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Rain infiltration mechanisms in ventilated façades: literature review, case studies, understanding common practice flaws

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ABSTRACT

Ventilated facades are contemporary construction systems, which present a number of benefits in comparison to a traditional facade (unventilated or vented air cavity). Nevertheless, there is a gap in the understanding of its watertightness performance. It is commonly accepted by manufacturers and building practitioners as a rule of thumb that ventilated facade systems are designed to deflect the largest part of the rainwater that impinges on them and only a minimal part infiltrates through the open joints of the cladding. 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. However, some authors have already reported some pathological lesions on ventilated facades (stains and soiling damages due to biological colonization, problems with wind pressures due to the use of linear connections between panels and substructure, etc.) This paper presents a broad literature review on the response to rainwater of ventilated facades and typical pathologies. Next to that, an analysis of the main guidelines relating to the construction of ventilated facades is conducted. Finally, rainwater infiltration problems from real buildings with ventilated facade systems have been collected in a field study of 20 buildings. From this field study, four study-cases have been selected and thoroughly analysed, first measuring the components of the ventilated façade fixing system in order to draw their constructive detail, second working out on its water management and third, relating the water management to the damages observed in the visual inspections.

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KEYWORDS: Ventilated façades, watertightness performance, damages, design guidelines.

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1 INTRODUCTION

Ventilated façades are contemporary construction systems, which present a number of benefits in comparison to traditional façades: unventilated walls or walls with a vented air cavity (top and bottom openings). They are composed of an exterior covering, an interior wall layer and a fully ventilated air cavity in between. In typical ventilated façades, the outer leaf is detached from the inner leaf, to which is mechanically fixed by specific anchorage points, and the overall system is supposed to be designed following the rainscreen principle [Garden 1963]. Inside the air cavity a thermal insulation layer can be placed on the exterior side of the inner leaf, which should be made airtight in order to have good pressure equalization [Suresh 2000; Van Den Bossche 2013]. The cladding of ventilated façades should deflect the largest part of the wind-driven rain (WDR) that impinges on its surface. So, the joints between panels must be designed to minimize water penetration caused by all the acting forces: kinetic energy of raindrops, surface tension, gravity action, pressure differences, capillary forces, local air currents and hydrostatic pressure [Van Den Bossche 2013].

Several authors have studied the effect of rainwater infiltration through vertical and horizontal open joints [Birkeland 1963; Szentivánszky & Bekes 1964; Avellaneda 1982; Fernández 2010; Huedo et al. 2010; Mas et al. 2011], most of them regardless of its application in real construction systems. For instance, whereas Seo and Yoda [1972] suggested an outwards tilted lower face for good drainage and an upper face provided with a barrier to prevent water from entering in horizontal joints, Mas A. et al. [2011] proposed a slit on the lower face as a drainage system. Moreover, their results confirmed that the influence of panel thickness and the beneficial effects of a shaped panel edge become insignificant for joint widths of more than 8 mm. The occlusion of the horizontal joint when its width is between 0.01 and 5 mm [CIB 1963] should be also contemplated since it avoids rain droplet from entering. In contrast, the infiltrated rainwater flows down in vertical joints, as in a pipe. In addition, there are no publications known to the authors that confirm rainwater infiltration in industrialised open joint coverings and there is still a lack of data regarding the quantification of rainwater infiltration through open joints. Next to that, there are little construction guidelines [Johanson & Seifert 2003; Pardal & Paricio 2006; Montero et al. 2007; Romila 2013] or sector documents for ventilated façades.

No publications are known to the authors where water infiltration problems on ventilated façades are reported in a systematic way. However, this does not necessarily indicate that no problems are found in practice. Several papers have already reported some pathological lesions due to environmental actions: corrosion problems of the fixing system [Maffei & Boccaccini 2002; Hartog &McKenzie 2004; Mas et al. 2011], stone panels rupture and falling off [Carramiñana et al. 2010; Mas et al. 2011; Gutiérrez et al. 2012], stone panel flacking and scaling [Mas et al. 2011; Gutiérrez et al. 2012; Hébert et al. 2012], stains, efflorescence and soiling damages in stone panels [Parnham 1999; Maffei & Boccaccini 2002; Chew and Ping 2003; Chew and Tan 2003; Hartog & McKenzie 2004; López & Alonso 2010; Mas et al. 2011; Hébert et al. 2012; Alonso et al. 2012]; problems with wind pressures due to the use of linear fixing systems [Grassi 2000; Maffei & Boccaccini 2002], cracking and spalling close to anchorage systems [Mas et al. 2011; Hébert et al. 2012; Ivorra et al. 2013], etc.

