. It does not consider key factors such as climatology, approach wind speed, and location on the building
    - Defining “failure” as a single drop passing into the building interior is not a representative measure of water damage, as the unmanaged accumulation of water over an entire hurricane episode is the principal driver for damage to walls, interiors, and building contents
2. There is no clear correlation between the units that passed the current test standards (which only provide a binary pass or fail) and performance under hurricane passage testing.
3. Nearly half of the water ingress rated specimens selected for this project failed the ASTM standard tests. Failures were due to identifiable reasons other than installation failure (e.g., leaking through apparently undamaged specimen components). The cause(s) of these failures are currently unknown.
4. The performance of a specimen during sine sweep testing is highly correlated with the performance during hurricane passage simulations. This indicates that system identification (discussed in Section 12) may be a promising option for future standard test methods of building envelop systems. However, more testing is required to confirm this initial observation.

11. Considerations & Limitations

- This research is an initial study. It is a starting point that involved a small, limited number of types and styles of windows and doors. It did not involve testing of all product types, like storefront, curtainwall systems that fall outside the North American Fenestration Standard, (AAMA/WDMA/CSA 101/I.S.2/A440, North American Fenestration Standard/Specification for windows, doors, and skylights (NAFS)), above 10 psf.
- It is important to note that the spectrum in this study is beyond the ASTM E331 (Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors and Curtain Walls by Uniform Static Air Pressure Difference) test for which the original product was designed.
- The research was not inclusive of all types of windows and doors, nor for the many other types of products that contribute to the building envelope, for all types of construction applications.
- Due to the small number and range of units tested, the project lacked a statistically significant sample size.
- Due to the limited sample size, further research may be warranted, especially to better understand

how all building products perform under sine sweep testing.

- In future phases of research in this area, emphasis should be placed on evaluating all materials that contribute to the performance of the building envelope, including cladding, roofing, etc.
- The research project involved a small number of off-the-shelf window and door products available at “big box” stores. For example, it did not include storefront, curtainwall or other architectural products typically designed for higher levels of performance.
- The off-the-shelf products sourced from “big box” stores to meet the tight timelines in this research likely were shipped and handled more than products that are typically manufactured and delivered directly to a dealer or to a jobsite. Therefore, questions remain as to how repeated shipping and handling that typically exceeds real-life conditions may have impacted the performance of products tested.

12. Guidance on the Implementation of Improved Standard Testing Procedures

Suggested Improvements to Current Standards: At this point it is difficult to relate the hurricane passage tests back to the ASTM tests. Passing the ASTM tests does not appear to predict the performance of a specimen, good or bad, in the simulated hurricane passages. Moving away from a binary pass-fail standard would be beneficial as a single drop through the plane approach to quantifying passing does not hold under hurricane-like conditions. More extreme loading inputs (pressure and wetting rate), less stringent pass/fail criteria, and a continuum of performance ratings beyond pass/fail are recommended. These parameters could be calibrated to better predict performance under the hurricane passage simulation.

Suggested Extension of Current Standards: Consideration of the frequency-dependent behavior in building envelope systems is recommended as this appears to be related to performance under hurricane-like conditions. Results from all rounds of testing indicate complex behaviors of window and door systems subjected to fluctuating pressure loads with variable wetting. A path forward may be a process known as system identification (Keesman and Keesman, 2011), which is common in many engineering fields where system dynamics produce complex behaviors. The field of system identification uses statistical methods to build mathematical models of dynamical systems from measured data. A common approach is to start from measurements of system behavior subjected to external influences (inputs to the system) and try to determine a mathematical relation between them without going into the details of what is actually happening inside the system; this approach is called black box system identification. A common black box system identification process uses a sine sweep input to measure an output of interest (e.g., flow out of the system) similar to Round 1 testing.

A key finding in Rounds 2 and 3 was that specimen water ingress resistance in sine sweep testing was highly correlated with water ingress resistance during the hurricane passage simulations. This indicates that it may not be necessary to simulate a specific hurricane event provided that a specimen resists water ingress during system identification. With the sine sweep process, a relationship between the magnitude and phase of the input pressure to the magnitude and phase of the flow through the specimen can be determined. If done frequency by frequency, this builds a transfer function model representing the system dynamics. The model can be used to predict performance under hurricane passage loading rather than direct physical testing using hurricane-like simulations.

One challenge to system identification in this case is that the system behavior is nonlinear and will depend on the magnitude of the pressure and the wetting rate. To remedy this, several linearized models could be identified at different operating conditions. Based on the wetting rate and RMS pressure in the hurricane simulation at a given point in time, the predicted water ingress could be interpolated from the linearized models that best match those conditions.

