Watertightness performance of face-sealed versus drained window-wall interfaces

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Abstract

Several research studies have identified window-wall interfaces as one of the major sources of water ingress through building envelopes. Window-wall interfaces can either be sealed by means of face-sealed or drained sealing systems. In general, it is assumed that drained window-wall interfaces show an improved rainwater resistance compared to face-sealed interfaces. However, only a limited number of studies can be found in literature evaluating the watertightness performance of both face-sealed and drained window-wall interfaces. The objective of this paper is to evaluate the performance of both face-sealed and drained sealing methods and to identify the primary factors affecting the water resistance of window-wall interfaces.

Various combinations of exterior seal, drainage layer, air barrier, airtightness level, installation method and wall assemblies were assessed by means of 5 face-sealed test specimens and 9 drained specimens. Both static and cyclic tests were performed. It was found that both tests showed corresponding results with regard to the pressure threshold value for water ingress. The results in this study also indicated that the airtightness of the interfaces and the presence of a separate air barrier at the interior side of the interface affected the watertightness performance to a great extent. The findings showed that it is very difficult to obtain water resistant face-sealed window-wall interfaces, even in lab conditions. It is therefore recommended to always provide drainage possibilities behind the exterior seal or cladding.

1. Introduction

Over the past decades, several research studies have reported that building pathologies related to moisture and rain water ingress are the main cause for premature deterioration of the building envelope [1, 2, 3]. One of the major sources of water ingress through the building envelope is through deficiencies at joints around façade details, in particular, at the window-wall interface. Research shows that it is very difficult to seal window-wall interfaces completely watertight due to their complex geometry, i.e. out-of-plane sealing, the presence of corners, … [4, 5, 6, 7].

Building envelopes can be sealed either by means of face-sealed systems or by means of drained sealing systems. Face-sealed systems rely only on the most exterior material layer to prevent rainwater from entering and reaching the interior layers of the exterior wall (e.g. undrained EIFS (External Insulation and Finish System), some prefab concrete panels, monolayer autoclaved aerated concrete walls, some insulated steel sandwich panels). In contrast, drained sealing systems provide drainage possibilities behind the most exterior layer and manage penetrated rainwater by draining it back to the exterior before it reaches the interior parts of the wall (e.g. brick cavity walls,

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ventilated façade systems, drained EIFS). The ASHRAE Standard 160 [8] assumes that facades are in general not completely watertight independent of the applied water management system and a small amount of rainwater will penetrate behind the cladding. A default penetration rate of 1% of the amount of rain impinging the façade is prescribed as there is a lack of test data for various facades systems [9]. This leads to an interest in a better understanding of the water management and infiltration rates of various façade systems including the water management of window-wall interfaces. However, only a limited number of studies can be found in literature evaluating the watertightness performance of face-sealed and drained window-wall interfaces.

Nelson and Norris [10] conducted a study on face-sealed window-wall interfaces for storefront windows in stucco walls. Six different sealing methods to ensure the watertightness of the window-wall interface were evaluated. Although all tested face-sealed systems, intended to be installed perfectly, initially failed, the concept of face-sealed systems is not questioned by the authors and they only recommended to make the systems more perfect.
Olsson [11] also evaluated the water resistance of face-sealed window-wall interfaces. Out of 27 tested window-wall interfaces, water leakage was measured at 16 interfaces. Many of the observed water leaks were already present without any pressure difference over the wall assemblies. The openings through which water leaked were almost imperceptible. The cause of the water leaks was however not specified.

Lacasse et al. [12] evaluated the performance of face-sealed and drained sealing methods for vinyl windows installed in wood-frame walls sheathed with extruded polystyrene foam insulation board. It was concluded that when a rubber gasket was installed at the exterior joint between the window frame and the cladding in a face-sealed manner, a significantly smaller amount of water was collected behind the cladding compared to the drained specimen. However, water entry was not eliminated. Water penetration towards the interior side of the window-wall interface was not observed as only a small amount of water reached the sill pan which could subsequently be drained between the cladding and the XPS foam board. The authors concluded that a clear drainage cavity at the window-wall interface should be provided to reduce water penetration towards the interior. It was also observed that when the most airtight plane was located at the interior side of the window-wall interface, the risk of water entry was reduced.
Salzano et al. [13] also assessed the watertightness of both face sealed and drained window-wall interfaces for ten wood frame wall assemblies and eight concrete masonry unit wall sections. For the wood frame walls which were constructed as drained façade systems, the drained window-wall interfaces performed better than the face-sealed

window wall interfaces. In contrast, for the face-sealed concrete masonry walls, the face-sealed window wall interfaces showed less water leakages. The authors concluded that the best water penetration performance of the window-wall interface was achieved when the interface was sealed in a manner that maintains the same water management principle as the surrounding wall assembly, i.e. face-sealed or drained. However, also six out of eleven drained interfaces of the wood frame test specimens and two out of five face-sealed interfaces of the concrete masonry specimens showed water leaks. For these test results, the leakage paths were not described. It was also not explained why a face-sealed or drained interface performs well in one specimen and poor in another.

Although it is generally assumed that drained systems perform better than face-sealed systems with regard to watertightness, face-sealed systems are often preferred in practice over drained systems as these systems are fast to install, relatively cheap and a larger insulation thickness can be obtained for a certain wall thickness compared to walls that include a drainage cavity. However, the industry is still struggling to provide watertight window-wall interfaces in these face-sealed systems. Additionally, based on literature it is not clear whether the concept of drained sealing methods should always be preferred over face-sealed methods.

To gain insight into the watertightness of both face-sealed and drained window-wall interfaces for different wall assembly types, three test series were setup in this study. Furthermore, the impact of the airtightness of the window-wall interfaces and the impact of installation errors on the watertightness was assessed and the failure mechanisms were evaluated. This paper first provides a description of the evaluated test specimens for each test series. Afterwards information is given on the test procedure followed by the performance criteria and the moisture tolerance of both face-sealed and drained window-wall interfaces. Subsequently, the results of the conducted watertightness tests are reported and the threshold values for water ingress and the impact of the airtightness on the performance of the window-wall interfaces are discussed. Finally, the effectiveness of both face-sealed and drained window-wall interfaces to manage rainwater infiltration is compared.

2. Methodology

2.1 Test specimens

The performance of both face-sealed and drained window-wall interfaces was evaluated by means of three test series.

In the first series of tests, the watertightness performance of different materials to seal window-wall interfaces in a face-sealed manner was assessed. Face-sealed systems are still being applied in Belgium in for example ETICS and systems with brick slips, requiring a perfect face-sealed window-wall interface, as rainwater passing the exterior seal cannot be drained to the exterior due to the absence of a drainage cavity in the wall assembly.

In the second and third series of tests, the rainwater resistance of drained window-wall interfaces was assessed for respectively brick cavity walls and wood frame walls. In Belgium, brick cavity walls are the predominant construction type, whereas wood frame walls are still a relatively new construction typology in Belgium. But because of the fast building process, the increased focus on bio-based building materials and the use of a lighter construction system, wood frame constructions are increasingly being preferred over brick cavity constructions. Both brick cavity walls and wood frame walls are drained wall systems. As it is recommended to maintain the same water management principle for both the wall and the window-wall interface, drained window-wall interfaces were evaluated in the second and third test series.

2.1.1 Test series 1: Face-sealed wall specimens

The performance of face-sealed window-wall interfaces was evaluated by means of five test specimens. Each specimen measured 2,39 m high and 1,07 m wide and incorporated a window with a height of 1,01 m and a width of 0,56 m. The wall type, cladding and window installation method varied depending on the tested sealing material (Table 1).

The interior side of the window-wall interface of specimens 1.1 and 1.2 was respectively sealed by means of a tape and an EPDM-foil providing a good and average airtightness (see section 2.2). The airtightness of the window-wall interface of test specimens 1.3-1.5 was good but no additional air barrier was installed. The applied pressure difference therefore, acted entirely over the exterior sealing materials. Specimens 1.3-1.5 were also evaluated without insulation or cladding in front of the window-wall interface, at the request of the manufacturers. The specimens were therefore directly exposed to simulated weather conditions. Hence, these tests were considered as a worst-case scenario.