2 OBJECTIVE AND METHODOLOGY

The aim of the study is to provide a clear understanding of the overall performance of the ventilated façade systems to WDR, relating the constructive detail with the preferential rainwater pathways and analysing typical damages. To this effect, a field study has been conducted over twenty buildings with ventilated façade systems in Madrid. The selection of the buildings has initially followed a proximity criterion. However, only four are going to be presented in the paper. The selection criteria are based on their typology and on their damages, which are described in each study-case. Visual inspections of the exterior and when possible interior side of the façades have been done, paying special attention to the externally visible damages (panel cladding and fixing system) and the bottom border of the façade in the porch areas (see Fig. 3). The components of the different fixing systems have been measured in order to draw the constructive details. Then, an analysis of the rain flow paths has been carried out based on the state of the art and on site tests of micro-runoff (see Fig. 9). These own designed tests have allowed us to differentiate the surface runoff over the panels and the rainwater flow in the horizontal joints. Subsequently, the rainwater flow pathways in each system have been classified by means of levels from I to VII (see Table 1), which are depicted in the draws of each study-case. Finally, the obtained models have been compared to the observed damages in field inspections. The results are summarised in the Table 6.

Level	*Description*	*Code*
I	Rainwater runoff along the exterior surface of the covering.	N I
II	Rainwater runoff or drainage in vertical joints up to the backside of the panel.	N II
III	Stagnant water in the top face of the panel (channel).	N III
IV	Rainwater runoff along the interior surface of the covering.	N IV
V	Stagnant water in a channel between the panel and the vertical profile (horizontal profile)	N V
VI	Rainwater runoff along the exterior surface of the vertical profile.	N VI
VII	Rainwater runoff along the air cavity or the surface of the thermal insulation layer.	N VII

Table 1. Description of the water management levels.

3 RESULTS

3.1 Study-case 1: Sanitary Centre

Year of construction: 2007.	*Horizontal Joints:* 2 cm width and overlapped.	*Vertical Joints:* 2 cm width and plane.
Fixing system: The zinc cassettes are screwed down on its bottom part with galvanized steel bolts to vertical omega profiles made of aluminium.		
Thermal insulation layer: 5 cm thick polyurethane foam not covered by a weather resistive barrier (WRB).		*Air cavity:* 3 cm width (including the profile).

Table 2. Basic data of the ventilated façade of the study-case 1.

Figure 1. General view.

Figure 2. Black stains.

Figure 3. Moisture stains.

In this type of metallic coverings, the direct entry of wind-driven raindrops in the cavity is rather unlikely because the horizontal joints between panels are overlapped (see A in Fig. 4) and in the vertical ones, the vertical profile prevents it (see A in Fig. 5). So, when rain droplets collide with the zinc cassettes water will run down along its exterior surface (level I) by gravity until it reaches the lower edge (see B in Fig. 4). Then, water might drip in the horizontal joint, where it can remain stagnant or can flow along the horizontal plane (level III) by wind forces (see C in Fig. 4). Note that surface tension allows water to flow sideways along the lower face of the cassette. If this water reaches the overlap, there might be some capillary uptake. However it might not be enough to reach the top of the overlap and drip in the backside of the overlap (see D in Fig. 4). When water flowing along level III reaches the corner of the cassette, it might infiltrate inside through its border opening and trickle down adhered to its inner surface by gravity (level IV; Fig. 6 and F in Fig. 4) unless it overflows the border opening of the cassette and continues its downward flow (level II). Note that there is a risk of wetting the bolt (see E in Fig. 6). Infiltrated rainwater (level IV) that reaches the inside bottom of the cassette remains stagnant until it is drained away through the openings on the corners of the cassette returning to level III again (see Fig. 6). Note that the shape of the overlap prevents water from reaching level VI in this pathway (see G in Fig. 4). On the other hand, the rainwater that collides with vertical joints (see Fig. 6) drains away along the exterior surface of the omega profiles (level VI; B in Fig. 5). Nevertheless, rainwater near the panel edges might infiltrate through the contact interface between the cassette and the vertical profile (level VII; C in Fig. 5), which is not sealed, by capillary forces or by wind pressure or by hydrostatic pressure. Infiltrated rainwater may be collected at the top of a panel, run down at the back and fall on the next panel, causing a splash, projecting water droplets onto the insulation. The visual inspection has corroborated the expected wetting pattern. The dark stains around the upper and lower borders of the cassettes (see Fig. 2) show the places where rain droplets combined with dirt particles have remained by surface tension. Moreover, the moisture stains at the bottom border of the façade demonstrate that rainwater has infiltrated until level IV and has flown down in the cavity (see Fig. 3).

