EPISODIC WATER INGRESS THROUGH THE BUILDING ENVELOPE DURING A HURRICANE PASSAGE

By

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To my angel, Maya Olivia

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Each year hurricanes threaten the Atlantic and Gulf coasts of the United States with extreme winds, heavy rains, and flooding from storm surge. In recent years, locations as far up the eastern seaboard as New York and New Jersey were severely affected by tropical systems. Windows in particular present opportunity for water to enter the building envelope, causing significant damage to the structure and its contents.

Residential windows are subjected to static pressure loads in conjunction with the horizontal rainfall to determine water ingress resistance. The loads applied to the windows during an actual tropical system are time-varying, inherent to the turbulent boundary layer. A system was developed at the University of Florida which applied both time-varying loads and multiple wetting rates to simulate the conditions of an actual wind driven rain event. Water ingress under static load was compared to water ingress during time-varying pressure sequences to correlate the behavior of residential windows under actual load to the results obtained during static pressure testing. The comparison of the two scenarios was made using a time-step analysis procedure outlined in this paper.

Four different manufacturers of single hung windows were investigated. The variability between each specimen prevented the formation of an empirical equation to predict ingress based on geometric properties of the window assembly. The accuracy of the time-step analysis in predicting water ingress was primarily dependent on the characteristics of each window specimen. The time-step analysis was able to replicate the water ingress and its variability during select tests which used conditions representative of an actual hurricane.

CHAPTER 1
INTRODUCTION

Wind Driven Rain

Wind driven rain is a complex interaction between individual raindrops of varying size and a wind-field varying in time and space which influences the trajectory of the drops. The behavior of the driving rain is further complicated by local climate, topography, geometry of the building, and the location of the raindrops impinging on the building façade. Water ingress through the building envelope may occur during extended exposure of vulnerable building components to extreme wind driven rain conditions, not unlike those consistent with hurricanes (Salzano, 2010).

The degree of wetting, frequency of application, and moisture ingress through the building is dependent upon the local climatology of the structure in question. The trajectory of the individual raindrops is affected by the drop size distribution of the rain event. Significant wind driven rain occurs during tropical cyclones and super-cell thunderstorms, where the wind speeds are high enough to cause significant wetting rates to be applied to the building façade. Higher wind speeds not only increase the wetting rate, but also increase the pressure applied to the windward wall, increasing the likelihood of water intrusion.

The threat of tropical systems has extended as far north as New England in the recent years with the landfall of Hurricanes Irene and Sandy, in 2011 and 2012 respectively. While neither of these storms was classified as a major hurricane at landfall, damage and economic costs associated with these storms were significant. Water ingress in particular is a factor in the economic loss associated with any tropical system (Lstiburek, 2005). There are often additional costs for the relocation of occupants during the remediation of the interior of a building. The culprit behind several cases of damage due to water penetration is wind driven rain.

Wind driven rain has had significant impacts on the built environment, particularly the building facade. When the exterior barrier is compromised, the intrusion of wind driven rain into the interior of the building can lead to mold, mildew and destruction of the contents inside (Day, 2007). While significant improvements to the wind resistance of structures due to more stringent building codes following hurricane Andrew, damage to structures due to water infiltration is still an issue. Following the 2004 hurricane season, the majority of losses incurred resulted from water penetration through the building envelope (Lopez, 2009). The objective of this research is to determine if the behavior of the window assembly under static loads can be used to predict the rate of water ingress in a scenario in which dynamic loads representative of hurricane conditions are applied to the system.

Water Penetration Resistance Requirements

The American Architectural Manufacturers Association specifies leakage must be prevented up to 15% of the windows design pressure (AAMA/WDMA/CSA 101/I.S.2/A440, 2005). The design pressure of the window is determined using wind load provisions of ASCE 7. ASTM E547 (2000) provides a method for determining the resistance to water ingress under cyclic loads, in which a constant pressure is applied for five minutes, and then no pressure is applied for 1 minute (ASTM E547, 2000). Similar to the dynamic loading applied in this study, ASTM E2268 (2004) provides a methodology to rapidly change the applied pressure between 50% and 100% of a mean pressure to determine water penetration resistance (ASTM E2268, 2004). Similar testing using negative pressures applied to the interior of the window specimen were conducted to determine the water penetration resistance of windows (Van Staaten et al, 2010).

Scope of Research

A new high airflow pressure loading actuator (HAPLA) was designed and constructed at the University of Florida to apply static pressure loadings to window specimens. The concept of the pressure loading actuator is based on the University of Western Ontario’s Three Little Pigs Project (Kopp, 2008) A multi-stage rain rack was added to the existing test chamber, featuring automated valves to regulate the flow, which can adjust the wetting rate from 150 mm/hr (5.91 in/hr) to 600 mm/hr (23.62 in/hr). This system was used to simulate wind driven rain conditions on window specimens to determine the amount of water of water ingress.

The first phase of testing followed current test standards using a wetting rate of 203 mm/hr (8 in/hr) to determine the static pressure threshold at which water ingress begins (AAMA/WDMA/CSA 101/I.S.2/A440, 2005). The next phase of testing subjected each window specimen to four wetting rates at four different pressure levels to form an array of ingress rates. Four dynamic pressure sequences were then applied to the window specimen at each wetting rate. This enabled investigation of the correlation between water ingress behavior under static and dynamic load scenarios. The final testing phase replicated pressure sequences and wind driven rain measurements from Hurricane Ike. The goal of this testing is to for a relation between the static testing and dynamic pressure sequences. This correlation allowed the prediction of behavior in actual hurricane conditions.

CHAPTER 2
BACKGROUND

Building Performance in Hurricane Conditions

Each year hurricanes threaten communities along the Atlantic and Gulf coasts of the United States. The majority of the national population lives on the coast, making these regions prone to large economic losses in the event of a natural disaster (Crossett, 2004). In recent hurricanes, the majority of losses incurred are due to water entering the building envelope. Water ingress through the building envelope may occur during extended exposure of vulnerable building components to extreme wind driven rain conditions, not unlike those consistent with hurricanes (Salzano, 2010).

During a hurricane, a building is subjected to both extreme pressure loads and driving rainfall. This combination causes water to be propelled through any open orifices in the building exterior. When roof covers such as shingles are lost, sheathing panels may become exposed, providing a path for water to enter the attic space. Clay and concrete tiles are susceptible to being removed if damaged by wind-borne debris, also exposing sheathing panels if the vapor barrier is breached. Another common point of entry for water during storms is where mechanical and electrical systems are attached to the roof of buildings. These systems can be subjected to loads larger than the connections are rated for, leaving large exposed areas for water to enter the building envelope. Wind borne-debris damage to the façade allows for wind driven rain to enter as well. Orifices on the windward wall of the structure where electrical or mechanical plumbing enters the building can provide an entry for water if not properly sealed. Unsealed entry doors or those not rate for the applied wind load can fail, allowing water to enter the building.

Water ingress is among the most common sources of damage and economic loss in hurricanes. Minor water penetration can cause the deterioration of the interior of a building, causing mold and/or mildew, which can result in significant remediation costs. Water penetration can also stain or damage interior furnishings, as well as degrade electrical and mechanical components. If the water ingress is undetected or goes untreated, it can rot structural components of timber construction. In severe cases, renovation may be necessary, which is accompanied by the cost of temporarily relocating the occupants.

The detrimental effects of wind driven rain on the built environment are not only limited to cases where water finds a path into the building, but can also negatively impact the façade and aesthetics of a structure. The repeated exposure of architectural finishes and features can accelerate deterioration. Sediment deposition on the façade can alter the aesthetics of a structure, as well as incurring remediation costs. While these are all mechanisms of building deterioration due to wind driven rain, this research specifically studied the mechanism of water ingress through the window assembly.

The fundamental process which fuels water ingress through any building component is the difference in pressure between the interior and exterior of the wall. This pressure difference is created by strong winds applied to the building façade via super-cell thunderstorm or tropical cyclone. Water ingress begins once the difference between the exterior applied pressure and the interior pressure exceeds the pressure required to advance water through the breach in the façade. The pressure that is required to overcome is based on the type of component that the pressure is being applied to. If the barrier is a small crack in the building façade, the static pressure is a function of the elevation difference between the exterior and interior, and the static pressure loss created by the friction between the water traveling through the small crack in the building façade. In typical soffit systems, it must overcome the pressure loss created by the small pores, similar to the pressure losses associated with forcing air through a dense mesh or screen. In windows, the primary barrier to water penetration is the difference in elevation between interior and exterior window components.

Single hung windows in residential structures are common points of direct application of water which are not completely sealed to prevent water penetration. The application of water horizontally alone is not enough to trigger ingress though any properly designed single hung window, which comprise the majority of windows in a residential structure. The window assembly is designed to require a certain static pressure to overcome the elevation difference between the interior exterior sill dams. The other point of entry in the window is at the meeting rail, through the seal between the top and bottom frames, where the window locks and unlocks to allow opening and closing. This location also depends on the difference in elevation to provide resistance to water penetration. Most windows have a gasket at this interface that helps to form a semi-watertight seal; however, the sliding requirements of the window prevent sealing across the entire section. If the void at the meeting rail becomes large enough, water droplets can be carried through void due to the jet of air flow through.

Water Ingress through the Window

Residential windows are specifically susceptible to leakage because they are not designed to be completely sealed from air or water passing through them. Instead, windows rely upon the elevation difference of the sill dam at the bottom of the window, and the difference in elevation between at the meeting rail. This convention is acceptable for rain applied to the window in nearly any amount possible. During preliminary calibration of the two phase rain rack, wetting rates up to 650 mm/hr were applied to each window specimen. This maximum wetting rate is much higher than what is possible in a tropical system. Therefore, it is assumed that the threshold at which ingress begins under statically applied loads is dependent on the pressure, not the wetting rate. The exact pressure required to cause leakage is dependent on the design of the window and its dimensions.

The windows tested as a part of this study were selected randomly, have similar overall dimensions, and have varying sill dam height dimensions, and meeting rail dimensions. It was considered to use only multiple replicates of only window to assess the prediction method. The use of multiple windows enables determination of whether water ingress is primarily dependent on design, or a function of applied wetting rate and wind loading. The different designs also provided the opportunity to observe the variability in performance between manufacturers. Single hung windows were chosen as the only window style to investigate because they are most commonly used in residential structures, and more prone to leakage than casement or awning windows.

Current test standards for windows require that the window must prevent water ingress up to 15% of its design pressure rating (AAMA/WDMA/CSA 101/I.S.2/A440, 2005). This test is conducted using a wetting rate of 203 mm/hr (8 in/hr). Dynamic loads, which provide a more realistic representation of what occurs during a hurricane, are in part accounted for by ASTM E2268 (2004). The test standard applies a load cycle of 50% to 150% of a mean static pressure a frequency of 0.5 Hz (ASTM E2268, 2004).

Once ingress begins, the amount of water that passes through the window is unrestricted.

This study analyzed a new method to characterize water ingress through the window. The intention was not to create a new standard, but to determine if the amount of water ingress measured using static pressure loads can be related to the water ingress experienced during actual hurricane conditions. The original goal of the study was an equation that can be used to predict water ingress based on the wind and rain conditions, that accounts for the design of the window in question.

Previous Research

Wind driven rain is a complex interaction between the wind, rain, and wetted surface. Water ingress results from the behavior of wind driven rain in relation to the building and applied pressures, and its orientation with respect to the primary wind direction. The following sections discuss this complex wind-rain interaction in more detail to form a foundation of the work that lead to component based investigation water ingress as a result of wind driven rain.

Individual droplets of distributed sizes comprise any given rainfall event. Different types of rainfall conditions can result in different raindrop size distributions (Ulbrich, 1983). Convective precipitation generally produces a larger concentration of smaller drops and a smaller concentration of large drops compared to stratiform precipitation (Tokay and Short, 1996). The behavior due to wind acting on an individual droplet is dependent upon the size of the droplet. The resulting trajectory and shape at impact of each individual raindrop must then differ slightly depending on its size. In order to approximate the behavior of the rainfall in a wind driven rain event, a drop size distribution must be measured and determined. The first rainfall dependent distribution was assumed to be linear in log space (Marshall and Palmer, 1948). A common distribution applicable to several events was determined using distributions collected on filter paper (Best, 1950).

Characteristics of the terrain in the vicinity of a building affect the wind velocity and turbulence intensity, thus affecting trajectory of rain drops and the overall wetting pattern of the façade (Blocken and Carmeliet, 2002). The turbulence intensity increases and the mean velocity decreases as the distance above the ground decreases (Counihan, 1975). The topography and terrain on a smaller scale is also an important parameter affecting the wetting of the building façade (Blocken et al, 2006).

A satisfactory approximation of the intensity for a given wind driven rain event can be expressed as a function of horizontal rainfall intensity and wind velocity, also shown in Eq. 5-13 (Lacey, 1964). However, the behavior of the individual raindrops for a specific event due to the wind must be taken into account to characterize the resulting wetting of a building façade. Differing building geometry, upwind terrain, and local climates further complicate the issue. Hoppestad (1955) and Lacy (1965) developed semi empirical equations to determine the wind driven rain intensity. Both models expressed the wind driven rain intensity as a function of horizontal rainfall intensity and wind velocity. Factors were later implemented that accounted for location on the building façade and wind direction to produce similar equations to estimate wind driven rain intensity (Straube and Burnett, 2000).

With the advent of the computer and computational fluid dynamics modeling, the wetting of a building façade could be investigated without the rigors of orchestrating a full-scale experiment (Choi, 1993). The total effect of wind driven rain on a given structure can be quantified using the Local Intensity Factor and Local Effect Factor (Choi, 1994). These factors account for the distortion in the approach flow using dimensions of the building and approach conditions. This is especially important for larger buildings, and the deterioration of the façade and architectural components. Numerical methods were employed by Choi (1993, 1994) to calculate the trajectory of rain drops approaching the facade by solving the Navier-Stokes equations with the k-E turbulence model.

There have been limited attempts to study the wetting of the façade in the wind tunnel due to difficulty of obtaining consistent results (Bitsuamlak et al, 2009). The process is complicated by the labor required to record and analyze water impacts on the water sensitive paper, the repeatability of results due to short test durations, and the scaling of the water droplets while producing a uniform distribution (Inculet and Surry, 1994).There have been limited attempts at full scale investigation of wind driven rain impacting the façade. More common, are standards and tests that analyze particular components of the façade for water resistance. The present study is of this variety, attempting to predict water ingress through windows under dynamic load conditions. The following three studies varied in scope, but subjected fenestration to wind driven rain conditions to determine water penetration resistance.

In recent hurricanes, water ingress damage occurred to a significant number of homes in which little or no visible damage occurred to the building envelope (Mullins, 2006). The results of a study conducted at the University of Florida quantified water ingress through residential fenestration (Salzano et al, 2010). The study investigated the water penetration resistance of the window/wall interface, focusing on installation methods for a variety of wall styles. Cyclic loads were used, opposed to realistic dynamic loads to evaluate performance of the window/wall assembly. The study concluded that poor construction methods often lead to decreased water penetration resistance of the sealants around the window.

Studies conducted at the University of Western Ontario applied cyclic loading to residential window systems (Van Straaten, 2010). Three vinyl windows were tested under negative pressure to evaluate their resistance to water ingress. Dynamic pressure sequences were derived from wind tunnel data. The study compared water ingress from static tests and dynamic pressure tests. However, the results were observations only, so that actual water ingress quantities were not recorded. The study concluded that no ingress occurred at higher peak pressures during the realistic dynamic pressures sequences compared to the static pressure tests.

The pressure loading actuator employed for the present study was developed based on pressure simulation conducted by Kopp et al. (2008). An investigation similar in structure employing the same test apparatus as the present study was conducted using dynamic pressure sequences to study water ingress through windows (Lopez et al, 2011). The first phase of testing determined the water resistance of the windows under static pressure, which was applied in suction. The second phase of testing applied seven dynamic pressure sequences that were derived from wind tunnel testing using a method identical to what was used in this study. The dynamic pressure sequences were increased by their peak at equal intervals. The first half of the dynamic pressure sequences referenced the wind tunnel record with the largest peak pressure. The second half of the dynamic pressure sequence referenced the wind tunnel record with the largest mean. It was concluded that while the windows did leak at higher pressures, the wetting rates applied were extreme values compared to what was typically observed in tropical cyclones.

While the aforementioned studies simulated windows to realistic dynamic loads, current test standards only specified cyclic or oscillating static pressures (ASTM E2268, 2004) and (ASTM E1105, 2005). The present study replicated loads generated from actual hurricane data, and pressure coefficient data from wind tunnel models. The study conducted by the University of Western Ontario used a suction chamber in contrast to positive pressure in the present study to create the pressure difference across the window (Van Straaten et al, 2010). The wetting rates were varied to determine a correlation between rainfall intensity and water ingress through the window assembly. The dynamic pressure sequences used in Phase III and Phase IV of testing in the present study were derived in a similar manner as those used by Lopez et al (2011) for evaluating water resistance of window specimens.