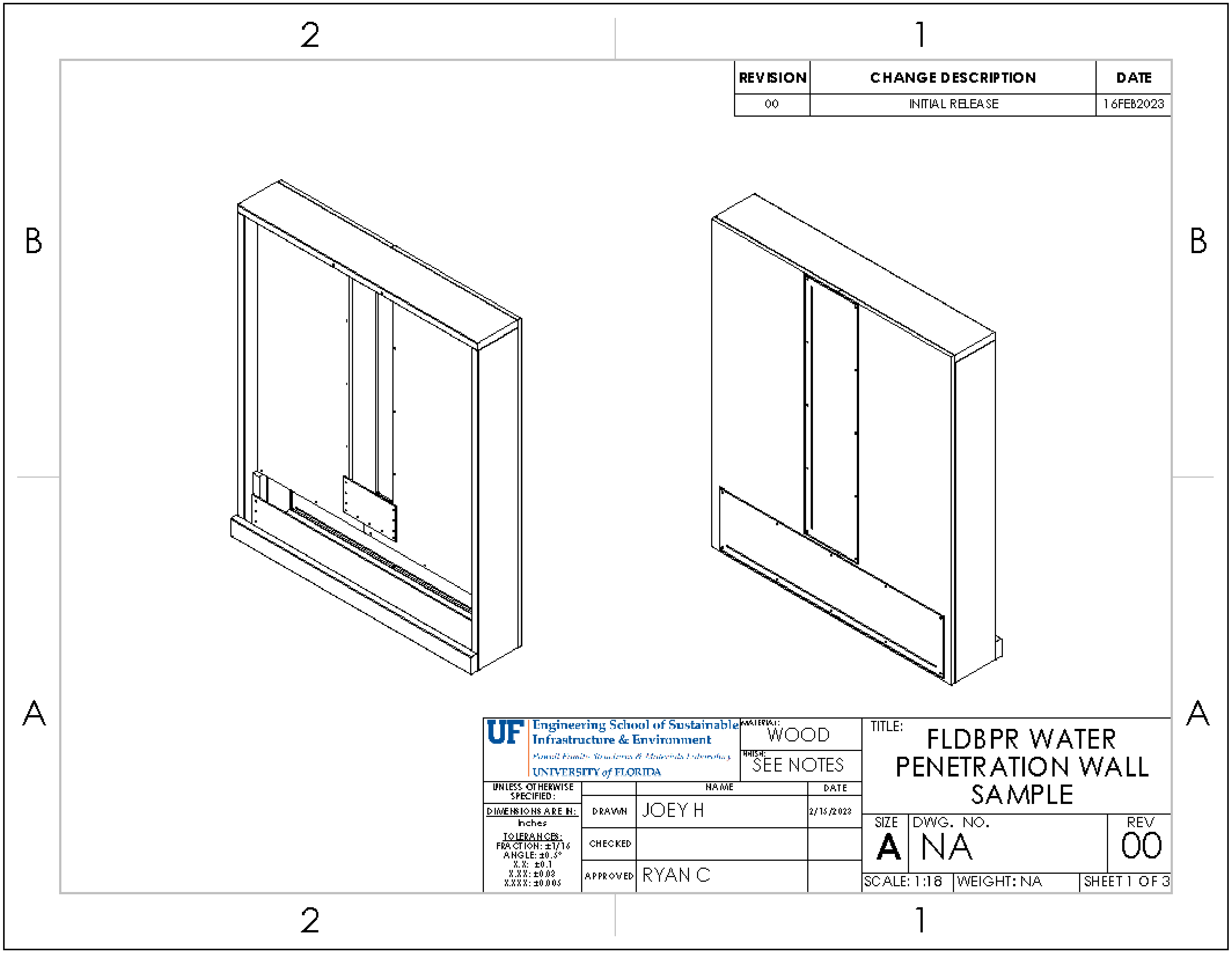
The benefit of this approach is that the industry already has a pulsed pressure test, so this is a smaller step forward than a full hurricane simulation.