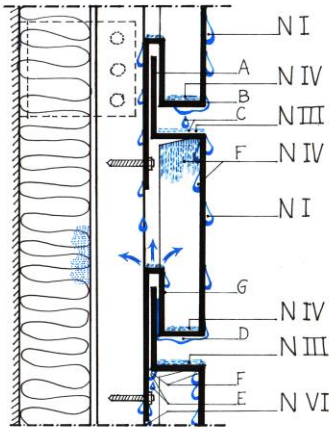

Figure 4. Vertical section.

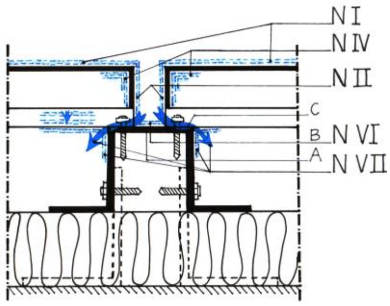

Figure 5. Horizontal section.

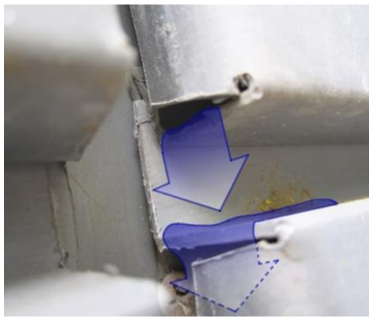

Figure 6. Detail of the cassette.

3.2 Study-case 2: Cultural Centre

Year of construction: 2007.	*Horizontal Joints:* 0.7 cm width and plane.	*Vertical Joints:* 0.1 cm width and plane.
Fixing system: The 3 cm thick limestone plaques are directly fixed at the top and bottom to the inner leaf by means of isolated pivot anchors made of stainless steel (see Fig. 8), which are mechanically fixed in the wall using resin.		
Thermal insulation layer: 5 cm thick mineral wool not covered by a WRB.		*Air cavity:* 3 cm width.

Table 3. Basic data of the ventilated façade of the study-case 2.

Unlike vertical joints, the width and shape of horizontal joints enables the direct entry of wind-driven raindrops to level VII (see A in Fig. 11 and 13). Rainwater impinging on the stone plaques will run down on its exterior surface by gravity (level I) until it reaches the lower edge. Note that whereas the zinc is an impermeable material, the limestone is a porous material that will absorb some of the water contained in the rivulet (see B in Fig. 11). Then, water might flow sideways along the border and the lower face of the plaque by surface tension (see A in Fig. 12 and Fig. 1). When the water bubble formed is big enough to enable the superiority of gravity action over surface tension, rainwater might drip in the top face of the adjacent panel (level III), where it can remain stagnant or flow sideways or leak down the inner surface of the plaque by gravity (level IV; C in Fig. 11). The rainwater running down in level I can also bridge the gap of the horizontal joint and continue its downward flow along the adjacent plaque (level I; D in Fig. 11). If the rivulet is located near the anchorages, rainwater coming from level I and flowing sideways along the lower face of the plaque might infiltrate into the gap by capillary forces (level I; B in Fig. 12). In contrast, the water retained in level III might drip into the gap by gravity creating some kind of tank (see C in Fig. 12). Thereby, as the infiltrated rainwater is not drained and has difficulties in being evaporated, it might cause the spalling of the plaque in that area if it freezes. This type of damage has been observed during the inspection of the building (see Fig. 10). Wind pressure might force the occluded water to drip down the threaded rod of the anchor (level VII) or the inner surface of the plaque (level IV; D in Fig. 12). On the other hand, rainwater infiltrates in vertical joints by means of capillary suction (level II) since the stone plaques are placed side by side in horizontal rows. Then, vertical joints are capillary pathways, in which water can be driven to the backside of the plaques by wind forces and by pressure differences (level IV; B in Fig. 13). Note that both horizontal and vertical joints can get easily occluded, leading to an airtight exterior leaf, corresponding poor pressure equalisation, and in turn high pressure differences over the cladding causing water to infiltrate more quickly into the cavity. The moisture stains at the bottom border of the façade demonstrate that water flows down along level VII.