Summary

The structural integrity of the building envelope with respect to extreme wind loading has greatly improved, supported by enhanced performance in recent storms. However, a significant amount of loss still occurs due to water damage following relatively weak hurricanes. Performance of windows in recent storms highlights the need for improved resistance to water ingress during significant wind driven rain events. This study proposes a method to investigate and predict the amount of water ingress observed during actual hurricane conditions.

CHAPTER 3
EXPERIMENTAL DESIGN

Test Wall Design

Test walls were designed and constructed to secure window specimens for water ingress testing, which prevent water ingress around the window. The window specimens were subjected to static and dynamic load sequences using a pressure loading actuator. Two phases of dynamic load testing was conducted, which were Phases III and IV of the testing sequence. The dynamic loads for Phase III were developed at specific peak pressures for the pressure sequence. Phase IV dynamic pressure sequences were developed using data recorded during Hurricane Ike. The following sections describe the test apparatus, test specimens, and the development of the dynamic pressure sequences.

8ft x 8ft walls were built to match the dimensions of the pressure chamber, with the window being tested centered on the wall. The wall which represents the exterior wall was constructed of APA Grade B, 11.9 mm (1/2 in) plywood fastened to 2x4 studs spaced at 0.4 m (16 in), as shown in Figures 3-1 and 3-2. The wall was covered with a Tyvek vapor barrier to allow the wall to shed water quickly. Each window was permanently installed and sealed into a 2x4 frame that allowed the specimen to be easily removed from the test wall and replaced by the next window specimen. The construction of the test wall and window/wall interface was not performed to an established building code; instead it was constructed to prevent water from migrating around the window specimen during testing. The framed window to be tested was placed in the center of the wall and sealed with GE clear silicone (model #LW5000) around its perimeter on both the exterior and interior to prevent water from migrating around the window, as shown in Figure 3-3. The seam running around the perimeter of the window frame and the test wall was covered with flashing tape once the silicone dries to prevent water from entering through the vapor barrier.

The walls were designed to allow specimens to be changed after each phase of testing so that results could be analyzed for all four window specimens prior to moving on to the next phase, to ensure no errors in the results or instrumentation. Walls were light enough to be manually moved by one person with a lift truck so that specimens could be rapidly interchanged. Legs two feet in length were secured to the base of the sides of each wall at a 10 degree angle to allow the walls to tilt backward slightly and rest on the legs while windows are installed.

Window Specimens

Dimension of each window specimen were recorded so that comparisons can be made with the amount of water ingress with respect to each design if necessary. The dimensions of primary concern are difference between interior and exterior sill dam height on the bottom of the window, and the difference in elevation of the top of the bottom siding frame, and the bottom of the top widow frame. The location of the seal at the locking meeting rail of the window varies greatly, and is assumed to have little effect on the amount of water ingress due to the lack of continuity at the edges of the window where the water typically penetrates, instead of the middle.

The height of water column is related to the applied static pressure in that it requires that amount of applied pressure to move a column of water a certain height. Below, the specifications for each of the four windows are provided. Accompanying this information is the equivalent pressure needed to raise the water the specified difference in elevation required to cause leakage at that part of the window assembly. The top and bottom differ in that water droplets must be forced through the air to penetrate the top of the assembly, while water collected at the bottom of the assembly is forced through by the applied static pressure.

Test Apparatus

The positive pressure for the window testing was supplied by a new high airflow pressure loading apparatus (HAPLA), shown in Figures 3-4 and 3-5. The HAPLA is powered by two backward inclined 75 HP centrifugal blowers. Each fan is capable of running at 1800 rpm. The fans are configured in series to maximize the pressure output capabilities of the system. The fans are connected by a series of ducts which are attached to a valve which controls the pressure.

The valve has five ports: intake from the fans, exhaust to the fans, atmospheric intake, atmospheric exhaust, and a port that connects to the test chamber. A circular aluminum disc with two sections cut out rotates between the ports to adjust the density of the air in the test chamber, thus changing the static pressure in the test chamber. The valve can oscillate the static pressure in the test chamber at a frequency up to three hertz.

The HAPLA incorporates a two-phase spray rack which enables both high and lower wetting rates to be simulated. For this testing only one rack was used, which was composed of a three by three grid of 120 degree nozzles. The spray racks are regulated using mechanical ball valves, and monitored with flow meters to ensure consistent wetting rates throughout all testing. Excess water collecting in the base of the test chamber is evacuated using a submersible 1/3 HP pump, which recirculates the water back to the storage tank. An emergency evacuation valve is also installed at the base of the chamber to reduce the load on the submersible pump. A V-shaped channel approximately 10 cm (4 in.) wide is welded the length of the test chamber below the specimen to collect any water that escapes through the gasket between the specimen and the bottom of the test chamber.

The method of measuring water ingress is shown in Figure 3-6. Water is collected in a shallow v-shaped trough at the base of the window, which is then directed into a bucket. A 6.3 mm (1/4 in.) thick sheet of polycarbonate is fastened to the exterior of the wall behind the window to deflect water droplets into the basin at the bottom. An aluminum lip at the bottom of the polycarbonate sheet ensures that all water droplets are collected and do not evade the basin. The bucket that the basin drains into is suspended from an Omega LC509-005 load cell with a 25 lb. capacity.

The program for the static and dynamic pressure sequences is executed in the LabView environment. Static pressure readings in the test chamber are taken at a frequency of 50 Hz in conjunction with load cell output. The wetting rate and valve position for the rain rack is recorded at the beginning and end of each test and then recorded to ensure that it remained constant throughout.

Testing Procedure

The testing procedure was separated into for phases of ingress testing. The first phase was initial static pressure testing to determine the pressure at which leakage begins. The second phase was testing at multiple wetting rates at four pressure intervals determined from the first phase. The third phase was dynamic pressure testing using the same pressure sequences for all windows at four equal intervals of five psf. The final phase was conducted using dynamic pressure sequences representative of conditions during Hurricane Ike.

Phase I: Initial Static Pressure Tests

The primary goal of the initial phase of testing was to determine the minimum applied static pressure at which each window began leaking at a constant wetting rate of 203 mm/hr (8 in/hr). This pressure level also established the four pressure levels at which Phase II testing was conducted. These four pressure levels were spaced at equal intervals between the initial leakage pressure and 75% of the positive design pressure of the window.

The wetting rate during this test was set, and held at a constant wetting rate of 203 mm/hr (8 in/hr) which was consistent with current test standards (AAMA/WDMA/CSA 101/I.S.2/A440, 2005). The pressure was manually increased in increments of 0.02 kPa (0.5 psf), pausing for 30 seconds at each level to observe the behavior of the window. Once ingress was observed through the window, the pressure was noted as the minimum pressure at which leakage begins, and the four pressure levels were determined. Testing was then performed at the four determined pressure levels using a constant wetting rate of 203 mm/hr (8 in/hr).

Phase II: Varied Wetting Rate and Pressure Levels

This phase of testing uses the four pressure levels determined in Phase I, which differ for each window specimen. The purpose of Phase II was to develop an array of water ingress rates for different pressure levels and wetting rates. The wetting rates were spaced at equal intervals within the range of the rain rack.

At each pressure level, the window was subjected to 10 minute durations of each wetting rate. The wetting rate array used was 150, 200, 250 and 300 mm/hr (5.91, 7.87, 9.84 and 11.81 in/hr). Wetting rates exceeding this range were also considered using both rain racks in conjunction, however, the performance of these in preliminary tests were highly inconsistent. This resulted in the use of the previously specified range, which are values typically observed strong tropical cyclones.

Phase III: Dynamic Pressure Sequences of Specified Interval

The first phase of dynamic pressure testing incorporated the procedure previously reviewed to develop the pressure sequence. This pressure sequence was specified to four levels with evenly distributed mean static pressures of 0.36, 0.44, 0.52 and 0.60 kPa (7.52, 9.19, 10.86 and 12.53 psf). The peak pressure load in each sequence is approximately three times the mean, and it was considered when developing the sequences that the static pressure must not exceed 75% of the design pressure to prevent any permanent damage to the window system. The wetting rates that were used are 150, 200, 250, and 300 mm/hr (5.91, 7.87, 9.84 and 11.81 in/hr), which correspond to the wetting rates that were used in the static testing. Using the same wetting rates for each testing provided the most efficient and accurate data to interpolate for the initial prediction of water ingress. Each wetting rate was tested at all four pressure levels to produce a total of 16 tests for each of the four windows.

Phase IV: Hurricane Ike Representative Pressure Sequences

The second phase of dynamic pressure testing used the data collected during Hurricane Ike in 2008 to develop pressure sequences and wetting rates that replicate the conditions during an actual storm. A 260 minute segment of wind velocity and direction data was taken from the time histories recorded during the storm. The direction that corresponded to perpendicular to the windward wall was determined by finding the highest 10 minute mean wind speed from the record and its corresponding direction which was denoted 90 degrees. The wind speeds from the record were then separated into 10 minute segments to determine the mean wind speed. The corresponding direction for each average velocity was also recorded and then rounded to the nearest value of five so that it could be correlated with a pressure coefficient sequence from the wind tunnel, which was performed in five degree increments on a turn table. The corresponding wind tunnel directions were oriented in the same direction as the assumed windward direction from the hurricane data. From the corresponding wind tunnel direction, the pressure coefficient time history with the largest mean was then selected for building the sequences. To replicate the wind driven rain component of the storm, the horizontal rainfall intensity data was taken and converted into wetting rate using the procedure previously outlined.

Selection of Dynamic Pressure Sequences for Phase III Testing

The dynamic pressure loading sequences were produced using wind tunnel modeling pressure sequence for building SS20 – Test 4, from the NIST Aerodynamic Database, with modeling and testing performed by the University of Western Ontario. This building and pressure tap location were also used by Lopez et al (2011). The subject building selected was a 1:12 slope gable-end structure with an eave height of 7.3 m (24 ft), and plan dimensions of 19 m x 12.2 m (62.5ft x 40 ft), constructed at a scale of 1:100. The condition of the upwind wind tunnel terrain was modeled to open country. For this study internal pressure measurements were due to distributed leakage. A Scanivalve pressure scanning system sampled the static pressure at 500 Hz. Pressure coefficient data was taken at wind angles divided into 5° increments.

The complete dataset for the model was analyzed to locate the highest mean positive pressure coefficient, C_p, defined as:

$$C_p = \frac{p - p_{ref}}{\frac{1}{2}\rho U_{ref}{}^2} \tag{3-3}$$

where p is the pressure measured at the location on the model that exhibited the highest mean positive pressure, p_{ref} is the pressure measured at the reference location, U_{ref} is the velocity taken at the reference height, and ρ is the air density. The roof height was used as the reference location, using referencing factors provided on the NIST website. The record was derived from tap 3901 at an approach angle of 55°, which produced the maximum mean C_p = 0.96, with a C_p maxima of 2.84. This peak C_p value of 2.84, $C_{p,max}$ is assumed to provide an accurate estimate of the peak load acting on the wall. Using this assumption, the design pressure, P_f, can then be calculated using the following equation:

$$P_f = \frac{1}{2}\rho U_h{}^2 C_{p,max} \tag{3-4}$$

where U_h is the mean velocity at the eave height and the full scale pressure. P_f is a predetermined vector of four static pressures based on the design pressures of the particular window to produce evenly distributed pressure levels. For Phase III testing, four pressure sequences of equal interval of specified peak will be selected. In this case the desired or target peak pressures used were 1.08, 1.32, 1.56, and 1.80 kPa.

The reduced frequency relationship is used to maintain consistency from model scale to full scale. The full scale frequency must be solved for using the reduced frequency relationship to determine the time step size required for the full scale pressure time history.

$$\frac{f_f L_f}{U_f} = \frac{f_m L_m}{U_m} \tag{3-5}$$

Solving for f_f,

$$f_f = f_m \frac{L_m}{L_f} \frac{U_f}{U_m} \tag{3-6}$$

where f_f is the frequency at full scale, fmodel is the sampling frequency at model scale, L_m is the test building scale, L_f is the building component scale, U_f is the velocity at the full scale reference height, and U_m is the velocity at the model reference height. The time increment *dt* is the inverse of f_f and used to create the pressure sequence. The data is then resampled to 50 Hz for compatibility with the HAPLA control system and desired rate of sampling for recording ingress data. The resulting pressure sequence is subjected to a 3-Hz Butterworth filter to create a pressure sequence that can be realistically duplicated by the HAPLA.

The pressure loading sequence can then be constructed using the desired P_f level and the f_f calculated for that particular case of P_f. The load sequence begins with a short ramp to 50% of the desired pressure level and then begins a 10 minute dynamic pressure sequence before returning to 50% of the desired static pressure for a brief period before ramping down. Shown in Figure 3-7 is the resulting target time history for pressure level three replicated using the HAPLA to fluctuate static pressures on residential windows.

The final phase of testing, Phase IV, used slightly different dynamic pressure traces than Phase III. Instead of specifying the intensity of the pressure sequence, the sequences were developed using data recorded during Hurricane Ike by the FCMP tower data for tower, T3. The wetting rate values were determined from radar estimates of horizontal rainfall intensity, which is described later.

Wind-speed and direction was recorded for 18 hours, at a height of 10 m, through the duration of the event. Because this study is only concerned with the wind and rain as it interacts with a windward facing window, a segment of data approximately six hours long was selected, shown in Figure 5-8. This particular six hour segment is of importance because it represents the time at which the direction of the wind and rain as it impacts the window is approximately perpendicular to the wall. The six hour segment was then evaluated in conjunction with the rainfall data, and a four hour segment of data isolated in brackets in Figure 5-9 was selected based on the higher rainfall intensity during the selected four hours to develop pressure sequences .This remaining segment of data was then separated into segments of 11 to 13 minutes, depending on the length of the corresponding rainfall data, of which the mean wind speed was extracted and applied to pressure coefficient sequences of 10 minutes.

The procedure previously outlined for obtaining pressure coefficient data from the wind tunnel was again used to produce the pressure sequence. Additional steps were then followed as outlined in the following paragraphs to develop pressure sequences from Hurricane Ike data.

The velocity measurements obtained from the FCMP tower were the one minute averages. Therefore, for comparison to the three second gust used in many design codes, the applied pressure would need to be scaled accordingly for comparison by converting the one minute average velocity to the equivalent three second gust. Because the velocity measurement in the wind tunnel and in the field was measured at different elevations, the velocity measurement in the field must be referenced to the eave height of the wind tunnel model. To do so, the velocity which is measured at 10 m must be referenced to the eave height of the model building, which is 7.3 m, using the log law relationship.

$$u_z = \frac{u_*}{k} ln\left(\frac{z}{z_0}\right) \tag{3-7}$$

Equating the full scale and model scale values, and then solving for the full scale velocity yields:

$$U_{7.3} = U_{10} \frac{ln\left(\frac{7.3}{0.03}\right)}{ln\left(\frac{10}{0.03}\right)} = 0.946\, U_{10} \tag{3-8}$$

where U_{10} is the velocity measured from the tower at a height of 10 m, $U_{7.3}$ is the velocity at the eave height of the building at a height of 7.3 m, and the roughness length is taken as 0.03 m.

Following the re-referencing of the velocity to the correct height, the pressure coefficient values must also be re-referenced to the eave height of the model building. The C_p data from the wind tunnel testing was extracted and scaled from the reference height to the full scale height of the building using the conversion factors provided in the NIST Aerodynamic Database. To match the full scale wind velocity data taken from the FCMP tower, C_p must be scaled using the following relationship:

$$C_{p,f} = C_{p,m}\left(\frac{U_m}{U_f}\right)^2 \tag{3-9}$$

where $C_{p,f}$ is the full scale pressure coefficient, $C_{p,m}$ is the pressure coefficient signal taken from the wind tunnel, U_m is the mean wind speed from the wind tunnel taken at the eave height, and U_f is the full scale velocity taken from the FCMP data analysis. The pressure sequence can now be constructed using the following:

$$P_f = C_{p,f} P_{v,h} \tag{3-10}$$

Taking P_f as the static pressure applied to the test specimen, and:

$$P_{v,h} = \frac{1}{2} \rho \, {U_f}^2 \tag{3-11}$$

The time scale for each pressure sequence must be calculated independently because it is dependent upon the velocity used to create the pressure time history. The reduced frequency relationship can be used, as done previously, and this process can be performed for each 10 minute segment of wind data to create multiple pressure sequences that can be used in conjunction with wetting rate histories that simulate the wind driven rain intensity during the velocity record. The construction of these wind driven rain simulations is outlined in the following section.