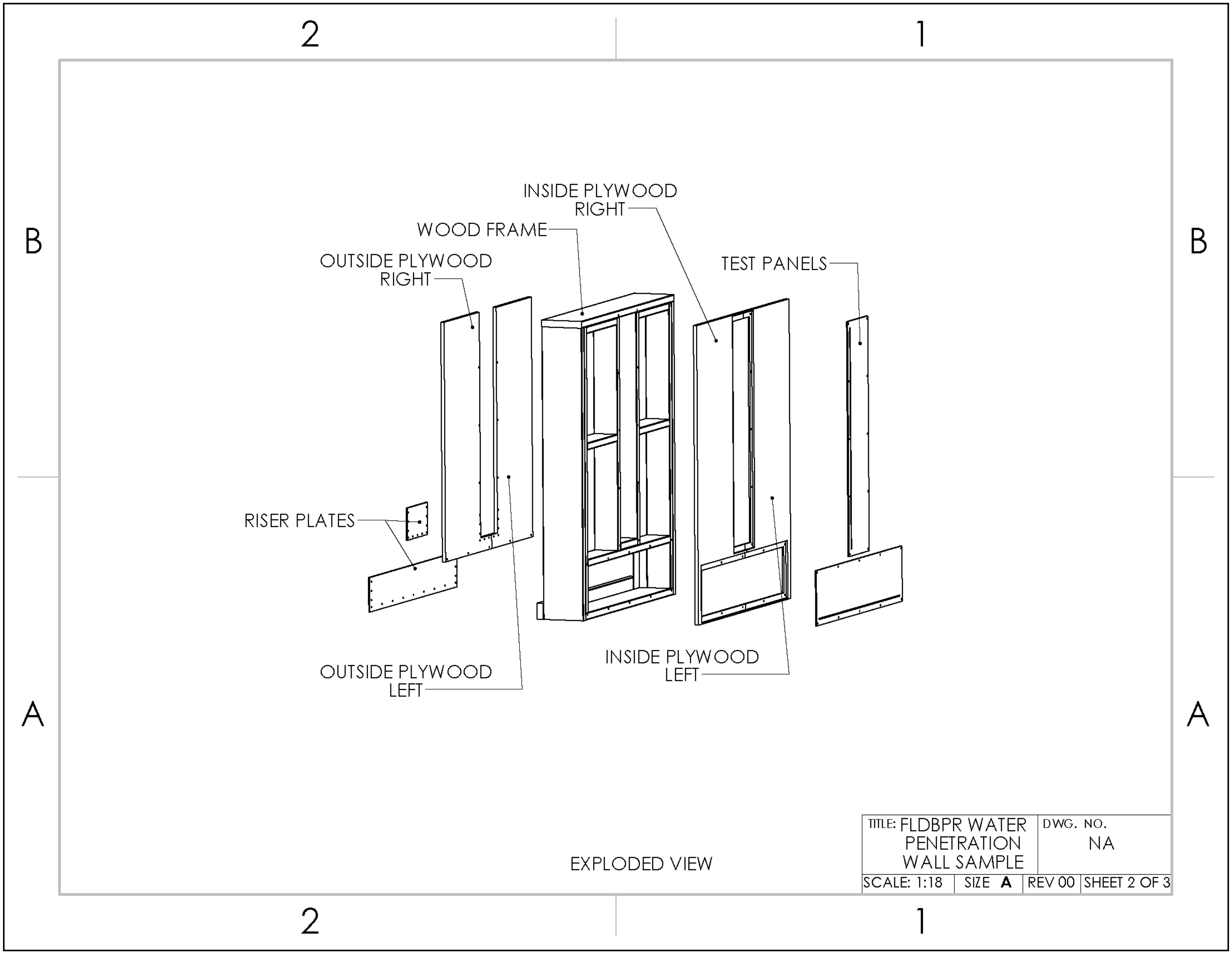
Suggested New Standards: Moving toward a standardized approach to creating a hurricane passage simulation following the procedure presented in Section 9.1 as an optional test is recommended. Many considerations are required in creating such a standard test procedure for building envelope systems including choice of geographic location, wind environment, location on building envelope, orientation of building, angle of attack, and upwind terrain conditions.

