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Inspecciones en la gestión del agua de fachadas ventiladas basadas en la evaluación in situ y pruebas de laboratorio
Insights in the water management characteristics of rear-ventilated façades based on on-site assessment and laboratory testing

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***Resumen*— Las fachadas ventiladas son sistemas de construcción de fachadas contemporáneas, que incorporan funciones para la gestión del agua en su diseño y construcción. Sin embargo, muy a menudo estas funciones para la gestión de agua no funcionan adecuadamente en todo el sistema del recinto debido a un mal diseño de los detalles constructivos, fallas de construcción en la fachada o lagunas en la comprensión de los mecanismos de infiltración de lluvia, causando que el agua penetre en estos sistemas. El objetivo de este trabajo es presentar algunas ideas sobre cómo funcionan las características de gestión del agua de las fachadas ventiladas en todo el recinto del edificio. Posteriormente, se ha probado una maqueta a escala completa en condiciones de laboratorio. Finalmente, se ha realizado una comparación entre el análisis in situ y los resultados obtenidos en las pruebas de laboratorio, concluyendo que es posible mejorar el comportamiento de gestión del agua de las fachadas ventiladas con la acción combinada de la lluvia y las presiones del viento, si los mecanismos que pueden causar infiltración de agua son bien comprendidos.**

Palabras clave— Lluvia, fachadas ventiladas, penetración de aguas pluviales, gestión del agua.

***Abstract*- Rear-ventilated façades are contemporary façade construction systems, which incorporate water management features into their design and construction. However, quite often these water management features do not properly work in the whole enclosure system due to bad design of the constructive details, construction flaws in the façade or gaps in the understanding of the rain infiltration mechanisms causing water to penetrate in these systems. Consequently, the aim of his paper is to present some insights of how the water management features of rear-ventilated façades perform in the whole enclosure system of the building. Subsequently, a full-scale mock-up has been tested in laboratory conditions. Finally, a comparison between the on-site analysis and the results obtained in the laboratory tests has been made, concluding that it is possible to improve the water management performance of rear-ventilated façades to the combined action of wind-driven rain and driving rain wind pressures if the mechanisms that might cause water infiltration are well understood.**

Index Terms— Wind driven rain, rear-ventilated façades, rain water penetration, water management.

I. INTRODUCTION

Rear-ventilated façades are contemporary construction systems which are widely adopted by architects and building practitioners as these offer a number of technical and aesthetic benefits in comparison to traditional façades (unventilated walls, vented walls and cavity walls). A ventilated wall has vent openings at the air cavity (top and bottom openings) to promote air circulation (Straube, 2009), whereas a vented wall only has vent openings at the bottom of the wall, usually provided for drainage (Straube, 1999). In contrast to traditional walls, the cladding of rear-ventilated walls is formed by independent pieces which are assembled using the open joinery system. They tend to incorporate water management features into their design and construction (drained and screened walls), unlike perfect barrier systems (e.g. most exterior insulation finish systems) and traditional construction (storage or mass buffering walls). In all cases (cavity walls, vented walls and rear-ventilated walls), the exterior layer is separated from the interior layer by an air gap or cavity. Furthermore, rear-ventilated façades are façade systems which can be used in renovation projects to improve the energy efficience of the building, by means of the addition of a rainscreen cladding in front of the old enclosure, or in new projects.

Rear-ventilated façades were first defined by Anderson and Gill (Anderson, 1988), who pintpointed the different role played by the distinct layers in the overall performance of the façade. These solutions are basically composed of two leaves and a fully ventilated air cavity in between. In typical ventilated façades, the outer leaf (cladding) is detached from the inner leaf (bearing wall or supporting wall), to which is mechanically fixed by specific anchorage points using or not a secondary structure, and the overall system is supposed to be designed following the rainscreen principle (Garden, 1963). When a secondary structure is used it can be made of timber or metal (steel, stainless steel, galvanized steel or aluminium). Inside the air cavity a thermal insulation layer can be placed on the exterior side of the interior wall leaf. This insulation material should be defined in accordance with an EN standard or an ETA (European Technical Assesssment). Basically, it can be assumed that rear-ventilated façades have arisen from the combination of multi-wythe enclosures and the rainscreen concept.