Wind Driven Rain Sequence Generation Using Hurricane Ike Data

Rainfall intensity estimates from Hurricane Ike are obtained using reflectivity measurements from the National Weather Service WSR-88D Doppler Radar KHGX. The wetting rate values used during the Phase IV pressure sequences were determined from Hurricane Ike measurements. Radar reflectivity was used to estimate the horizontal rainfall intensity at the location of the FCMP tower which recorded wind velocity and direction (Lopez, 2011). Reflectivity is the strength of the energy that is measured from the reflection of microwaves off of the precipitation in the atmosphere (Rosenfeld et al, 1993). The accuracy of the reflectivity measurements is sensitive to the drop size distribution as well. The following relationship was use to estimate the horizontal rainfall intensity,

$$Z = 24.8 + 14.0 \log R \tag{3-12}$$

where Z is measured reflectivity, and R is the estimated horizontal rainfall intensity. The rainfall intensity was estimated at the four points nearest the FCMP tower. A linear interpolation was performed between these points to estimate the horizontal rainfall intensity at the location of the FCMP tower. The average rainfall intensity is taken for each ten minute velocity segment to produce an average wetting rate for the pressure sequence.

The rain racks inside the test chamber of the HAPLA are connected to servo-valves which can adjust the flow rate to the racks to control the wetting rate of the test specimen. Data was collected near FCMP tower T3 during Hurricane Ike to determine horizontal rainfall intensity over the duration of the storm. The data must first be separated into 11 to 13 minute segments with time scales that match the 10 minute velocity segments. Using the following equations, the wind driven rain intensity, R_{wdr}, can be determined using the known mean wind velocity, U_h, and horizontal rainfall intensity, R_h (Lacy, 1965).

$$R_{wdr} = 0.22\, {R_h}^{0.88} U_h \tag{3-13}$$

Once the wind driven rain intensity is determined the equivalent wetting rate, W_r, that should be applied to the specimen can be calculated, and is defined as:

$$W_r = C\ R_{wdr} \cos(\alpha) \tag{3-14}$$

where C can range from 0.3 – 0.5 (BS EN ISO 15927-3:2009). The quantity is multiplied by $\cos(\alpha)$ to correct for the attack angle, α, of the wind relative to the wall. The wetting rate was then calibrated to the positions of the valves that control flow rate, enabling the rain rack to fluctuate the wind driven rain intensity similar to actual hurricane conditions. Below are figures that show the complete pressure and wetting rate time history for the data extracted from Hurricane Ike.

Individual nozzles were tested to determine the nozzle type and spray angle that yielded the most uniform wetting applied to the test specimen. This was carried out using a circular apparatus with bins equally spaced around the center. Nozzles were investigated at varying distances from the target to determine the distance at which greatest uniformity could be achieved. Once the appropriate nozzle was selected, multiple variations of spray nozzle arrays were tested to develop a design with the most uniform wetting rate across the entire test specimen. An array with nine equally spaced nozzles was selected and offset 0.53 m (1.75 ft) from the wall to create the most uniform wetting possible in the chamber, in addition to its ability to operate in the desired range of wetting rates.

Summary

Four single hung windows were selected for an array of testing to determine if dynamic pressure sequences representative of real tropical cyclone conditions could be related to behavior under static pressure conditions. Phase I testing determined the pressure at which leakage begins. An array of ingress rates for varying pressure levels and wetting rates was determined in Phase II. During Phase III, each window was subjected to dynamic pressure sequences of a specified interval. Phase IV testing used data from Hurricane Ike to apply pressure sequences and wetting rates representative of actual tropical cyclone conditions. A time step analysis using the pressure measured during the final phases of testing was then conducted to determine the accuracy of using the ingress rates from the static pressure testing to predict water ingress under dynamic load conditions.

Table 3-1. Summary of window specimen design and dimensions

Window Specimen	Height (m)	Width (m)	Design Pressure (kPa)	15% of Design Pressure (kPa)	Bottom Sill Dam Height (mm)	Static Pressure Require to Over-top Bottom Sill Dam (kPa)	Elevation Difference at Meeting Rail (mm)	Static Pressure Required to Over-top Meeting Rail Elevation (kPa)
B-1	1.58	0.91	2.72	0.41	41.3	0.41	15.9	0.16
B-2	1.52	0.91	2.39	0.36	28.6	0.28	47.6	0.47
C-1	1.59	1.11	1.68	0.25	41.3	0.41	22.2	0.22
C-2	1.59	1.11	3.11	0.47	30.2	0.3	41.3	0.41

Table 3-2. Test matrix for window specimens

Phase	Pressure Levels	Wetting Rates	Windows	Total Tests
I	4	1	4	16
II	4	4	4	64
III	4	4	4	64
IV	7	-	4	28

Table 3-3. Summary of pressure sequences derived from Hurricane Ike data

Mean Velocity, V_{10min_avg} (m/s)	Horizontal Mean Wind Direction, θ (deg.)	Horizontal Rainfall Intensity, R_h (mm/hr)	Wind Driven Rain Intensity, R_{wdr} (mm/hr)	Wetting Rate, W_R (mm/hr)
35.8	65	19	379	172
43.5	90	12	306	153
44.7	90	13	331	166
48.6	90	16	441	221
52.2	85	16	474	237
52.2	90	18	514	257

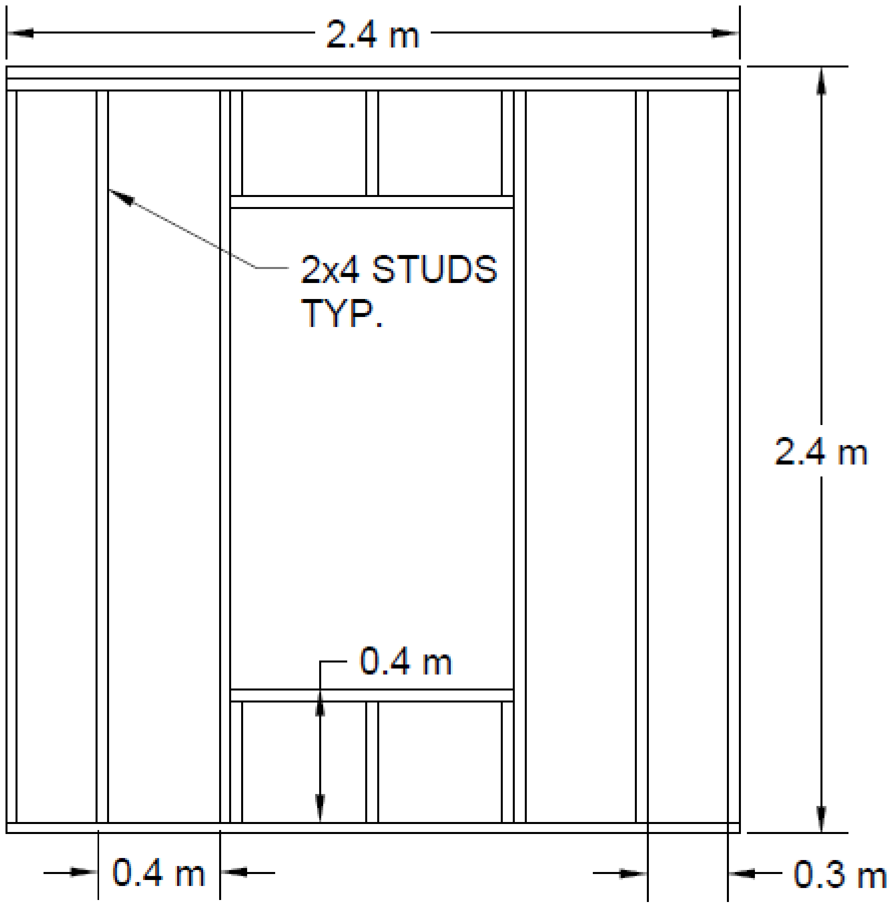

Figure 3-1. Typical test wall frame design.

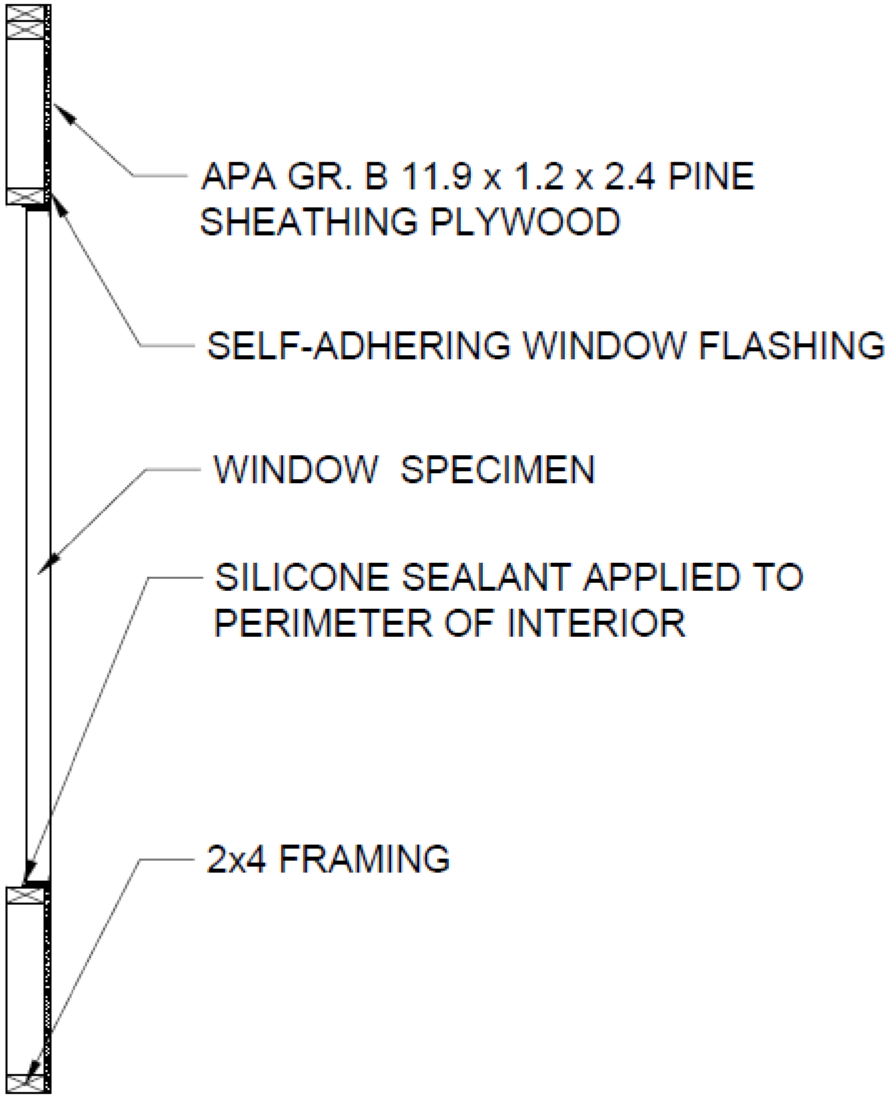

Figure 3-2. Typical section detailing window/wall interface.

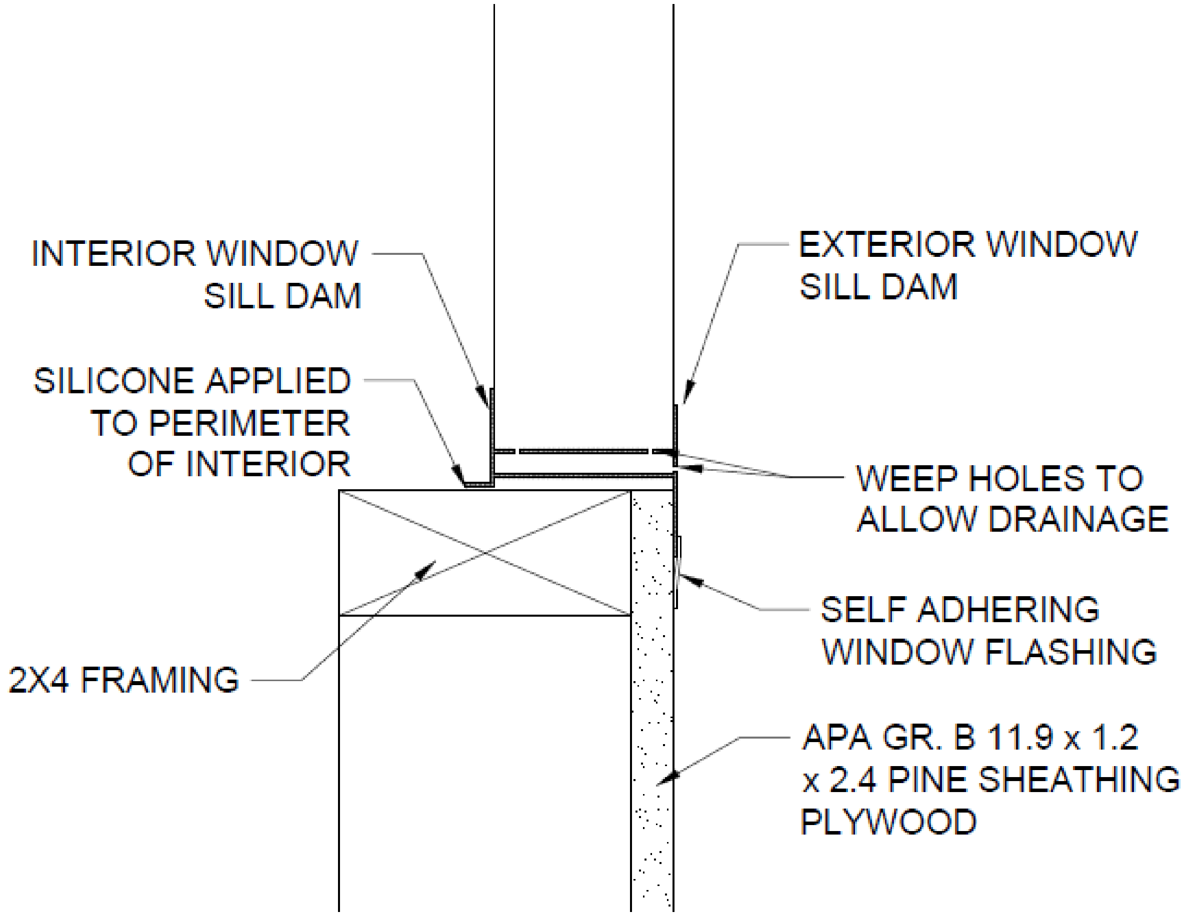

Figure 3-3. Bottom of window/wall interface detail

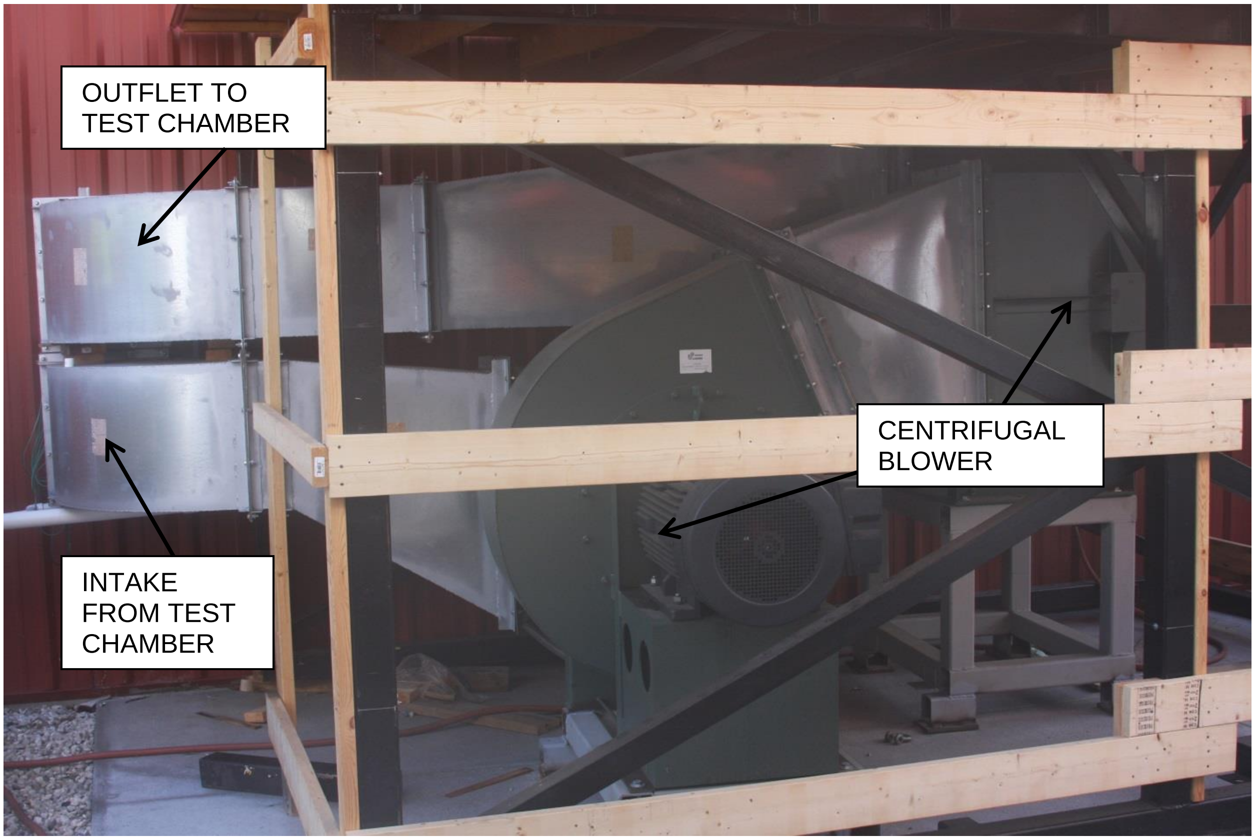

Figure 3-4. Third generation high airflow pressure loading apparatus (HAPLA) (Photo courtesy of Brian Rivers)

