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Water penetration resistance of residential window installation options for hurricane-prone areas

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ABSTRACT

While recent building code advancements have reduced structural failures in residential buildings during hurricane events, water intrusion through the building envelope is a recurring problem. Water ingress poses a significant threat to the building interior and its contents. The interface between the window and the wall system has been identified as a significant source of this water ingress. The fenestration industry has made extensive efforts to develop installation methods to improve water tightness; however, the body of research needed to guide window installations in high-humidity, hurricane-prone areas is sparse. The goal of this research is to investigate the water penetration resistance of selected window installation options consistent with current construction practice of single-family homes when exposed to wind-driven rain.

Static, cyclic, as well as amplitude- and frequency-modulated sinusoidal pressure load sequences were applied with simulated wind-driven rain scenarios to 18 finished wall assemblies with integrated windows. The specimens varied in their unique combination of fenestration, installation methodology, wall structural system, and exterior finish. General conclusions were drawn regarding the effectiveness of the window installation methods to manage water intrusion, as well as the effects that the components of the surrounding wall system have on their performance. The performance of the various sealants used to create the interior moisture/air seal in drainage method window installations is also investigated. It was found that the water barrier and drainage installation methods can provide sufficient water penetration resistance in wood frame construction, while the water barrier method is preferable for windows integrated into masonry walls.

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1. Introduction

Tropical cyclones annually threaten the U.S. Atlantic and Gulf Coasts. With an average annual economic loss estimated at $5 billion [1], the devastation caused by these natural disasters has a lasting national impact. While every state from Maine to Texas is affected by hurricane impacts, none are more frequently affected by landfalling storms than the state of Florida; its combination of exposure and stringent building codes constitute the perfect benchmark with which to assess the adequacy of current coastal construction practices [2].

Over half of the hurricane-related damage in the U.S. occurs in Florida, and will likely grow as recent construction has increased the building stock appreciably around its 1926 km (1197 mi) of coastline. The total value of insured coastal property in Florida as of 2007 was $2.5 trillion, up nearly 27 percent since 2004, and that number is expected to double by 2014 [3]. As the coastal exposure of insured property increases, so does the looming threat of significant losses due to hurricanes impacting the coast. The possibility of such losses underscores the need to further investigate the efficacy of current design standards for construction in hurricane-prone regions, a task that has been ongoing in the state of Florida since 1992.

On August 24, 1992 Hurricane Andrew tracked along the southern tip of Florida as a Category 4 hurricane. Andrew wrought extensive damage on Florida with total costs estimated upwards of $30 billion and more than $15 billion in insurance claims (in 1992 dollars) [4]. In response, the state formulated the enhanced South Florida Building Code adopted in September of 1994, which was modified and ultimately enveloped into the 2001 Florida Building Code (2001 FBC) on March 1, 2002 as the High Velocity Hurricane Zone (HVHZ) provisions [5]. The 2001 FBC instituted more rigorous

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guidelines for structural design and required contractors to use only products that complied with the standards set for hurricane-force winds.

Damage investigation reports published by the Federal Emergency Management Agency (FEMA) following the 2004 hurricane season suggest that the 2001 FBC appears to adequately address the structural design of residential buildings. There was little wind damage to the structural systems in code-compliant buildings. The majority of the damage from these storms was confined to building envelope systems such as roof coverings, soffits, doors, and windows. The failures of these systems allowed wind-driven rain to enter building interiors causing damage to building contents and subsequent mold growth [2].

With the improvements to the structural capacity of residential buildings, attention must now be focused on improving the water penetration resistance of the building envelope to reduce significant property loss. One of the major sources of water ingress through the building envelope is through openings in walls caused by windows and other fenestration, in particular the interface between the window and the wall [6]. Water that migrates to the building interior can lead to wood rot, peeling paint, and microbial growth, which if left unchecked can bring about conditions that would necessitate refurbishment of the dwelling that in turn, may oblige the occupants to vacate their homes. In order to preclude the deleterious effects of water intrusion observed following recent hurricane events, the vulnerability of the building envelope to water intrusion must be addressed. This study investigates the window-wall interface and provides an evaluation of current North American window installation standards common to the hurricane-prone regions of the coastal United States.

In this paper, the four critical barriers of the building envelope and key window installation methods are briefly reviewed. Information about the test specimens is then presented, followed by the experimental design. Finally, results and conclusions are offered to create a useful context in which to discuss the effectiveness of different approaches to managing water entry at the window-wall interface. This paper gives insight into how current window installation standards attempt to provide a means to assess the expected performance of window installation practices in laboratory conditions.

2. Water ingress and the window-wall interface

There are four critical barriers specific to the integration of a window into a wall system in North American construction practices (Fig. 1). Starting from the exterior of the wall assembly and moving toward the building interior these critical barriers include the water shedding surface, exterior moisture barrier, vapor barrier, and air barrier. While these critical barriers may not always appear in the same location or in the same form, their presence is essential for the proper function of the building envelope.

For example, the location of the vapor barrier within the wall is dependent on the hygrothermal conditions of the geographical area to which the wall is exposed. The vapor barrier should always be placed on the high (humidity) vapor pressure side of the exterior wall assembly [7]. In cooler northern climates the vapor barrier is placed on the interior side of the wall assembly. In warmer southern climates, like the hurricane-prone regions of the Southeastern U.S., the vapor barrier is located at the exterior side of the wall assembly. Although this paper pertains to window installation practices specific to hurricane-prone regions, the vapor barrier in Fig. 1 is shown in its location for cold weather climates on the interior side of the wall assembly. This was done to distinguish its location and function apart from the exterior moisture barrier, which oftentimes overlaps the vapor barrier in warm southern climates.

All four of the critical barriers listed above serve a specific purpose to ensure that the building envelope successfully protects the building interior from the outside environment. However, it is the water shedding surface and the exterior moisture barrier that prevent water intrusion into the building interior. Thus, it is these two critical barriers that are vital to the water penetration resistance of a window's installation.

The water shedding surface is the initial barrier in preventing water intrusion. The components of the typical window and wall assembly forming the water shedding surface consist of the glazing, the sealant between the glazing and the frame, the surface of the window frame, the sealant between the frame and the sill, the sill, and the exterior surface of the wall cladding. The water shedding surface acts to deflect the bulk of the water impinging on the façade.

Water that bypasses the water shedding surface through the window joinery, gaps or cracks in the exterior wall cladding, or deficiencies in the components composing the water shedding surface that may have occurred due to degradation over their service life must be managed by the exterior moisture barrier. The exterior moisture barrier is usually provided by the glazing, the sealant between the glazing and the window frame, the window frame surface (or some surface interior to the window frame designed to provide drainage), the sealant between the window frame and the sill pan flashing, the sill pan flashing, and the house wrap applied overtop the sheathing. The exterior moisture barrier represents the farthest point into a wall assembly that moisture may be accommodated. Liquid water that breaches this barrier is able to flow unimpeded to the building interior.

The continuity and proper sequencing of the four critical barriers should be the foundation for the successful wind-driven rain penetration resistance of window installation guidelines. With this in mind, window installation methodologies for extreme wind-driven rain areas have begun to shift focus. Newer drainage installation methods seek to manage intruding water by redirecting it to the drainage plane of the wall rather than relying on the more traditional approach of completely preventing water intrusion at the exterior surface of the assembly. In order to assist this progression, research must be performed to evaluate the effectiveness of the traditional and the proposed installation options.

This research was developed to support these activities, and is based on prior research derived from numerical and experimental modeling of wind-driven rain on buildings (e.g., [8–10]), field documentation following windstorm events (e.g., [2,5,11–17]), assessments of insurance records that relate the magnification of insured losses with building envelope damage (e.g., [18]), damage prediction models to assess building failure (e.g., [19,20]), and full-scale experimental testing to investigate building envelope performance in hurricane conditions (e.g., [21]).

3. Window installation techniques

Liquid water migrating into the window opening must be managed by the details of the window installation. The moisture management strategy used to control this intruding water separates window installations into two basic categories: water barrier methods and drainage methods.

The water barrier method seeks to wholly prevent water migration into the cavity between the window and the rough opening (the framed opening in the wall into which the window is to be installed) by creating a water shedding barrier that is coincident with the exterior moisture and air barrier of the wall

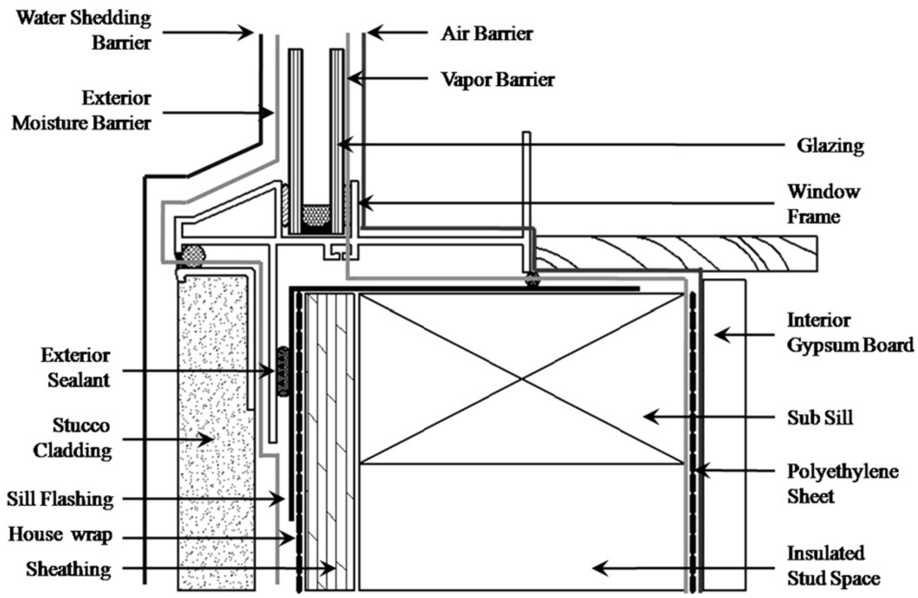

Fig. 1. Critical barriers of the typical window-wall interface.

assembly [22]. In installations using the traditional water barrier method, such as those outlined in ASTM E2112 prior to the 2007 revision [23], the interior surface of the window's mounting flange receives a continuous bead of sealant to provide a moisture and air barrier at the external interface of the window opening. The details of a water barrier method installation are shown in Fig. 2 on a cross-section of a typical window installed in a wood frame wall. While this method is widely considered to be common practice for the installation of fenestration products, several shortcomings have been identified in the literature [24]. This installation technique makes no provisions to control leakage that may occur through the window-wall interface due to incorrect installation or through the window itself due to fabrication error or the deterioration of the window's components over its service life. The effectiveness of water barrier installations is critically dependent on the ability of either an external wall cladding system or a concealed barrier to prevent water ingress into the building.