The aim of the present study is to provide a clear understanding of the mechanisms that might cause water infiltration in rear-ventilated façade systems. So, the water management features of rear-ventilated façades to the combined action of wind-driven rain and driving rain wind pressures, can be improved. To this effect, the mechanisms of rainwater penetration through vertical and horizontal open joints have been studied and analyzed in the first section of the paper. Secondly, the enclosure design of an existing building executed with a rear-ventilated façade system has been described and discussed by means of an on-site assessment. In the on-site analysis the constructive details have been related to the preferential rainwater pathways and the typical observed damages. As a result, a water management hypothesis of the façade has been proposed, based on a new methodology published in previous works (Arce, 2015; Arce, 2016). Then, this water management hypothesis has been validated by means of laboratory experiments. Finally, the obtained results from both analysis have been compared and the conclusions have been drawn.

II. MECHANISMS OF RAINWATER PENETRATION THROUGH JOINTS

Garden (Garden, 1963) summarises that the emerging of water leakage in building envelopes requires the simultaneous action of the following regarded factors:

- Presence of water on the wall.
- Existing opening(s) on the wall (such as cracks or joints) to permit its passage.
- Forces driving the water into the opening.

So, when one of these factors is cancelled out, the water is then not able to cause leakage on the building envelope. As Garden (Garden, 1963) hypothesized, if all of the acting forces can be controlled or eliminated, then water even if present on the wall will not infiltrate through it.

The acting forces for water ingress in open joint claddings are: kinetic energy of raindrops (direct entry), surface tension, gravity action, pressure differences, local air currents, hydrostatic pressures and capillary forces. Of these, kinetic energy and differential pressure are a function of weather events (Chew, 2001) as well as local air currents. The rest are a function of material properties and constructive design of the joints. This list of forces has been studied in several papers by different authors (Garden, 1963; Birkeland, 1963; Chown, 1997; AAMA, 2000; Bassett, 1996…), but curiously, they do not always gather hydrostatic pressure and local air currents.

When considering the water management features of the rear-ventilated façade typology, the analysis might be carried out taking into account two levels: (a) the response to wind driven rain of the open joint itself and (b) the response to wind driven rain of the panel.

In the following lines the possible response scenarios to wind driven rain of the joint are briefly analysed and discussed.

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A. *Gravity action*

Gravity is the tendency of water to flow downwards the face of a wall and into the openings that lead inwards and downwards (Bassett, 1996; Straube, 2005) (see a in Fig.1). Note that in horizontal joints of less than 0.5 mm rainwater will not flow through the opening by gravity due to surface tension (Birkeland, 1963).

B. *Surface tension*

Surface tension is the contractive tendency of the surface of a liquid that allows it to resist an external force. The surface tension between the interface of two different means depends on their nature and represents an equilibrium that corresponds to the minimum part of the free surface forces of the whole system. A consequence of this equilibrium is that the mean with minor internal cohesion forces will tend to surround the one with major internal cohesion. This is why the surface tension can be described as the tendency of water to stick to the surface of the wall that is already wetted (Bassett, 1996) (see b in Fig.1).

In small openings, the surface tension of water will introduce a meniscus on the interior sides of the joint when no water is supplied at that location due to rivulet formation (Van den Bossche, 2013). It means that the opening can be occluded creating a bridge that will allow the water of the rivulet to overflow it and continue its way down. Water will enter the joint gap once the surface tension is breached by another acting force, like gravity or pressure differences.

C. *Capillary action*

Capillarity is the ability of a liquid to flow in narrow spaces without the assistance of, and in opposition to external forces. According to Branz (Bassett, 1996), the cappillary action is the tendency for liquids to fill small openings, lifting water up against the force of gravity (see c in Fig.1).

Capillary action is influenced by the diameter of the gap. The smaller the radio of the gap is, the higher the capillary action is. It is an effect that acquires major importance when the joint width is less than 0.5 mm (Birkeland, 1963). According to Mas et al. (Mas, 2011), capillary action and surface tension have less importance in joints of 0.8 cm or above. Furthermore, the process of evaporation of this rainwater is longer.