Figure 8. General view.

Figure 9. Micro runoff test.

Figure 10. Stone-panel spalling

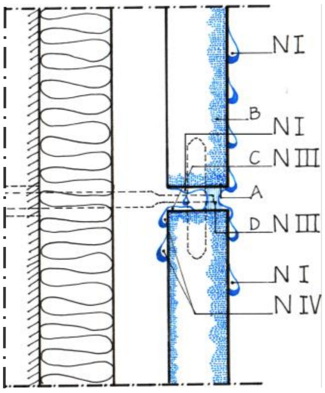

Figure 11. Vertical section (middle of the stone plaque).

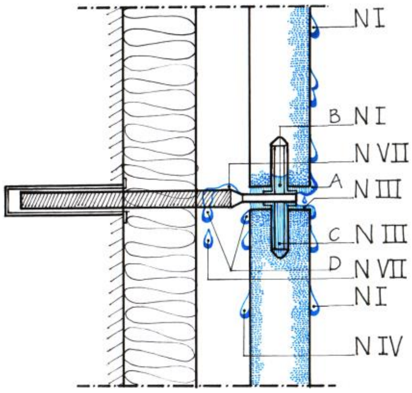

Figure 12. Vertical section (anchorage system).

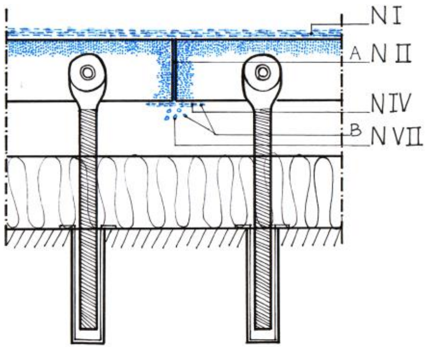

Figure 13. Horizontal section.

3.3 Study-case 3: Sanitary Centre

Year of construction: 2005. Closed since 2008.	*Horizontal Joints:* 0.5 cm width and shaped edges.	*Vertical Joints:* 0.5 cm width and plane.
Fixing system: The 1.3 cm thick fibre cement panels are linearly supported and retained by means of horizontal profiles made of aluminium. These profiles are screwed down on its top and bottom part with self-tapping screws to vertical square profiles made of aluminium.		
Thermal insulation layer: 5 cm thick polyurethane not covered by a WRB.		*Air cavity:* 8 cm width (including profiles).

Table 4. Basic data of the ventilated façade of the study-case 3.

In this case, the entry of WDR in the cavity through the horizontal joints between panels is rather unlikely since the horizontal aluminium profile blocks its pathway (see A in Fig. 17). Contrarily, the kinetic energy of wind-driven raindrops will allow water entrance through the vertical ones easily (level II; Fig. 18). However, whether water will reach the thermal insulation layer (level VII; B in Fig. 18) or only come into contact with the horizontal profile (level V; B in Fig. 17 and A in Fig. 18) and the vertical profile (level VI; C in Fig. 17) is uncertain. The rainwater that collides with the horizontal profile (see B in Fig. 18) will run down and accumulate at the bottom part (level V; A in Fig. 18) by gravity. Albeit, if it comes into contact with the screws it might be forced through the gap to the rod of the screw and / or the backside of the vertical profile by means of wind pressure and capillary suction (see D in Fig. 17). The rainwater impinging on the exterior surface of the vertical profile (level VI; C in Fig. 17) will trickle down by gravity until it reaches the top border of the horizontal profile. Then, it can flow down through the contact interface between the profiles (level VI; E in Fig. 17) or it can be held in the horizontal profile (level V; F in Fig. 17). If the stagnant rainwater reaches the connection between two horizontal profiles by local air currents and / or wind pressure, it might leak and run down either the inner surface of the panel (level IV) or the vertical surface of the horizontal profile (level V; G in Fig. 17). Finally, the rainwater that collides with the panel (level I; H in Fig. 17) will run down by gravity until it reaches the lower border, where it might flow sideways by surface tension and drip down in level III by gravity. Note that whereas the water flowing along the lower face of the panel (level I) might infiltrate in the anchor gap by capillary suction, the water flowing in level III might drip in the gap by gravity (see I in Fig. 17). Like in the before mentioned case, the freezing of this infiltrated rainwater might cause the spalling of the panel (see Fig. 15). In addition, red and black stains over the fibre cement panels and moisture stains over the bottom border of the façade have been identified during the inspection (see Fig. 16).

