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Watertightness and water management of curtain walls

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ABSTRACT

Curtain wall systems typically rely on pressure equalization to achieve a good watertightness. The insulating glass unit is clamped to the mullion between two gaskets, functioning as a rain screen and airtightness layer. When the curtain wall system is subjected to wind driven rain and a pressure difference, water may penetrate past the first gasket into the drained cavity. Depending on the airtightness of the interior and exterior gaskets, the pressure equalisation will determine the actual pressure over the exterior gasket. That pressure, in combination with hydrostatic pressure from water runoff, is the most important driving forces for water ingress. In this paper, the watertightness and drainage of water in curtain wall systems is investigated. In an experimental setup, a full-scale curtain wall system was subjected to a range of pressure differences under static and cyclic test procedures. For each condition, the water ingress into the drained cavity was measured. Next to that, the phenomenology of water ingress was analyzed based on airtightness measurements, dynamic watertightness tests, and pressure equalisation.

KEYWORDS: Watertightness, airtightness, drainage, curtain walls.

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1 INTRODUCTION

For many decades, curtain walls have been gaining popularity. Not only because of the esthetic value but also for reasons of prefabrication and fast construction, curtain walls are frequently being used in a wide range of building projects. Although watertightness problems frequently occur, little to no literature or experimental data can be found on this phenomenon. Experimental research on watertightness can provide fundamental insights into the origin and development of water infiltration. Water ingress through building components is one of the most important pathologies in buildings in respect to both occurrence and the consequences resulting from ingress (Chew, 2005; Rodrigues et al. 2011), and building practitioners often report water leakage in fenestration (Paterson et al., 2005; Rutila, 1998, Weinstein & Del Rosso, 1999).

Since the invention of curtain wall, the building industry has undergone a long painful design struggle against the water leakage problem through curtain walls. The first generation of curtain walls, known as wet seal systems, was based on the perfect seal system often using caulking. In the second generation curtain wall systems it was taken for granted that infiltration would occur and a gutter system was provided the shed infiltrated water to the exterior. The third generation system is based on the rain screen principle with pressure equalization (Ting, 1997).
Also the IFT testing institute reports that water leaks are by far and away the most frequent source of damage to façades and glass roofs (Egli, 2002). It was reported that the most frequent cause of water penetration was insufficient care in carrying out the internal sealing layer, especially at the corners. When windows are used as fillings in curtain wall systems, water leakage often occurred through badly glued mortised corners of the aluminum windows, or through wrong or missing seals in the frame. Furthermore, a study on building envelope failures in British Columbia (MHL,1996) indicated that 25% of the moisture problems associated with water ingress into wall assemblies were directly attributed to penetration through the windows or the window-wall interface. Most publications on watertightness of window frames or curtain walls focus on test protocols (e.g. Lopez et al., 2011;Van Straaten et al., 2010), are typically very descriptive in nature, and do not elaborate on the failure phenomena that determine the watertightness performance level of a specific window. Matthews et al. indicate that about half of all the buildings employing curtain walling suffer leaks, and a third deteriorate unacceptably before the end of their design life (Matthews et al. 1996).

The performance of different types of cladding in which pressure equalisation is considered has been well studied over the last 40 years (Suresh Kumar, 2000), but little information on pressure equalization in windows and curtain walls has been found. As window frames and curtain wall systems only have a small cavity volume, a relatively small phase shift of the pressure can be expected because the major determinant of response speed is the compressibility of the air (Straube, 1998). The principles of pressure equalization in curtain wall systems were described by (Ganguli and Quirouette, 1987), for which it was found that pressure equalization was mainly determined by the ratio of the venting area A_{rs} and leakage area A_{ab}, and the ratio of the cavity volume to the venting area.