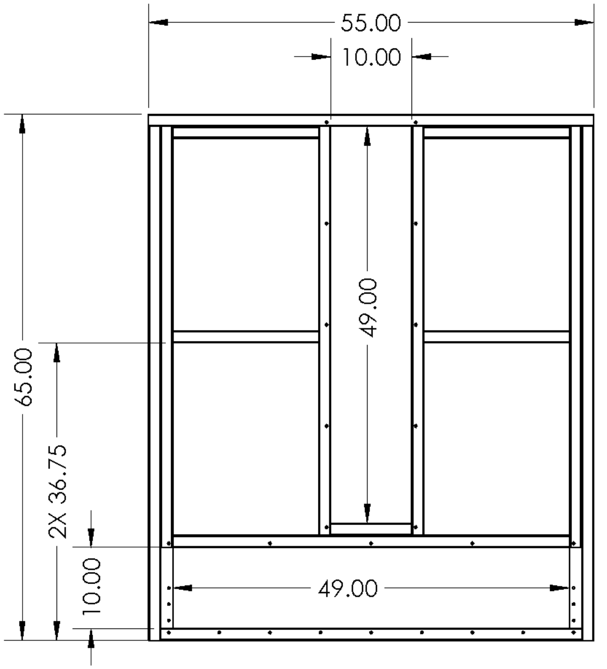
13. References

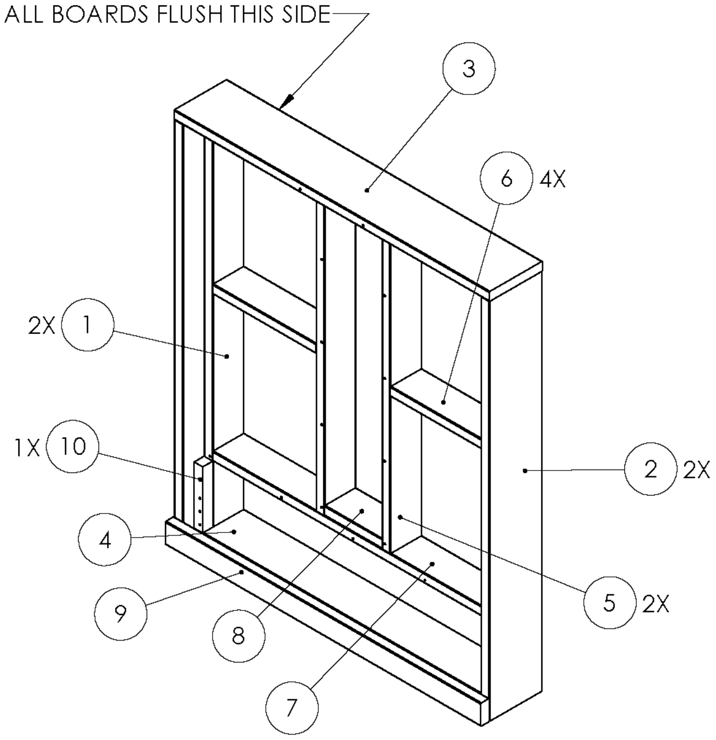
- AAMA/WDMA/CSA101/I.S.2/A440-22 (2022) Standard/Specification for Windows, Doors, and Unit Skylights.
- AAMA/WDMA/101/I.S. 2/NAFS-02 (2003) Voluntary Performance Specification for Windows, Skylights and Glass Doors.
- ASTM E331-00 (2016) Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference.
- ASTM E547-00 (2016) Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Cyclic Static Air Pressure Difference.
- ASTM E1105-15 (2016) Standard Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors and Curtain Walls by Uniform or Cyclic Static Air Pressure Difference.
- ASTM E2128-20 (2020) Standard Guide for Evaluating Water Leakage of Building Walls.
- Blocken, B., & Carmeliet, J. (2004). A review of wind-driven rain research in building science. Journal of wind engineering and industrial aerodynamics, 92(13), 1079-1130.
- Ho, T. E., Surry, D., Morrish, D., & Kopp, G. A. (2005). The UWO contribution to the NIST aerodynamic database for wind loads on low buildings: Part 1. Archiving format and basic aerodynamic data. Journal of Wind Engineering and Industrial Aerodynamics, 93(1), 1-30.
- Ho, T. E., Surry, D., & Morrish, D. (2003). NIST/TTU cooperative agreement–windstorm mitigation initiative: Wind tunnel experiments on generic low buildings. London, Canada: BLWTSS20–2003, Boundary-Layer Wind Tunnel Laboratory, Univ. of Western Ontario.
- Jancauskas, E. D., Mahendran, M., & Walker, G. R. (1994). Computer simulation of the fatigue behaviour of roof cladding during the passage of a tropical cyclone. Journal of Wind Engineering and Industrial Aerodynamics, 51(2), 215-227.
- ISO 15927-3 (2009) Hygrothermal Performance of Buildings–Calculation and Presentation of Climatic Data–Part 3: Calculation of a Driving Rain Index for Vertical Surfaces from Hourly Wind and Rain Data.
- Keesman, K. J., & Keesman, K. J. (2011). System identification: an introduction (Vol. 2, p. 47). London: Springer.
- Kopp, G. A., Morrison, M. J., Gavanski, E., Henderson, D. J., & Hong, H. P. (2010). “Three little pigs” project: hurricane risk mitigation by integrated wind tunnel and full-scale laboratory tests. Natural Hazards Review, 11(4), 151-161.
- Krajewski, W. F., Ciach, G. J., McCollum, J. R., & Bacotiu, C. (2000). Initial validation of the Global Precipitation Climatology Project monthly rainfall over the United States. *Journal of Applied Meteorology*, *39*(7), 1071-1086.
- Lopez, C., Masters, F. J., & Bolton, S. (2011). Water penetration resistance of residential window and wall systems subjected to steady and unsteady wind loading. Building and Environment, 46(7), 1329-1342.
- Pierre, L. S., Kopp, G. A., Surry, D., & Ho, T. C. E. (2005). The UWO contribution to the NIST aerodynamic database for wind loads on low buildings: Part 2. Comparison of data with wind load provisions. Journal of Wind Engineering and Industrial Aerodynamics, 93(1), 31-59.
- TAS 202-94 (2007) Criteria for Testing Impact and Nonimpact Resistant Building Envelope Components Using Uniform Static Air Pressure Loading.
- Walker, G. R., Reardon, G. F., & Jancauskas, E. D. (1988). Observed effects of topography on the wind field of Cyclone Winifred. Journal of Wind Engineering and Industrial Aerodynamics, 28(1-3), 79-88.