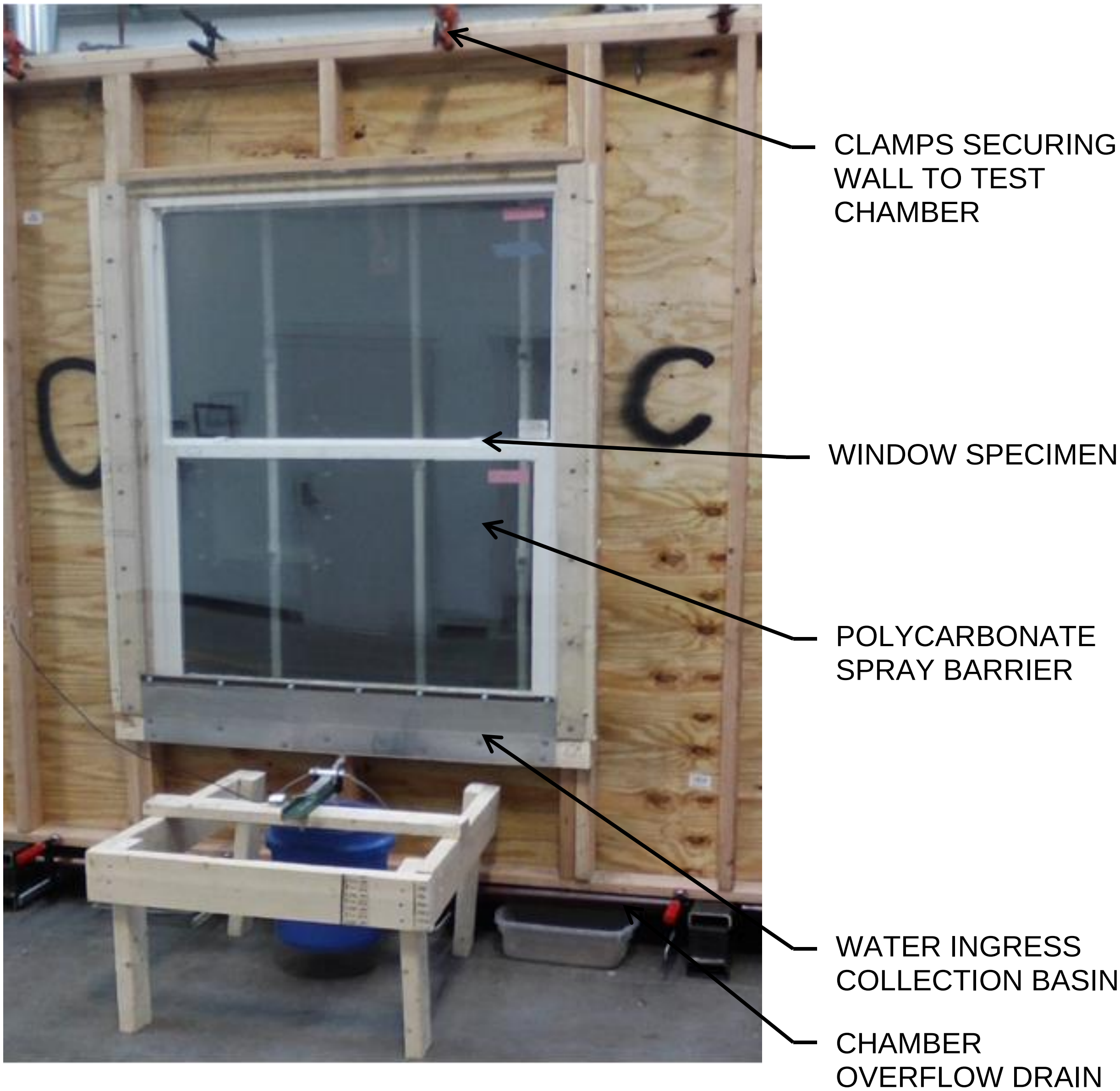

Figure 3-5. Typical view of a test wall and specimen attached to the test chamber. (Photo courtesy of Brian Rivers)

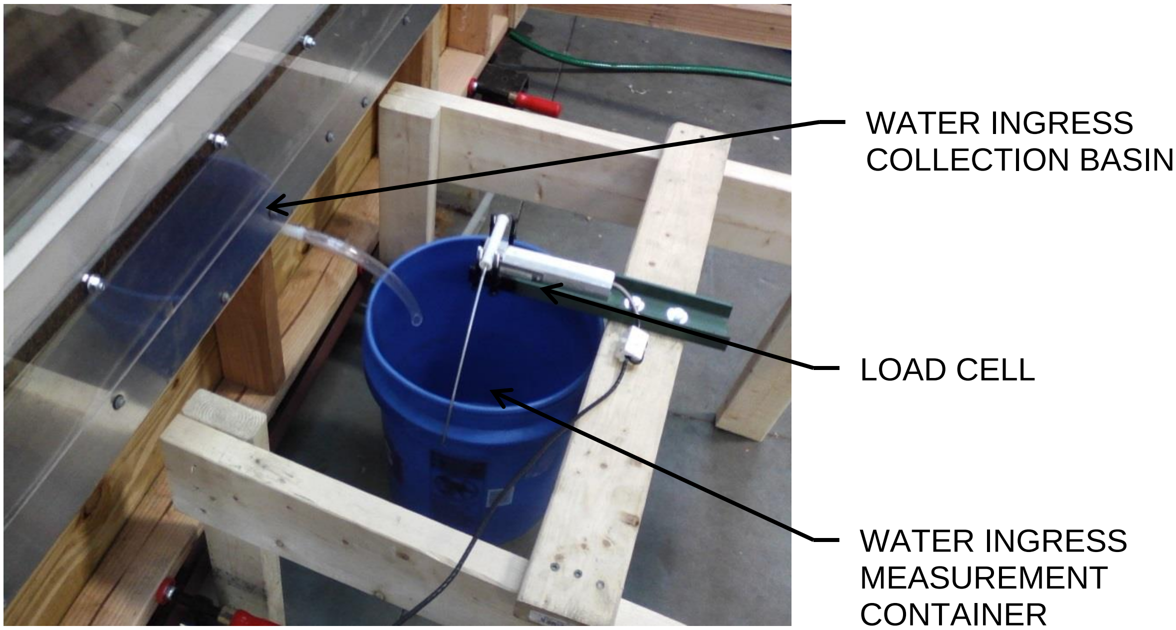

Figure 3-6. Load cell, water container and drain from window during testing. (Photo courtesy of Brian Rivers)

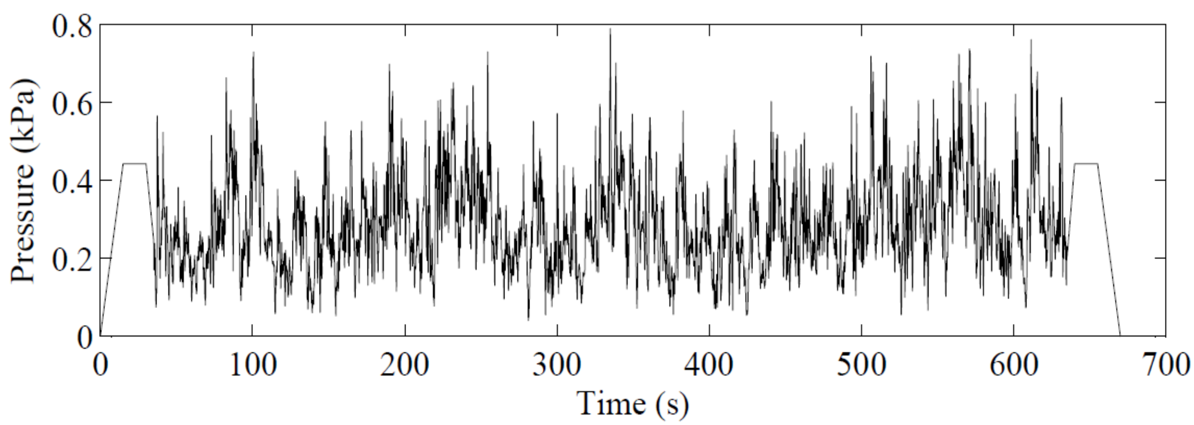

Figure 3-7. Typical dynamic pressure sequence produced for Phase III testing.

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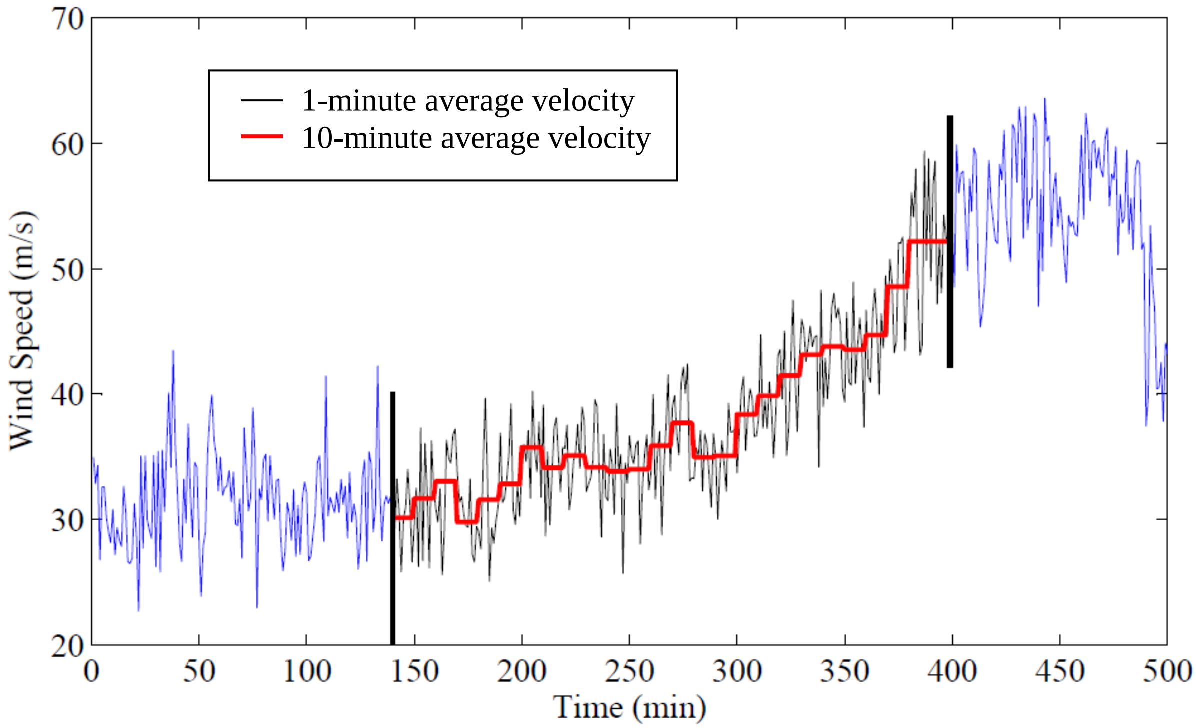

Figure 3-8 Selected segment of Hurricane Ike data for use in pressure sequences

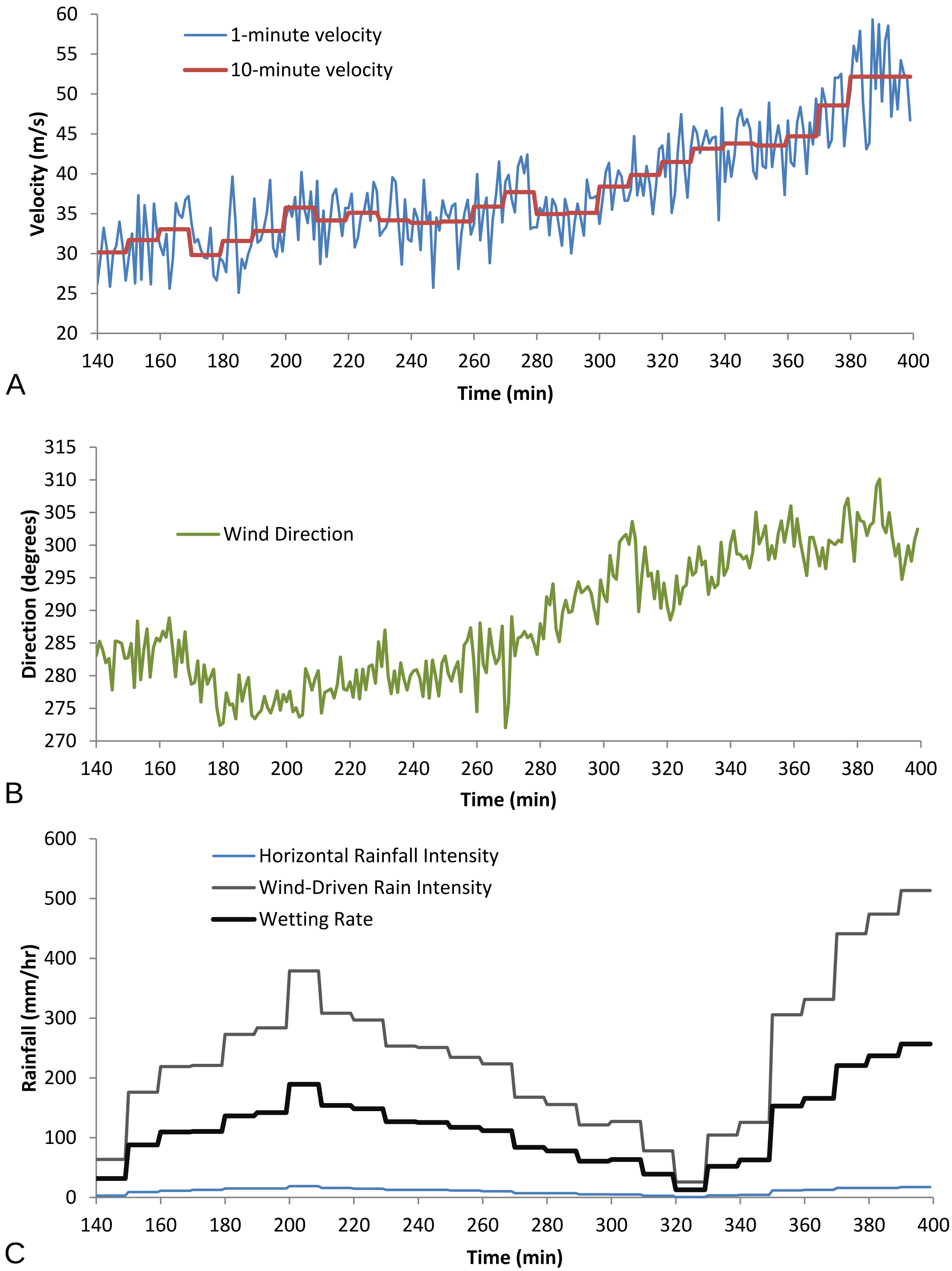

Figure 3-9. Selected segments of Hurricane Ike data for pressure sequence generation

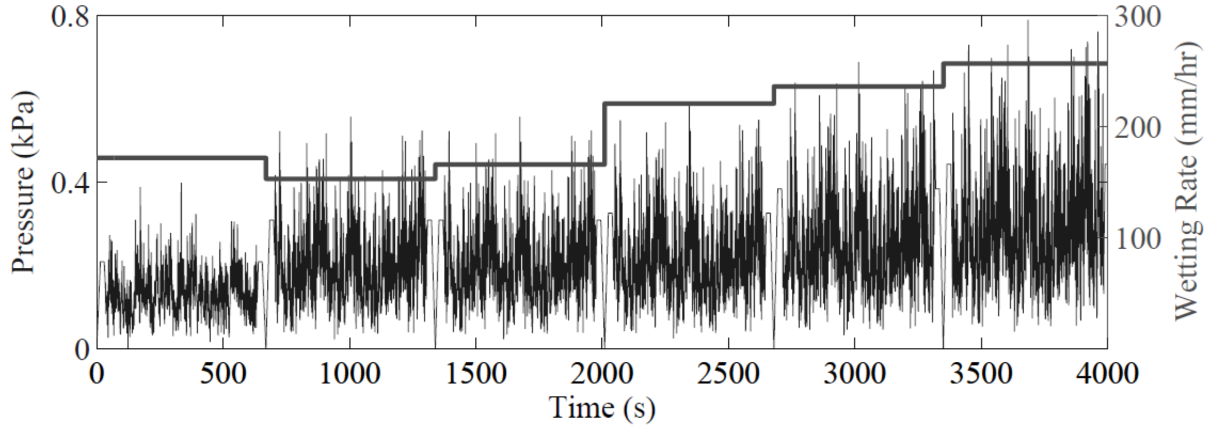

Figure 3-10. Pressure sequences derived from Hurricane Ike data.