The exterior side of the evaluated window-wall interfaces was sealed by means of a pre-compressed foam sealing tape, a butyl tape consisting of a PE foil with an acrylate modified butyl adhesive, a prefabricated EPDM-frame which was adhered by means of a butyl adhesive, and a liquid applied coating based on a polymer technology applied on top of a spray-in-place polyurethane foam, respectively.

All the wall assemblies and window-wall interfaces were constructed by trained installers. The specimens were first tested as constructed by the installers (Figure 1). Afterwards, several optimisations of the sealed window-wall interfaces were evaluated to obtain “best lab optimized” specimens that were able to pass the test, meaning that no water penetration was observed up to a pressure difference of 600 Pa.

Table 1: Overview of face-sealed window-wall test specimens

Specimen	Wall		Window	Window-wall interface		
	Type	**Cladding**	**Installation**	**Exterior seal**	**Airtightness**	**Air barrier**
1.1	Wood frame	ETICS	Frame	Sealing tape	Good	Yes
1.2	Brick	Brick slips	Brackets	Sealing tape	Average	Yes
1.3	Concrete	Absent	L-brackets	Butyl tape	Good	No
1.4	Brick	Absent	Brackets	EPDM-frame	Good	No
1.5	Wood frame	Absent	Brackets	Liquid coating	Good	No

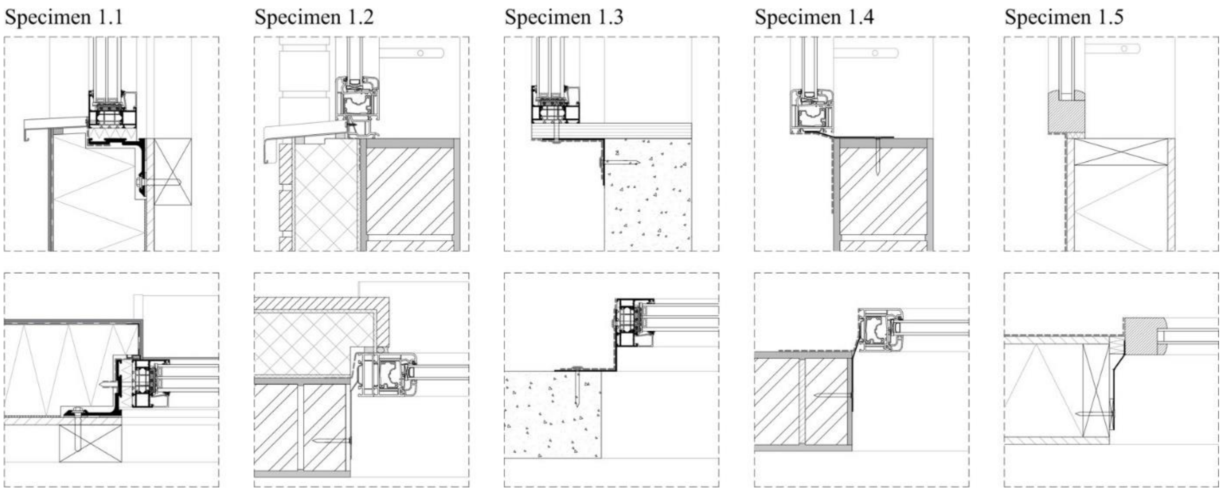

Figure 1: Cross-sections of face-sealed window-wall test specimens

2.1.2 Test series 2: Brick cavity wall specimens

A non-operable vinyl window frame (1,48 m high by 1,23 m wide) was installed in a brick cavity wall of 2,28 m high by 1,96 m wide. The window was installed according to the regulations prescribed by the Belgian Research Institute (BRI) [14]. Above the window and at the bottom of the wall cross-cavity flashing was installed to drain infiltrated water to the exterior. The window was fixed to the interior leaf by means of metal brackets which are typically used in Belgium. The window was installed just behind the exterior leaf, with an overlap of 3 cm at the side and top. Two types of interior finishes are typically considered in Belgium for the window reveal: either a wood casing or a gypsum finish. The airtightness can be ensured by means of self-adhesive foils adhered to the window frame on one side and to the interior side of the inner leaf on the other side, or by means of spray-in-place polyurethane foam (SPF) applied in between the window frame and the inner leaf [15, 16]. For the tests in this study, abstraction was made of the specific finish of the reveal and the airtight layer by means of a PMMA reveal. The PMMA reveal allowed to vary the airtightness by means of a range of orifice openings which were distributed along the perimeter of the interface and at the same time allowed visual inspection during the tests. In between the rigid cavity insulation and the window frame SPF was installed, in line with current practice to reduce the thermal bridge effect. The SPF acted as a drainage layer for the window-wall interface. In the standard configuration, the exterior seal consisted of a foam sealing tape installed between the window and the exterior leaf of the wall (Figure 2). The parameters that were varied to assess the risk of water ingress were: the level of airtightness, the sealing tape between the window and outer leaf, the condition of the exterior sill (Figure 3) and the effect of the SPF bridging the drainage cavity (Table 2 specimens 2.1 - 2.4).

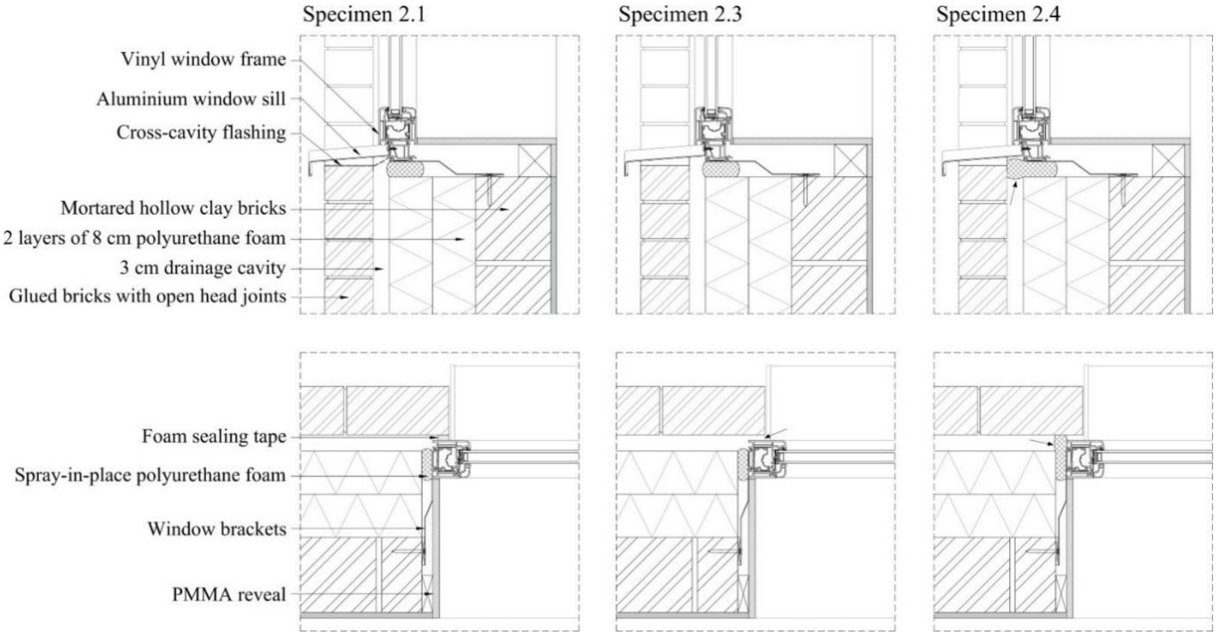

Figure 2: Cross- sections brick cavity wall specimens 2.1, 2.3 and 2.4

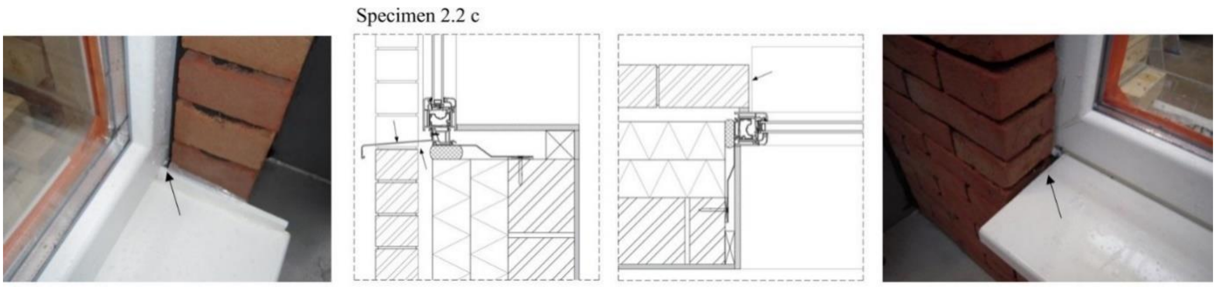

Figure 3: From left to right: Missing sealing length in corner of sill test specimen 2.2a; Cross-sections of specimen 2.2c; Missing end dams at sill test specimen 2.2c