Due to the complex geometry of windows and curtain walls (caused by thermal and mechanical requirements) and the fact that they have to open and close, it is practically impossible to create a face-sealed watertight system that is impervious to water and air through time under all circumstances. As a result it can be taken for granted that failure will occur: the system should be designed as a drained construction with a water barrier, an air barrier, and drainage paths as separated functions. The air barrier is utterly important for the performance of the system because it must withstand high pressure loads to enable pressure equalisation at all times. Any penetration of the airtight barrier by hinges, joggles or fittings may be crucial to the overall performance. Water that penetrates into the cavity should be drained to the exterior by weep holes at the bottom or in transoms, and the mullions are typically open at the top and act as vent.

There are reservations concerning all of the currently available watertightness tests, and research is needed on the principles and requirements of dynamic testing (Kerr et al., 1997). Boundary conditions for watertightness testing should be based on typical failure mechanisms for that specific component, and derived from climatic analysis that takes into account the co-occurrence of rain and wind (Van Den Bossche et al, 2013). Different failure mechanisms require different test protocols that relate to different frequencies and averaging periods for wind and rain events.

Whether or not dynamic conditions are more severe for window frames or curtain walls compared to static boundary conditions is unclear. Lopez et al. (2011) compared the watertightness of window frames under static, cyclical and dynamic testing. For 9 out of 14 tests the static pressure at which water ingress occurred lied in the range of the median cyclical pressure plus or minus the amplitude. For the other windows water ingress started at lower pressures during cyclical testing compared to static testing. Eggen (1994) found that 8 out of 20 windows failed under static pressure differences, whereas all window passed the test under cyclical conditions (step function with peak pressure equal to static pressures, lower pressure 0 Pa). Contrarily, Van Straaten et al. (2010) found that windows fail at lower pressures when subjected to dynamic loads. McDonald et al. (1997) also reported significant more failure for windows and curtain walls subjected to an aero-engine watertightness test compared to static test conditions (test pressures were not reported). Only 9 out of 66 curtain wall systems passed at the first try. Out of 50 systems that were subjected to both static as dynamic tests, 16 samples failed the dynamic test. Out of those 16, 5 failed both outright, 5 had previously passed the static test the first time, 4 had received remedial work following the static test due to infiltrations. The components which were found to require the greatest need for remedial work following water penetration testing were sealants and gasket. Of the sealant joints which required remedial work, water leakage occurred most frequently at glazing rebate and profiles around the window perimeter, while leakage at gaskets was caused by poor sealing at the corners, incorrect gasket selection or design or by poor installation. Sakhnovsky (1991) confirms that curtain wall systems typically allowed water leakage at significantly lower dynamic than static test conditions.

2 TEST METHOD AND PRINCIPLES

Existing watertightness test methods can be categorized into four distinct classes: static, cyclic, dynamic, and wind tunnel testing. The first three test methodologies provided in standards use a similar approach: wind and rain are decoupled and treated independently. Wind effects are represented by pressure differences generated by a fan, and rain is provided by means of a water spray system in front of the test specimen. Conversely, in the fourth test method, which is based on an integrated approach in a wind tunnel, water is not sprayed directly on the test specimen itself contrary to that presented in the previous test methods.

Most static watertightness test standards require a static pressure difference for a period of time (in the range 5 to 15 minutes), which is stepwise augmented to assess the performance level of a component. Classification is done based on the pressure difference achieved without water ingress, and the required level of performance for a component in a specific building is typically incorporated in National guidelines for each country. For curtain walls, EN 12155 (2000) is typically used in Europe to evaluate the watertightness in lab conditions.

Test standards in which cyclic tests are prescribed within the test protocol are undertaken by subjecting the test specimen to rapid pressure pulses; the pressure fluctuation of these pulses is typically either a rectangular function or a sine-wave function. The duration of one pulse varies depending on that given in the standard (range 2s – 15s) and these pulses are repeated for a period of 10 minutes. The pressure levels and their corresponding lower and upper limits of pressure for a pulse are also provided in the standards. A lower limit of zero is only set in EN 12865 (2001).