In installations using the drainage method as a water penetration control strategy, such as FMA/AAMA 100-07 [25], gaps are left in the exterior seal at the sill behind the mounting flange, the bottom of the rough opening is covered with a sill pan flashing, and the interior perimeter of the window receives a continuous seal. In the absence of wind loading, the interior seal acts as a secondary water barrier.

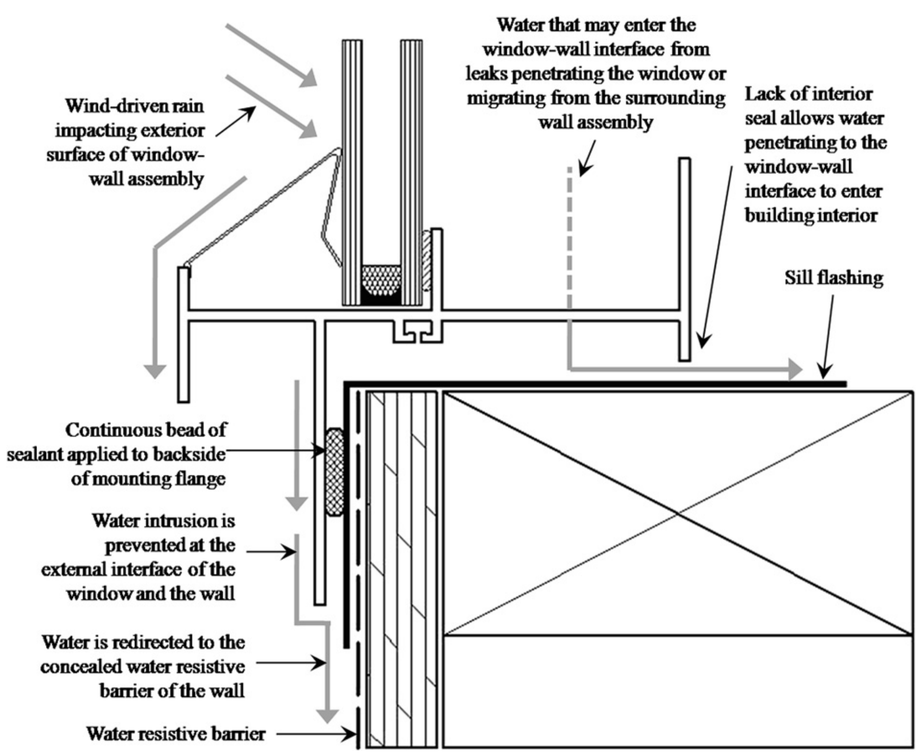

Fig. 2. Water barrier method installation detail.

In contrast to the exterior water barrier method, the moisture and air barrier for the drainage method is located at the interior interface between the fenestration product and the rough opening. Water that may leak into the window opening through the window joinery or at the interface with the adjacent wall assembly is stopped at this interior barrier and is redirected to the drainage plane of the wall through the openings at the exterior seal. Details of a drainage method installation are shown in Fig. 3 on a cross-section of a typical window installed in a wood frame wall. The drainage method takes a practical approach to handling any water that may enter the cavity between the window and the rough opening. Due to the manner in which they manage water ingress, drainage installation methods have been recommended for use in buildings susceptible to extreme wind-driven rain exposure [26].

4. Approach

Three standard practices of installation were selected for this study in order to test the effectiveness of the water penetration resistance of the two installation methodologies. Standards were selected based on their commonality of use in the construction of residential homes in hurricane-pone regions along with their ability to demonstrate the techniques of a water barrier or drainage method installation for wood framed or concrete masonry unit (CMU) wall systems. The selected standards along with the installation methods detailed in their procedures are shown in Table 1.

5. Configuration and construction of test specimens

The test specimens are considered to consist of a representative sample of common residential wall assemblies from the coastal southeastern United States. A total of ten wood frame and eight concrete masonry unit (CMU) wall sections measuring 2.4 m by 2.4 m (8 ft by 8 ft) were designed and constructed with assistance from industry partners (Fig. 4). Wood frame wall specimens were designed in accordance with Section R602 of the 2004 FBC [21]. CMU walls were designed in accordance with Section 2104 of the 2004 FBC [26]. The test specimen matrix, shown in Table 2, provides an overview of the wall construction, window size, window operator type, window frame material, installation methodology, flashing and interior sealant option (where applicable), as well as the sill type unique to each of the 18 test specimens.

Table 1
Installation standards selected for testing.

Standard	Installation Method	Wall Type
ASTM E2112-07	Barrier	Wood and CMU
FMA/AAMA 100-07	Drainage	Wood
FMA/AAMA 200-07	Barrier and Drainage	CMU

In order to isolate the leakage paths of the window-wall interface, the test matrix initially consisted of only fixed windows. It was assumed that by using fixed windows instead of operable windows less leakage would occur through the components of the window assembly, thus allowing test observers to distinguish between water intrusion occurring through the window-wall interface and the window. Logistical and procurement issues later necessitated the incorporation of two awning windows and one single hung window into this project. However, these substitutions did not interfere with any of the testing procedures or results derived from tests on the wall assemblies.

5.1. Wood frame wall specimens

The wood frame wall specimens were constructed off-site by a licensed general contractor and shipped to the testing facility at the University of Florida. The wood walls were framed using No. 2 Hem Fir 2 × 4 stud and plate members at 406 mm (16 in) on center (o.c.). Sheathing consisted of 11.1 mm (7/16 in) oriented strand

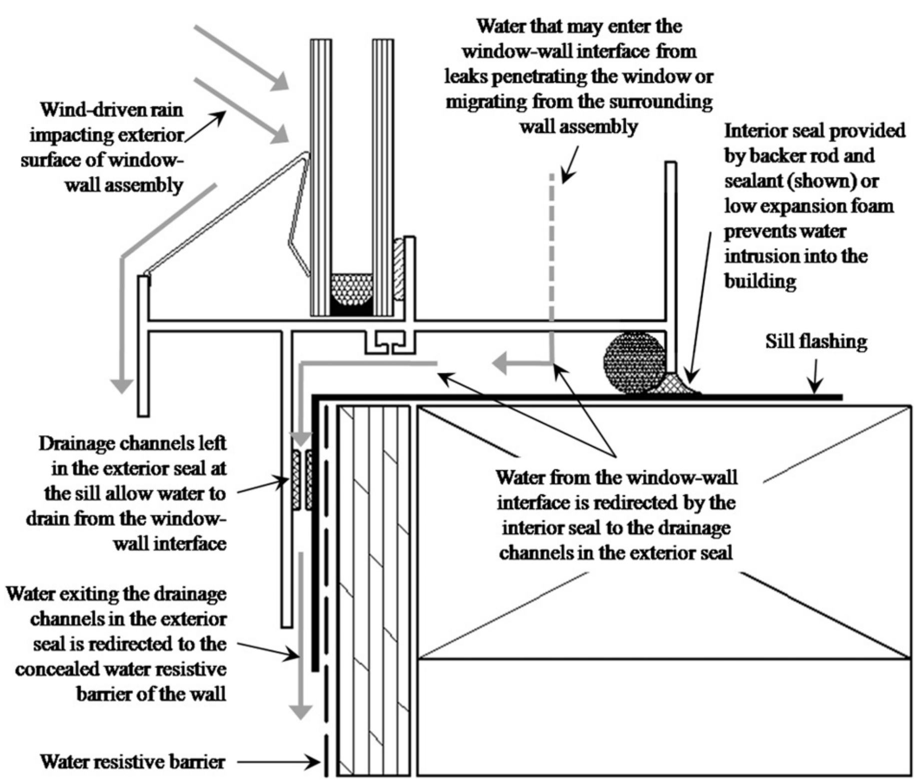

Fig. 3. Drainage method installation detail.