CHAPTER 4
RESULTS

Prediction of Water Ingress: Time Step Analysis

Window species were subjected to four phases of pressure testing, two under static loads, and the final two used dynamic pressure sequences. The results Phase I was summarized in a table that highlights the pressure at which water ingress began. Phase II testing was presented as a series of wetting rate curves as a function of static pressure which correspond to an ingress rate for the particular window specimen. Results for dynamic testing were summarized as average ingress rates in the figures for each window.

The method for prediction was developed under the assumption that the duration or rate of loading does not change the ingress rate for a given static pressure level and wetting rate. The array of ingress rate produced from testing a combination of wetting rates and static pressure was produced using tests approximately 10 minutes in length. It was then assumed that the duration could then be decreased significantly, and the result of static pressure. The time increment was decreased to 20 milliseconds, which corresponds to the 50 Hz sampling frequency of the static pressure transducer. The pressure sequence was evaluated at each point at this interval, similar to integration to determine the area under a curve. Evaluation at each point produces a value which is then summed to produce a total amount of water ingress at that instant in time. The process of creating the algorithm to predict the water ingress is outlined in the following paragraphs.

During the dynamic tests, pressure load as well as the total amount of water passing through the window is recorded for each pressure test and wetting rate. The output was recorded at 50 Hz for the duration of each test, which is roughly 10 minutes. The static pressure is then analyzed at each time step using the following procedure to build a predicted accumulating total of water ingress through the window based on the initial static testing results.

Initially, vectors of ingress rate, *I(j)*, for each wetting rate as a function of pressure level, *j*, are produced from the analysis of the static pressure testing results. The pressure levels for the window being tested are also included. A vector of length *n* is created from the pressure recorded in the test chamber throughout the simulation, and is denoted *p(i)*, where *i* is the time step at which the pressure is being evaluated. The wetting rate vector of length n is also imported, and is denoted as *w(i)*, where *i* is the time step at which the wetting rate is being considered. The time step size is:

$$\Delta t = \frac{1}{f} \tag{4-1}$$

where *f* is the frequency at which the data is recorded, in this case, 50 Hz. A new water ingress rate curve is determined by interpolating between the known curves to produce a curve on which the pressure at time step *i* can be interpolated between the known pressure levels, yielding an ingress rate, *R(i)*, for that time step. The total amount of water ingress for each time step, $I_{total}(i)$, is then calculated:

$$I_{total}(i) = R(i) * \Delta t \tag{4-2}$$

The total water ingress curve is then produced by summing I_{total} at each time step *i*, to replicate the output of the load cell during the test.

Testing

The following sections detail the four phases of testing that were applied to the window specimens. Initial testing determined the threshold that causes ingress. An array of wetting rates and pressures were then simulated to form an array of ingress rates for each window. The test specimens were then subjected to two phases of dynamic pressure sequences.

Static Pressure Testing

Initial static pressure testing was performed with a constant wetting rate of 203 mm/hr (8 in/hr). The objective of this phase of testing was to determine the initial static pressure required to initiate water ingress through the window. The initial leakage values for each window are summarized in Table 4-1. All windows met the requirement set forth by AAMA/WDMA/CSA 101/I.S.2/A440 (2005), preventing water ingress up to 15% of the design pressure. Window B-1 withstood the largest static pressure without allowing water penetration, making it less likely to be affected in weaker storms, which have smaller wetting rates and positive pressures. These initial pressures were used to create the test matrix for the next phase of testing which uses multiple wetting rates and static pressure levels.

Varied Wetting Rate Testing

Four wetting rates equally spaced between 150 and 300 mm/hr (5.91 and 11.81 in/hr) were tested at each of the four pressure levels determined for each individual window. An array of ingress rates with respect to pressure as a function of wetting rates is formed. This array was used in the final two phases of testing to predict water ingress during dynamic pressure sequences. The importance of this phase was the substantial effect it had on the accuracy of the subsequent predictions. The results for this phase are summarized for the respective window specimen in figures 4-1, 4-5, 4-9, and 4-13.

Target Dynamic Pressure Sequences

Each window was subjected to four dynamic pressure sequences with mean pressures of 0.39, 0.47, 0.56, and 0.64 kPa (8.2, 9.8, 11.7 and 13.4 psf). Each window specimen was subjected to wetting rates of 150, 200, 250, and 300 mm/hr (5.91, 7.87, 9.84 and 11.81 in/hr) at each pressure level. The pressure sequences used in this phase were repeated in a time step analysis in conjunction with the ingress rate data obtained in the previous phase to predict the amount of ingress based on the behavior of each window specimen under static load conditions.

Hurricane Ike Pressure Sequences

Pressure sequences were developed using wind velocity and rainfall rate data measured during Hurricane Ike. Six sequences of varying wetting rate and mean pressure were simulated on each window specimen. The wetting rate and pressure sequence were then replicated in a time-step analysis, using the data from the second phase of testing to predict the amount of water ingress during the test. The following section examines the performance of each window during each phase of testing.

Window Specimens

The following sections examine the results of all phases of testing for each window. The review of each tests are done in the order that the phases are mentioned above. Also included are descriptions and justifications of the behavior of each window specimen.

Window B-1

The ingress rate with respect to wetting rate at the lowest pressure level is evenly distributed. However, at the three higher pressure levels, ingress rates for wetting rates of 200 and 250 mm/hr (7.87 and 9.84 in/hr) are nearly the same. The initial increase in water ingress rate from the first pressure level to the second is rather large for all wetting rates, but tapers between subsequent pressure levels. This indicates an upper bound at which the ingress rate ceases to steadily increase as a function of static pressure may exist. The shape of the ingress curves with respect to wetting rate was similar, making it an adequate candidate for use in predicting the dynamic behavior, as interpolation was likely be an adequate representative of actual behavior.

The plot shown in Figure 4-2 presents the volume of water measured as it accumulates during the dynamic pressure sequence with a mean pressure of 0.64 kPa (13.4 psf), and a wetting rate of 250 mm/hr (9.84 in/hr). Also plotted is the predicted accumulation of water based on the time-step analysis using the pressure time-history and wetting rate measured during the test. The general shape and associated peaks are similar for both measured and predicted. There is an apparent lag between the predicted and the actual for the first half of the test, possibly due to the accumulation of water that must occur before water overtops the sill dam. As the test approaches the end, the predicted amount of total ingress falls below the measured ingress, and the final prediction slightly underestimates the actual total.

Figure 4-3 displays the predicted and measured average ingress rate for the target pressure sequences with multiple wetting rates. For all combinations of wetting rate and mean pressure, the predicted ingress rate underestimates the measured ingress rate. One likely possibility is the clustering of the 200 and 250 mm/hr (7.87 and

9.84 in/hr) wetting rates during the static testing. The amount that the predicted falls short of the actual is similar for nearly all tests, with the most accurate predictions occurring for the higher wetting rates. The lowest pressure levels yielded the smallest difference in predicted compared to actual for each wetting rate.

The predicted average ingress rate for the pressure sequence and wetting rate derived from Hurricane Ike are presented in Figure 4-4. As shown in the figure, there was no measurable water ingress during any of the six pressure sequences. This particular window specimen could withstand a significant static pressure load, 0.67 kPa (14.0 psf), before allowing water penetration. No ingress occurred due to the pressures being relatively low, which allows time for the water that accumulates between the sill dams to drain before the peaks can force it to overtop. The applied static pressure rarely exceeded that value in the two strongest cases, which predicted only a small amount of ingress. The strongest case yielded an average predicted flow rate of approximately 34 mm^3/sec, which is equivalent to a small droplet of water per second. This indicates that the strongest peaks during the pressure sequence rarely exceeded the threshold for ingress to begin.

Window B-2

Ingress rates as a function of mean pressure and wetting rate are shown in Figure 4-5 for window specimen B-2. At the lowest pressure level, which is the threshold for water ingress, the ingress rate is small, particularly for the 150 mm/hr (5.91 in/hr) wetting rate. The rate at which ingress increases with respect to pressure accelerates slightly as the pressure is increased for all wetting rates. The increment in water ingress rate between each wetting rate is similar, with the curves for 200 and 250 mm/hr (7.87 and 9.84 in/hr) being slightly closer together, similar to window specimen B-1. The consistency and spacing of the curves may indicate that predictions during the following phase would be accurate with respect to measured ingress. However, this is not the case, which is displayed in Figure 4-5.

The volume of water ingress measured by the load cell versus the predicted water ingress for a mean pressure of 0.39 kPa (8.1psf) and a wetting rate of 300 mm/hr (11.81 in/hr) is shown in Figure 4-6. The predicted amount of water ingress has a slightly steeper slope than the measured ingress resulting in an over-estimation that increases with time. The peaks and general shape of the predicted ingress are not apparent in the measured data, which is nearly linear the entire test with slight increases at few points. The portions of the predicted water ingress curve which have a constant slope of zero indicate that the pressure measured during the time history was below the threshold needed for ingress as determined by the first phase of testing.

The predicted and measured average ingress rates for the target pressure sequences with multiple wetting rates are shown in Figure 4-7. In all case, the predicted average ingress rate exceeds the measured rate. It is suspected that the over prediction results because the water is able to drain prior to the peaks in the pressure sequence, reducing the total amount of water penetration occurring. The time-step analysis consistently over estimates the measured ingress rate by 30 to 50% for the three highest wetting rates. A small amount of water ingress occurs at the 150 mm/hr (5.91 in/hr) wetting rate compared to the predicted. The difference between the measured and predicted appears to be less severe for higher wetting rates at the lowest mean pressure level.

The predicted average ingress rate for the pressure sequences and wetting rates derived from Hurricane Ike are presented in Figure 4-8 for window specimen B-2. The predictions are accurate for the fourth and fifth pressure sequence, which have mean pressures of 0.21 and 0.26 kPa (4.4 and 5.4 psf) respectively, and wetting rates of 221 and 236 mm/hr (8.70 and 9.29 in/hr) respectively. However, the prediction for the strongest time-history with a mean pressure of 0.29 kPa (6.1 psf) and a wetting rate of 257 mm/hr (10.12 in/hr) severely over estimates the average water ingress rate. This is likely due to a significant amount of peaks in the pressure sequence that were of short duration, which would prevent water from accumulating and overtopping the interior window sill dam. Little or no predicted water ingress occurred for the three weakest pressure sequences, due in part to the low wetting rates, and in part because the pressure rarely exceeded the threshold for ingress during the pressure sequence.

Window C-1

Initial static pressure testing for window C-1 determined that water ingress began at a static pressure of 0.36 kPa (7.5 psf). Ingress rates as a function of mean pressure and wetting rate are shown in Figure 4-9. At the two lowest pressure levels, the water ingress rare associated with a 150 mm/hr (5.91 in/hr) is relatively small. At 75% of the windows design pressure, the water ingress rate due to wetting rates of 150 and 200 mm/hr (5.91 and 7.87 in/hr) are nearly identical, and slightly higher for a wetting rate of 250 mm/hr (9.84 in/hr). The peak water ingress rate corresponding to the peak wetting rate and pressure is much higher than would be expected by the next closes pressures and wetting rates. The inconsistency of the general shapes of each curve with respect to water ingress would imply that the predicted water ingress rates associated with dynamic pressure sequences would be inaccurate.

The plot shown in Figure 4-10 presents the volume of water measured as it accumulates during the dynamic pressure sequence with a mean pressure of 0.56 kPa (11.7 psf), and a wetting rate of 200 mm/hr (7.87 in/hr). The response of the measured total ingress compared to the predicted water ingress is nearly identical until the end of the sequence. There is initial lag in the actual ingress due to the time it takes for water to accumulate in the testing apparatus before accumulating in the bucket suspended from the load cell. This particular sequence is an outlier for this window, as the majority of the predicted ingress rates exceeded the measured ingress rates by a considerable amount.

Figure 4-11 displays the predicted and measured average ingress rate for the target dynamic pressure sequences with multiple wetting rates. For this particular window, the most intense dynamic pressure sequence was not tested due to concerns of window failure. The measured ingress far exceeded the predicted ingress for wetting rates of 150 and 200 mm/hr (5.91 and 7.87 in/hr). For wetting rates of 250 and 300 mm/hr (9.84 and 1.81 in/hr), the predicted average ingress rates were approximately twice the actual ingress rates. The predicted and measured are nearly identical for the case of 0.56 kPa (11.7 psf) mean pressure and a wetting rate of 200 mm/hr (7.87 in/hr). This case can most likely be regarded as coincidental, as the rest of the predictions are far from the measured.

The predicted average ingress rate for the pressure sequences and wetting rates derived from Hurricane Ike are presented in Figure 4-12 for window specimen C-1. No water ingress was measured for the first five pressure sequences. A small amount of water ingress, less than a small drop per second, was measured for the strongest pressure sequence, which has a mean of 0.29 kPa (6.1 psf), and a wetting rate of 257 mm/hr (10.12 in/hr). The predicted water ingress rate for the two strongest pressure sequences was significantly higher than the actual. This is most likely due to an adequate drainage system of the window assembly, preventing water from accumulating and then penetrating when peaks were reached during the pressure sequence. The design pressure of this particular window was also higher, making ingress less likely at lower pressures.

Window C-2

Ingress rates as a function of mean pressure and wetting rate are shown in Figure 4-13 for window specimen C-2. The water ingress rate for a wetting rate of 150 mm/hr (5.91 in/hr) is nearly zero at the lowest pressure, and slowly increases in a linear fashion. The ingress rate curves for wetting rates of 200 and 250 mm/hr (7.87 and 9.84 in/hr) are nearly identical in slope, with the magnitude of the 250 mm/hr (9.84 in/hr) wetting rate curve approximately 0.6 cm^3/sec higher at each pressure level. For the lowest three pressure levels, the ingress rate curve for a wetting rate of 300 m/hr (11.81 in/hr) is slightly greater than the values for a wetting rate of 250 mm/hr (9.84 in/hr). The peak water ingress rate corresponding to a wetting rate of 300 mm/hr (11.81 in/hr) and largest static pressure is much higher than would be expected compared to the adjacent static pressures and wetting rates.

The volume of water ingress measured by the load cell versus the predicted water ingress for a mean pressure of 0.39 kPa (8.1 psf) and a wetting rate of 300 mm/hr (11.81 in/hr) is shown in Figure 4-14. The threshold for water ingress for this window specimen exceeds the mean pressure of the pressure sequence, which is evident by the plateaus and peaks comprising the predicted water ingress curve. Similar to the previous window specimens, the beginning of the predicted curve is sloped steeper than the measured curve. This is partly due to the lag caused by the time it takes for the water to penetrate the window and drain to the bucket suspended from the load cell. This is also caused by the lack of water accumulation between the window sill dam at the beginning of the pressure sequence. At the end of the pressure sequence, the presence of two significant peaks in the time history is accompanied by the two sharp spikes in both curves.

Figure 4-15 displays the predicted and measured average ingress rate for the target dynamic pressure sequences with multiple wetting rates for window specimen C-2. It can be inferred from the figure that there is agreement between the predicted and measured water ingress rates for the lowest pressure level at wetting rates of 200, 250, and 300 mm/hr (7.87, 9.84 and 11.81 in/hr). For all cases, the predicted water ingress rate exceeds the actual ingress rate. At higher pressure levels the predicted value exceeds twice the measured. Almost no ingress was measured for a wetting rate of 150 mm/hr (5.91 in/hr), which is consistent with the initial static pressure testing.

The predicted average ingress rate for the pressure sequences and wetting rates derived from Hurricane Ike are presented in Figure 4-16. The predicted water ingress rate at the highest mean pressure level is relatively accurate, slightly exceeding the measured. For the second strongest case, the predicted is approximately twice the measured average ingress rate. Almost no water ingress was predicted for the intermediate levels, and no ingress was predicted for the lowest levels, evidence that there were no peaks in the pressure sequence that exceeded the threshold for leakage of this window.

Method of Predicting Water Ingress

Initial static testing was used to determine the minimum static pressure to cause leakage at a wetting rate of 203 mm/hr (8 in/hr). Four pressure levels equally spaced between the minimum pressure determined in the first phase, and 75% of the windows design pressure were then determined for the second phase of testing. An array of ingress rates was formed testing the four pressure levels and four equal wetting rate intervals in every possible combination. The results from this phase, while not representative of actual hurricane conditions with respect to intensity, enable the interpolation between points to aid in the prediction of window performance under dynamic loads.