Figure 14. General view.

Figure 15. Spalling of the panel.

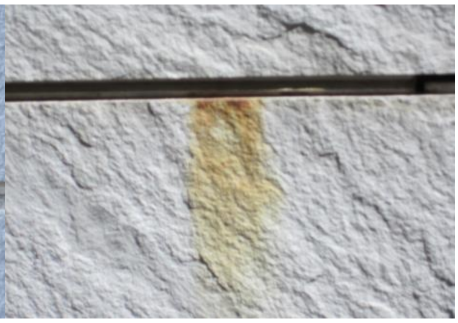

Figure 16. Red runoff stain.

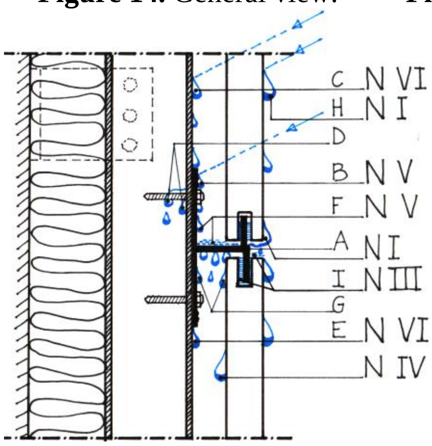

Figure 17. Vertical section.

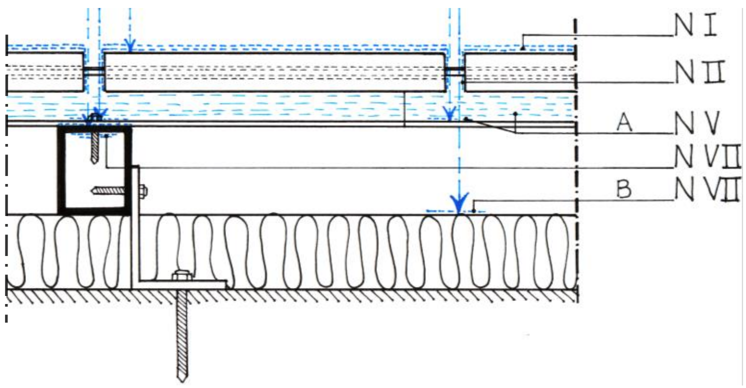

Figure 18. Horizontal section.

3.4 Study-case 4: Residential compound

Year of construction: 2014.	*Horizontal Joints:* 7 cm width and plane.	*Vertical Joints:* 1.1 cm width and plane.
Fixing system: The 1 cm thick fibre cement panels are joined to vertical omega profiles made of aluminium by means of rivets 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 stainless steel brackets. Behind each omega profile an aluminium horizontal profile is located (see Fig. 20).	
Thermal insulation layer: 5 cm thick mineral wool covered by a WRB.	*Air cavity:* 12 cm width (including the profile).

Table 5. Basic data of the ventilated façade of the study-case 4.

Figure 19. General view.

Figure 20. Horizontal profile.

Figure 21. Construction process.

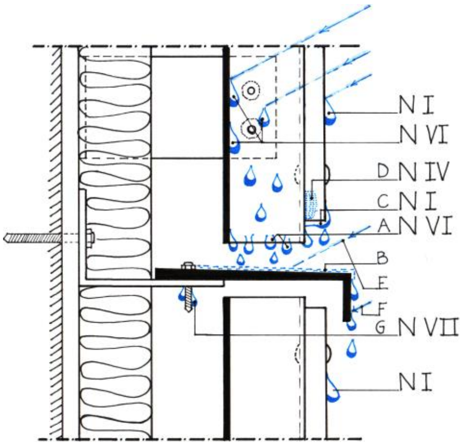

Figure 22. Vertical section.