2.1.3 Test series 3: Wood frame wall specimens

A non-operable wooden window (1,55 m high and 1,23 m wide) was installed in a typical wood frame wall of 2,28 m high and 1,96 m wide. On the exterior side, the cladding was composed of slender horizontal planks and open joints (Figure 4). It is assumed that a rather large amount of water infiltrates through this cladding, reaching the window-wall interface. The window-wall interface test is hence conceived as a worst-case scenario. At the sill and top of the window, cross cavity flashing was installed by means of an aluminium profile, with end dams at the sill. As mentioned in section 2.1.2 metal brackets are typically used in Belgium to fix windows to the wall. An alternative method is the use of a plywood frame around the window frame which replaces the brackets and provides a solid substrate for the finish of the window reveal. Both methods to fix a window were evaluated in this series of tests. Other tested parameters were the position of the window in respect to the wall and the presence of a finishing lath reducing the amount of rainwater reaching the drainage layer. The joint between the window and the impregnated fibreboard was sealed either by means of a pre-compressed foam sealing tape, a self-adhesive flashing membrane or spray-in-place polyurethane foam. These materials acted as the drainage layer as they were situated behind the drainage cavity of the wall assembly (Table 2 Specimens 3.1 – 3.5)

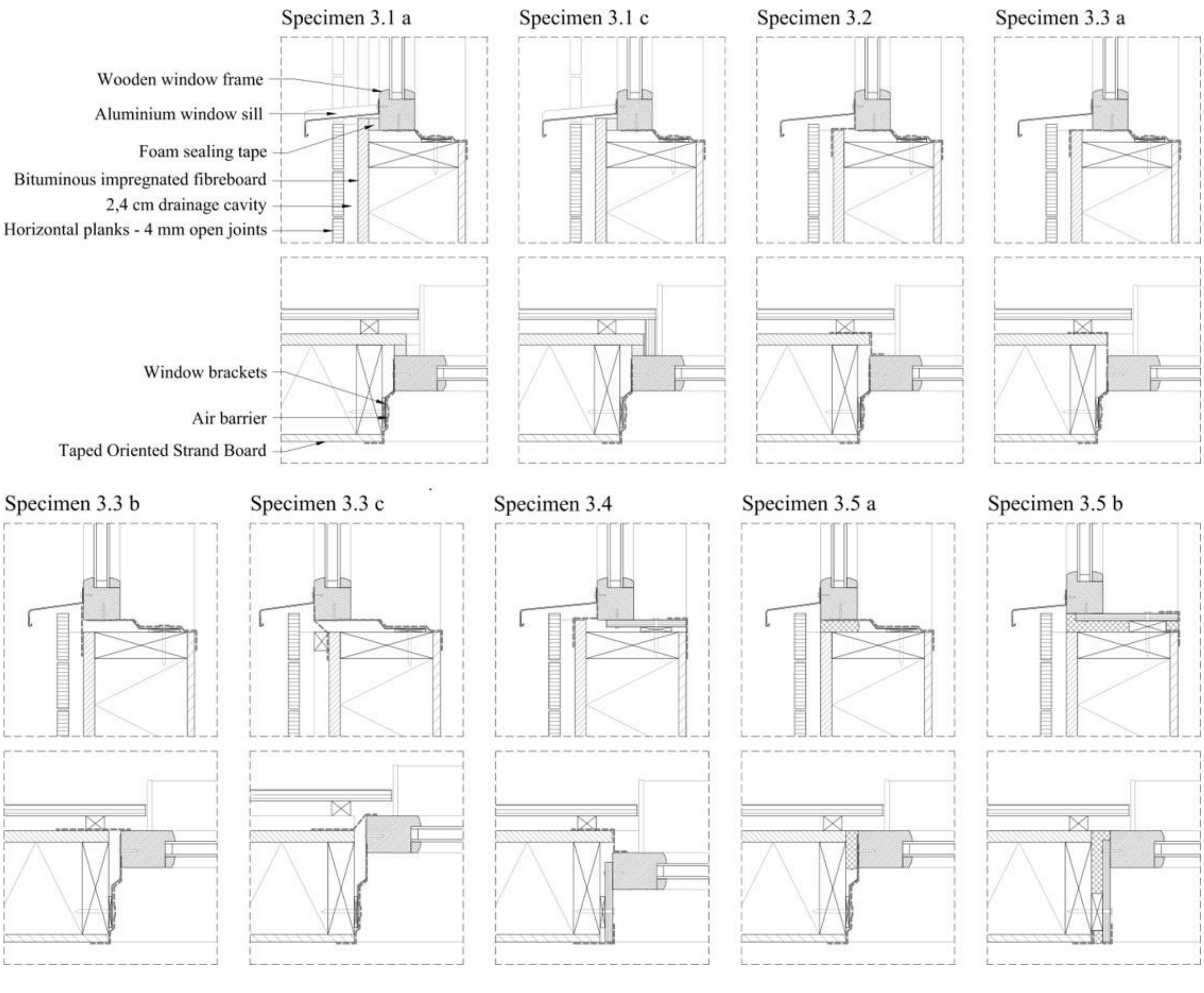

Figure 4: Cross-sections wood frame wall specimens

Table 2: Overview of drained window-wall test specimens (2.1-2.4 = brick cavity wall; 3.1-3.5 = wood frame wall)

Spec.		**Window**			**Window-wall interface**		
		Sill	**Position**	**Installation**	**Exterior seal**	**Drainage layer**	**Airtightness**
2.1	a	Intact	Behind cladding	Brackets	Sealing tape	SPF	Good
	b	Intact	Behind cladding	Brackets	Sealing tape	SPF	Average
	c	Intact	Behind cladding	Brackets	Sealing tape	SPF	Poor
2.2	a	Sealant missing	Behind cladding	Brackets	Sealing tape	SPF	Average
	b	No foil	Behind cladding	Brackets	Sealing tape	SPF	Average
	c	No foil, no end dams	Behind cladding	Brackets	Sealing tape	SPF	Average
2.3	a	No foil	Behind cladding	Brackets	Absent	SPF	Good
	b	No foil	Behind cladding	Brackets	Absent	SPF	Average
	c	No foil	Behind cladding	Brackets	Absent	SPF	Poor
2.4	a	No foil	Behind cladding	Brackets	Absent	SPF bridges cavity	Average
	b	No foil	Behind cladding	Brackets	Absent	SPF bridges cavity	Poor
3.1	a	Intact	Behind fibre board	Brackets	Absent	Sealing tape	Good
	b	Intact	Behind fibre board	Brackets	Absent	Sealing tape	Average
	c	Intact	Behind fibre board	Brackets	Finishing lath	Sealing tape	Average
3.2	a	Intact	Behind fibre board	Brackets	Absent	Flashing	Good
	b	Intact	Behind fibre board	Brackets	Absent	Flashing	Average
	c	Intact	Behind fibre board	Brackets	Absent	Flashing	Poor
	d	Intact	Behind fibre board	Brackets	Finishing lath	Flashing	Average
3.3	a	Intact	Behind fibre board	Brackets	Absent	Flashing[2]	Poor
	b	Intact	In plane of fibre board	Brackets	Absent	Flashing	Poor
	c	Intact	Out of plane	Brackets	Absent	Flashing	Poor
3.4	a	Intact	Behind fibre board	Frame	Absent	Flashing	Good
	b	Intact	Behind fibre board	Frame	Absent	Flashing	Poor
3.5	a	Intact	Behind fibre board	Brackets	Absent	SPF	Good
	b	Intact	In plane of fibre board	Frame	Absent	SPF	Good

1. The flashing was installed continuously over the perimeter of the window

2.2 Test procedure

Within the European framework there is no specific test standard to evaluate the watertightness of joints or interfaces. For windows on the other hand, a static test sequence is provided in EN 1027 [17] and the standard EN 12865 [18] describes a test procedure to determine the resistance of external wall systems to driving rain under pulsating air pressure. Although there is no specific standard for window-wall interfaces, it can be assumed that the interface has to perform well according to both the test sequence for windows and the sequence for walls.