The method used to predict the water ingress through the windows under dynamic loads is a time-step analysis which interpolates between wetting rates from static testing. The first step in the method is to obtain the array of ingress rates as previously described. The real-time dynamic pressure and wetting rate data from the dynamic pressure testing is then analyzed at increments of two-hundredths of a second. At each increment, an ingress rate is extracted from the curves determined during the second phase of testing. This wetting rate is multiplied the time increment, which gives a weight of water. This weight of water is summed after each step to create a predicted load cell vector which can be directly compared to the load cell vector obtained from the actual dynamic testing.

During the preliminary stages of developing the study, it was theorized that semi-empirical equations could be developed to describe and predict the behavior of the windows under dynamic loads. Following the initial phases of static testing, it was apparent that due to the complex shapes of the curves, empirical equations would be complex and in. Following the phase III testing, a brief attempt was made to fit first and second order curves to the array of ingress values determined from phase III. The preliminary findings were inaccurate and inconsistent, often varying by 200 to 300%. Following this conclusion, it was concluded that continuation of the attempt to develop equations had no merit with regard to prediction of dynamic ingress. It was decided to pursue and analyze the time-step analysis, which only relied on results from static testing to predict the behavior under dynamic loads.

The prediction method was developed based on principles of statics, dynamics and fundamental calculus. It was assumed that the rate at which loading occurs has no effect on the result. A loading scenario, static pressure in this case, produced a certain result for a given duration of time, and the results were simple to duplicate. It was then assumed that the duration could then be decreased significantly, and the result of the load scenario would remain the same. In this case, the load is the pressure applied to the water on the window specimen, and the result is the quantity of water that is measured to have passed through the window. The time increment at which the pressure was evaluated was decreased to 20 milliseconds, which was the sampling frequency of the static pressure transducer. Adjusting the duration at which the pressure time-history was integrated was not investigated in this study. The pressure sequence was evaluated at each point at this interval, similar to integration to determine the area under a curve. Evaluation at each point produces a value which is then summed to produce a total amount of water ingress at that instant in time.

The prediction method did not perform similarly for each window specimen. At lower pressure levels, particularly on windows that were relatively resistant to penetration at lower levels, the resulting prediction was more characteristic of a step and hold pressure sequence. For the majority of the pressure sequences derived from hurricane Ike data, this was typically the observed behavior. The pressure sequence may only exceed the minimum pressure required for water ingress a few times throughout the test. The duration was also too short much of the time, preventing appreciable amounts of water ingress from occurring.

The prediction method was accurate in predicting the water ingress in specific sections pressure sequences with higher pressures and peaks nearing the 75% of the design pressure. However, when the extreme peaks were reached, it was observed that the actual ingress rate typically exceeded the predicted ingress rate. If the analysis divided the time history into smaller segments, accuracy is better defined by the comparison of the slopes of each plot. Applying this method, simultaneously analyzing the pressure sequence, the prediction method was much more consistent in the prediction of ingress under less turbulent loads. In several cases the slopes of the curves would be identical for the majority of the test, but the total would be significantly off due to inaccurate predictions during the portion of the pressure sequence with the most extreme loads and turbulence.

This study did not investigate iterating and improving the method of prediction. However, the following suggestions are made for the benefit improving performance of the method. The method is not easy to replicate for more windows due to the time required to duplicate the test setup and conduct the static pressure testing. An adjustment factor may be required to account for more turbulent segments of the pressure sequences. The frequency at which the pressure sequence is integrated could also be changed to decrease the resolution. This may reduce over prediction by removing peaks that may not have had a significant effect on the water ingress.

Comparison to Previous Testing

Similar testing of windows for water penetration resistance under dynamic loading was conducted by Lopez et al (2011). For Phase III testing both studies used the same pressure tap record to produce the dynamic pressure sequences. The magnitude of the pressure levels used varies between the two investigations, as does the number of wetting rates tested.

It was assumed during this investigation, that the pressure at which initial leakage began that was determine under static pressure loads during Phase I would remain the same under dynamic pressure loads. During the investigation by Lopez et al (2011) the pressure at which first leakage was observed was recorded under static loads, and under a rapidly pulsed pressure load. In many instances, the pressure at which leakage began during the pulsed test was at or around the value determined from the static tests. There were isolated window specimens that leaked at levels either much higher, or much lower than the value determined from the static tests.

The implications of this portion of testing on the prediction of water ingress may be significant depending on the behavior of the particular window specimen. If the pressure at which leakage begins is lower under dynamic conditions than static conditions, the resulting prediction will likely under estimate water ingress. If the pressure to cause leakage is larger under dynamic loads, then it is likely that an over prediction will result, making the prediction method conservative.

Two different dynamic pressure sequences were used during the previous testing by Lopez et al (2011). One sequence corresponded to the wind tunnel record with the highest peak, and the other corresponded to the record with the highest mean. At higher peak pressures, generally associated with strong tropical cyclones, the test with the highest mean produced a larger water ingress rate; while at lower pressures the pressure sequence with the largest peak produced a higher water ingress rate. The present study used only the record with the highest peak to develop pressure sequences. The use of this record causes the pressure sequence to exceed the pressure required for leakage less often, making the accuracy of the value more significant in terms of accuracy of the prediction method.

The wetting rates observed during Hurricane Ike were primarily below 150 mm/hr. The wetting rate used during the study by Lopez et al (2011) used a wetting rate of 240 mm/hr throughout. This can be regarded as an extreme wetting rate observed in an actual storm, and may have also affected the behavior of the water ingress during the dynamic pressure sequences. At a wetting rate of 150 mm/hr, it is likely that the drainage through the weep holes would be much more effective, mitigating water ingress at all but the largest peaks in the pressure sequences.

Summary

Four single hung windows were tested to determine if dynamic pressure sequences representative of real tropical cyclone conditions can be related to water ingress behavior under static pressure conditions. Initial static testing determined the pressure at which leakage begins. An array of ingress rates for varying pressure levels and wetting rates was determined in the next phase of testing. Each window was then subjected to dynamic pressure sequences of a specified interval. Data from Hurricane Ike was used to apply pressure sequences and wetting rates representative of actual tropical cyclone conditions to each window specimen in the final phase of testing. A time step analysis using the pressure measured during the final phases of testing was then conducted to determine the accuracy of using the ingress rates from the static pressure testing to predict water ingress under dynamic load conditions.

Table 4-1. Summary of Phase I results.

Window Specimen	Design Pressure (kPa)	Minimum Pressure at which ingress began (kPa)	Percent of Design Pressure
B-1	2.71	0.67	25
B-2	2.39	0.43	18
C-1	1.68	0.36	21
C-2	3.11	0.49	16

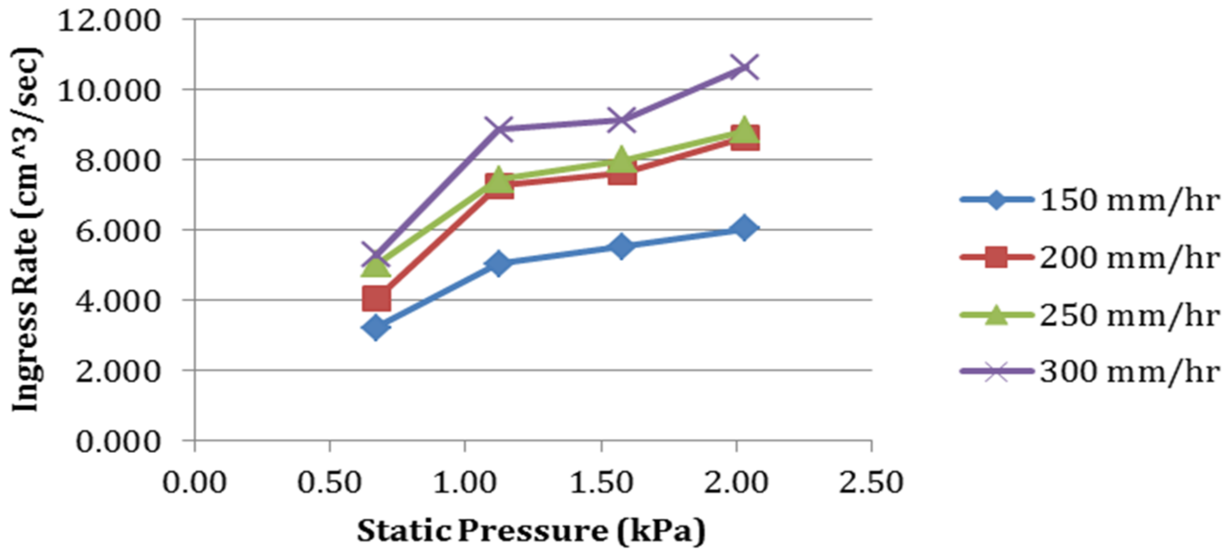

Figure 4-1. Phase II results for window B-1.

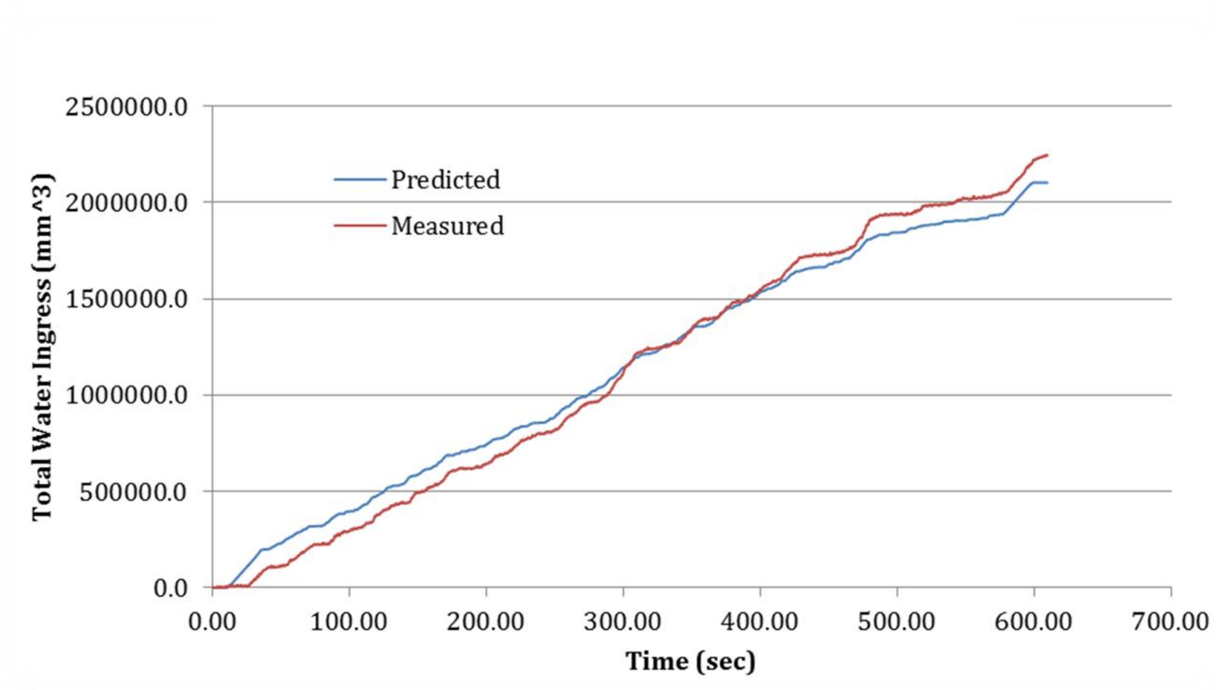

Figure 4-2. Comparison of measured vs. predicted time history for window B-1.

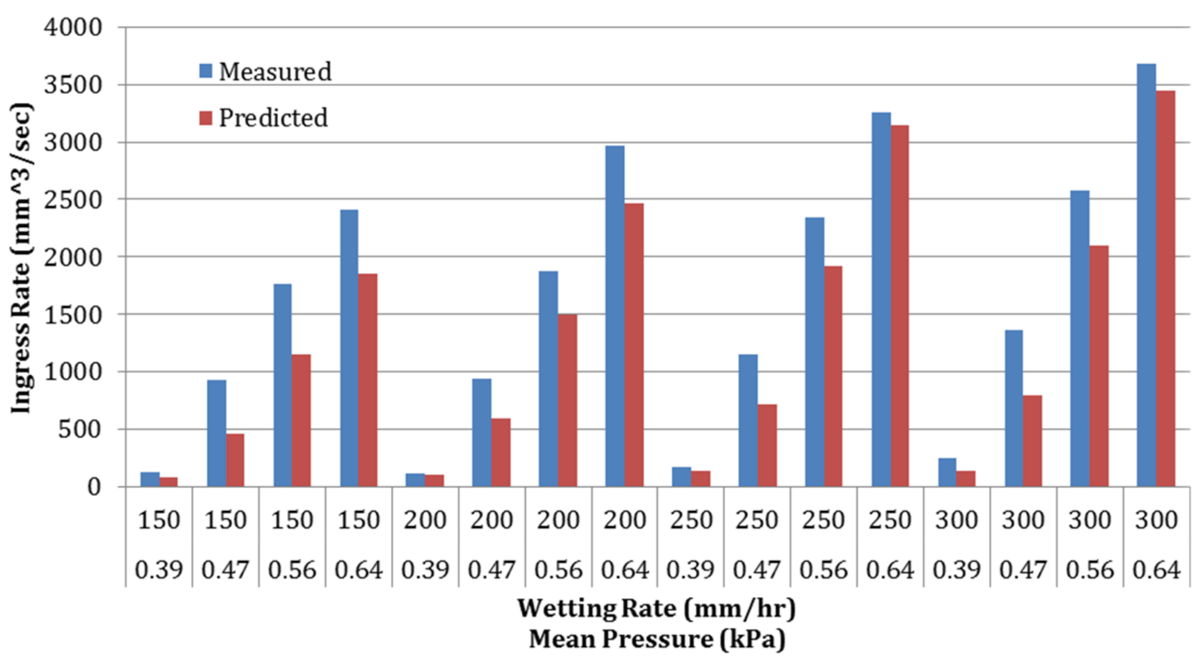

Figure 4-3.Phase III results for window B-1.

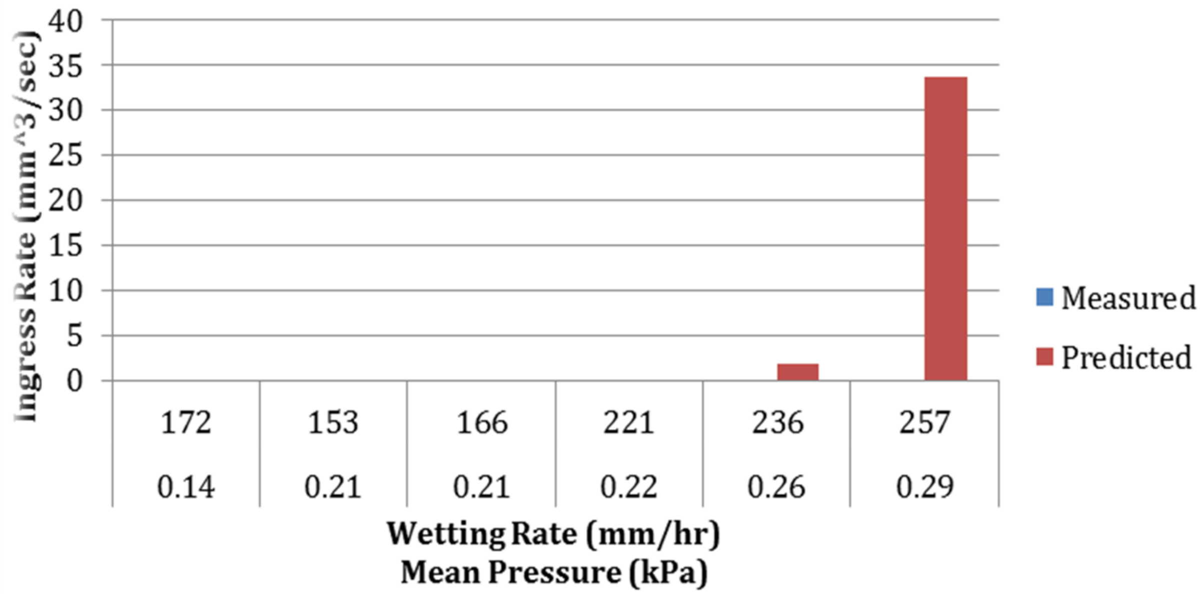

Figure 4-4. Phase IV results for window B-1.