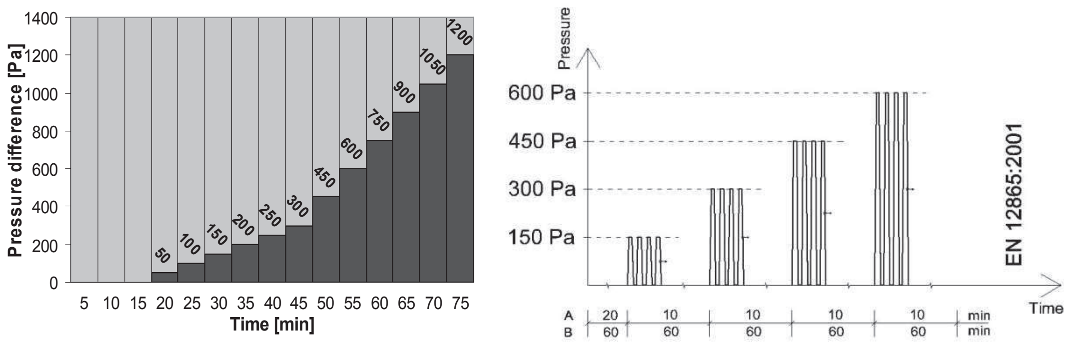

Figure 1. Watertightness test protocol according to EN 12155:2000 (left) and EN 12865:2001 (right)

In order to evaluate the watertightness of curtain walls, the designated European test method EN 12155 for watertightness is applied here: a curtain wall is framed into a plywood box, and put against the test wall that can simulate rain and wind pressure differences. The first 15 minutes of the test, water is sprayed on the window (2 L/min.m^2) without any pressure difference. After 15 minutes a pressure difference of 50Pa is imposed while the spray rates remain the same. Every 5 minutes the pressure difference is changed according to the following sequence: 0-50-100-150-200-250-300-450-600-750-900-1050-1200 Pa (figure 1). The level of watertightness of the curtain wall tallies with the highest pressure difference that is achieved without any water infiltration during that stage. The moment water is visible on the inside surface of the curtain wall, this is considered as failure. Water should not infiltrate to spaces which are not drained to the exterior. The European standard EN 12865:2001 describes a test protocol to determine the resistance of external wall systems to driving rain under pulsating air pressure. According to this standard, water is prayed at two locations: 72l/h-m at the top as run-off, and 90L/h-m^2 on the whole area to simulate direct wind driven rain. The pressure difference is applied in a step-wise approach to determine at which level water entry occurs.

The first and most prevalent type of water infiltration has to do with the accumulation of water in the cavity between the mullion or transom and the IGU. When the water is not drained sufficiently, hydrostatic pressures across little cracks may cause water to flow to the interior. The second type of water infiltration relates to the local velocity of the air flow through the curtain wall assembly. If the airtightness is insufficient, the wind will flow into the interior of the building at a high air velocity and the kinetic energy of the water droplets will enable water to reach the airtightness barrier and infiltrate. The first failure type can be understood as water movement, the second one is dominated by air movement.

3 TEST SAMPLE

An aluminum stick system curtain wall test specimen was designed in collaboration with a large commercial company. Containing as many different connections as possible, it allows to evaluate different types of junctions and sensitivity to varying boundary conditions. Contrary to the setup described in EN 13830 (2003), it was decided to consider the connection between curtain wall and the structure of a building as an essential part of the test sample as well. In traditional testing the window-wall interface is often discarded, whereas this connection is quite delicate and requires thorough investigation. The realistic connection with the structure leads to a more realistic test specimen. Moreover, the mechanical fixation of the curtain wall to the substructure might have major implications on the mechanical behavior of the mullions (and to a lesser extent the transoms), in turn affecting the compression and tension in the gaskets. The overall size of the specimen measures 3m x 4m, and the sample contains a turn-and-tilt window, a tilted transom, and different types of T-connections. From a mechanical point of view, it was decided to design the curtain wall for a rather limited design wind pressure, which would allow to assess the effect of significant deflection of mullions or transoms.