According to EN 1027:2016 water is sprayed at a spray rate of 2 l/(min.m^2) by means of a spraying rack installed at a distance of 250 mm from the window and not more than 150 mm above the top of the window frame. First, water is sprayed without any pressure difference onto the specimen for 15 minutes. Afterwards, the pressure is raised every 5 minutes in steps of 50 Pa up to 300 Pa. From then on, the pressure is raised in steps of 150 Pa every 5 minutes.

EN 12865:2001 provides a cyclic test sequence with pulsating air pressure. According to this standard, water is sprayed at two locations: 1,2 l/(min.m) evenly distributed at the top of the test specimen to simulate run-off water and 1,5 l/(min.m^2) over the external surface of the test specimen to simulate wind driven rain. First water is sprayed for 20 minutes without any pressure difference. Then the pulsating air pressure difference is increased in steps of 150 Pa. Each pressure pulse consists of four stages: a rising stage of (3 ± 1) s, a maximum pressure stage of (5 ± 1) s, a falling pressure stage of (2 ± 1) s and a zero pressure stage of (5 ± 1) s. The total duration of a pulse is (15 ± 2) s. The pulses are repeated for each pressure step for a period of 10 minutes.

Both standards prescribe that the surface of the test specimen should be observed and that the maximum air pressure difference when water penetration occurs and the location of the penetration areas should be noted.

Other studies found in literature also evaluated the watertightness performance of window-wall interfaces according to standardized test procedures to either evaluate windows or to evaluate exterior wall systems. Salzano et al. and Lopez et al. both applied static test procedures based on ASTM E331 [19] for laboratory testing and ASTM E1105 [20] for field testing and cyclic test procedures based on ASTM E2268 [21] and AAMA 520-09 [22]. Nelson and Norris also performed testing using the standard test method ASTM E1105 [20] for field testing. Lacasse et al. developed a test procedure based on the test standards ASTM E331 [19] and CSA A440.4 [23] and Olsson performed testing according to the procedure of EN 12865 [18]. Evaluating the window-wall interface according to both the procedure for windows and exterior wall systems can therefore be considered as a reliable method.

All of the abovementioned standards describe a procedure where the test specimen is subjected to a specific water spray rate and an increasing pressure difference to simulate exposure to wind-driven rain and driving rain wind pressure. To the knowledge of the authors, there are no studies available that relate lab performance to on-site performance. Similarly, there is almost no scientific literature that proves that the combination of the described spray rates and pressure differences represents realistic boundary conditions [24]. However, as these test parameters and corresponding performance criteria have been in use for about half a century, it can be expected that the described boundary conditions will not entail a significant underestimation, as the performance levels are typically the result of a consulting group of research institutes, industry, and building practitioners.

Lopez et al. [25] compared the watertightness performance of window-wall interfaces subjected to both a static test according to ASTM 331-00 [19] and pulsed cyclic wind loading according to ASTM E2268-04 [21]. In contrast with EN 12865:2001, the lower limit of the applied pressure pulses was different from zero.
The authors concluded that pulsed testing appeared to be more effective at diagnosing potential leakage paths. However, most of the leaks that were caused only by pulsed testing and not by static testing were very minor. The authors also found that a functional relationship can be developed between the two tests if the median or upper limit of the pressure pulse and the steady pressure threshold value are known.

To verify these findings, the drained window-wall specimens in the presented study were also subjected to both static (EN 1027:2016 [17]) and cyclic tests (EN 12865:2001 [18]). The face-sealed specimens were only subjected to the static tests, as the peak pressure threshold value is of primary importance. The test specimens were evaluated by means of a standard calibrated test rig. The specifications and accuracy of the test rig lie well within the limits required by the abovementioned standards (EN 1027 and EN 12856) and the lab complies with EN ISO 17025 for testing and calibration. The test rig contains a frequency-controlled fan system capable of generating a steady-state air pressure. The pressure pulses were generated by means of an electronically controlled valve system. The valves allow to bypass 4 parallel tubes with orifice openings (which have a different range of flow rates and are separately controlled with pistons) to induce a rapid pressure build-up whereas a direct valve to lab conditions allows for a rapid pressure drop. The pressure was measured by means of pressure sensors having an error below 0,5% in the range of 50-200 Pa and below 0,2% in the range of 200-600 Pa. A spraying rack was installed at a distance of 250 mm from the external face of the test specimens. Spray rates of 2 l/(min.m^2) and 1,2 l/(min.m) – 1,5 l/(min.m^2) were generated according to the static and cyclic test procedure respectively. The delivered spray rate was measured with an accuracy of ± 5%. According to calibration measurements, the error on the measured spray rate was below 5%. However, to take into account the pressure variations of the tap water an error of ± 5% was taken into consideration. The test specimens were mounted into steel frames, able to withstand the pressures applied during the test. After mounting of the test specimens and installation of the spraying rack, the frames were closed at the exterior side of the specimens and connected to the test rig by means of a flexible tube and a water hose

(Figure 5). The maximum tested pressure was 600 Pa. The pressure difference at the first sign of water leakage at the interior side of the test specimens was reported.

Figure 5: Left: Spray racks installed in front of the brick cavity wall specimens according to EN 12865 [18]; Right: Test specimen connected to test rig with flexible tube

Prior to each watertightness test, an airtightness test was conducted to assess the effect of the airtightness of the specimens on the risk of water ingress. The airtightness was determined according to EN 12114:2000 [26]. Based on 40 calibration measurements, the 95% t-distribution confidence interval of the test rig was defined by an error of 3,965%, which lies well within the limits required by EN 12114:2000, i.e. 5%. After submitting the test specimens to three pressure pulses of 110% of the maximum tested pressure difference, i.e. 600 Pa, the airflow was determined by measuring the pressure difference over a calibrated orifice opening at eight pressure differences between 0 and 600 Pa. The airflow measurements were then calculated for reference conditions, i.e. 20°C, 50% RH, 101.325 Pa, by means of eq. (1):

$$V_0 = V * \sqrt{\frac{p_a - 0.378802 * 610.5 * RH * e^{\frac{21.975*(T-273.15)}{T-7.65}}}{287.055 * T * \rho_0}} \quad (1)$$

With V_0 the air flow at reference conditions [m^3/h], ρ_0 the density of the air at reference conditions (=1,1988 kg/m3), V the measured airflow [m^3/h], p_a the atmospheric pressure [Pa], RH the relative humidity [%] and T the temperature [K]. The atmospheric pressure, relative humidity and temperature were measured with an accuracy of 20 Pa, 2% RH and 0,5 K respectively. The results were then curve fitted using the power law (eq. 2) to obtain the air leakage at eight fixed pressure differences 50 – 100 – 150 – 200 – 250 – 300 – 450 – 600 Pa and the leakage coefficients, C and n.

$$\mathrm{V} = \mathrm{C}.\Delta \mathrm{P}^{\mathrm{n}} \quad (2)$$

With V the airflow through the setup [m^3/h], ΔP the pressure difference over the test setup [Pa], C the leakage coefficient [$m^3/(h.Pa^n)$] and n the leakage exponent [-]. The confidence interval of the results was determined by the combination of the error on the measuring equipment, the propagation error by curve fitting eight measurements and the extrapolation of the curve to one air leakage rate at 50 Pa. Van Den Bossche et al. [15] provides more information on the conducted airtightness measurements and the error analysis and describes reference values for the airtightness of window-wall interfaces based on the overall building airtightness of newly detached residential buildings in Flanders. A value of 10% of the overall building air leakage was suggested as a limit for the air leakage through the window-wall interface. This results in maximum air leakage values of 0,33 $m^3/(h.m)$ for a good airtightness, between 0,33 and 3,3 $m^3/(h.m)$ for an average airtightness and above 3,3 $m^3/(h.m)$ for a poor airtightness at a pressure difference of 50 Pa.