Appendix A. Round 1 Reconfigurable Test Specimen Details




2
1
B
A
INSIDE PLYWOOD RIGHT
WOOD FRAME
OUTSIDE PLYWOOD RIGHT
TEST PANELS
RISER PLATES
OUTSIDE PLYWOOD LEFT
INSIDE PLYWOOD LEFT
EXPLODED VIEW
TITLE: FLDBPR WATER PENETRATION WALL SAMPLE
DWG. NO.
NA
SCALE: 1:18
SIZE A
REV 00
SHEET 2 OF 3





ITEM NO.	QTY.	DESCRIPTION	LENGTH
1	2	2X6 PINE LUMBER	62
2	2	2X10 PINE LUMBER	63.5
3	1	2X10 PINE LUMBER	55
4	1	2X8 PINE LUMBER	52
5	2	2X6 PINE LUMBER	50.5
6	4	2X6 PINE LUMBER	18
7	1	2X6 PINE LUMBER	49
8	1	2X6 PINE LUMBER	10
9	1	2X4 PINE LUMBER	55
10	1	2X2 PINE LUMBER	10

FRAME DETAIL

TITLE: FLDBPR WATER PENETRATION WALL SAMPLE	DWG. NO. NA
SCALE: 1:18 SIZE **A**	REV 00 SHEET 3 OF 3

Appendix B. Wall Specimen Detail for All Experimental Configurations

DESIGN DATA

THE WORK DEPICTED HEREIN WAS DESIGNED TO MEET THE REQUIREMENTS OF THE FLORIDA BUILDING CODE, 6TH EDITION (2017) - RESIDENTIAL BUILDING CODE & ASCE 7-10

THE FOLLOWING LOADINGS WERE USED:
WIND LOAD: 175 MPH (ASCE 7-10) 3 SECOND GUST, EXPOSURE D, RISK CATEGORY II

BUILDING ASSUMPTIONS
LOCATED IN HIGH VELOCITY HURRICANE ZONE (HVHZ)
30'X60' FOOTPRINT
12' MEAN ROOF HEIGHT, SINGLE STORY
5:12 GABLE END ROOF 12" OVERHANG
WALL SECTION NOT LOCATED NEAR CORNER OF STRUCTURE

FASTENER SCHEDULE

[A]. PLATE TO PLATE - 16d COMMON ($3\frac{1}{2}$"X0.162") @ 16" O.C. FACE NAILED
[B]. STUD TO STUD - 16d COMMON @ 24" O.C. FACE NAILED
[C]. PLATE TO STUD - (2) 16d COMMON END NAIL
[D]. STUD TO SOLE PLATE - (2) 16d COMMON TOE NAIL
[E]. STUD TO WINDOW SILL - (2) 16d COMMON END NAIL
[F]. STUD TO HEADER - (3) 16d COMMON TOE NAIL
[G]. HEADER/WINDOW SILL TO STUD - (4) 16d COMMON END NAIL
[H]. WALL BLOCKING TO STUD - (2) 8D COMMON TOE NAIL, EACH END
[J]. SOLE PLATE TO FOUNDATION - $\frac{1}{2}$" GALVANIZED ANCHOR BOLT AT 2' O.C. W/ 3" SQUARE WASHER
[K]. BUILT UP HEADER - 16d COMMON @ 16" O.C. ALONG EACH EDGE, FACE NAILED (TYP. BETWEEN EACH 2X PLY)

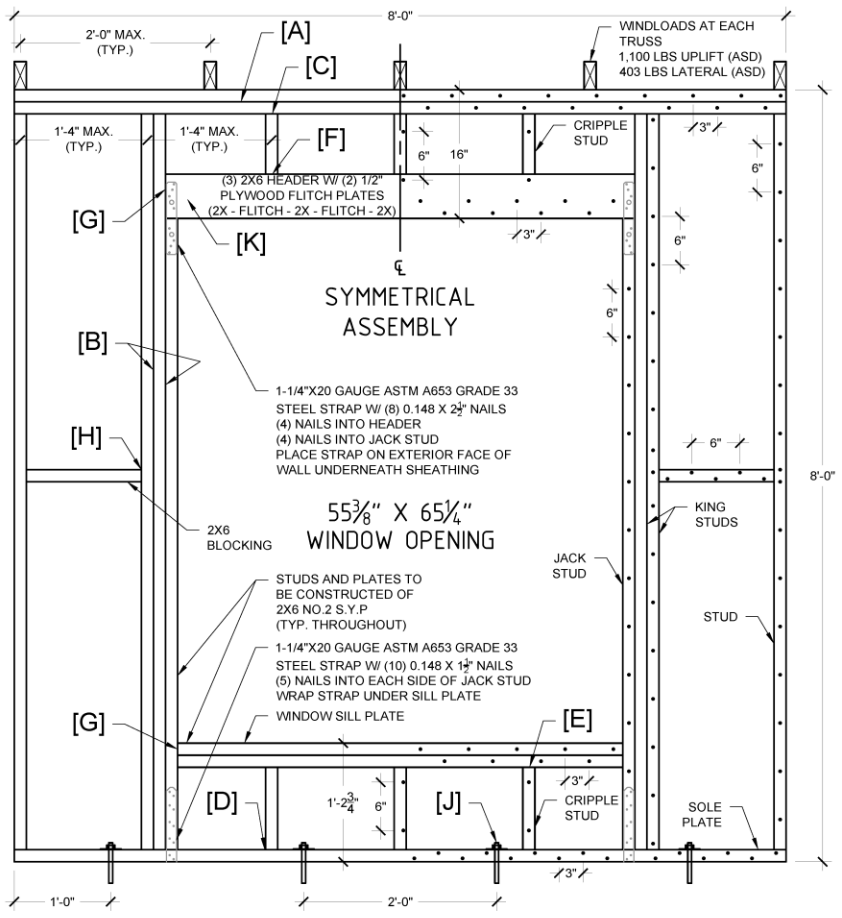
NOTE: WHEN STUDS ARE FASTENED TO DOUBLE TOP PLATE AND DOUBLE WINDOW SILL PLATE, 16d COMMON NAILS SHALL BE INSTALLED IN FIRST PLY PRIOR TO INSTALLING THE SECOND PLY (TO ENSURE 2" NAIL PENETRATION INTO STUD)