First of all, the mechanical anchors are installed, followed by the mullions and the transoms. Subsequently, the interior gaskets are installed carefully. Then the IGU's are fixed to the interior tubular frame by means of a pressure plate that is fixed every 30 in the screw chase. In this case also a polyamide separator was mounted to compartmentalize the cavity. Finally, the exterior snap was installed. At the interface with the wall, a steel rectangular profile was mounted with the same thickness as the IGU, to ensure that the pressure plate is level with the IGU. Next to that, an additional profile was mounted to install the EPDM-flashing, that was sealed to the test rig by means of caulking. The top of the curtain wall is shielded from direct rain impingement, to ensure that no water could enter into the system that way.

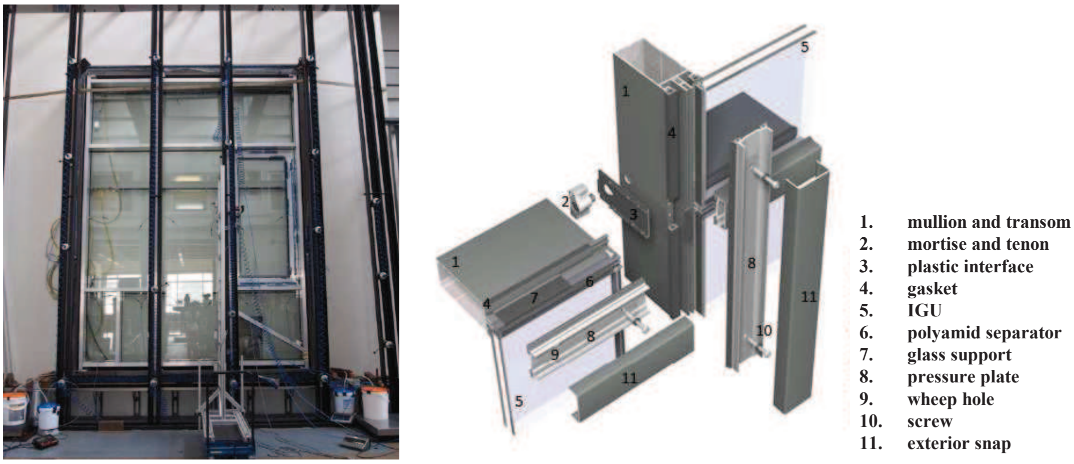

Figure 2. Overview of test setup (left), composition of curtain wall at mullion-transom joint (right)

At the bottom of each mullion, a standard drainage gutter was installed carefully. By means of tubes these gutter systems discharged into buckets that collected the water that infiltrated into the curtain wall system. These buckets were weighed automatically every 30 seconds and logged for further analysis. To avert any influences of the spraying rack on the weighing system, the buckets were located outside of the test rig. As a result, it was important to ensure that the gutter system did not affect the drainage or pressures in the curtain wall system. The buckets were closed off carefully, with an additional pressure tube connecting the bucket to the drainage chamber in the mullions to ensure identical pressures even when temporary occlusion of the drainage system would occur doe to large infiltration rates. This approach is based on similar constructions in previous research project related to the quantification of water in drainage systems. Note that weep holes were provided in the transoms, in accordance with the specifications of the manufacturer. Due to the compartmentalization, a part of the water that infiltrated into the transom will still be drained into the mullion. Additional tests showed that the removal of the compartmentalization in the transom reduced the drained water at the bottom of the mullion by half.