2.3 Performance criteria and moisture tolerance

To the knowledge of the authors, no classification system or performance criteria exist within the European framework specifically for the water resistance performance of window-wall interfaces. EN 1027 does however, define water penetration as the continuous or repeated wetting of parts of the inside face of the test specimen or any parts of the test specimen intended to remain dry, not being part of the water drainage system to the outside or any parts of the test specimen where water does not drain to the outside in a controlled way. In case of drained window-wall interfaces the three different functions – exterior seal, drainage layer and air barrier – are separated at every location (Figure 6). Most of the rainwater is kept out at the exterior seal. The water that infiltrates and reaches the drainage layer is not subjected to large pressure differences as these primarily act over the air barrier taken into consideration that the air barrier will be the most airtight layer of the assembly. Once water penetrates through the drainage layer however, the risk of failure significantly increases as water is able to reach the structural parts of the wall or make contact with the air barrier. Since the imposed pressure difference primarily acts over the air barrier, water is then able to penetrate further into the wall even through very small openings in the air barrier. Drained window-wall systems should therefore be designed in a way that water is not able to pass the drainage layer. In case of face-sealed window-wall interfaces, no clear distinction can be made between the exterior seal and the drainage layer. In some cases, the exterior seal is also the most airtight layer of the window wall interface. This means that water is able to infiltrate even through very small openings due to the acting pressure difference. Once water infiltrates through the exterior seal, it cannot be drained back to the exterior and the window-wall interface fails.

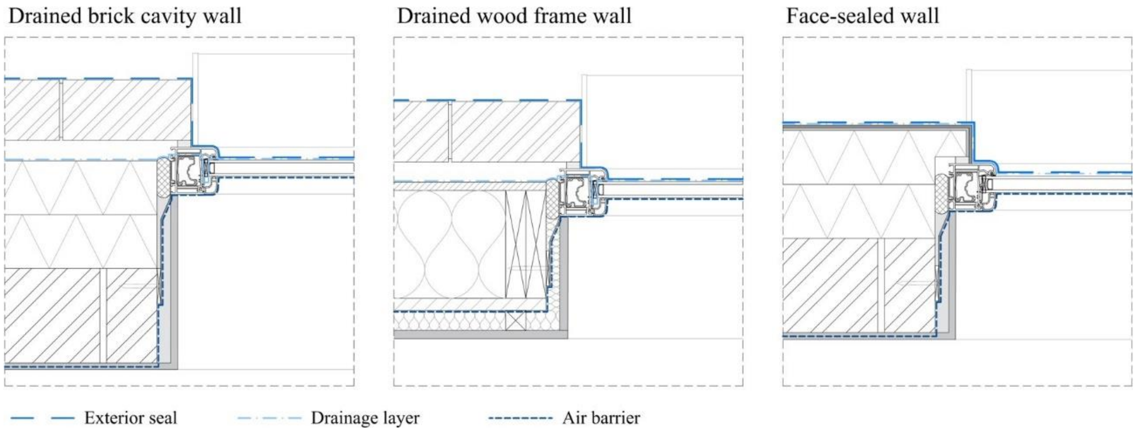

Figure 6: Cross-sections of typical drained and face-sealed window-wall interfaces

The only classification system that exists for the watertightness of building components in the European context, focusses on the watertightness of windows and doors. One can assume that the window-wall interface should at least be as watertightness as the adjoining window. Therefore, the classification system described in EN 12208:2000 [27] for windows and doors is applied in this study. The standard distinguishes watertightness classes based on the maximum pressure difference at which no water penetration was observed, e.g. class 9A corresponds to no water penetration at a pressure difference of 600 Pa. 600 Pa is often used in Belgium as a criterion for the watertightness of building components and interfaces. According to NBN B 25-002-1:2019 [28] – which relates the watertightness classes to a terrain category, base wind speed and building reference height – building components and interfaces classified as 9A may be applied to buildings near the coast with a base wind speed up to 26 m/s and a reference height up to 42 m. 200 Pa or a class 5A is the lowest limit value for components to be used in cities in Belgium with a base wind speed of 26 m/s and a reference height up to 15 m.

3. Test results

3.1 Test series 1: Face-sealed wall specimens

Table 3: Test results of face-sealed specimens (x = no water penetration up to 600 Pa; Best lab () = number of attempts between brackets)

Specimen			Airtightness	Air barrier	Initial leakage
					Static (Pa)
1.1	a	Initial	Good	Yes	x
1.2	a	Initial	Average	Yes	200

	b	Best lab (3)	Average	Yes	450
1.3	a	Initial	Good	No	0
	b	Best lab (7)	Good	No	x
1.4	a	Initial	Good	No	250
	b	Best lab (6)	Good	No	x
1.5	a	Initial	Good	No	150
	b	Best lab (2)	Good	No	x

All face-sealed specimens initially showed water penetration at rather low pressure differences (Table 3). Only specimen 1.1 showed no water penetration during the initial test. It is hypothesized that the good airtightness and the presence of an additional air barrier at the interior reduced airflows through the window-wall interface entailing droplets and reduced the pressure difference acting over the foam sealing tape respectively. Combined with an adequate installation and sufficient compression of the foam sealing tape, a water resistant face-sealed window-wall interface was obtained.

The window-wall interface of test specimen 1.2 on the other hand, was also sealed by means of a foam sealing tape but already showed water leakage at a pressure difference of 200 Pa during the initial test. Water leaked through the connection between two tapes and through the connection of the vertical foam sealing tape and the window sill. The foam sealing tapes were reinstalled with an excessive length to obtain sufficient compression at the connection between two tapes or at the sill. However, after three attempts, water was still able to penetrate through the window-wall interface. It is hypothesized that the average airtightness of the test specimen introduced airflows entailing water droplets towards the interior side of the window-wall interface.

Specimen 1.3 with butyl tape initially showed water leaks without any pressure difference. Water leaks occurred due to insufficient adhesion at locations where the butyl tape overlapped the L-brackets which were used to fix the window to the wall. By applying diagonal patches to these locations, the water resistance already significantly improved. These patches ensured that run-off water continued flowing down along the oblique sides of the patches (Figure 7).

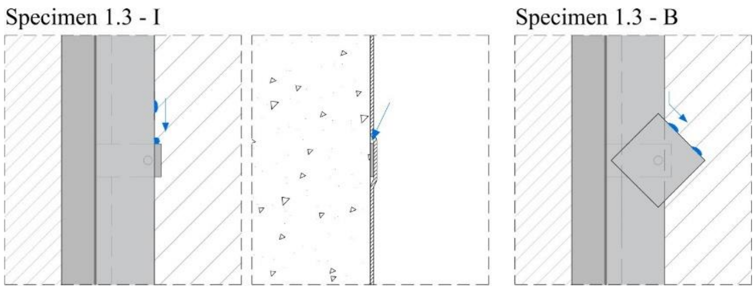

Figure 7: Front view and cross-section of initial and best lab optimized specimen 1.3 with butyl tape

It was observed that in case butyl tape (specimen 1.3) or EPDM (specimen 1.4) was applied to the top and bottom of the window frame, water build-up onto the frame or the sealing materials causes a hydrostatic pressure and combined with the imposed pressure difference lead to water penetration. It is therefore recommended to apply the sealing materials more outwards relative to the front of the window at the top and vice versa at the bottom of the window to stimulate water run-off (Figure 8).

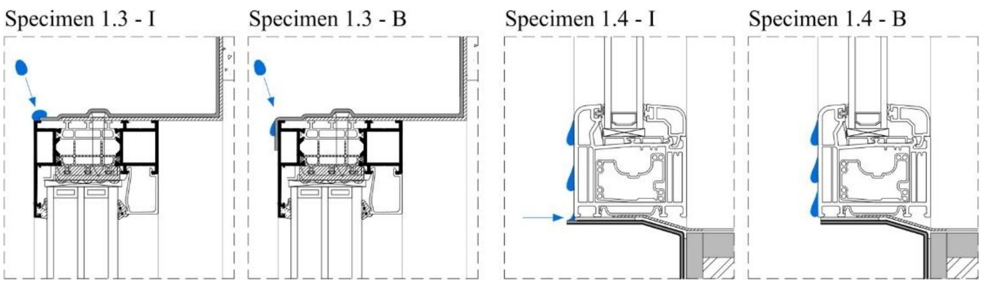

Figure 8: Alignment of initial and best lab optimized test specimen 1.3 with butyl tape and 1.4 with EPDM-frame

During the initial test on the window-wall interface sealed with a liquid applied coating (specimen 1.5), water leaks were visible at a pressure difference of 150 Pa. After inspection of the test specimen, very small openings in the coating were still visible on top of the window. Due to water accumulation at this position, the resulting hydrostatic pressure combined with the applied pressure difference caused water infiltration. After application of a second layer of the liquid applied coating, all openings were covered and no water penetration was observed.