NAILING OF WALL SHEATHING

1. ALL EXTERIOR SURFACES SHALL BE SHEATHED WITH $\frac{19}{32}$ C-D EXPOSURE 1 PLYWOOD
2. EXTERIOR WALL SHEATHING SHALL EXTEND FROM TOP OF TOP PLATE TO BOTTOM OF SOLE PLATE.
3. THE LONG DIMENSION OF THE PLYWOOD SHEATHING SHALL BE INSTALLED PERPENDICULAR TO THE STUD FRAMING AND BE CONTINUOUS OVER THREE OR MORE SUPPORTS
4. END JOINTS SHALL BE STAGGERED AND OCCUR OVER STUDS OR BLOCKING.
5. SHEATHING SHALL BE FASTENED TO WALL FRAMING WITH 8d COMMON NAILS AT 6" O.C. ALONG PANEL EDGES, 6" O.C. IN THE FIELD AND 3" O.C. ALONG TOP/BOTTOM PLATE(S) STAGGERED.

EXTERIOR COVERING

1. EXTERIOR WALL COVERINGS SHALL BE PER FBC R703 HAVING A MIAMI-DADE COUNTY NOTICE OF ACCEPTANCE (NOA) MEETING THE REQUIRED WIND PRESSURES
    -52.7 PSF (ASD)
    +48.7 PSF (ASD)
2. IF A WATER RESISTIVE BARRIER (SUCH AS A HOUSEWRAP) IS UTILIZED AS PART OF THE APPROVED EXTERIOR WALL COVERING SYSTEM; IT SHOULD BE INSTALLED PER FBC R703.2 AND MANUFACTURER SPECIFICATIONS
3. FLASHING SHALL BE PROVIDED PER FBC R703.4



CIVIL ENGINEERING • REGULATORY PERMITTING • CONSTRUCTION MANAGEMENT
PEREZ ENGINEERING
& DEVELOPMENT, INC
CERTIFICATE OF AUTHORIZATION No. 8579

Key West Office
1010 East Kennedy Drive, Suite 202
Key West, Florida 33040
Tel: (305) 293-9440

REVISIONS:
1
2
3
4
5
6
ORIGINAL: JULY 2019

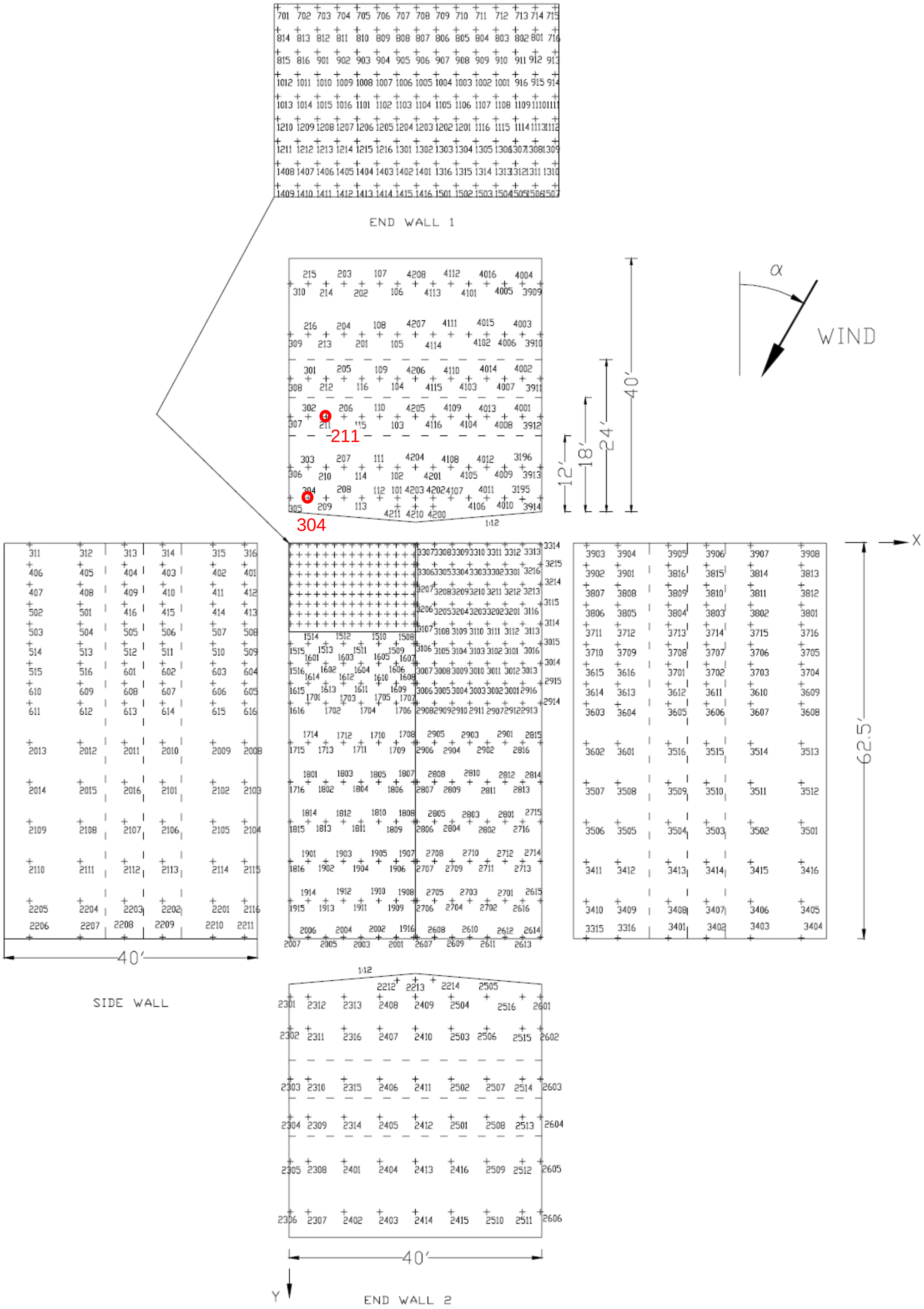
UNIVERSITY OF FLORIDA
POWEL FAMILY STRUCTURES LABORATORY
2070 NE WALDO RD.
GAINESVILLE, FL 32609