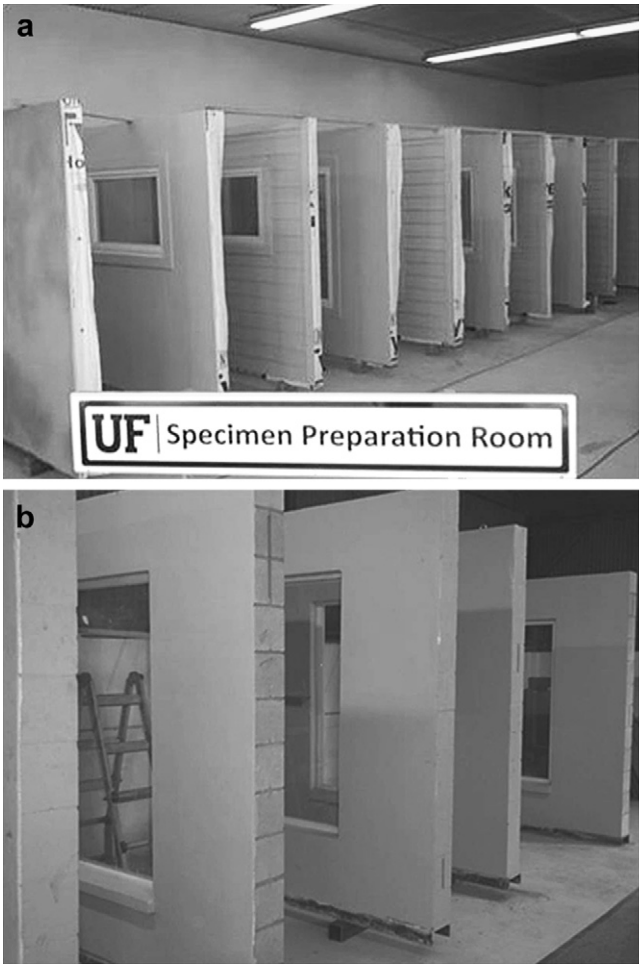

Fig. 4. Wall specimens. (a) Wood frame wall specimens staged during construction. (b) Concrete masonry wall specimens staged during construction.

board (OSB) installed in the vertical direction and attached with 8d common wire nails spaced 152.4 mm (6 in) along vertical edges, 304.8 mm (12 in) in the field, and 101.6 mm (4 in) staggered along horizontal edges. The headers of the window openings were framed using two No. 2 Hem Fir 2 × 6s connected with a minimum of two 16d common nails per 304.8 mm (1 ft). To transfer uplift loads 31.8 mm (1–1/4 in) steel straps (20 gage ASTM A653 [27] grade 33) with four 10d common nails in each end were installed underneath the sheathing and wrapped around the plates and the header of the wall specimens. The bottom plates of the wall specimens were affixed to a steel C4 × 7.5 channel to facilitate the transport of the specimens and the attachment to the testing apparatuses. The steel channels were fastened with 12.7 mm (1/2 in) bolts with 76.2 mm × 76.2 mm × 6.4 mm (3 in × 3 in × 1/4 in) washers through the channel at 609.6 mm (24 in) o.c. in order to simulate a typical slab-on-grade base plate connection.

A polymer based house wrap material was installed on all wood wall specimens to serve as the water resistive barrier (WRB) for the wall assembly. The windows were then installed by certified window installers and flashed. For installations using a barrier method as a water penetration control strategy, the procedures of ASTM E2112-07 Method A1 [23] were followed, which is the basis of most window manufacturer's installation instructions.

The standard practice described in FMA/AAMA 100-07 [25] was used as the basis for installations employing a drainage method as a water penetration control strategy. This standard allows the option to use either a 101.6 mm (4 in) self-adhered flashing or a 228.6 mm (9 in) mechanically attached flashing to flash the exterior jambs and head of the window as well as the option to use either a low expansion foam or backer rod and gunnable sealant to provide the interior perimeter seal. Different combinations of these installation options were tested. All sealants used in these installations met the requirements of either or both ASTM C920-05 [28] and AAMA 808.3-05 [29] for gunnable sealants and AAMA 812-04 [30] for low expansion foams.

After the windows were installed the wall specimens' exterior cladding system, consisting of either fiber cement siding board (FCB) or stucco, was applied. The FCB was attached by a professional installer in accordance with the manufacturer's installation instructions. The fiber cement siding planks were blind nailed to the structural framing of the wall using siding nails (2.28 mm shank × 5.61 mm HD × 51 mm long) installed 10 mm (3/8 in) from the edge of the planks and 25 mm (1 in) from the top. A minimum 32 mm (1–1/4 in) overlap was maintained between planks. The windows, as well as the top and sides of the walls were framed with fiber cement trim pieces to provide a clean finish on all the fiber cement siding planks. Horizontal flashing was provided at the head of each window.

The stucco was applied to a thickness of 19.1 mm (3/4 in) over wire lath in a three coat application consisting of a scratch coat, brown coat, and finish coat in compliance with ASTM C926-06 [31] and ASTM C1063-06 [32]. Vertical expansion joints were placed at all four window corners in these walls to allow for the proper movement of the stucco while curing. It was necessary to provide 101.6 mm (4 in) decorative banding around the windows to accommodate the large projection from the window's integral mounting flange. These bands are purely decorative and were installed onto a scratched surface around the window after the proper stucco application had been applied to the rest of the wall.

The stucco was allowed to cure a minimum of 7 days before being tested with a pH pen to ensure that a pH level below 13 was obtained prior to the application of paint to prevent alkali burn. All wall specimens, FCB and stucco, received a three coat paint finish. The first coat was an alkali resistant primer applied in a 2 mil thickness. The second and third coat was a construction grade acrylic paint with a slight tint applied to a thickness of 4 mil wet. A minimum cure time of 3 h was allotted between coats and the walls were not tested until a minimum of 10 days after the finish coat was applied.

5.2. Masonry wall specimens

The CMU walls were constructed in accordance with the requirements of Sections 2104.1.1 through 2104.5 of the 2004 FBC [21] and ACI 530.1-05/ASCE 6-05/TMS 602-05 [33]. A licensed professional masonry contractor built the walls directly on top of a 203.2 mm (8 in) steel MC8 × 21.4 channel. Number 5 rebar was welded to the base channel prior to construction to provide the vertical reinforcing steel for the walls as well as to prevent the wall sections from overturning while moving them between testing sites. The wall specimens were constructed from normal weight 203.2 mm (8 in) CMUs [34] in a typical running bond with Type S mortar [35]. Down-cells on both sides of the window and at both ends of the wall were filled with a coarse grout [36] to provide flexural rigidity. Bond beams were poured at the top and the base of each wall.

The windows were sized to accommodate 19.1 mm (3/4 in) pressure treated wood bucking in the rough opening. However, due to the slight variations in the construction of the wall specimens and the sizes of the windows, some leniency was required and a maximum of 25.4 mm (1 in) bucking was accepted. Bucking was not required at the sill of the openings because the CMU walls were constructed with precast concrete sills. Two precast sill designs were utilized. Some sills were flush with the exterior block surface (flush sill) and others featured a protruding edge (face sill).

The windows were installed in the CMU walls following the guidelines of the traditional exterior barrier installation described in ASTM E2112-07 [23] or the installation details of either the modified exterior barrier method or the drainage method given in FMA/AAMA 200–09 [37]. Under the "barrier method" provided in the FMA/AAMA 200–09 standard, a continuous exterior seal between the window and the wall system is required as well as an interior seal around the entire window perimeter. The interior seal may be achieved using either a backer rod with a gunnable sealant or a low expansion foam compliant with the specifications listed above for the wood wall systems. Both of these options were tested. The "drainage method" described in this standard follows the same installation procedures as the "barrier method" with the exception that two 51 mm (2 in) gaps are left in the exterior seal located 38 mm (1–1/2 in) from each corner of the window sill.

After the windows were installed into the rough openings of the CMU walls, the exterior cladding was applied. All the wall sections received either a 15.9 mm (5/8 in) three coat stucco application or a decorative cementious coating (DCC) consisting of a stucco skim coat applied directly over the block with a thickness that varied from a paint thickness to approximately 6.4 mm (1/4 in). The stucco was allowed to cure under moist ambient conditions until the appropriate pH level was achieved to accept paint. The paint was applied in the same three coat application as the wood walls and allowed to dry for a minimum of ten days before the wall specimens were tested.

6. Experimental test procedures

Each window-wall specimen was cycled through four rounds of pressure loading and water testing. In order, specimens were evaluated under static (Section 5.1.1), cyclic (Section 5.1.2), and amplitude- and frequency-modulated pressure load sequences (Section 5.1.3), followed by a repeat of the initial static test. The second static test was performed to determine whether the occurrence of a leakage path in a particular test predisposed the window to water intrusion through the same path in subsequent tests. Such behavior would compromise the validity of comparing the water penetration behavior of the specimens between testing methods. Similar leakage times and pressures during the initial and final static tests confirmed the integrity of the specimens. A minimum dry time of 2 days was allotted between tests, and to prevent damage accumulation, the maximum test pressure did not exceed 50 percent of the design pressure (DP) of the installed window.

As will be discussed in the results, a key outcome in the performance of the interior air/water seal prompted additional testing to quantify the water penetration resistance of the seal options (detailed in Section 5.2).

6.1. Window-wall specimen testing

6.1.1. Static air pressure difference test

The static air pressure difference test (static test) was derived from Procedure A in ASTM E1105-00 [38] in which a test specimen is subjected to a specified static air pressure difference along with a specified rate of water spray for a period of 15 min. In the static test of this study, specimens were loaded with an initial pressure of 137 Pa (2.86 psf) for 5 min before the pressure was linearly increased over the next 15 min to half of the window's DP rating (Fig. 5). The initial pressure difference was chosen because it is the standard test-pressure difference at which water penetration is to be determined per ASTM E331-00 [39]. The duration of linear pressure ramp was selected to maintain consistency with ASTM E1105-00 Procedure A.

The static test was performed on a specially designed pressure chamber that applied a negative air pressure difference to the interior side of the wall specimens (Fig. 6). The wetting conditions for the test was supplied by a custom built spray rack calibrated according to the procedures set forth in ASTM E1105-00 [38] to deliver 241 mm/h (9.5 in/hr) evenly across the specimen. Certified Testing Laboratories, Orlando, Florida, independently validated the results.

6.1.2. Cyclic static air pressure difference test

The cyclic static air pressure difference test (cyclic test) was performed on the same pressure chamber used during the static

Table 2
Test specimen matrix.