D. *Kinetic energy of raindrops caused by wind velocities*

Wind forces can easily lead rainwater droplets through openings along the building enclosure during rain events, since wind gives the rain a horizontal velocity component that provides the droplets with an oblique trajectory (see d in Fig.1).

In order to have rainwater infiltration by means of this phenomena, it is required joints of more than 4 mm (Birkeland, 1963). Pardal and Paricio (Pardal, 2006) studied this phenomenon in rear-ventilated façades. They assume that in order to prevent the impact of the wind driven rain droplet onto the exterior side of the inner leaf, the air cavity thickness should be enough to minimize the kinetic energy of the droplet acquiring then a perpendicular trajectory. Avellaneda (Avellaneda, 1997) assessed that an air cavity thickness between 7 and 29 cm has not an impact on the water infiltration rate onto the inner leaf. However, the design of the joint (widht, thickness and shape) is a key factor when working with air cavity thicknesses below 7cm (Pardal, 2006).

E. *Pressure differences*

Pressure differences between the exterior and interior sides of the enclosure can allow water to enter the wall inwards through small openings that might otherwise resist leakage (see e in Fig.1). Many studies have shown that it is the acting force with the greatest contribution to water leakage (Straube, 2001).

Rear-ventilated façades are typically conceived or perceived as PER (Pressure Equalized Rainscreen) walls, where the pressure difference across the rainscreen is typically lower than 25 Pa under static conditions (Rousseau, 1998). As the exterior pressure is not constant, the pressure in the cavity will also vary depending on the degree of pressure equalisation or pressure moderation. The predominant parameters affecting the degree of pressure equalisation is the airtightness of interior and exterior plan and the air volume in the cavity. Even in static conditions air flows will arise from windward to leeward side in the cavity, causing lateral air movements in the cavity. It is a variable situation in the building that depends upon the direction of the wind at each case. Consequently, it is highly recommended to compartmentalize the air cavity between areas and/or façades where significant pressure differences can be expected (Pardal, 2006; Huedo, 2010). A lack of pressure equalization (due to inadequate compartmentalization) may induce higher wind loads on the façade components and change the overall behaviour of the system in terms of watertightness as well. Note that rear-ventilated façades in practice are not compartmentalized.

F. *Local air currents*

Water can penetrate a wall by being transported along a stream of moving air. It will percolate across barriers or through openings, cracks and holes. Control of penetrating water usually also requires considering the control of air movement of the surrounding environments.

In the case of rear-ventilated façades, two possible sources for local air currents are the airflow induced by thermal buoyancy and the airflow induced by the wind. The airflow induced by thermal buoyancy or stack effect that takes place inside the air cavity of rear-ventilated façades is supposed to generate an upwards air stream with velocity values ranging from 0.2 to 0.6 m/s with wind speeds between 0 to 5 m/s [19 (studies on top and bottom ventilated façades), 20 (studies on 5 mm open joint ventilated façades)]. On the other side, wind induced airflow is irregular along the vertical enclosures of the building. In addition, it has frequent changes in both velocity and direction (wind gusts) and its magnitude is significantly larger than the airflow induced by thermal buoyancy. The impact of the likely air-currents through joints caused by the pressure differences originated in the stack effect and depending upon air slit (joint width and panel edges) on the watertightness performance of rear-ventilated façades is not clear so far.

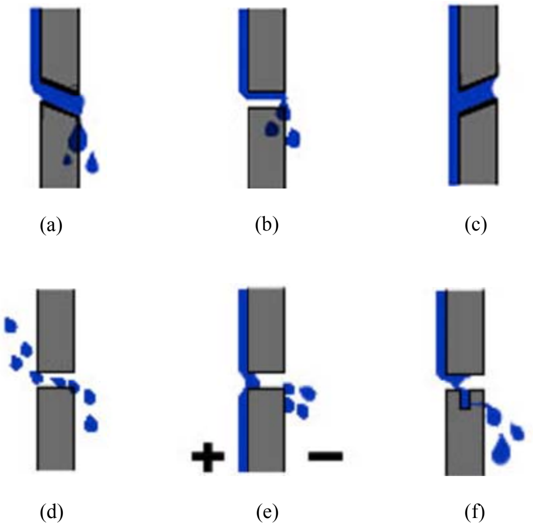
(a) (b) (c)
(d) (e) (f)

Fig. 1. Rain penetration mechanisms through vertical and horizontal joints of rear-ventilated façades.