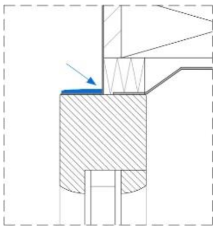

Figure 9: Water accumulation on top of specimen 1.5 with liquid applied coating

3.2 Test series 2: Brick cavity wall specimens

Table 4: Test results brick cavity wall specimens (x = no water penetration up to 600 Pa)

Specimen		**Airtightness**	**Initial leakage pressure**	
			Static (Pa)	**Cyclic (Pa)**
2.1	a	Good	x	x
	b	Average	x	x
	c	Poor	200	0-150
2.2	a	Average	x	x
	b	Average	x	x
	c	Average	x	x
2.3	a	Good	x	x
	b	Average	x	x
	c	Poor	50	0-150
2.4	a	Average	100	0-450
	b	Poor	50	0-150

The impact of the airtightness of the window wall interface was evaluated by means of test specimen 2.1 and 2.3, respectively with and without a sealing tape at the exterior (Table 4). In case of a good or average airtightness no water infiltration was observed during both the static and cyclic test sequences. It was assumed that without the exterior sealing tape (specimen 2.3) a larger amount of water would infiltrate and reach the SPF but no water leaks were observed for a good and average airtightness. In case of a poor airtightness however, water leaks were observed at low pressure differences both during the static and cyclic test. The poor airtightness entailed high air flow rates transporting water droplets to the interior side. Infiltration typically occurred at locations where small openings were present due to incomplete filling with SPF, i.e. at the corners of the window and at the window brackets.

Changing the installation of the window sill (specimen 2.2) did not increase the risk of water ingress. Bridging the cavity with SPF (specimen 2.4), installed in the joint between the window frame and the rigid insulation did however, cause water leakage through both the specimen with an average and poor airtightness. In the specimen with average airtightness, some water drops were visible without any pressure difference at the lower corner of the window but did not reach the window reveal. At a pressure difference of 100 Pa water was running down on the sides of the window frame and was directed inwards due to surface tension along the bottom side of the mounting brackets. At 250 Pa, a significant amount of water started infiltrating at another mounting bracket. During the cyclic test, again a few drops were recorded without pressure difference and water started infiltrating at the mounting bracket at pressure pulses of 450 Pa. For the specimen with a poor airtightness water droplets were projected up to the PMMA reveal due to the kinetic energy as a result of the large airflows entailed by the poor airtightness.

3.3 Test series 3: Wood frame wall specimens

Table 5: Test results wood frame wall specimens (x = no water penetration up to 600 Pa)

Specimen		**Airtightness**	**Initial leakage pressure**	
			Static (Pa)	**Cyclic (Pa)**
3.1	a	Good	x	x
	b	Average	0	0-150
	c	Average	50	0-150
3.2	a	Good	x	0-450
	b	Average	x	x
	c	Poor	150	0-150
	d	Average	x	x
3.3	a	Poor	50	0-150
	b	Poor	300	x
	c	Poor	100	0-300
3.4	a	Good	x	x
	b	Poor	50	0-150
3.5	a	Good	150	0-300
	b	Good	100	0-150

Specimen 3.1 with a good airtightness showed no water leaks through the foam sealing tape applied at the window-wall interface (Table 5). The specimen with an average airtightness, already showed water leaks without any applied pressure difference. At the sill, the sealant tape of this specimen was installed more downwards relative to the top of the fibreboard which led to accumulation of water at the corners of the window, causing a hydrostatic pressure onto the interface between the sealing tape and the window. When direct exposure of the foam sealing

tape was reduced by the installation of a finishing lath, water leaks were still visible at the interior at a static pressure difference of 50 Pa and pressure pulses of 150 Pa. However, the amount of infiltrated water was significantly less compared to the specimen without finishing lath. Water accumulation on top of this type of tape should therefore be avoided.

The performance of the flashing membrane was very dependent on the airtightness of the window-wall interface (specimen 3.2). In case of a poor airtightness, water penetration was already observed at a pressure difference of 150 Pa during the static test and pressure pulses of 150 Pa during the cyclic test. In contrast, no water penetration was observed during the tests with an average airtightness, most likely because the increase in airtightness entails a decrease in the pressure difference over the flashing membrane. During the cyclic test for the specimen with a good airtightness, a water leak was observed when pressure pulses of 450 Pa were applied. However, this leak was caused by an insufficient adhesion of the membrane onto the window due to a repeated testing. This implies that a good adhesion of the flashing membrane is crucial to obtain a water resistant window-wall interface. The addition of a finishing lath in front of the flashing membrane (specimen 3.2d) ensured that most of the rainwater was diverted from the flashing. No water penetration was observed during both the static and cyclic test.

Also the impact of the position of the window relative to the impregnated fibreboard on the risk of water ingress through the flashing was evaluated. When the window was positioned inwards relative to the fibreboard (specimen 3.3a), the flashing at the bottom was more exposed and water was able to accumulate which in turn lead to a hydrostatic pressure and water penetration at the corners. When the window was positioned more outwards relative to the fibreboard (specimen 3.3c) the flashing membrane at the top was similarly exposed. The window-wall interface of the window positioned in-plane with the fibreboard showed the best results, i.e. a small amount of water infiltrated at a static pressure of 300 Pa and no water leakage was observed during the cyclic test.

The test specimens with the window fixed to the wall by means of a plywood frame (specimen 3.4) showed similar watertightness results compared to the window fixed by means of window brackets. It was however, observed that by fixing the window to the wall by means of a plywood frame, the airtightness foil could be installed more easily.

The water resistance of the window-wall interface sealed with SPF (specimen 3.5) was primarily affected by the presence of local deficiencies at the window brackets and the wooden spacers between the plywood window frame and the wall. At the interface between the SPF and the window frame water leaks were only observed at a pressure difference of 600 Pa during the static test and at pressure pulses of 450 Pa during the cyclic test. Similar results were obtained for the window fixed with a plywood frame.

4. Discussion

4.1 Static versus cyclic testing

The drained test specimens in this study were subjected to both static and cyclic testing. In general, the results from the static pressure tests corresponded well with the results from the cyclic tests. Only specimen 3.3b showed water leakage during the static test and not during the cyclic test (Figure 11). The amount of infiltrating water was however, very minor.

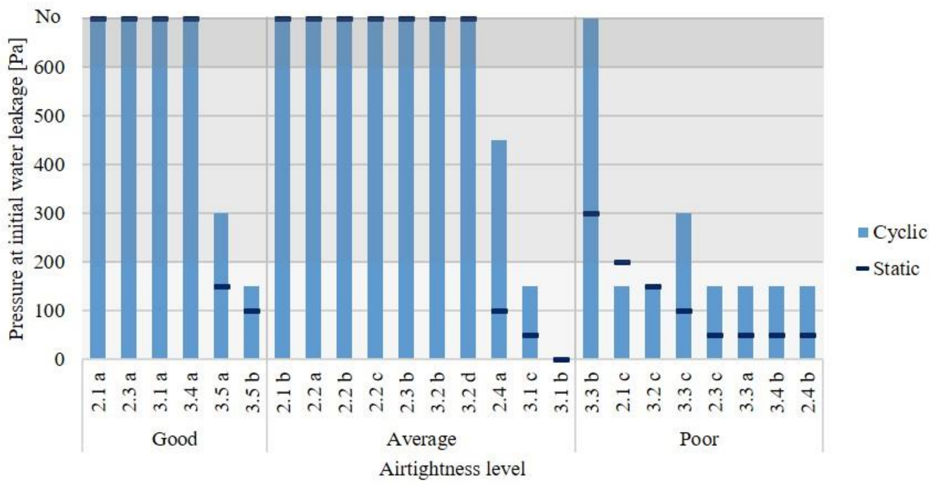

Figure 10: Pressure pulse and static pressure difference at first sign of water leakage at the interior side of the window-wall interface both during static and cyclic tests per test specimens with good, average and poor airtightness (No = no water penetration at 600 Pa)

Lopez et al. [25] also found corresponding results for both static and cyclic testing and determined a functional relationship between the static pressure and the median and upper limit of the applied pressure pulse associated with the first water leaks. When the first water leak was observed at a static pressure difference either lower than 600 Pa or above 600 Pa, generally the static threshold pressure difference corresponded with the median pressure pulse or the upper limit respectively, of the applied pressure pulse associated with the first sign of leakage.