Specimen	Wall			Window				Installation			
	Type	Ext. Finish	Sill	Operator Type	Dimensions (cm)	Mat.	Design Pressure (Pa)	Standard	Method	Flashing	Int. Seal
17	Wood	Stucco	Flush	Fixed	110.5 × 158.8	Alum.	1915	ASTM E2112	Barrier		
017B	Wood	Stucco	Flush	Fixed	110.5 × 158.8	Alum.	1915	FMA/AAMA 100	Drainage	SA	BRGS
017C	Wood	Stucco	Flush	Hung	110.5 × 158.8	Alum.	2633	FMA/AAMA 100	Drainage	SA	LEF
017D	Wood	Stucco	Flush	Fixed	110.5 × 158.8	Alum.	1915	FMA/AAMA 100	Drainage	MA	BRGS
017E	Wood	Stucco	Flush	Fixed	110.5 × 158.8	Alum.	1915	FMA/AAMA 100	Drainage	MA	LEF
18	Wood	FCB	Flush	Fixed	110.5 × 158.8	Alum.	1915	ASTM E2112	Barrier		
018B	Wood	FCB	Flush	Fixed	110.5 × 158.8	Alum.	1915	FMA/AAMA 100	Drainage	SA	BRGS
018C	Wood	FCB	Flush	Fixed	110.5 × 158.8	Alum.	1915	FMA/AAMA 100	Drainage	SA	LEF
018D	Wood	FCB	Flush	Fixed	110.5 × 158.8	Alum.	1915	FMA/AAMA 100	Drainage	MA	BRGS
018E	Wood	FCB	Flush	Fixed	110.5 × 158.8	Alum.	1915	FMA/AAMA 100	Drainage	MA	LEF
19	CMU	DCC	Flush	Fixed	110.5 × 158.8	Alum.	1915	ASTM E2112	Barrier		
019B	CMU	DCC	Flush	Fixed	110.5 × 158.8	Alum.	1915	FMA/AAMA 200	Barrier	LAF	BRGS
019C	CMU	DCC	Face	Fixed	110.5 × 158.8	Alum.	1915	FMA/AAMA 200	Drainage	LAF	BRGS
35	CMU	DCC	Flush	Awning	120.7 × 74.9	Vinyl	2523	FMA/AAMA 200	Drainage	LAF	LEF
20	CMU	Stucco	Face	Fixed	110.5 × 158.8	Alum.	1915	ASTM E2112	Barrier		
16	CMU	Stucco	Flush	Awning	120.7 × 74.9	Alum.	2523	FMA/AAMA 200	Barrier	LAF	BRGS
020C	CMU	Stucco	Flush	Fixed	110.5 × 158.8	Alum.	1915	FMA/AAMA 200	Drainage	LAF	BRGS
020D	CMU	Stucco	Flush	Fixed	110.5 × 158.8	Alum.	1915	FMA/AAMA 200	Drainage	LAF	LEF

FCB = fiber cement siding board for the exterior wall finish, DCC = decorative cementitious coating for the exterior wall finish.
SA = 101.6 mm self-adhered flashing, MA = 228.6 mm mechanically attached flashing.
BRGS = backer rod and gunnable sealant, LEF = low expansion foam, LAF = liquid applied flashing.

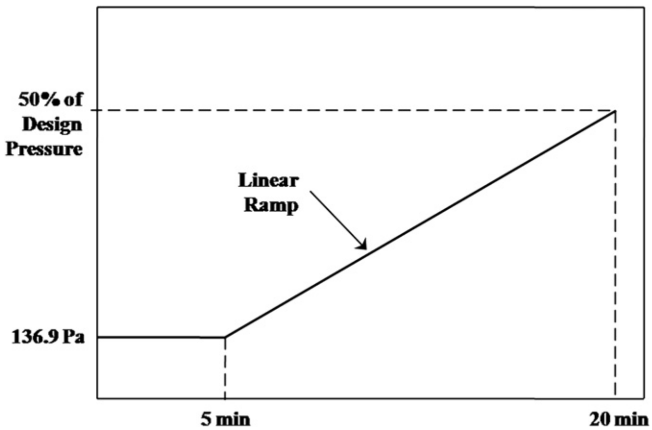

Fig. 5. Loading function for the static air pressure difference test.

test and was derived from a combination of ASTM E2268-04 [40] and a draft version of AAMA 520-09 [41]. ASTM E2268-04 prescribes that a fenestration specimen be pulsated between 50% and 150% of a median pressure of 137 Pa (2.86 psf). The AAMA 520-XX specification provides a range of increasing performance levels from 1 to 10, where level one pulsates from 240 to 720 Pa (5–15 psf) and level ten pulsates from 670 to 2010 Pa (14–42 psf). For the specimens tested in this study, a pulsating pressure schedule with multiple levels was developed. The pressure ranges established for the performance levels of this test were lower than those specified in the AAMA draft specification in order to accommodate the pressures of ASTM E2268-04. The pressure loading function for this test, as shown in Fig. 7, begins by loading the specimen without water for 1 min at an air pressure difference equal to 50 percent of the DP rating for the window followed by a rest period of 1 min where the specimen is equalized to atmosphere. Water is then incorporated for the remainder of the test, which consists of 60 cycles over 3 min periods at each of the varying pressure levels such that 50 percent of the window's DP rating is not exceeded. For example, a wall system with a DP60 window was loaded to the performance level that pulsed from 479 to 1436 Pa (10 to 30 psf).

6.1.3. Dynamic pressure test

The dynamic pressure test consisted of the amplitude- and frequency-modulated sinusoidal pressure loading sequence shown in Fig. 8. The loads were designed by converting wind speed observations collected during landfalling tropical cyclones by the Florida Coastal Monitoring Program (fcmp.ce.ufl.edu) to velocity pressures. It was conservatively assumed that there was perfect aerodynamic admittance between the free stream velocity pressure and the stagnation pressure on the windward wall. Ten minute records with a mean velocity greater than 20 m/s (44.7 mph) and a longitudinal turbulence intensity range of 15–20% (open exposure conditions) were extracted and linearly de-trended. The longitudinal turbulence intensity is defined as the standard deviation of the longitudinal (along-wind) component divided by the mean wind speed. The longitudinal velocity component was passed through nine band-pass filters in 0.1 Hz pass-band increments. The lowest three frequencies were used (0.15, 0.25 and 0.35 Hz). The peak amplitude for each pass-band was recorded and divided by

Fig. 6. Negative pressure chamber. A) Test specimen attached to chamber. B) View from interior of Negative Pressure Chamber. C) Wetting chamber containing the calibrated spray rack. D) Wetting chamber is sealed to the front of the test specimen to collect water.

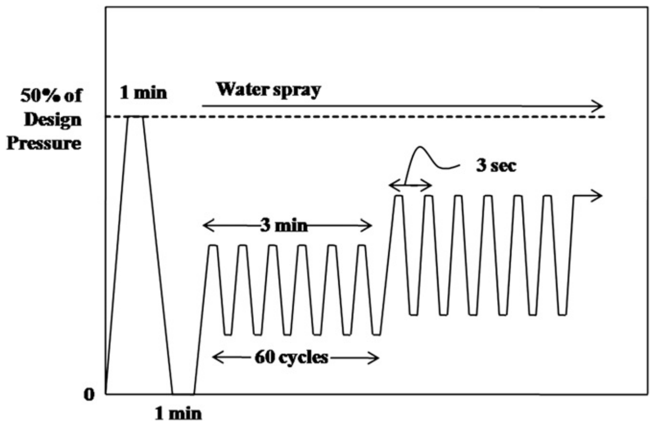

Fig. 7. Loading function for the cyclic static air pressure difference test.

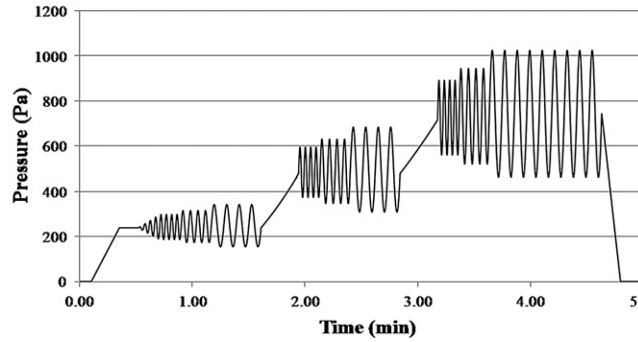

Fig. 8. Loading function for the dynamic pressure test.

the mean velocity over a 10 min record to determine the peak amplitude to mean velocity ratios. The 50th percentile peak values were employed to construct a sinusoidal loading pattern at three different velocity thresholds that correspond to 239, 479, and 718 Pa (5, 10 and 15 psf).

The dynamic test was performed using the University of Florida Hurricane Simulator (Fig. 9). The 2.09 MW (2800 hp) simulator is capable of replicating turbulent wind and rain loads on building systems. Four 0.52 MW (700 hp) diesel engines spin eight hydraulically actuated vaneaxial fans to produce stagnation pressures of 1676 Pa (35 psf) on the windward wall. Specially designed venturi inlets force the air to travel perpendicular to the fan discs for maximum efficiency. Air accelerates through the contraction and passes a series of custom designed neutral shape NACA airfoils positioned at the exit. The airfoils are connected to a hydraulic rotary actuator which changes the wind direction; however, lateral turbulence was not incorporated into the loading for this testing. Water is injected into the flow field using nozzles located along the trailing edge of the airfoil. The uniformity of the rain field on the window-wall specimens was calibrated in a similar fashion as the spray rack used in the static pressure chamber.

To recreate hurricane conditions an active computer control system modulates wind speed by varying fan RPM, creates directional effects by articulating the airfoils at the exit, and injects water into the flow field to simulate rain. The control system utilizes a 16.6 ms time increment PID-control operated in the LabVIEW 8.5 environment.