G. Hydrostatic pressure

Hydrostatic pressure is the pressure exerted by a fluid at equilibrium conditions at a given point (with a paticular hydrostatic height) within the fluid, due to the force of gravity. It increases in proportion to depth measured from the surface because of the increasing weight of fluid exerting downward force from above. For instance, if there is a closed container full with water and you make a hollow in it, water will leak outside due to hydrostatic pressure (see f in Fig.1). The bigger diameter the hole has, the higher hydrostatic pressure will be and the lower external pressure difference applied should be in order to breach the meniscus of the outwards water flow (Van den Bossche, 2013).

The influence of the negative pressures introduced by the hydrostatic pressure of the water runoff by means of the Venturi Effect on the watertightness performance of rear-ventilated façades is uncertain.

The second level of analysis is the response scenario to wind driven rain of the cladding element. There are many cladding materials with different properties available in the market (e.g. ceramic tiles, stone plates, fibre cement panels…), and consequently, several responses to wind driven rain are possible. In general, three main groups can be made: (a) completely impervious materials, (b) materials that absorb rainwater by the surface and (c) materials that absorb rainwater by the edges (lateral sides). Each group is prone to promote different rainwater mechanisms through both, the cladding and the open joints of rear-ventilated façades. Nevertheless, this level of study remains out of the scope of the present paper.

The cladding of rear-ventilated façades is expected to deflect the largest part of the wind-driven rain that impinges on its surface. It is commonly assumed by manufacturers and building practitioners as a rule of thumb that only a minimal part infiltrates through the open joints, and this residual amount of water is supposed to be drained at the bottom, temporarily stored in materials, or dry out to the interior, or to the exterior by means of the chimney effect inside the air cavity. In this way, the air gap of ventilated façades as well as being a capillary break for rainwater, acts as a channel for drainage of the infiltrated rainwater. So, the joints between panels must be designed (a) to minimize water penetration caused by all the acting forces, (b) to allow the contraction and expansion movements of the panels and (c) to offer little resistance to the airflow promoting the pressure equalization across the cladding.

Fig. 2. General view of the building.

III. STUDY-CASE: RESIDENTIAL COMPOUND

This residential compound was built in Madrid in 2014 (see Fig. 2). It is composed of two box elements of eight floors. The four façades of the buildings are built using the rear-ventilated typology and are exposed to weather conditions.

The cladding is made of fibre cement panels in dark grey colour from slab to slab, whose size is 293 cm. tall, 34 cm. long and 0.8 cm. wide. These panels are arranged in the façade creating a grid of 7 cm. wide horizontal joints and 1.1 cm. wide vertical joints (see Fig. 3). The four edges of the panels are plane (see Fig. 4). The plane of the cladding is separated from the inner leaf (a brick masonry wall rendered with water-repellent mortar) 17 cm approximately, leaving an air cavity in between of 12 cm. including the width of the vertical profiles. The thermal insulation layer is made of 5 cm. thick fiberglass, which is covered by a weather resistant barrier.

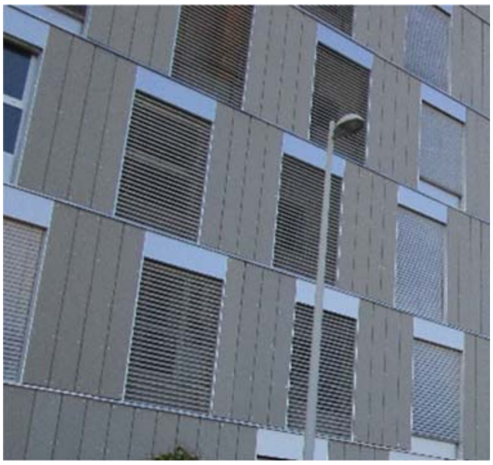

Fig. 3. Joint pattern of the façade.