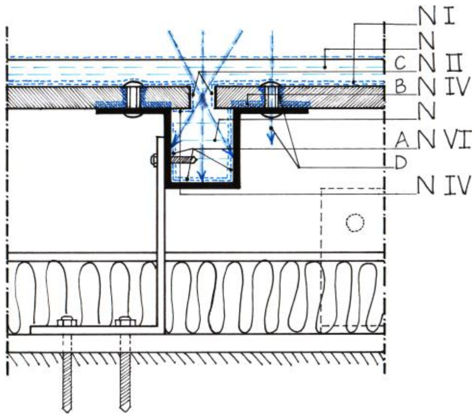

Figure 23. Horizontal section.

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. 22). 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. 23). 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. 22). 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. 23). This phenomenon might also occur when rainwater coming from level II reaches this contact interface by wind forces (see C in Fig. 23) or if water running down level I reaches this interface by surface tension (see D in Fig. 22). 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. 22). 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. 23) 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. 22), 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. In contrast, the entry of rainwater through the lower area of the joint (see F in Fig. 22) 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. 22). No damages have been identified during the inspection of the building.

4 CONCLUSIONS

Below, a table is presented that summarizes all the study-cases showing the supposed levels reached by the rainwater.

Study-case 1	Zinc cassettes	Water management:	I	II	III	IV	V	VI	VII
		Observed damages:	1- Moisture stains and detachment of the paint on the bottom border of the façade (beneath the cavity). 2- Runoff stains (black). 3- Corrosion of bolts. 4- Local corrosion on horizontal surfaces of the cassettes (white stains).						
Study-case 2	Stone plaques	Water management	I	II	III	IV	V	VI	VII
		Observed damages	1- Runoff stains (black and white). 2- Panel spalling close to the anchorage areas. 3- Reported problems of leaks inside the building due to water infiltration through the façade.						
Study-case 3	Fibre cement panels	Water management	I	II	III	IV	V	VI	VII
		Observed damages	1- Runoff stains (black and red). 2- Local interior moisture stains likely due to water infiltration from the façade. 3- Panel spalling on the areas near the horizontal profile. 4 - Corrosion of metallic elements.						
Study-case 4	Fibre cement panels	Water management	I	II	III	IV	V	VI	VII
		Observed damages	1- No moisture stains on the bottom border of the façade.						

Table 6. Summary of the analysis carried out in the study-cases.

It can be concluded that rainwater often infiltrates through the open joint cladding, trickles down the interior surface of the panels (likely wetting in some cases the thermal insulation layer) and drains away at the bottom of the façade. So, in all of the study-cases rainwater reaches the four first levels, with the exception of the fourth study-case, where the horizontal profile prevents that rainwater reaches the level III. The runoff flow along level I might not cause serious damages (only the fouling of the façade) unless the imperviousness of the cladding is vulnerable, as happens in study-case 1. The design of the zinc cassettes fails. It has many openings through which the water infiltrates easily. If no drainage is provided for the runoff flow of level IV, VI and VII the typical moisture stains at the bottom border of the façade might appear, like occur in study-cases 1, 2 and 3. In contrast, in study-case 4 these stains do not turn up since the runoff film of level VI is collected by a component specifically designed to shed it to the exterior. In addition, there is no runoff flow in level IV (only moisture penetration in the panels). Another key aspect of these systems is the drainage of the stagnant rainwater. As shown in Table 1, the retained water in level III and V might cause the most severe damages (spalling of panels and metals corrosion) if it is not drained away, as was evident in study-cases 2 and 3. The damages originated by rainwater flowing at level VII are extremely difficult to detect since it would require the dismantling of the façade. Only when the problem has induced a huge damage it may come to front. Whereas the rainwater penetration in level VII is by means of capillary suction in study-cases 1 and 2, the wind-driven rain can also affect in study-case 3. It is rather unlikely that rainwater reaches level VII in study-case 4.

The visual inspection and the observed damages have corroborated the expected wetting pattern and the rainwater pathways in each study-case. Damages in ventilated façades can occur in visible (cladding panels) and in non-visible components (fixing system and thermal insulation layer). On one side, the problems arising in cladding panels are directly related to the fixing mechanism. The most dangerous fixing systems are those that act as horizontal channels (level III and V), where water might be retained corroding the metallic elements located somewhere around or causing the fracture of the elements that enclose it when it is frozen. On the other side, the damages that sprung in non-visible areas are closely linked with the design of the vertical joints, where the largest amount of rainwater infiltrates. This is the reason why the façades that exhibit more damages are those who have larger and non-protected vertical joints.

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