The major difference between this test and the static and cyclic tests is that the Simulator creates a wind field that impinges on the wall surface. As the streamlines diverge, the kinetic energy of the wind converts to a static pressure to create the load that acts on the wall. In contrast, the pressure is directly applied to the wall in the static and cyclic tests. A key advantage is that water can be injected into the windstream to simulate the dynamics of wind-driven rain. The trade-offs are a substantial increase in the power requirement and a decreased accuracy in the load representation.

6.2. Interior moisture and air barrier testing

During the initial four rounds of pressure and water testing, varying performance of the different sealing methods used to create the interior moisture/air barrier was observed. Allowance is provided in the installation procedures given in both the FMA/AAMA 100-07 (for wood frame walls) and the FMA/AAMA 200 (for CMU walls) for the interior seal to be formed using either a backer rod with a gunnable sealant or a low expansion foam [25,37]. Specifically in the wood frame walls, which used a translucent sealant for the interior seal, it was observed that frequently under median pressure differentials a water column developed inside the jamb of the window frame. At increased pressures, this water bypassed the interior seal at the interface with the sill flashing membrane thus penetrating the exterior moisture barrier of the window-wall interface. The water penetration was attributed to the inability of the interior sealant to maintain adequate adhesion with the sill flashing membrane at increased pressures. While similar leaks were observed in the CMU walls the opaque nature of the sealant used for the interior perimeter seals of these specimens made it difficult to observe the development a water column as in the wood frame counterparts. Therefore, the breadth of the sealant testing was focused around the observed leakage in the wood frame walls.

To test this hypothesis, a selection of gunnable sealants and low expansion foams were subjected to a hydraulic leakage pressure test that was developed to determine the water penetration thresholds of the sealants when installed as an interior seal. The hydraulic leakage pressures for the gunnable sealants were further compared to their adhesion-in-peel strengths according to ASTM C794-01 [42] to determine if a correlation existed between the two performance criterions.

Sealant samples were selected for testing based on composition, availability, and frequency of use in practical construction. Three siliconized acrylic latex and four one-component polyurethane gunnable sealants conforming to either or both ASTM C920-05 [28] and AAMA 808.3-92 [29] along with five one-component polyurethane low expansion foams conforming to AAMA 812-04 [30]

Fig. 9. University of Florida Hurricane Simulator.

were selected for testing. The anonymity of the products used was maintained using a four character alpha-numeric indexing system. The first two characters indicate whether the specimen was a gunnable sealant (S) or a low expansion foam (F) and the product number within this classification. The last two characters refer to the sill material, aluminum (A) or vinyl (V), and the test number (1, 2, or 3). Table 3 lists the sealant samples used in the interior moisture/air barrier testing, along with their composition.

6.2.1. Hydraulic leakage pressure test

In order to test the leakage pressures of the interior seals, sealants were applied to fabricated sill specimens replicating an interior moisture/air barrier as it would occur in a drainage method installation. Sill specimens were created from 457.2 mm (18 in) pieces of both aluminum and vinyl extruded sill stock (Fig. 10). The sill pieces were sealed on both sides and mounted on a mock-sill such that the gap for the interior seal was consistently 6.4 mm (1/4 in) for all specimens. The sills were then sealed to hold water within the cavity of the sill frame. Two valves were installed into the sills. One valve was used to allow water to enter the sill cavity, while the other valve was used to evacuate air from the sill cavity as it filled with water.

Three vinyl and three aluminum sill specimens were constructed for each of the 12 sealants, totaling to 72 specimens. All of the sealants were applied in the same manner as the original window-wall test specimens so that the results could be compared. Gunnable sealants were installed with a 9.5 mm (3/8 in) backer rod to prevent “three-point” adhesion and hand tooled to ensure proper sealant shape. Every seal was tooled by the same installer with the utmost attention to maintain consistency among specimens. Low expansion foam seals were not trimmed prior to testing. Following application, the sill specimens were allowed to cure for a minimum of 72 h before testing.

For each test run, a sill specimen was connected to a reservoir constructed from a 37.9 L (10 gal) aquarium with vinyl tubing, as shown in Fig. 10(d). Water was siphoned into the reservoir from two 18.9 L (5 gal) buckets through 6.4 mm (1/4 in) vinyl tubing. As the water level in the reservoir increased, the sill cavity filled and a hydraulic pressure was applied to the backside of the interior seal. Once water was observed to bypass the outer plane of the seal the height of the water level in the reservoir, the water temperature, the leak location, along with a brief description of the leak was recorded. The first two leaks for each test were documented. In the case that the interior seal showed no signs of water intrusion when the reservoir was completely filled, specimens were slowly lowered below the testing table to gradually increase the pressure on the seal. Due to the limiting factors of the testing table height and the vinyl tubing lengths the maximum achievable pressure for the testing apparatus was 4788 Pa (100 psf).

Table 3
Sealant sample matrix.

Index	Sealant type	Composition
S1	Gunnable sealant	Siliconized acrylic latex
S2	Gunnable sealant	Siliconized acrylic latex
S3	Gunnable sealant	Siliconized acrylic latex
S4	Gunnable sealant	One-component polyurethane
S5	Gunnable sealant	One-component polyurethane
S6	Gunnable sealant	One-component polyurethane
S7	Gunnable sealant	One-component polyurethane
F1	Low expansion foam	One-component polyurethane
F2	Low expansion foam	One-component polyurethane
F3	Low expansion foam	One-component polyurethane
F4	Low expansion foam	One-component polyurethane
F5	Low expansion foam	One-component polyurethane

Using the testing table as a datum the hydraulic head was determined by subtracting the elevation of the seal from the elevation of the water level in the reservoir. The hydraulic head was then converted to a pressure applied to the backside of the interior seal by multiplying the head by the density of water at the recorded temperature. The resulting pressure was determined to be the hydraulic leakage pressure.

6.2.2. Adhesion-in-peel strength

The adhesion strengths of the gunnable sealant samples were determined based on the procedures of ASTM C794-01 [42]. The adhesion strengths of the low expansion foams were not tested because a comparable standard does not exist for these types of sealants and the results of the hydraulic leakage pressure testing yielded inconsistent results, as discussed in Section 7.2.1. The ASTM C794-01 standard specifies adhesion testing to anodized aluminum, mortar slabs, and plate glass material samples. However, because these are not materials commonly adhered to in the application of the interior moisture/air seal the adhesion strengths of the sealants were also tested to SPF grade wood, painted aluminum coil stock, extruded vinyl window stock, and the sill flashing membrane used in the original testing. The adhesion of the sealants to the sill flashing membrane was of particular concern as the majority of the water intrusion observed during the initial testing occurred at this interface. Two specimens per sealant per substrate were prepared and tested in accordance with the procedures outlined in ASTM C794-01 [42]. For each test the peak and average peel strengths as well as the failure mode were recorded. Failure modes were classified as adhesive, cohesive, or mixed mode (a combination of adhesive and cohesive).

7. Results

When reviewing the results it is important to recognize that the testing performed in this study was relatively extreme compared to the test standards currently in place for fenestration products. According to AAMA/WDMA/CSA 101/I.S.2/A440-05 Section 0.2.6, the minimum water penetration resistance test pressure shall be 15% of the DP rating of the window [43]. Slightly more rigorous, the FMA/AAMA standards [25,37] test the water penetration resistance of their installations for “extreme exposure” conditions at 574.6 Pa (12 psf). The pressure loading sequences of this study test the wall specimens under wind-driven rain conditions to pressures equaling 50 percent of the DP rating of the window, which for a subset of the windows was in the order of 1436 Pa (30 psf).

A full analysis of the leakage sources observed in this study would have required the systematic dismantling of the test specimens to trace the leakage paths. There was interest to maintain the integrity of the specimens such that future water penetration testing could be conducted on the specimens following a period of natural aging. Hence, the test specimens were reserved for future use and destructive methods typically used to locate sources of observed water intrusion were not employed. Thus, where installation and construction deficiencies were not obvious the precise origins of the observed leakage paths could not be determined.

A leak was defined in this study as any liquid water observed from the interior of the test specimen to have bypassed the exterior moisture barrier of the window-wall assembly. When a leak was observed during testing the time into the test, the pressure, the location, and a brief description of the leak was recorded. These leakage results were then used to evaluate the performance of the window-wall specimens and draw conclusions on the effectiveness of their water penetration performance.