Description of the secondary structure and fixing system:

The fiber cement panels are pointy attached to vertical omega profiles made of galvanized steel by means of stainless steel rivets. These fasteners are placed every 60 cm at both sides of the panel. The omega profiles go from slab to slab and are fixed to the brick masonry leaf by means of aluminum angle brackets. Behind each omega profile an aluminum horizontal profile is located, which is directly connected to the slab edges by aluminum brackets (see Fig. 5).

Fig. 4. Vertical and horizontal joint connection.

A. On-site assessment: water management hypothesis

The design of the horizontal and vertical joints in the ventilated façade of this building is quite original. So, the vertical joints are designed as pipes and, an aluminium cross-cavity flashing is installed in the horizontal ones, collecting and shedding the water drained from the omega profiles (see B in Fig. 6). When the kinetic energy of wind carries the raindrops into the vertical open joints (level II), the water can only collide with the omega profile (level VI; A in Fig. 7).

Fig. 5. Construction process of the façade.

The infiltrated water flows down in the omega profile by gravity dripping down over the horizontal profile, whose slope drives it to the exterior (see A and B in Fig. 6). However, if the water adhered to the surface of the omega profile reaches the interface between the profile and the panel by means of wind forces, capillary suction might cause the penetration of moisture in that area (see B in Fig. 7). This phenomenon might also occur when rainwater coming from level II reaches this contact interface by wind forces (see C in Fig. 7) or if water running down level I reaches this interface by surface tension

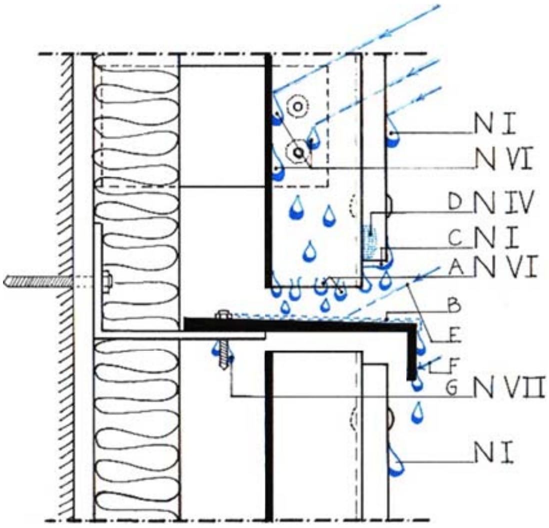

Fig. 6. Water management over the vertical section of the façade.

(see D in Fig. 6). Note that this material is hygroscopic and retained water may give rise to premature deterioration.

On the other hand, when rainwater impinges on the surface of the panel (level I), it will run down until it reaches the bottom border, where it might drip down over the horizontal profile and be shed (see B in Fig. 6). Nevertheless, if rainwater reaches the rivets (level I), there might be capillary uptake through the gap between the panel and the rivet (see D in Fig. 7) and the resulting soaking of the rivets and the panel in that area. Wind pressure forces might force the water in that gap to the inner surface of the omega profile (level VII). Regarding the horizontal joints, the aluminium profile divides the joint in two areas: the top and the bottom area. So, when rainwater infiltrates through the upper part of the joint (see E in Fig. 6), it might collide with the aluminium profile, which will drain it directly outside the façade. Note that if the splash caused by the rainwater colliding with the horizontal profile might project water droplets onto the insulation is uncertain.

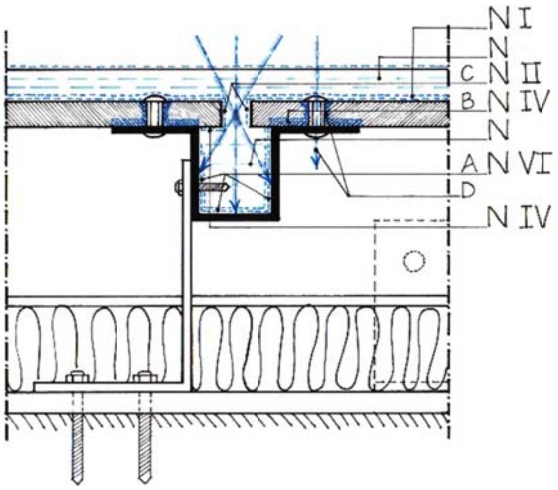

Fig. 7. Water management over the horizontal section of the façade.