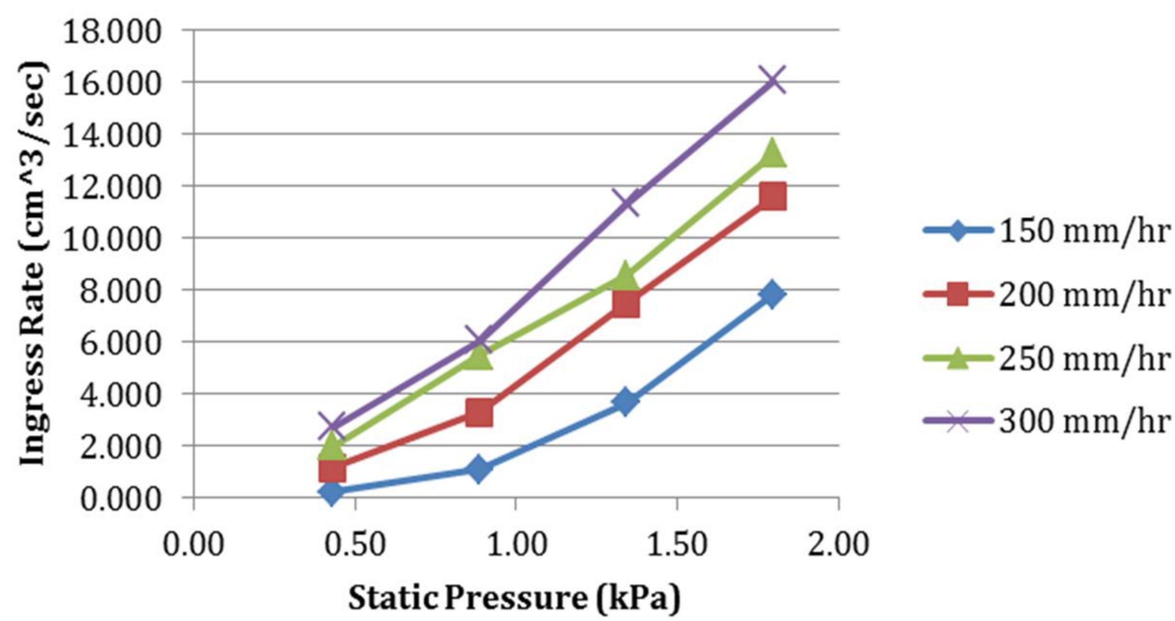

Figure 4-5. Phase II results for window B-2.

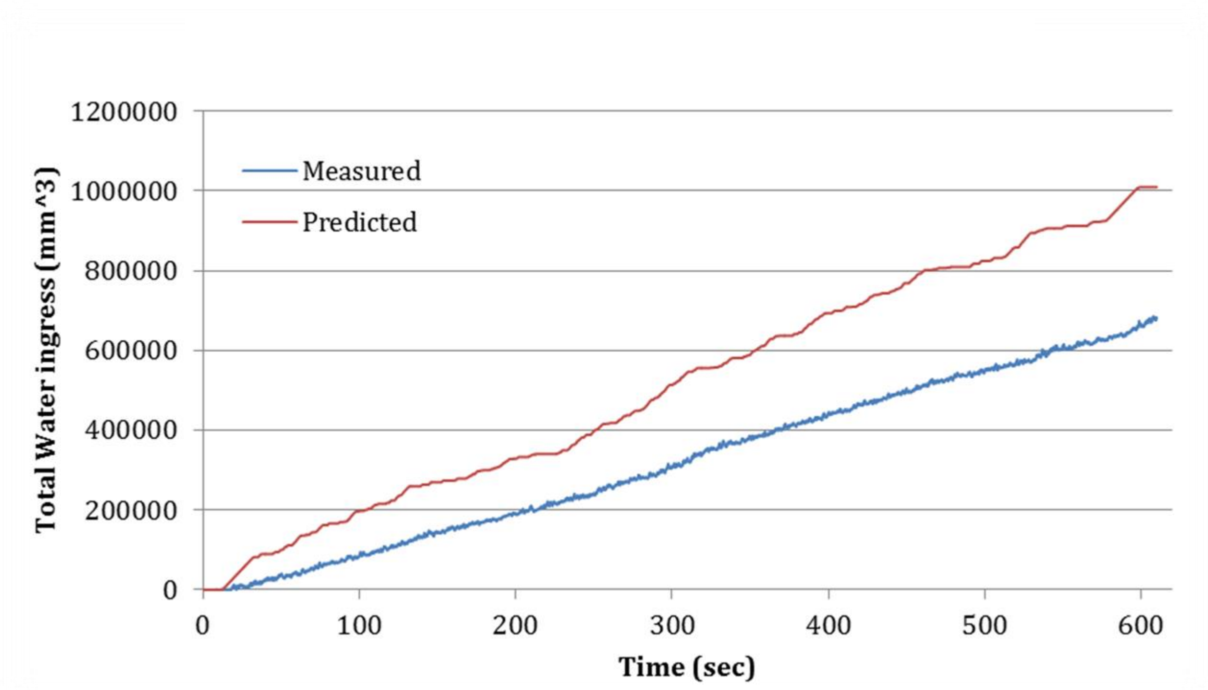

Figure 4-6. Comparison of measured vs. predicted time history for window B-2.

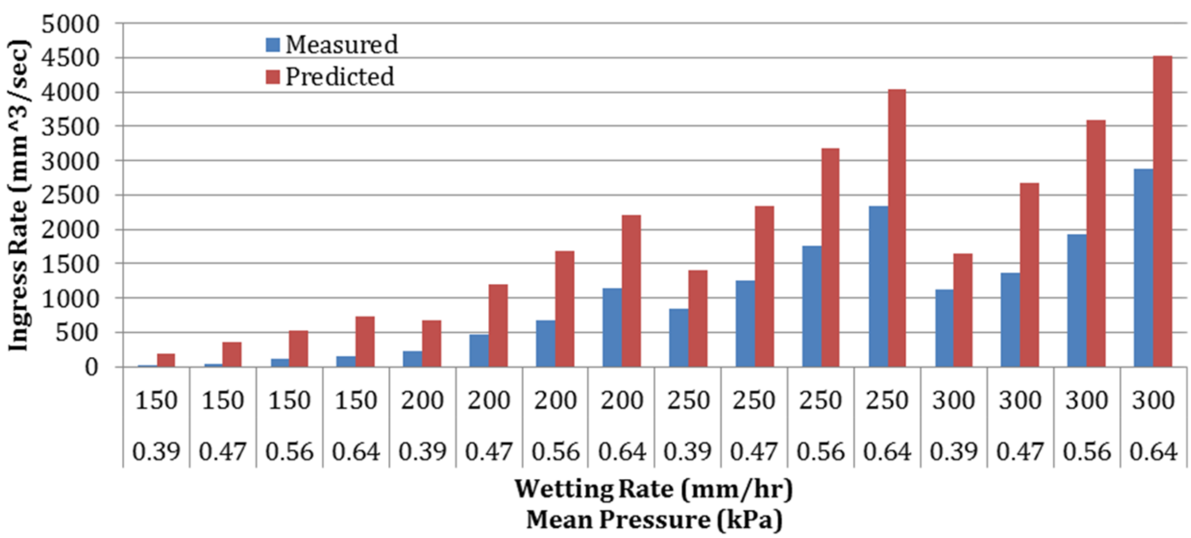

Figure 4-7. Phase III results for window B-2.

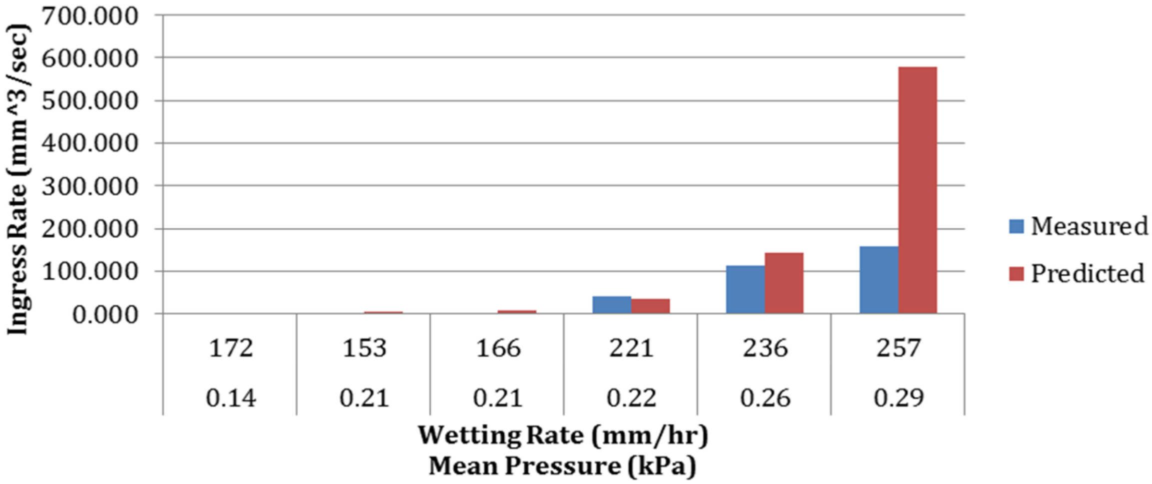

Figure 4-8. Phase IV results for window B-2.

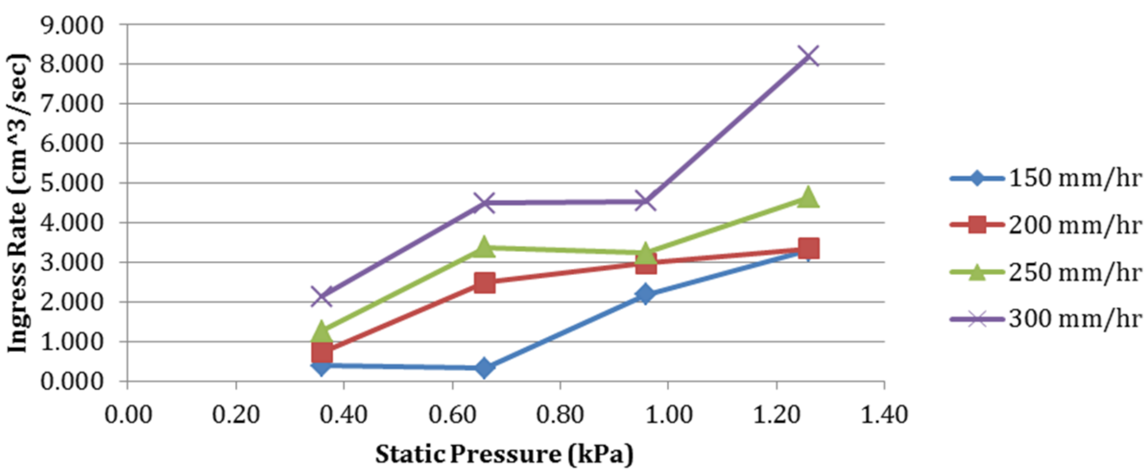

Figure 4-9. Phase II results for window C-1.

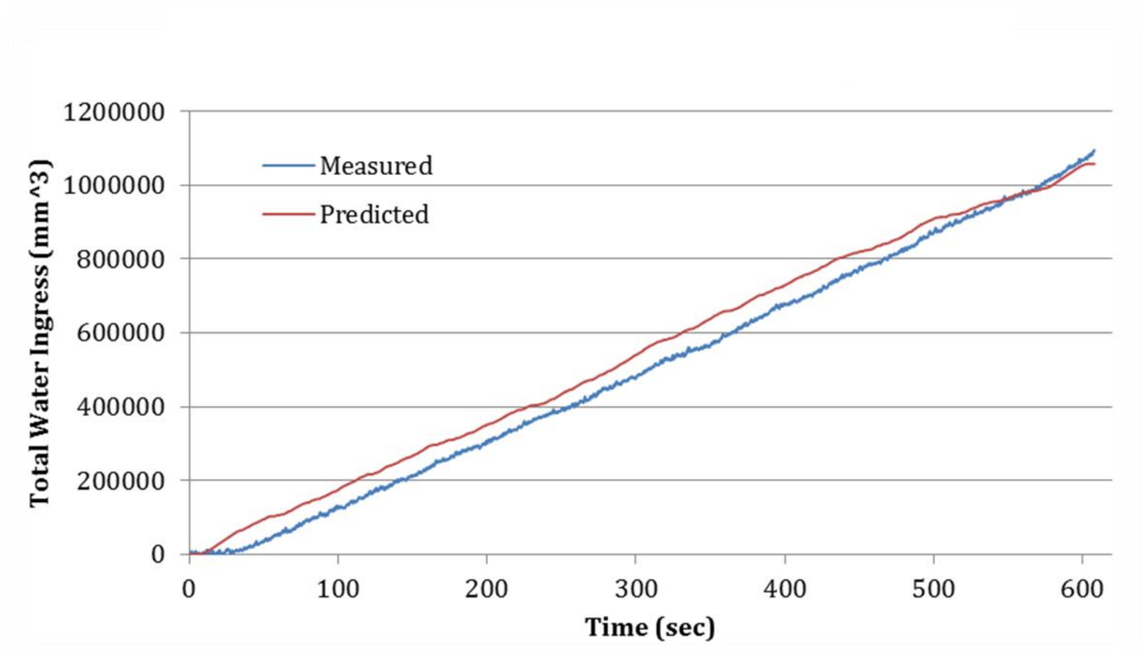

Figure 4-10. Comparison of measured vs. predicted time history for window C-1.

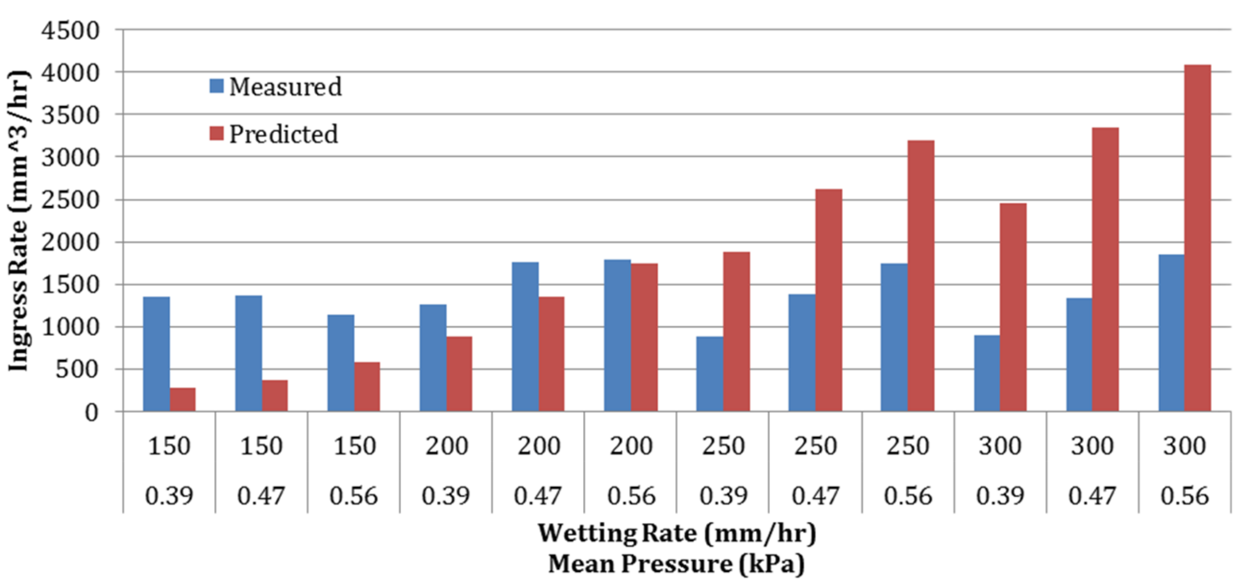

Figure 4-11.Phase III results for window C-1.

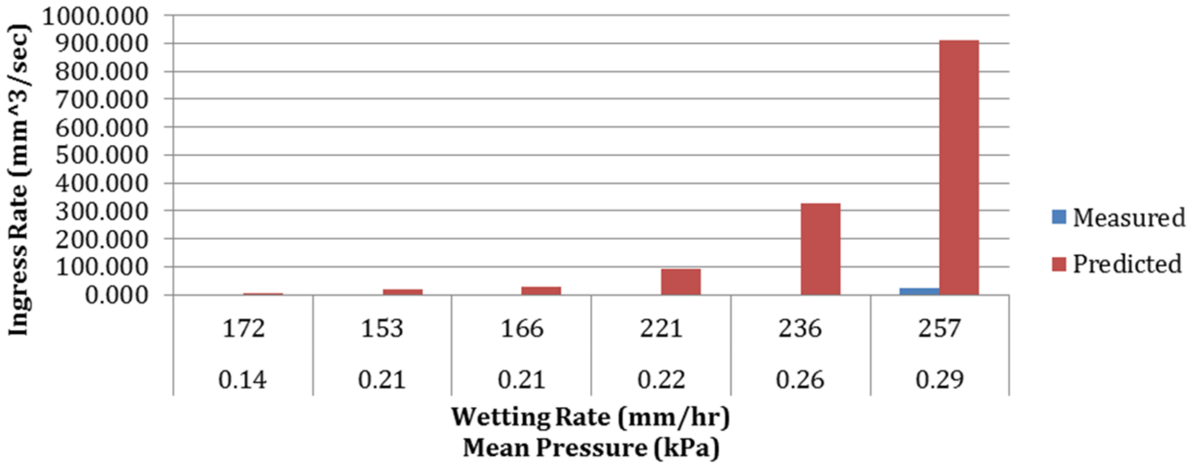

Figure 4-12. Phase IV results for window C-1.