The maximum tested pressure difference in the presented study was 600 Pa. Similar to the results found by Lopez et al. [25], the median pressures of the pressure pulses match well with the static pressure at first sign of water leakage, in particular for the specimens with a good and average airtightness (Figure 11). On the other hand, for some of the specimens with a poor airtightness (specimen 2.1c and 3.2c) the peak pressure of the pressure pulse corresponded with the static pressure at water leakage. This can be attributed to the fact that water leakage can be the results of different failure mechanisms. Water leakage can occur either when the amount of water reaching potential leakage paths becomes too large due to direct exposure, insufficient drainage capacity or large airflows entailing water droplets or when the pressure difference forces water through pinholes towards the interior. The threshold values for water leakage will then either be the amount of infiltrating water over the course of the test which will be related to the median value of the pressure pulse or the pressure threshold value which will be related to the upper limit of the pressure pulse respectively.

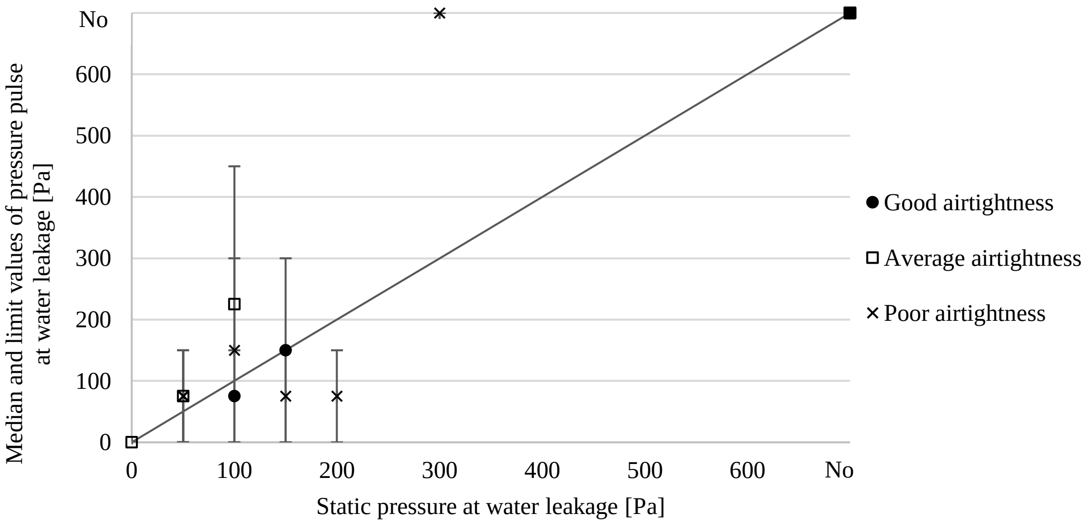

Figure 11: Median and limit values of pressure pulse and static pressure difference at first sign of water leakage at the interior side of the window-wall interface both during static and cyclic tests for test specimens with good, average and poor airtightness (No = no water penetration up to 600 Pa)

4.2 The impact of the airtightness on the water resistance of the window-wall interface

If the concept of water infiltration is simplified and abstracted to a plate with a single circular opening, it would be possible to calculate the required external pressure to balance the capillary pressure, hydrostatic pressure and pressure due to surface tension of water at the opening and therefore also the required external pressure to breach the meniscus of the water at the opening [29]. Larger openings have a larger diameter, which will proportionally reduce the required pressure before the meniscus brakes and water infiltrates. Conversely, it is possible to calculate which minimum diameter corresponds to a certain watertightness threshold: for a given watertightness level one can hence calculate the corresponding diameter of the deficiency. Poor watertightness corresponds to large openings, whereas high levels of watertightness indicate very small openings. Similarly, for each diameter one can calculate the corresponding air leakage at a pressure difference of 50 Pa. The line in Figure 12 shows the correlation between the theoretical pressure difference at water leakage and the corresponding airtightness for one opening in a hydrophobic material with a contact angle of 138°, e.g. foam sealing tapes.

Theoretically, a good airtightness corresponds with a good watertightness, i.e. first sign of water leakage is observed at high pressure differences. However, in practice, a good airtightness does not necessarily ensure a good watertightness, primarily attributed to local deficiencies or installation errors. On the other hand, a poor airtightness increases the risk of water leaks at low pressure differences. The poor airtightness causes high air flow rates which entail water droplets towards the interior side of the window-wall interfaces.

Only one of the measured data points lies below the theoretical minimum curve. In theory, it is not possible that water was able to infiltrate through the opening with a diameter related to the measured airtightness at a pressure lower than the minimum required pressure to breach the meniscus. However, when calculating the theoretical minimum, the additional pressure caused by water running off the specimens in front of the openings or water build-up onto the sealing materials resulting in a lower required external pressure was not taken into account.

All other measured data points lie well above the defined theoretical minimum curve, meaning that the measured air leakage was larger than the air leakage related to the minimal opening for water ingress to occur at the corresponding pressure difference. It is hypothesized that either multiple openings were present through which air could flow or that the openings had larger diameters than the minimal diameter but were not exposed to water runoff or water spray up to a certain pressure difference step larger than the theoretical minimum. This explains why several specimens showed water leakage at the same pressure difference but at different airtightness values.

On the other hand, for the same airtightness value some specimens leaked at pressure differences between 0-200 Pa whereas other specimens showed no water leaks. This phenomenon can be attributed to the fact that a lot of very small openings were present compared to a few larger openings in the other specimen resulting in the same airtightness value but no water leakage through the small openings. Another plausible explanation is that water exposure of larger openings was prevented by for example the exterior seal or that water was not driven towards the interior by the pressure difference acting over the material layers which were exposed to direct water spray or runoff due to good pressure equalization. To obtain good pressure equalization (PEP > 90%), the airtightness of the air barrier should be at least ten times higher than the airtightness of the exterior seal and drainage layer [30]. In case of an applied pressure difference of 600 Pa, the pressure acting over the exterior seal and drainage layer will then be reduced to only 60 Pa. Water build-up onto the sealing material or water runoff above an opening can also cause an additional hydrostatic pressure resulting in water leakage at a lower pressure difference compared to the situation where no additional hydrostatic pressure is present for the same airtightness value.

The approach in Figure 12 highlights that the watertightness level cannot be derived directly from the airtightness. However, it is clear that this theoretical approach fits better for the face-sealed solutions compared to the drained solutions.

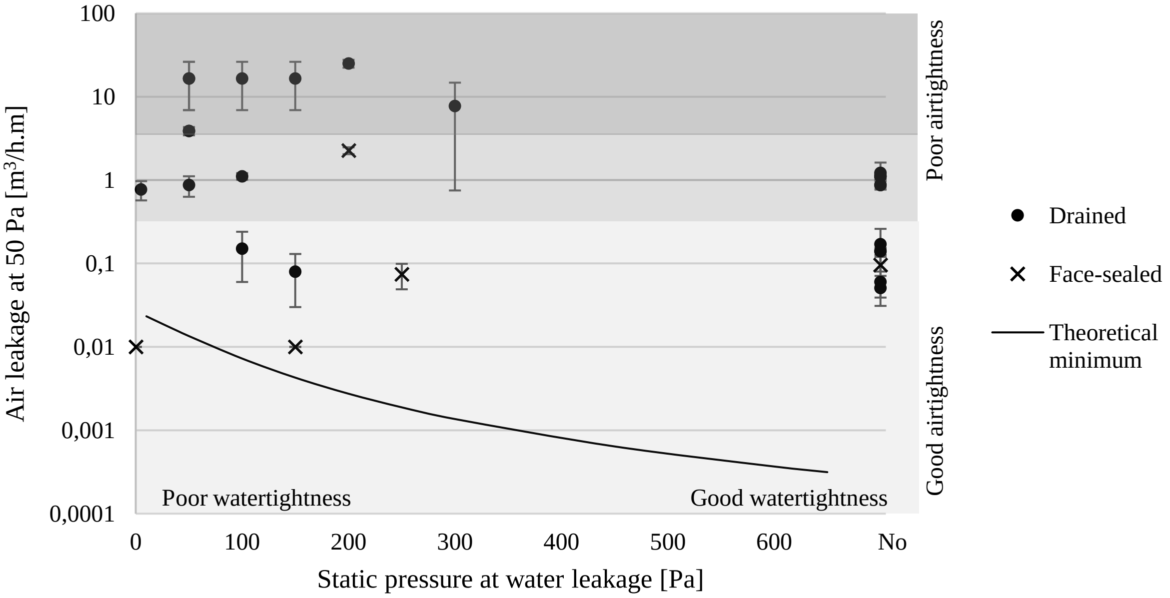

Figure 12: Pressure difference at first sign of water leakage at the interior side of the window-wall interface during the static tests for test specimens with good, average and poor airtightness and for both face-sealed and drained test specimens (No = no water penetration up to 600 Pa)