In order to evaluate the degree of pressure equalization in the curtain wall system, 18 pressure taps were installed in the mullions. It is important to prevent occlusion of the pressure taps due to drained water; otherwise capillary forces and surface tension of water droplets may disturb the pressure measurements. Although this paper focusses on the watertightness, extensive testing was carried out in respect to airtightness and resistance to wind loads. These aspects will be discussed in future publications. Tests according to EN 12153 (2000) showed that the curtain wall system is very airtight (class AE900). At a pressure difference of 50Pa the air flow rate was 0.13m³/h.m and 0.44m³/h.m² at overpressure, and 0.14m³/h.m and 0.48m³/h.m² at underpressure (excluding the turn-and-tilt window and extraneous air leakage of the test rig). Note that in a standard test sequence two airtightness test are carried out, one before the watertightness test and one afterwards. To evaluate the effect of water on the airtightness, the airtightness was measured before the watertightness test, immediately after the test, after 11 days, and after 18 days. The airtightness was significantly better immediately after the test at overpressure. After 11 and 18 days the air loss increases, but the original air flow rate was not achieved yet, at underpressure no significant difference was measured.

4. TEST RESULTS

First of all, the pressure equalisation (PE) in the curtain wall system was evaluated during both the airtightness test as well as the watertightness test. The degree of pressure equalisation is important to assess the driving forces that act on the water and cause infiltration into the system. When the PE is 100%, the pressure in the cavity is equal to the pressure on the exterior side, eliminating wind pressure as driving force. Note that this also entails that the complete pressure difference over the façade is transferred to the interior airtight seal. One can reasonably assume that good PE will reduce the infiltration rate in the system, but it will also increase the pressure over the interior seal. Currently it is unclear whether the amount of water in the curtain wall (resulting in hydrostatic pressures) or the wind pressure differential is the dominating force leading to water ingress into the interior. In that respect, it is not self-evident that a high PE by definition decreases the risk for water ingress.

Recorded water infiltrations during static test according to EN 12155
450 Pa – junction mullion 4-lower transom
750 Pa – junction mullion 1-lower transom
900 Pa – lower right corner turn-and-tilt window

Recorded water infiltrations during cyclical test according to EN 12865
0-300 Pa – junction mullion 1 and 4-lower transom
0-450 Pa – lower right corner turn-and-tilt window
0-750 Pa – lower left corner turn-and-tilt window

During the test sequence according to EN 12155 the water infiltration rate in the transom and mullions was collected. Calibration tests showed that the infiltration rate became stationary very quickly. The cumulated infiltration rates were plotted as a function of time, and based on the slope in the stationary period the infiltration rate as a function of pressure difference is established.

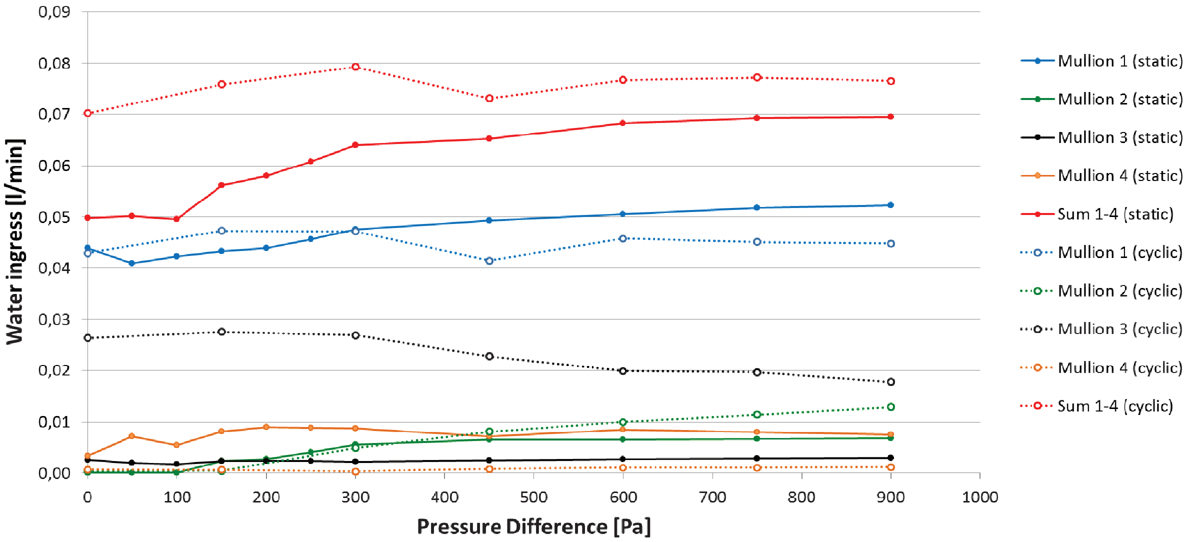

Figure 3. Recorded water ingress collected at the mullions during static (EN 12155) and cyclic (EN 12865) watertightness testing