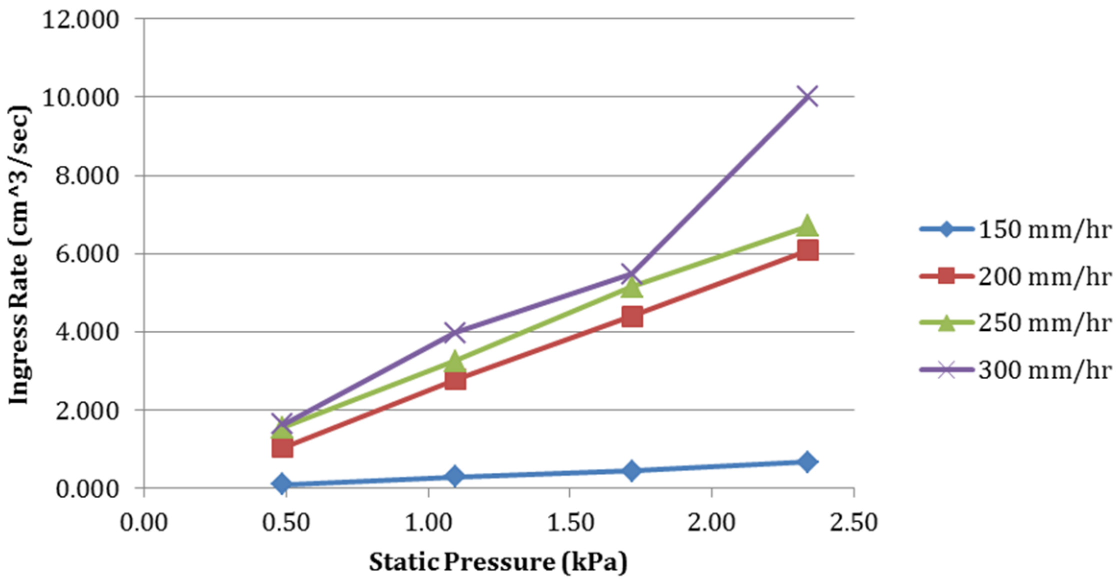

Figure 4-13. Phase II results for window C-2.

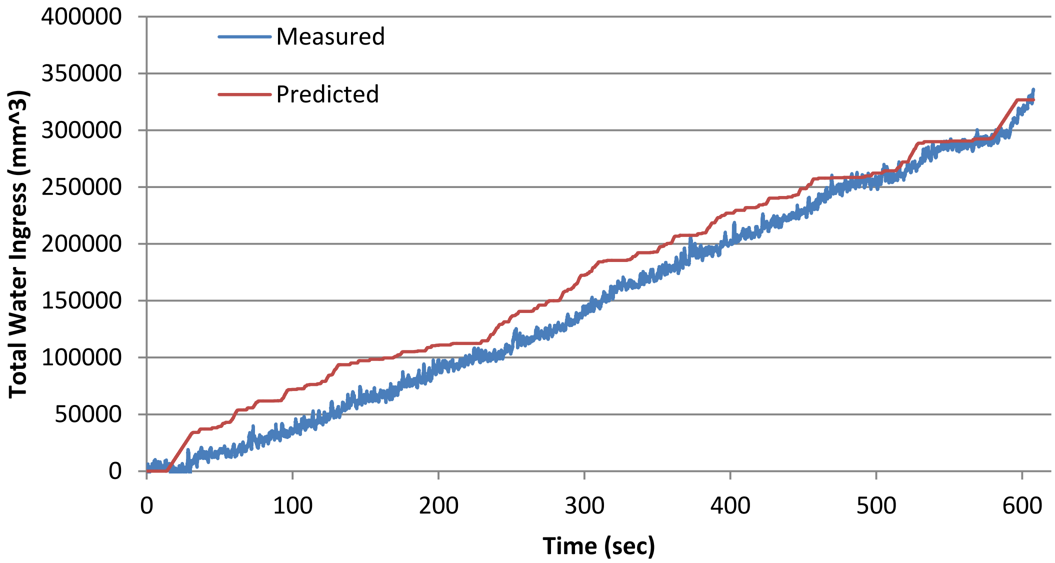

Figure 4-14. Comparison of measured vs. predicted time history for window C-2.

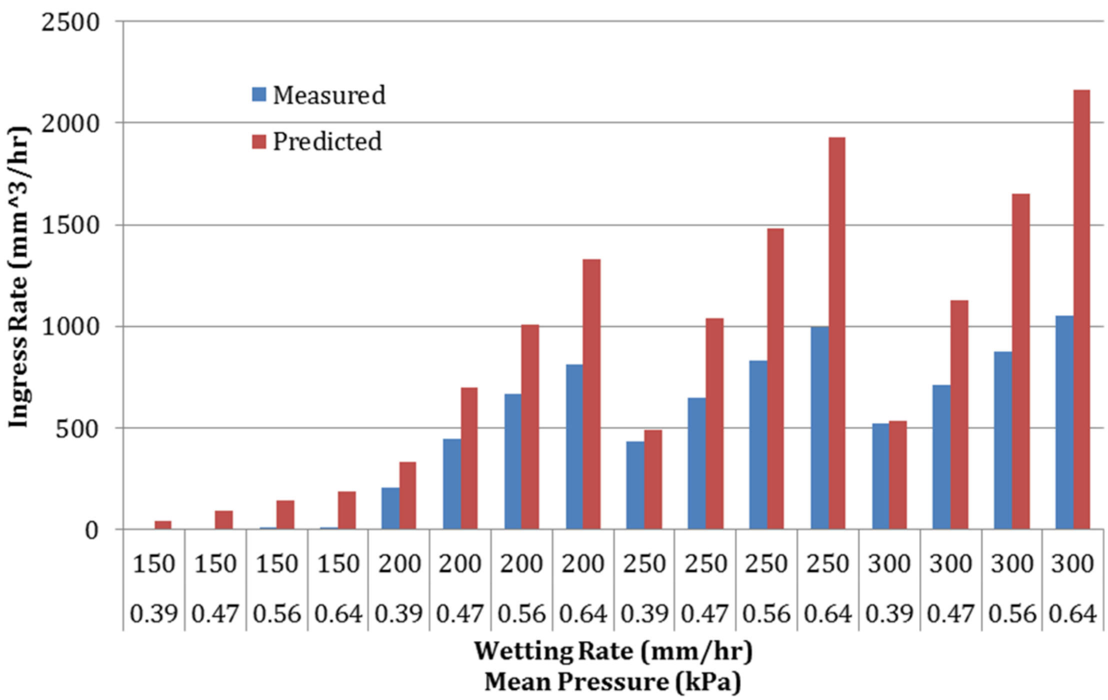

Figure 4-15. Phase III results testing for window C-2.

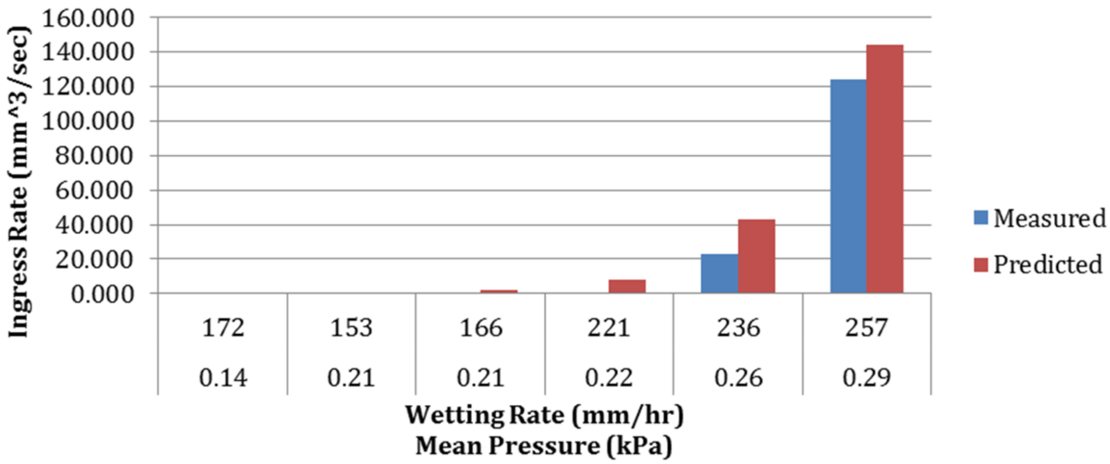

Figure 4-16. Phase IV results for window C-2.

CHAPTER 5
CONCLUSIONS

Initial Static Testing

The complete accuracy of this portion of testing is subject to human judgment, noting the moment when water begins to overtop the bottom sill dam. The exact pressure at which the water begins to enter is also subject to the error caused by turbulence in the flow. The turbulence is inherent to the servo-valve system design used to adjust the static pressure. Those factors being considered, the results still present less than 0.05 kPa (1 psf) of error in the initial pressure at which leakage begins with a wetting rate of 203 mm/hr (8 in/hr).

It is proposed that the pressure at which ingress begins is approximately the pressure which is required to raise a column of water the distance between the interior and exterior of the bottom sill dams. A comparison of the predicted pressure at which ingress begins and the actual is presented in Table 5-1. For most of the window specimens, it was shown that the pressure required to raise a column of water the elevation difference between the interior and exterior sill dams is approximately equal to 15 percent of the design pressure. All window specimens were able to withstand greater than 15 percent of the design pressure before water ingress began.

Varied Rainfall Rate and Pressure

The purpose of the phase of testing was to determine an array of water ingress rates with respect to pressure and wetting rate. It is likely that the accuracy of these can greatly the hinder the ability to predict the behavior under dynamic loads. The general shape of the water ingress curves with respect to pressure differs depending on window manufacturer, making it difficult to predict ingress based on size or pressure rating. It is assumed that an increase in the number of pressure intervals and wetting rates would greatly increase the accuracy of interpolation in the time-history analysis. The downfall of increasing pressure and wetting rate levels is the large increase in testing duration, making the process impractical.

There were results during this portion that were contrary to the expected trend of increased ingress with increased wetting rate and pressure. For window C-1, the ingress rate is nearly identical for the first three wetting rates at the highest static pressure. This suggests an upper bound to the amount of water that can be forced through this particular window assembly. However, the ingress rate at the highest wetting rate at the same static pressure is much larger. Trends without clear meaning need further investigation, and could benefit from an increase in the number of wetting rates tested.

During this phase of testing, the ingress mechanism through the meeting rail of the window differed greatly depending on the design and construction of the particular window assembly. For several windows, it appeared that the water was being forced though the joint due to the pressure differential. In other instances, the gap between the frame and the sliding windows was large enough that a significant jet of air was able to pass through at the corners. This jet of air carried significant amounts of moisture through, particularly at greater wetting rates. This phenomenon increases the difficulty of predicting behavior solely on design and dimensions of a window. In this study, a time-step analysis was deemed most appropriate because it used data acquired during static testing to predict the response of the system under dynamic loading conditions.

Prediction of Dynamic Behavior

In general, there was no clear trend of over or under predicting the water ingress during the dynamic sequences. The accuracy of the predictions and the associated trend were primarily dependent on the individual window assembly subjected to testing. Significant error was present in several comparisons between predicted and measured performance. The duration of the test was approximately ten minutes, which is rather short compared to the typical duration hurricane conditions. The error may be magnified greatly if the length of tests were increased to better match actual conditions. Error in the tests can be attributed in the lag between the predicted and actual total ingress curves. This lag is inherent and unavoidable due to the time it takes for the water to drain from the window sill dam, through the collection apparatus, and into the container suspended from the load cell. The variability of performance with respect to manufacturer contributes to the difficulty of producing an all-encompassing standard to assess the performance of fenestration under dynamic loading.

The goal of this testing was to determine if the water ingress behavior of the windows could be predicted using results from static pressure testing. The method used to predict the dynamic behavior was a time-history analysis of the pressure sequence applied to the window. The ingress rate curves developed in the initial testing phases were interpolated from using pressure and wetting rate at each time step. The method was successful in its ability to predict the general ingress behavior during the sequence, as the fluctuations in total ingress due to pressure is apparent at nearly the same time for both predicted and actual measurements. While the general prediction of behavior was accurate, the overall estimation of ingress totals had significant error. This is primarily due to the mechanics of water ingress through the window assembly. At constant static pressures, the water is collecting and flowing through the window at a constant rate. During a dynamic pressure sequence, the water is able to drain at lower pressures, and therefore has not built-up when large peaks arrive, causing an overestimation of the water ingress through the window. Further improvements upon this method and future testing are cited in the following chapter.

Table 5- 1. Summary of water resistance for window specimens.

Window Specimen	Design Pressure (DP) (kPa)	Minimum Pressure at which ingress began (kPa)	Percent of Design Pressure	Height of bottom sill dam (cm)	Calculated pressure required to overcome bottom (kPa)	Minimum Pressure Required (15% DP) (kPa)
B-1	2.71	0.67	25	4.4	0.44	0.41
B-2	2.39	0.43	18	2.9	0.28	0.36
C-1	1.68	0.36	21	3.0	0.30	0.25
C-2	3.11	0.49	16	4.8	0.47	0.47

CHAPTER 6
SUGGESTIONS FOR FUTURE RESEARCH

Identification of Critical Leakage Path

During the testing of each window, there were two primary leakage paths identified. The first is at the bottom of the window, where water collects, and is then forced through gaps at the bottom due to the pressure differential. The second water ingress mechanism occurs at the meeting rail of the window where the upper and lower sections seal. The majority of the water penetration at this location occurred near the edges of the window where the gasket seal ends.

While mechanics of water ingress occurring at the bottom is simply due to the pressure differential, the cause of occurrence at the meeting rail is less apparent. Observations during the testing of each window varied with respect to the action of the water penetrating the edges of the window at the meeting rail. During isolated tests it appeared the water was simply being carried through due to the presence of a large orifice, which the air could accelerate through. In other situations, it appeared as through the water ingress was fluctuating in severity similar to the bottom of the window, due to differential pressure and excessive water on the surface.

In future testing the portion of water ingress through each of the two primary paths could be accounted for. This enabled determination of the critical path and mechanism of ingress for each window. This also aided in the prediction of performance in actual wind driven rain conditions by accounting for the proportion of the ingress that is caused by each mechanism.

Aging

Several of the components that comprise the window assembly are vulnerable to the effects of aging, especially due to direct heat and sunlight. The gaskets and seals that ensure the integrity of the window with respect to water penetration are of particular interest, as they typically become less resilient as they harden and deteriorate over time due to the aforementioned effects. The majority of windows experiencing extreme weather were installed more than five years prior to the weather event.

The next step in looking at the realistic performance of the window system is to conduct a multi-year study examining the effect of aging on the windows ability to prevent water ingress. A more ideal situation would be to harvest windows installed for a number of years, when they are being replaced, and test them using a similar test procedure. This would enable the comparison of performance prior to installation with windows subjected to the diurnal cycle and the associated temperature changes for a number of years.

Increase Accuracy of Data for Dynamic Prediction

While the windows resisted water ingress below 15% of the design pressure, several of the windows allowed significant water to enter once this threshold was reached. The results of the current study suggest that an equation to predict the amount of water ingress during an event would differ for each window manufacturer. It can also be assumed that the method presented for the prediction of ingress could be improved if more intervals of both wetting rate and pressure were tested for use interpolating between levels. Instead of focusing on a selection of multiple window sizes and manufactures, I propose a study that investigates multiple sizes of a certain model window for a random manufacturer.

The amount of wetting rates and pressure levels would be increased to improve the resolution of the dynamic ingress prediction curves. Multiple replicates of each window would be tested to better increase accuracy of results as well. Using multiple sizes of a window that is designed the same in every other aspect would also enable correlation between window size in water ingress.

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BIOGRAPHICAL SKETCH

Brian Matthew Rivers was born in 1989 in Gainesville, Florida, destined to attend the University of Florida. As the son of a practicing structural engineer, he was exposed to residential and commercial construction at an early age. Following his graduation from high school in 2007, he began working towards a civil engineering degree from the Department of Civil and Coastal Engineering at the University of Florida. As an undergraduate, he was awarded a University Scholars grant, and began working as a research assistant with Dr. Forrest J. Masters. Under his mentorship, he began studying the resistance of building materials exposed to extreme wind and rains. As a member of the University of Florida Hurricane Research Program, he was able to administer and assist on multiple projects to upgrade laboratory facilities and testing equipment. In 2011, he deployed as member of the Florida Coastal Monitoring Program for Hurricane Irene in North Carolina.

Brian is a student member of the American Association for Wind Engineering, American Society of Civil Engineers, and American Concrete Institute. Upon completion of the required coursework for the Master of Engineering degree, he accepted a position with PENTA Engineering Group.