Fig. 8. Porch area during construction time.

Fig. 4. Vertical and horizontal joint connection.

In contrast, the entry of rainwater through the lower area of the joint (see F in Fig. 7) is rather unlikely as the shape of the profile prevents it. Note that the rainwater channelled outwards by the horizontal profile might leak down through the connection between profiles by gravity. There might be a critical point in the connection of the horizontal profile with the bracket if the slope of the profile is not sufficient. If rainwater reaches that point it might leak down through the gap of the screw by gravity (see G in Fig. 6). No damages have been identified during the inspection of the building. Nevertheless, despite the overall good water management characteristics of the whole façade, the drainage of the water infiltrated inside the air cavity has not been foreseen in the porch areas. In Figures 8 and 9 are shown some photos of the plinth: the one on the left was taken during the construction time and the two on the right some time later. In the latter, it can be seen the moisture stains appeared on the bottom surface when this water is not led outside.

Fig. 9. Porch area during service life of the building.

B. *Laboratory testing*

An experimental approach was adopted for validating the above described water management hypothesis of the façade. The façade system was evaluated on its ability to drain the water that infiltrated the system. Evaluations were made using sprayed water to simulate wind driven rain and stepwise increased pressure differences to mimic driving rain wind pressures. These parameters were set in the tests according to the prescriptions established in European watertightness test standards EN 12155:2000 (European Standard EN 12155, 2000) and EN 1027:2000 (European Standard EN 1027, 2000).

A mock-up of 2.0 by 2.3 meters approximately was designed based on the constructive details of the study-case. The same material and panels size were used for the specimen. The specimen was built using best construction practices in the laboratory facilities of Ghent University. The entry of water at every level was collected in a gutter system beneath the specimen, where: (see Fig. 10).

- Gutter A1 was a longitudinal tray located below the specimen at the front side that collected the water running down the exterior surface of the fibre cement panels (level I).

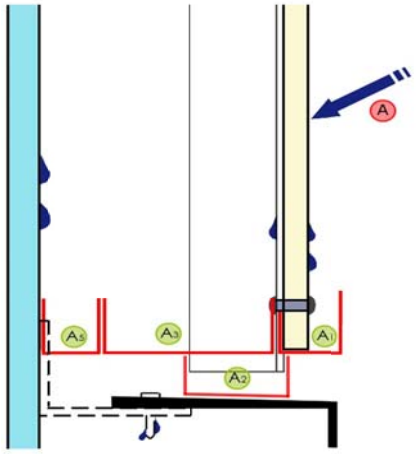

Fig. 10. Scheme of the gutter system and placement.

- Gutter A2 were boxes placed below every omega profile, which collected the infiltrated water through the vertical open joints (level II).

- Gutter A3 was a longitudinal tray installed below the specimen at the rear side to collect the infiltrated inside the air cavity (level IV and VI).

- Gutter A5 was divided into two parts. It collected the rainwater reaching the transparent acrylate plate (PMMA) of 1 cm thickness, which replaced both, the interior leaf and the thermal insulation layer, and acted as the air barrier system in the specimen (level VII).

Fig. 11. Photo taken from the backside of the mock-up.

These gutters drained away the collected water to buckets, whose weight was recorded continuously over time (see Fig. 11).

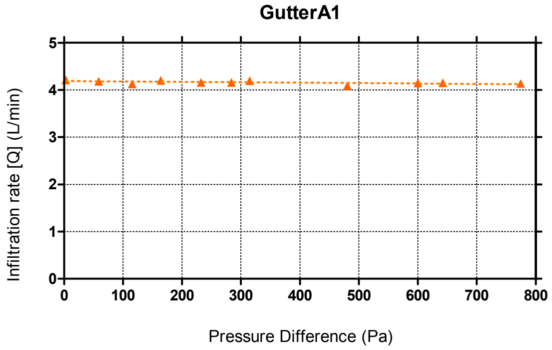

Fig. 12. Water collection rates measured in gutter A1 as function of applied pressure differences.