First of all, it can be noticed that the infiltration rate does not show a clear correlation with the pressure difference across the curtain wall. It was found that the PE in all transoms steadily decreased from 100% to 98% when the pressure differential over the façade increased from 50Pa to 200Pa. At higher pressures, the PE remained constant at 98%. No significant differences were found between PE during airtightness and watertightness testing. As a result, the pressure differential over the gasket at the exterior side are rather moderate; even at an overall pressure difference of 900Pa, the pressure over the exterior gasket is limited to about 18Pa. Bearing this in mind, one can easily understand that hydrostatic pressures caused by the direct impingement or runoff film may have a larger influence than the wind pressure. Furthermore, more water seems to infiltrate into mullion 1 (the one most left in figure 2), even though this is an identical configuration as mullion 4, and no differences in PE was found. The difference may likely be attributed to a small deficiency (e.g. gap between gasket of mullion and transom). As the infiltration rates proved to be slightly higher during the cyclical test according to EN 12865, additional tests were conducted to analyze this effect. In a first test procedure the curtain wall was subjected to a mean pressure of 300Pa and pulses with an amplitude of 50Pa, in a second test procedure it was subjected to a mean pressure of 300Pa and pulses with an amplitude of 150Pa. Both tests were conducted for a period of 10 minutes, and a spray rate of 18L/min was applied (identical to the EN 12865 test).

Note that the applied pulsations according to EN 12865 caused a slight phase shift in the pressure response in the curtain wall. During the rapid pressure increase the pressure in the curtain wall system shows a time lag, resulting in slightly lower PE values. For larger amplitudes of the pulses the shift increased: the lowest PE during pulses of 150Pa was 92%, and decreased to 87% for pulses of 900Pa. Consequently, the maximum pressure difference over the outer gasket was maximum 12Pa and 117Pa for pulses of 150Pa and 900Pa respectively. Mind that the PE during the pulse (after the phase shift due to the pressure increase) was identical to the one measured under static conditions. Likewise, the PE increased at the end of the pulse when the exterior pressure decreased to zero again. The identical phase shift entailed PE values up to 102%.

Finally, the effect of a number of typical installation errors was evaluated. One of the most striking results relates to the use of the tubular profiles at the sides of the curtain wall. These are installed instead of an IGU to ensure that the pressure plate is installed level. In an additional test the thickness of the tubular profile was 2mm smaller than that of the IGU, which resulted in a slightly tilted pressure plate. Mind that this effect could easily be overviewed during visual inspection; as it was not visually prominent. Results indicated that this small defect entailed an infiltration rate that was typically 2,5 times higher than the reference case.

5. CONCLUSIONS

Curtain walls systems are widely used, offer a number of benefit in terms of construction cost and speed, but seem to be rather susceptible in respect to water ingress. Little information has been published on the performance of curtain walls and the typical failure phenomena. In this paper, the results from experimental analysis on a curtain wall system are presented and analysed. The amount of water that infiltrated into the cavity was measured during static and cyclic boundary conditions.
It was established that the amount of water ingress does not show a correlation with the overall pressure differential over the system, which indicates that the mail force causing water to infiltrate past the first barrier is the hydrostatic pressure exerted by the runoff film. These findings are confirmed by the degree of PE that was measured and the absolute pressure difference over the exterior gasket.

Cyclic test sequences resulted in water ingress into the interior at lower pressure differences as compared to static test sequences, and the amount of water that infiltrates into the cavity is higher as well.

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