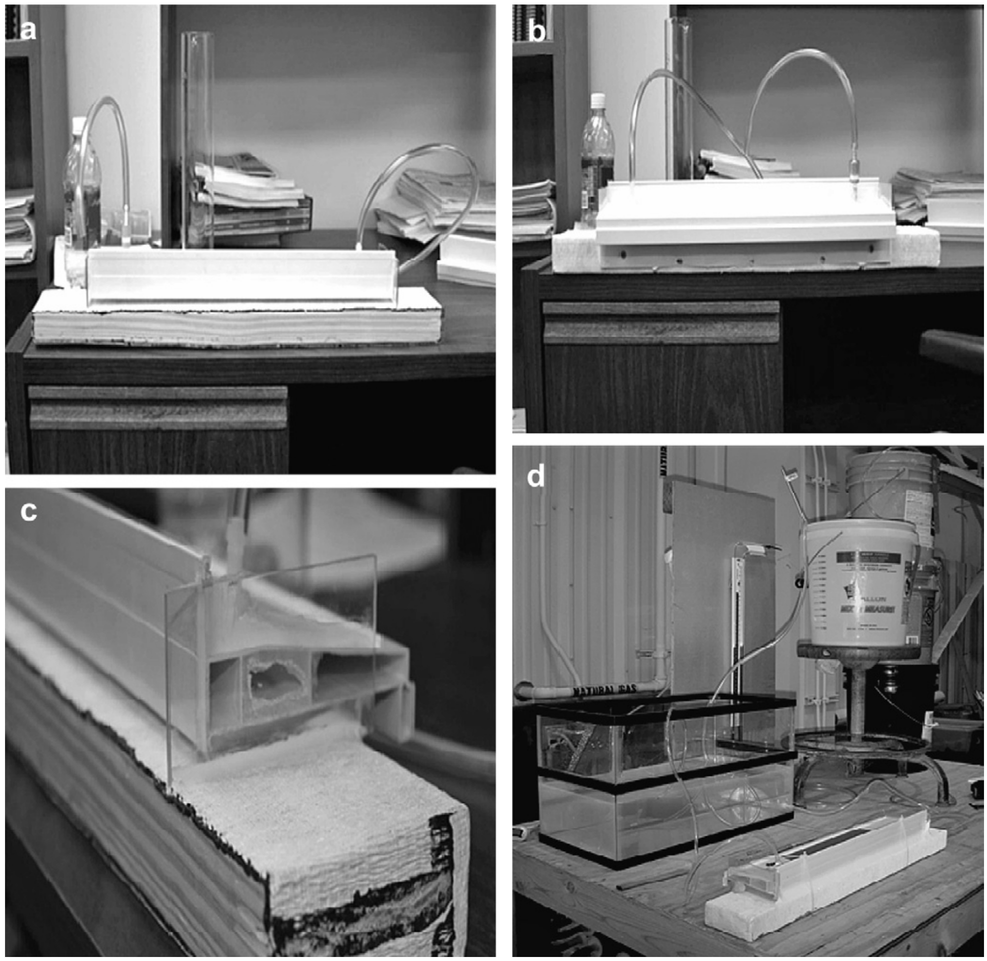

Fig. 10. Sill specimen for hydraulic leakage pressure test. (a) Sill specimen mounted to maintain 6.4 mm (1/4 in) gap for seal. (b) Sill extrusion affixed to mock-sill with screws through mounting flange. (c) Ends of specimens sealed to hold water inside sill cavity. (d) Hydraulic leakage pressure testing apparatus.

7.1. Window-wall specimen results

The installation methods and the moisture management strategies utilized by the test specimens along with their corresponding leakage pressures are summarized in Table 4. Comparison of the leakage results from the CMU and the wood frame wall specimens indicate that the highest water penetration resistance occurs when the installation option and the wall system share a consistent moisture management strategy.

When analyzing the leakage results in Table 4, it is important to realize that only the leakage occurring through the window-wall interface is displayed for the test specimens. Leakage occurring through the window assembly was not included in this table. Also test specimen 035 was intended to employ a drainage installation, but the window was installed so tightly against the wood bucking that the drainage channels at the sill were reduced to almost crack-sized openings (Fig. 11c). The application of paint most likely sealed these drainage channels marginalizing their draining effectiveness. Hence, in the tabulated results test specimen 035 is listed as a water barrier installation to reflect its inability to allow proper drainage through the gaps in the sealant.

The drainage approach performed better than the barrier method in the wood frame wall systems. A total of 8 wood frame wall specimens employed a drainage installation method and 5 of these (017C, 018B, 018C, 018D, 018E) passed all four rounds of pressure and water testing without any observed signs of water intrusion. While specimen 017B and 017D did leak, they both leaked in only three of the four rounds of testing (neither leaking in the dynamic test) at an average pressure of 733.8 Pa (15.3 psf), which is almost 40 percent of the DP rating for the windows of these walls. Specimen 017E, which utilized a low expansion foam interior water seal, showed insufficient water intrusion performance (leakage pressure 138.9 Pa), leaking at pressures below the criteria of both AAMA/WDMA/CSA 101/I.S.2/A440-05 (287.3 Pa) and the "extreme exposure" conditions in the FMA/AAMA standards (574.5 Pa). For the wood frame walls, the voids in the sealant behind the integral mounting fin at the sill required for drainage method installations are coincident with the concealed barrier of the wall system and are not directly exposed to the wind-driven rain simulated environment. This allows the drainage voids to properly function and redirect any leakage down the WRB of the wall.

The only wood frame wall specimens that employed a barrier installation method were 017 and 018. Although both of these walls leaked, Table 4 shows that they only leaked during a single test and at relatively high pressures. Specimen 017 leaked during the dynamic test while the pressure oscillated around a median value of 742.2 Pa (15.5 psf) and specimen 018 leaked during the static test at a pressure of 866.6 Pa (18.1 psf).

For the CMU wall specimens, the drainage method installations did not perform as well as their wood frame counterparts. A total of three CMU walls had windows installed using drainage method

Table 4
Leakage results for varying window-wall moisture management combinations.

Specimen	Moisture Management Strategy		Wall Ext. Finish	Initial leakage time/pressure (Pa)			
	Wall System	Installation		Static test	Cyclic test	Dynamic test	Static test 2
017	Concealed Barrier	Barrier	Stucco	DNL	DNL	4:25/459.7–1025	DNL
018	Concealed Barrier	Barrier	FCB	18:17/866.6	DNL	DNL	DNL
019	Surface Barrier	Barrier	DCC	15:00/957.6	11:25/191.5–574.6	3:15/565.0–890.6	8:55/354.3
019B	Surface Barrier	Barrier	DCC	DNL	DNL	DNL	DNL
020	Surface Barrier	Barrier	Stucco	DNL	18:00/335.2–1006	DNL	DNL
016	Surface Barrier	Barrier	Stucco	DNL	DNL	DNL	DNL
035[a]	Surface Barrier	Barrier	DCC	DNL	DNL	DNL	DNL
017B	Concealed Barrier	Drainage	Stucco	17:45/842.7	16:30/287.3–861.8	DNL	20:00/957.6
017C[b]	Concealed Barrier	Drainage	Stucco	DNL	DNL	DNL	DNL
017D	Concealed Barrier	Drainage	Stucco	19:30/943.2	16:00/287.3–861.8	DNL	17:27/818.8
017E	Concealed Barrier	Drainage	Stucco	6:20/215.5	1:46/67.0–205.9	2:53/306.4–679.9	3:18/138.9
018B	Concealed Barrier	Drainage	FCB	DNL	DNL	DNL	DNL
018C	Concealed Barrier	Drainage	FCB	DNL	DNL	DNL	DNL
018D	Concealed Barrier	Drainage	FCB	DNL	DNL	DNL	DNL
018E	Concealed Barrier	Drainage	FCB	DNL	DNL	DNL	DNL
019C	Surface Barrier	Drainage	DCC	7:20/272.9	6:20/143.6–430.9	0:40/181.9–296.9	6:00/191.5
020C	Surface Barrier	Drainage	Stucco	6:38/239.4	2:30/67.0–205.9	2:47/306.4–679.9	4:15/138.9
020D	Surface Barrier	Drainage	Stucco	10:45/502.7	6:30/143.6–430.9	1:45/373.5–593.7	11.09/521.9

DNL designates walls that did not leak during a particular test.
FCB designates fiber cement siding board for the exterior wall finish.
DCC designates decorative cementitious coating for the exterior wall finish.
[a] Specimen 035 was changed from a drainage method to a water barrier method type installation due to constricted drainage channels.
[b] The leakage times and pressures shown for specimen 017C are for leaks through the window-wall interface only.

installations (019C, 020C, 020D) and water bypassed the interior moisture/air seal in all of these walls at pressures below the 574.5 Pa (12 psf) required by the FMA/AAMA 200 standard. Specimen 020C was the least performing installation method, leaking at pressures as low as 138.9 Pa (2.9 psf) which conservatively converts to an approximate wind speed of 15.1 m/s (33.7 mph). In order for the window-wall interface of these walls to properly drain, drainage channels must be incorporated into the exterior seal at the sill allowing intruding water to be redirected to the exterior surface of the wall assembly. This location for the drainage channels makes them susceptible to water intrusion when exposed to wind-driven rain.

The barrier method performed better in the CMU wall specimens. Of the five CMU walls with windows installed using a barrier approach (019, 019B, 020, 016, 035) three walls did not exhibit any signs of water intrusion through all four rounds of pressure and water testing (019B, 016, 035) and specimen 020 only leaked during the cyclic test. The exterior seal in these walls is continuous around the perimeter of the window creating a consistent drainage plane along the exterior surface of the window-wall system.

With the exception of a few instances, the leakage observed through the window-wall interface during this testing was concentrated to the area around the window sill extending up the jambs approximately 304.8 mm (12 in). This is to be expected as gravity causes the water penetrating into the window-wall interface to migrate down the jambs of the window and collect at the sill. Several of the interior seals for the wood frame wall specimens with windows installed using drainage method installations were formed with a translucent acrylic latex sealant allowing test observers to visually observe this water accumulation. In these walls, water collected to such excess that a water column developed in the jambs of the windows. It is suggested that this water column applies a hydraulic pressure to the backside of the interior moisture/air barrier thus causing the sealant to