Six watertightness tests have been randomly conducted over the specimen in order to assess the water ingress rates at every level, expecting that most of the infiltrated water inside the system was collected in the boxes beneath the omega profiles (gutter A2), which may act as pipes in the designed rear-ventilated façade system. No water was expected to reach the surface of the PMMA sheet.

Results, which are reported in terms of water collection rates at each particular location, are not affected by the transitions in pressure differences and the changes of buckets. In addition, the air barrier system of the specimen is supposed to be completely airtight.

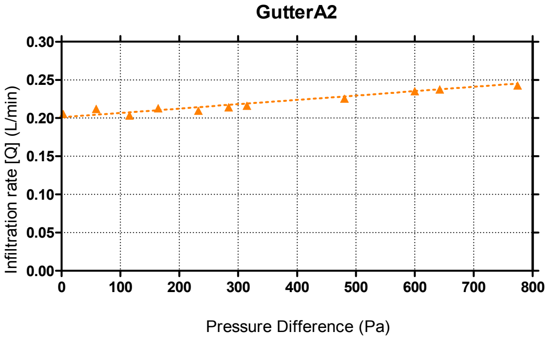

Fig. 13. Water collection rates measured in gutter A2 as function of applied pressure differences.

Figure 12 reports the infiltration rates in gutter A1 (runoff along the exterior surface of the panels, level I) as function of applied pressure differences in front of the cladding for a spray rate of 2 L/min per m2. Constant water collection rates are recorded for increases in applied pressure differences, which indicates that the runoff film in level I is largely insensitive to the applied pressure differences in front of the cladding. All the measurements obtained are within the 95 - 105% confidence interval. The average obtained deposition rate is around 4.2 L/min, which implies that close to 93 - 94% of the collected rainwater creates the runoff film of the exterior surface of the cladding (level I).

Figure 13 plots the water deposition rates in gutter A2 (level II) in relation to the applied pressure differential steps. It is the water infiltrating through vertical joints and flowing down the exterior surface of the omega profiles that played the role of pipes. The graph shows that water ingress rates slightly increased with applied pressure differences in front of the cladding, unlike as could be expected for a system with perfect pressure equalization. Once again, all the measurements obtained are within the 95 - 105% confidence interval. Between 0.20 and 0.25 L/min of water infiltrated through vertical joints, which means the 5.0 – 6.2% of the total collected rainwater. This value shows the weakness of that point and the importance for a good design and execution.

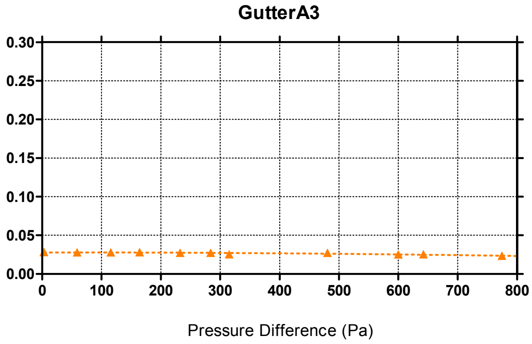

Fig. 14. Water collection rates measured in gutter A3 as function of applied pressure differences.

Figure 14 displays the water collection rates in gutter A3 as function of applied pressure differences in front of the cladding for the spray rate of 2 L/min per m2. This gutter gathers the water flowing down inside the air cavity (levels IV and VI). It is the water infiltrating not only through the gaps of the screws, which fixed the vertical profiles to the brackets, but also through the contact surfaces between the panel and the wings of the omega profiles (see Fig. 16). It seems that water entry rates are constant for rising pressure differences. Apparently, the water drained along the capillary pathways between the panels and the omega profiles is not necessarily influenced by the applied pressure differential step. Nevertheless, this time, 90% of the measurements obtained are within the 95 - 105% confidence interval. An average value of 0.026 L/min of water infiltrated inside the air cavity, which represents a range between the 0.3 and 0.65% of the total collected rainwater.