4.3 The watertightness performance of face-sealed versus drained window-wall interfaces

When water leakage was observed, this occurred at low pressure differences – averagely below 200 Pa – for both the face-sealed and drained wall assemblies. However, a significantly larger percentage of face-sealed specimens failed, i.e. 88%, compared to the percentage of failed drained specimens, i.e. 29% (good and average airtightness) during the tests up to a pressure difference of 600 Pa (Figure 13). Assuming that the imposed pressure difference acts entirely over the sealing material of face-sealed specimens and taking into account a hydrophobic material, theoretically water is already able to penetrate openings with a diameter of less than 1 mm at a pressure difference of 600 Pa. As it is very difficult to seal window-wall interfaces perfectly due to the complex geometry, the presence of small openings can be expected resulting in water leaks over the course of a watertightness test on face-sealed systems even in lab conditions. This was apparent in the reported study as only after several attempts, no more water leaks were observed at a pressure difference of 600 Pa. It is therefore recommended to provide drainage possibilities behind the exterior seal in both the window-wall interface and the adjoining wall assembly. The exterior seal is then supposed to keep out most of the rain and can either be a separate sealing material or be part of the cladding. It was observed that in case only a cladding was applied, preventing direct exposure of the window-wall interface, also no water penetration up to a pressure difference of 600 Pa occurred when a good airtightness was provided (e.g. specimen 2.3a). This implies that the cladding and the pressure equalized cavity in front of the drainage layer ensured that the amount of water reaching the drainage layer was limited. The cavity in between the exterior seal and the drainage layer should provide a capillary break to avoid water transport towards the interior and more airtight side of the window-wall interface. Bridging of the cavity should therefore be avoided as water leaks were already observed at low pressure differences (specimen 2.4a) when the SPF of the drainage layer bridged the cavity towards the exterior leaf compared to no water leaks at a pressure difference of 600 Pa when no bridging occurred (specimen 2.3b) (Figure 14).

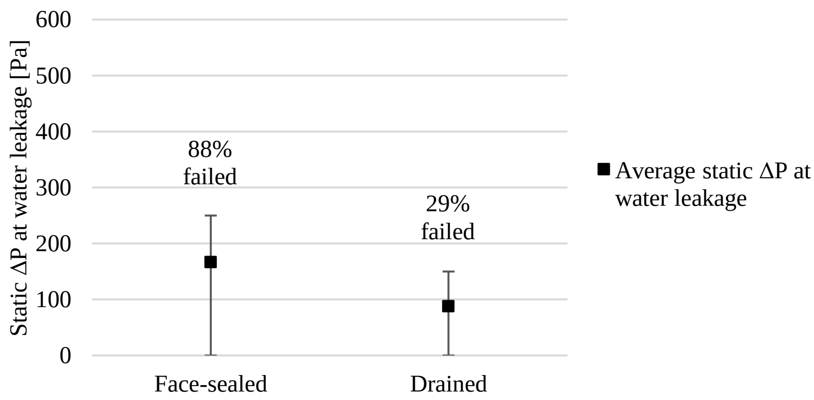

Figure 13: Static pressure differences at first sign of water leakage and the percentage of failed specimens for both the face-sealed and drained specimens with a good and average airtightness

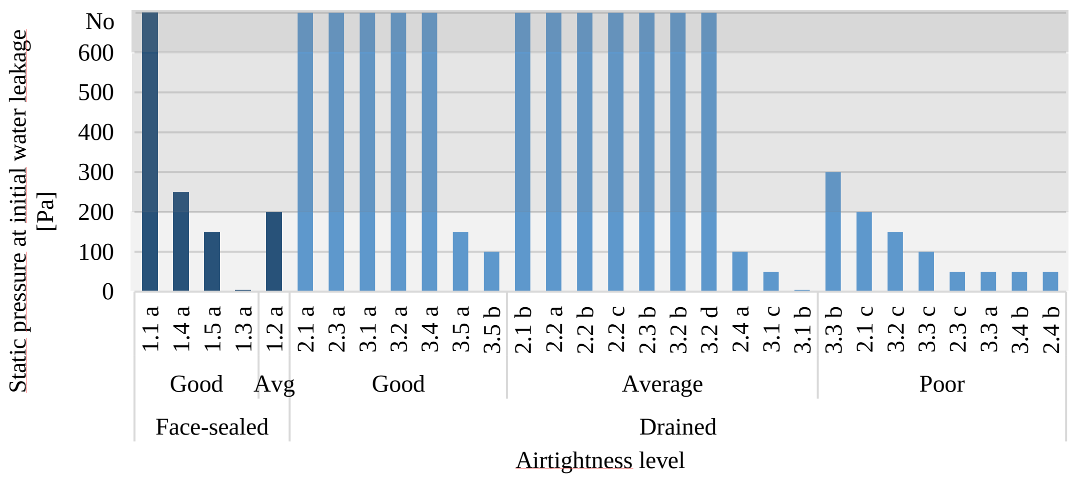

Figure 14: Pressure difference at first sign of water leakage during the static tests for test specimens with good, average and poor airtightness and for both face-sealed and drained test specimens (No = no water penetration at 600 Pa)

5. Conclusions

Based on the results reported in this study, it can be stated that it is very difficult to obtain water resistant face-sealed window-wall interfaces up to a pressure difference of 600 Pa, even in lab conditions and that the risk of water leakage is significantly reduced when applying a drained principle. It is thus recommended to prefer the use of drained window-wall interfaces to the use of face-sealed window-wall interfaces. Attention should be paid to correctly draining the infiltrated water either to the drainage cavity of the wall assembly or directly to the exterior to avoid water ingress towards the interior. The following conclusions and recommendations can be made with regard to the evaluation method of the watertightness performance of window-wall interfaces and the sealing method:

- The results of the static and cyclic test corresponded well. From a scientific point of view, it may be advisable to conduct both tests to determine the threshold values for water leakage, but a static test is simple and typically a conservative approach.
- It is important to document whether or not the window-wall interface is evaluated with the presence of an additional air barrier at the interior side as this may result in a reduction of the pressure difference acting over the sealing layer and thus a reduced risk of water ingress.
- It is recommended to start the test program with an airtightness test and report the airtightness level of the test specimen as it was observed that a poor airtightness level increased the risk of water leakage.
- To reduce the risk of water leakage, it is advisable to seal the window-wall interface in a drained manner; the amount of water reaching the drainage layer should be minimized, a good airtightness level should be ensured and an additional air barrier with an airtightness significantly larger than the airtightness of the drainage layer should be installed at the interior side to reduce the pressure difference acting over the drainage layer, forcing water through pinholes.
- Great care should be taken when installing the sealing materials as small installation errors or unperceivable openings may already result in failure at pressure differences of 200 Pa or lower, which is considered as a minimum criterion for components applied in Belgium.

Although it is recommended to always provide drainage possibilities behind the exterior seal or cladding, face-sealed systems are often being used in practice, e.g. ETICS. The fact that these systems have not yet led to a large amount of damage cases so far can presumably be attributed to the moisture buffering capacity of the inner leaf of the wall assembly, e.g. ETICS on masonry. It is however, still advisable to provide a drainage cavity in these assemblies as moisture within the wall assembly can cause accelerated degradation of the materials, additional heat losses or an increased risk of damage.

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