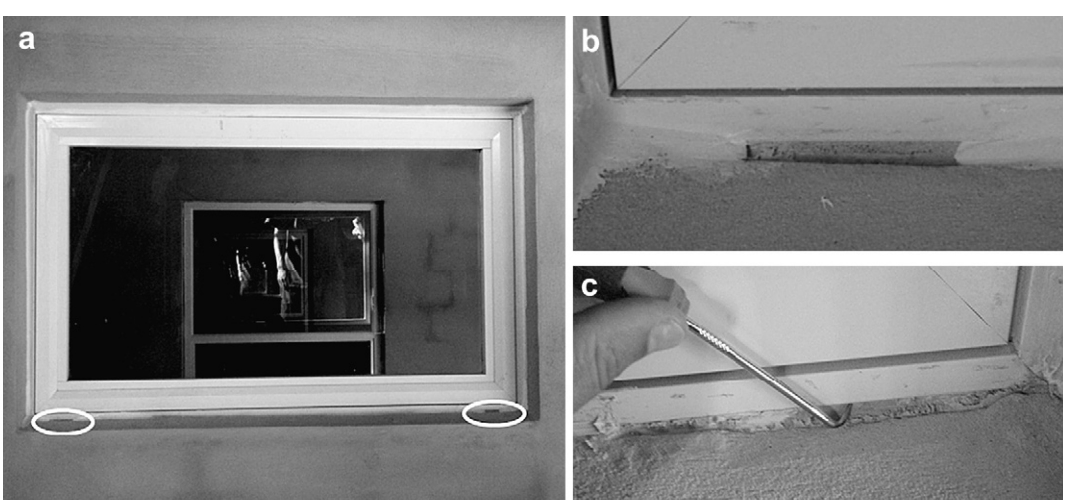

Fig. 11. Drainage channels in exterior moisture barrier wall systems. (a) Location of drainage channels in CMU wall specimens with windows installed using a drainage method window installation. (b) Inability to seal the drainage channel creates an inconsistency in the exterior moisture barrier of the wall which could allow intruding water to penetrate behind the wall cladding. (c) The window of test specimen 035 was installed so tightly against the bucking that the drainage channels were constricted.

fail adhesively at the interface with the flexible sill flashing membrane. Once the interior moisture/air barrier fails at this interface the accumulated water is able to bypass the seal, leaking to the interior side of the specimen (note that as stated above, all of the wood frame walls utilizing the backer rod and sealant interior air seal exceeded the FMA/AAMA 100 pressure threshold of 574.5 Pa before this leakage occurred). This type of leakage was thought to be the cause of the increased pressure provided by the water column in combination with the inability of the sealant's adhesion with the flexible sill flashing membrane to withstand the high pressures.

Similar leakage occurred at the sills of the CMU wall specimens with windows installed using drainage method installations. Unlike the wood frame wall specimens, these walls did not use the flexible sill flashing membrane; however, water from within the window-wall interface still leaked through the interior moisture/air barrier at the interface of the sealant and the sill. In some cases this leakage occurred at pressures lower than their wood framed counterparts. An opaque sealant was used for the interior seals of these walls and thus the exact cause of this leakage was less apparent than it was for the wood frame walls. Further investigation is required to explain the leakage performance of these walls.

In order to test the effect that the observed water column had on the adhesion of the sealants and the leakage results for the wood frame walls additional tests were designed and performed. The experimental procedures for these tests are described in Section 5.2 and the results are discussed in the sections that follow.

7.2. Interior moisture/air barrier results

7.2.1. Hydraulic leakage pressure

A total of 72 sill specimens were tested to determine their hydraulic leakage pressure according to the procedures outlined in section 5.2.1. The interior seals for 42 of the specimens were created using backer rod and a gunnable sealant while the remaining 30 specimens employed low expansion foam for the interior seals. Each sealant was used to create 6 test specimens, three vinyl and three aluminum. For each sealant, the first and second leakage pressures for the three tests of a particular sill material were averaged. The average pressures of the first and second leaks were then compared as a measure of the sealant's continuity of application. If the pressure difference between the first and second leak was large, the first leak was considered to have occurred due to a lapse in the sealant resulting from poor application and/or

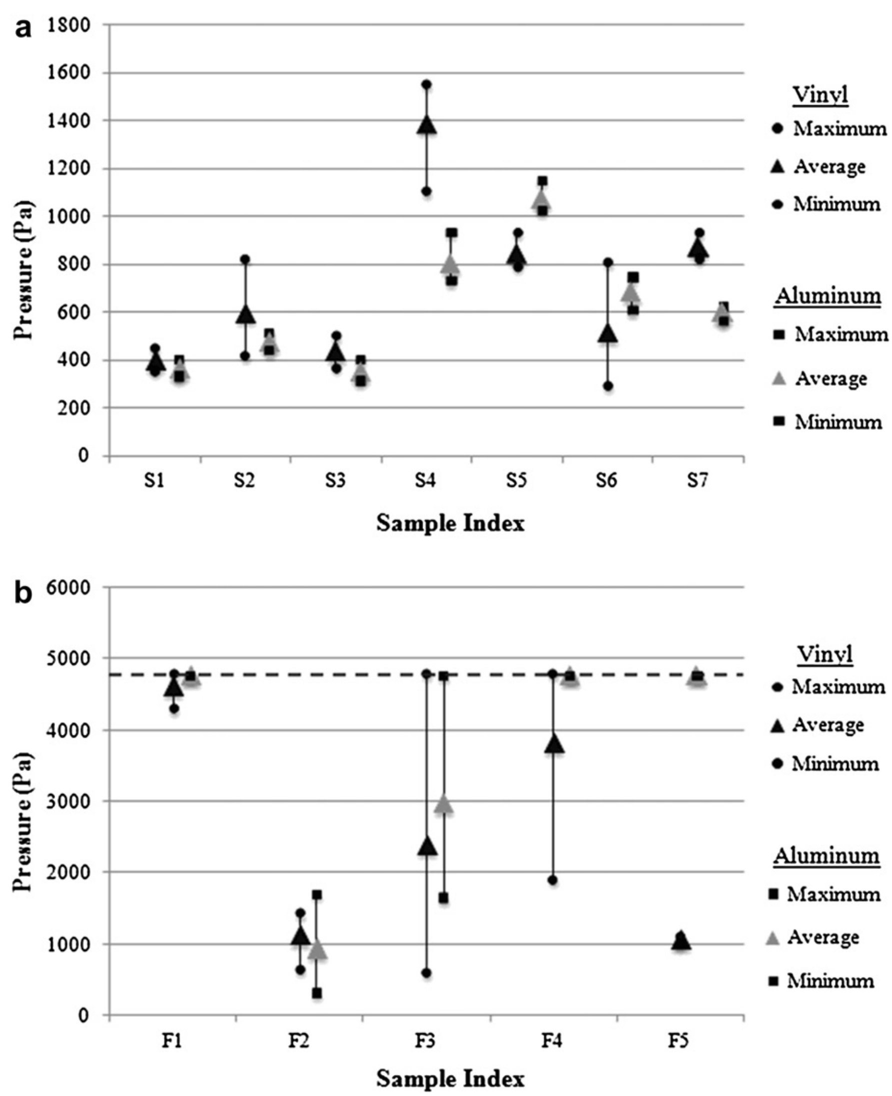

Fig. 12. Hydraulic leakage pressure results for products listed in Table 3. (a) Gunnable sealant water penetration resistance. (b) Low expansion foam water penetration resistance. The dashed line in the figure represents the maximum achievable pressure for the test, equivalent to 4788 Pa (100 psf).

tooling. Since the average pressure differences between the first and second leaks for all the specimens was less than 10 percent, the sealants application was considered to be continuous. With this established, the sealants were further compared based on the initial leakage pressures only.

The initial leakage data was further reduced for each sealant by determining the maximum, minimum, and average initial leakage pressure for each sill material. These values are displayed in Fig. 12 for the gunnable (Fig. 12a) and low expansion foam (Fig. 12b) sealants. Note the dotted line in Fig. 12b represents 4788 Pa (100 psf), the maximum attainable pressure for the test apparatus. The average pressure values allow for easy comparison among specimens, while the maximum and minimum leakage pressures give a sense of the variability associated with the sealants performance.

The leakage results for the gunnable sealants in Fig. 12a show a distinct difference in the performance of the sealants based on composition. The siliconized latex acrylic sealants did not perform as well as the polyurethane sealants. The worst performing sealant of the seven selected was S1, a siliconized acrylic latex sealant. The most performing sealant was S4, a polyurethane sealant. Furthermore, the siliconized acrylic latex sealants (S1-S3) leaked on average at a pressure of 439.5 Pa (9.18 psf). The polyurethane sealants (S4–S7) leaked on average at a pressure of 848.4 Pa (17.72 psf). No definitive difference was observed in the performance of the gunnable sealants based on the sill material.

Significant variability may be observed in the leakage results for the low expansion foam sealants. Many of the sealants reached the maximum attainable pressure for the test apparatus without leaking. According to the leakage results shown in Fig. 12b the most performing sealant of the five sealants tested was F1. Sealant F1 performed with the least variability and reached the maximum attainable test pressure for all but one test where it leaked at a pressure of 4627 Pa (96.64 psf). The least performing sealant was F2 which leaked on average at a pressure of 1152 Pa (24.06 psf). No definitive trend was observed in the performance of the low expansion foam sealants based on the sill material.

7.2.2. Adhesion-in-peel strength results

The adhesion-in-peel test was used to test two sealant specimens for each substrate. The average and peak peel force was recorded as well as a description of the failure mode for each test run. The two test values do not constitute enough data for a significant average; therefore, the values were compared as a measure of the repeatability of the tests. The values for the two tests are fairly consistent; hence, further comparisons are based solely on the peel strength values from the first test run (Fig. 13).

The adhesion-in-peel values for the sealants exhibit relatively low adhesion to the sill flashing membrane used in this study. The lack of adhesion to the sill flashing membrane is likely due to the low surface energy (which adversely affects adhesion) associated with the high density polyethylene (HDPE) laminate used to manufacture the flashing membrane. Since the adhesion-in-peel values of the sealants to the sill flashing membrane are so much less than adhesion-in-peel values to the other substrates, the values are isolated from Fig. 13 and reproduced in Fig. 14 according to sealant index.

The main concern of the adhesion testing was to determine whether the leakage observed at the interface of the sealant and the flashing could be attributed to low adhesion strength. In order to compare the water penetration resistance of the gunnable sealants with their corresponding adhesion strength to the sill flashing membrane, Fig. 15 was created by overlaying Fig. 12a onto Fig. 14. However, no clear trend emerged. The sealant with the largest peel force was also one of the least performing sealants in regards to water penetration. Although its effects cannot be directly attributed to the leakage observed in this testing, good adhesion to the materials being sealed remains an important factor in the performance of a sealant. It is important to note that the 72 h cure time allowed for the sealants is lower than the manufacturer recommended cure times for most of the sealants used in this test, which may have significantly impacted the results.