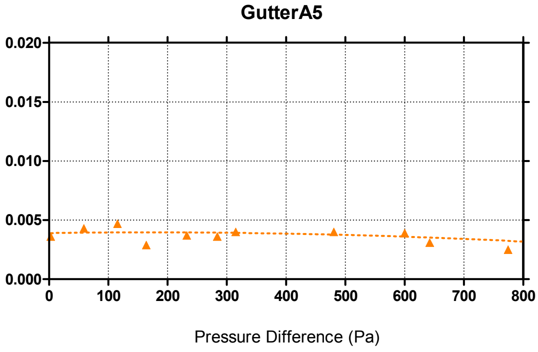

Fig. 15. Water collection rates measured in gutter A5 as function of applied pressure differences.

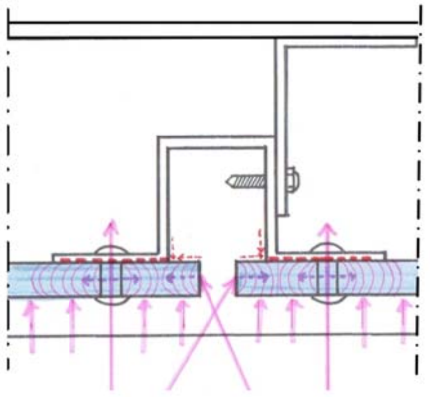

Fig. 16. Scheme of the water infiltration pathways inside the air cavity (gutter A3).

Finally, figure 15 shows the water collection rates in gutter A5 in relation to the applied pressure differences in front of the cladding. The stagnant water (capillary water) between the contact surfaces of the panel and the omega profiles, and within the gaps of the rivets splashes onto the PMMA sheet (level VII) when certain pressure differences are applied over the cladding (see Fig. 17). Note that in this case, the scale of the "y" axis in the graph is around 100 times smaller than in the case of gutter A1. In this instance, more dispersion among measurements within applied pressure differentials were obtained. Only 50% of the measurements obtained are within the 90 - 110% confidence interval. Unlike expected, around 0.004 L/min of water reached the exterior surface of the PMMA sheet, which means from the 0.04 to 0.1% of the total amount of collected rainwater.

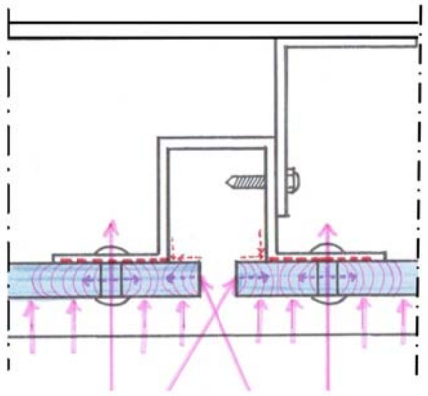

Fig. 17. Scheme of the water infiltration pathways onto the exterior surface of the PMMA sheet (gutter A5).

IV. CONCLUSIONS

First of all, it is worth to pinpoint that there is a lack of knowledge concerning the water management features of rear-ventilated façades. It is possible to improve the water management performance of rear-ventilated façades to the combined action of wind-driven rain and driving rain wind pressures if the mechanisms that might cause water infiltration are well understood. It is not a good strategy to assume that no water will be able to reach the exterior surface of the thermal insulation layer in rear-ventilated façades and/or infiltrate inside the air cavity, as demonstrated the obtained results when subjecting the specimen to European water tightness test procedures.

The study-case was chosen because of the expected good water management skills of the constructive details of the vertical and horizontal joints. Nevertheless, even with $\Delta P = 0$ Pa, 0.05% of the impinging rainwater on the cladding may reach the insulation layer and 0.25% might infiltrate inside the air cavity. Hence, a key aspect of these types of systems is to foresee the drainage of the stagnant rainwater at the bottom border of the façade. It is an aspect that has been corroborated during the visual inspection of the building and the on site assessment the study-case.

The results also showed that water infiltration rates were not closely dependent on the applied pressure differences in front of the cladding in any collection location, apart from gutter A2. In this case, a slightly upwards infiltration trend was observed for rising pressure differences.

The vertical profile can be implemented in order to reduce and drain the retained capillary rainwater between the contact surface of the profile and the panel.

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