8'X8' WALL SECTION

JOB NO. 191039
DRAWN MSB
DESIGNED JDH

SHEET 1 of 1

Appendix C. NIST Aerodynamic Database Model jp1 Tap Layout



Appendix D. NIST Model Pressure Coefficient Records

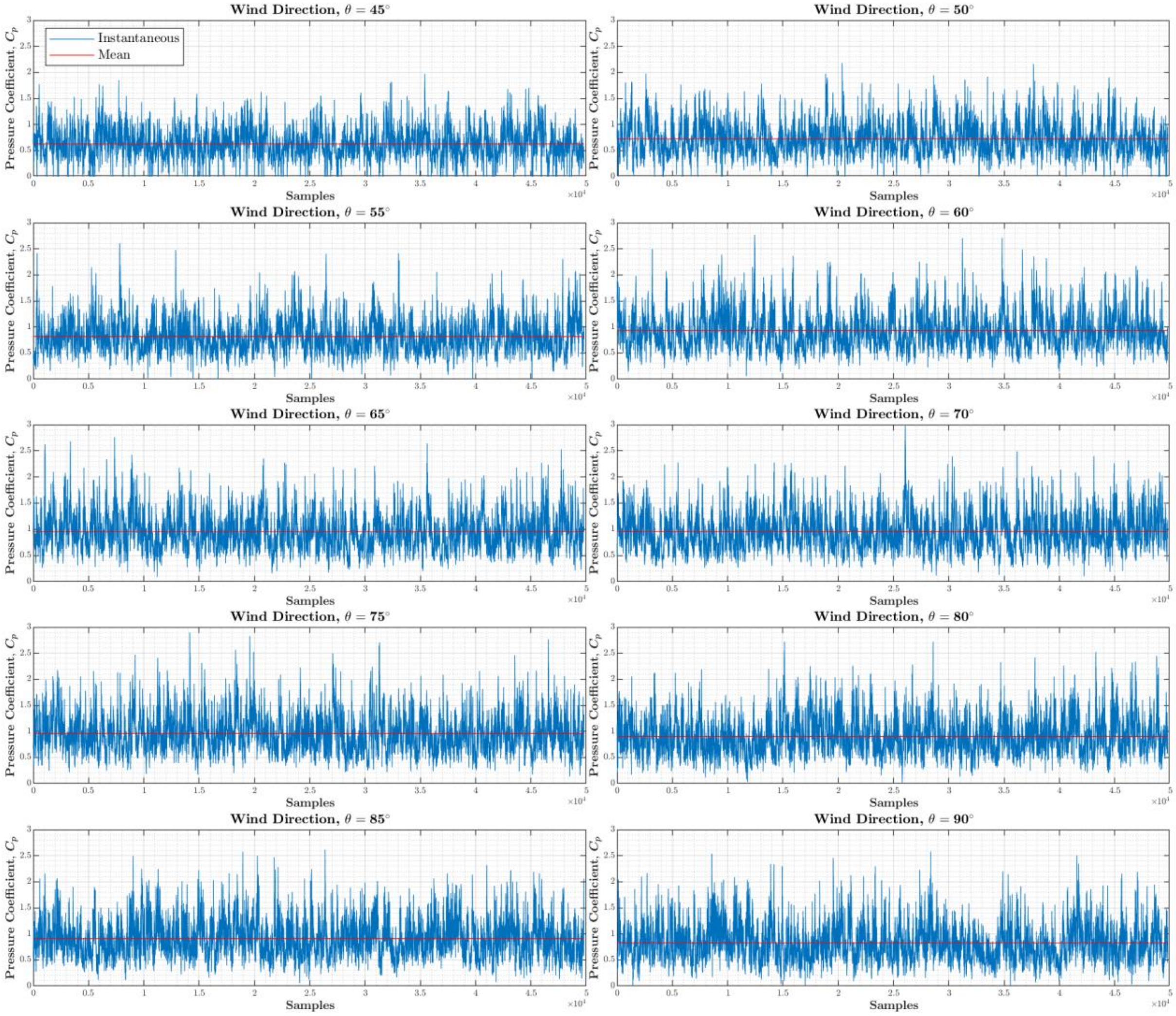


Figure 18. Worst-case $\bar{C}_P$ time histories found at Tap No. 211.

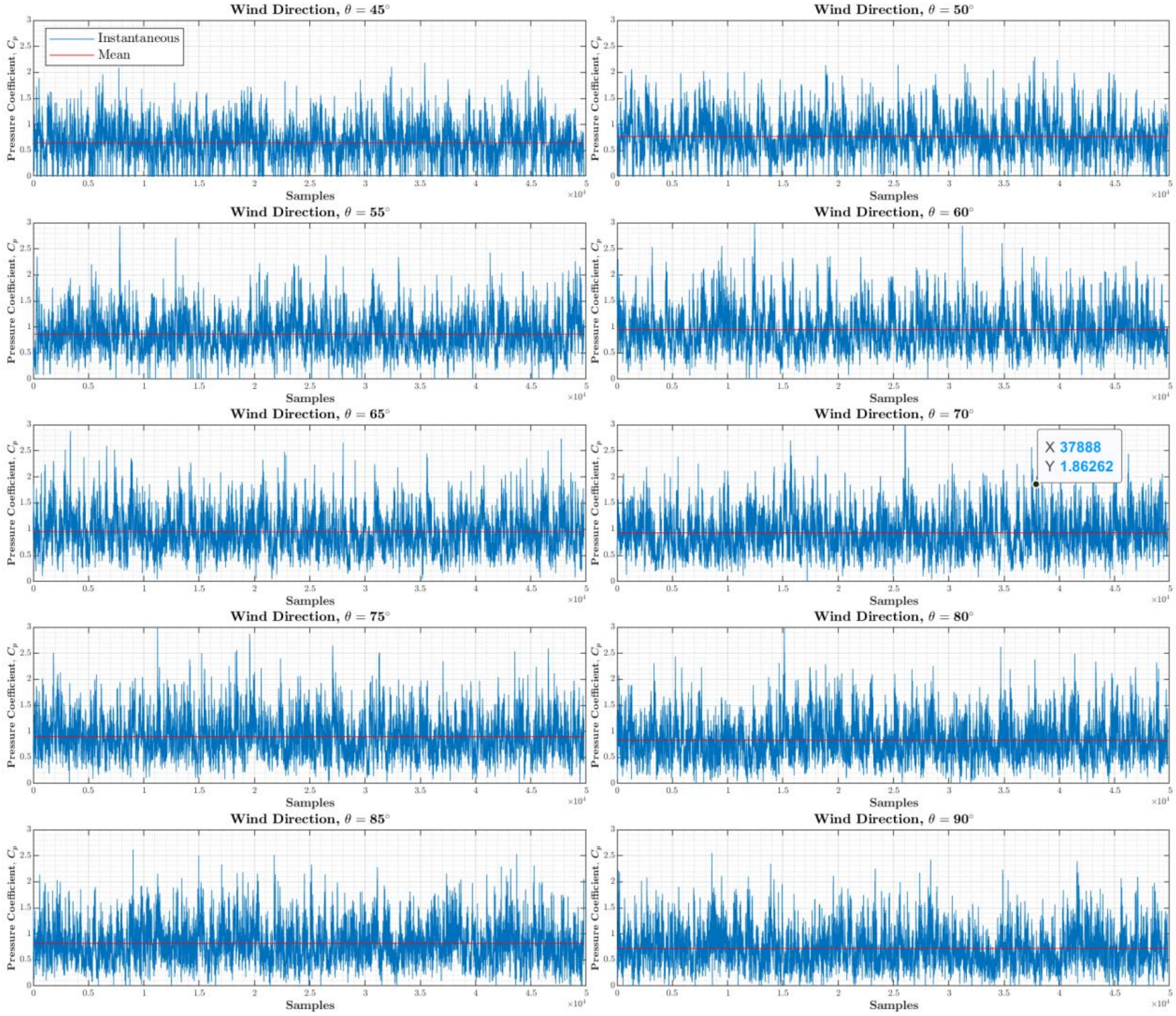


Figure 19. Worst-case $\hat{C}_p$ time histories found at Tap No. 304.