8. Discussion of results

8.1. Water barrier method vs. drainage method

The results of this testing show that the best water penetration performance of the window-wall assembly is achieved when the fenestration unit is integrated into the surrounding wall system in a manner that maintains the continuity of the four critical barriers required for a successful moisture management strategy. In order for the wall system to properly perform the key functions of the building envelope these barriers must maintain consistency with those of the installed window assembly.

The drainage method installations did not perform well on the CMU wall specimens tested because an inconsistency exists in both the water shedding surface and the exterior moisture barrier of the window-wall system. The effectiveness of drainage method installations relies on the ability to redirect infiltrating water to the

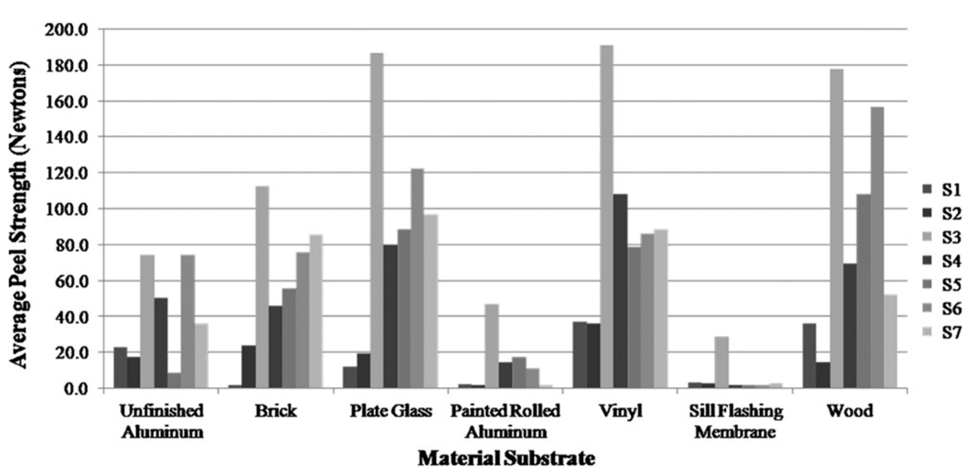

Fig. 13. Test 1 adhesion-in-peel values.

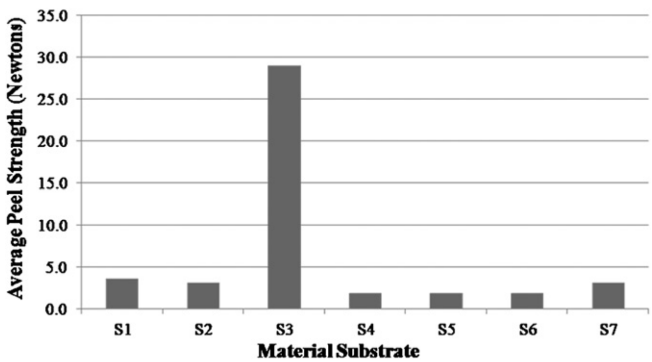

Fig. 14. Adhesion-in-peel values to sill flashing membrane.

drainage plane of the wall. To accomplish this, drainage channels are provided in the exterior seal of the window at the sill as close to the drainage plane of the wall as possible. In the case of the CMU walls, the drainage plane of the wall system is located at the exterior surface of the assembly; therefore, drainage channels are located at the surface of the wall creating a migration passage through the water shedding surface. These channels drain water to the building exterior but typically only in the absence of any significant wind loading. In instances where positive pressures are applied to the drainage channel openings water is prevented from draining and increased amounts of water accumulate inside of the window frame.

The exterior moisture barrier of the CMU/drainage window-wall assembly consists of the interior seal and the surface of the wall system. Since the drainage channels are located at the exterior surface, a proper termination of the stucco returning to the window is difficult to achieve (Fig. 11a and b). The stucco return in these areas cannot be sealed like the rest of the window perimeter because an unimpeded drainage channel must be maintained. The result is an inconsistency in the exterior moisture barrier of the window-wall assembly. Liquid water is thus able to infiltrate the stucco rendering at these points and if the rate of wetting exceeds the rate of drying for the stucco, accumulation will occur and possibly lead to water intrusion.

Conversely, water barrier installation methods employ a continuous exterior seal around the window perimeter. These installation methods preformed well on the CMU wall specimens because the continuous seal preserves the continuity of both the water shedding surface and the exterior moisture barrier at the surface of the wall assembly. Although the redundancy of the interior and exterior seal is lost, the critical barriers are maintained.

For windows installed into the wood frame walls, both water barrier and drainage installation methods provided sufficient water penetration resistance. This is due to the fact that both methods adequately maintain the consistency of the critical barriers. The water shedding surface of the wood frame walls is created by the surface of the exterior cladding. For installations employing the drainage method, because the drainage channels are located on the backside of the mounting flange of the window, coincident with the concealed WRB of the wall, the consistency of the water shedding surface is preserved. The continuity of the exterior moisture barrier is achieved through the proper shingle lap flashing of the sill pan and the WRB of the wall. In water barrier installations for wood frame walls the critical barriers are simply maintained by the use of an exterior perimeter seal to integrate the window into the concealed WRB of the wall.

8.2. Interior moisture/air barrier performance

During the original window-wall specimen testing it was noticed that in some instances a water column developed in the jambs of the windows. In order to replicate the observed conditions, sealants were applied to mock sills and tested in a manner that maintained a cavity in the sill specimens which was to be filled with water in the development of a hydraulic head.

8.2.1. Use of low expansion foams

In comparing the performance of the two sealant types based on Fig. 12, low expansion foam sealants appear to be the superior choice for the interior moisture/air seal in the installation of fenestration products. While the low expansion foam products showed a greater degree of variability than the gunnable sealants, the leakage pressures were much greater. Many of the low expansion foam seals reached the maximum attainable pressure for the testing apparatus of 4788 Pa (100 psf) without leaking. None of the gunnable sealants ever reached this maximum test pressure. However, the water penetration resistance data obtained from testing the foam products is misleading for two reasons. First, applying a low expansion foam in accordance with the product manufacturers' application instructions effectively compromises the ability of a drainage method window installation to properly drain. Foams sealants are to be injected into the deepest portion of the sill cavity filling anywhere from 1/3 to 1/2 of its volume (based on the expansion properties of the foam). The foam then expands out of the opening, filling any voids along the way as it cures. Foam applied in this manner would prevent any expected water from entering the window-wall interface and may even prevent the

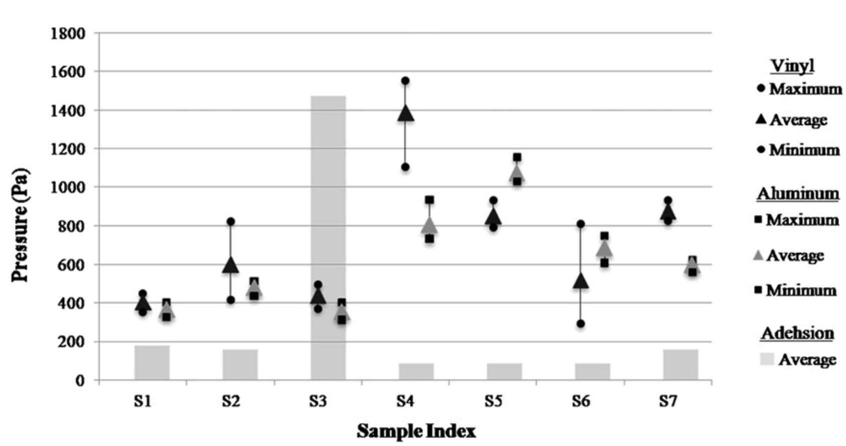

Fig. 15. Comparison of water penetration resistance and adhesion-in-peel values for gunnable sealants.

proper functioning of the drainage channels at the sill. Second, it is expected that the excess foam will be trimmed to accommodate drywall and the interior sills. Once the foam specimens were cut, virtually every sample offered little to no water resistance.

8.2.2. Use of gunnable sealants

Although the gunnable sealants leaked at lower pressures than the low expansion foam sealants, their application was consistent with the manufacturer's instructions, with the exception of the 72 h cure time. In order to use a low expansion foam sealant in conjunction with a drainage method installation, the sealant must be applied in a manner that violates the sealant manufacturer's installation instructions as explained in Section 7.2.1. Therefore, the use of low expansion foams in drainage method installations may be ill-advised. Further testing of low expansion foam sealants used in water barrier applications is recommended.

8.2.3. Adhesion strength

While the results disproved a definitive correlation between the leakage results and adhesion alone, they did show a broad range in the performance of sealants complying with the current standards [28–30]. The selection of an appropriate sealant for the installation of fenestration products is paramount to their water penetration performance. A high quality sealant with good workability, low shrinkage, and superior adhesion to the materials used in the installation was found to work the best. With such a wide range of performance offered from "compliant" sealants, it is difficult to select the proper product for the application. More definitive guidance must be offered in the selection of sealants used in the installation of fenestration products. Currently ASTM E2112-07 [23] leaves the selection of the sealant to the discretion of the builder or designer based on the guidance provided in Tables A4.1 and A4.2 of the standard. Other installation standards simply require that sealants be chosen based on compliance with ASTM C920 [28] or AAMA 808.3 [29] for elastomeric joint sealants and AAMA 812 [30] for low expansion foam sealants. Clear and distinct guidelines, such as sealant composition and material compatibility, should be given for the selection of sealants used for the installation of fenestration products.

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