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Driving Rain Tightness, Intrusion Rates and Phenomenology of Leakages in Defects of Façades: A New Calculation Algorithm

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Cover: Recently rain exposed surface at window-wall interface in laboratory experiment.

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To Christel, Ville

& Hollie

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Abstract

This thesis presents the driving rain tightness of façades with façade details as well as the water leakage flows that can be expected. Furthermore, it describes the key mechanisms for water leakage in defects in the outermost layer of external walls. A new algorithm has been developed and validated based on the empirical measurements of water leakage. In order to produce accurate calculations for water leakage, the geometry and dimensions of the defects need to be precisely defined. Extensive data is presented in this thesis that facilitates relatively reasonable assumptions of the water leakage flow, even though the geometry and dimensions of the defects are unknown.

The aim is to improve knowledge, generate more data and developing a calculation algorithm for water leakage flow. This would increase the ability to produce more accurate two or three-dimensional moisture calculations and reliable probabilistic risk moisture analyses.

The research is mainly based upon laboratory testing and experiments, and field measurements.

The results point out that water leakages are almost always expected in small concealed or invisible defects in façades with façade details such as window-wall interfaces, etc., regardless of the façade type and façade systems such as unventilated, ventilated and pressure-equalized façades.

Four of the greatest importance for the water leakage flow in experimental trials were; façade material, the size of the hole, the size of the dam and hydrostatic pressure derived from the building. Additional two factors are pressure difference across the façade layer and water flow on the façade due to driving rain which derives mainly from the prevailing weather conditions.

In order to use the algorithm, the important factors, as mentioned above, need to be considered together with a table that has been prepared with the constituent constants.

Based on an assessment of all the results and assuming carefully completed assembly, it is reasonable to assume that the water leakage flow through each point leakage corresponds to 0.5-2% of the vertical water flow cross a unit width of the façade at the given height.

The lower proportion within the range only refers to holes/slits, while the higher proportion refers to holes/slits with dams.

Key words: driving rain, water leakage, rain resistance, hole, obstacle, dam, protrusion, deficiency, water flow, catch area, leakage flow, façade details, window-wall interface, fenestration, EN 12865

Driving Rain Tightness, Intrusion Rates and Phenomenology of Leakages in Defects of Façades: A New Calculation Algorithm
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Summary

Damage has occurred in recent years to external walls caused by rain intrusion. The background is that the rain resistance of façades, joints and connecting details has been insufficient, which has contributed to moisture damage issues inside moisture sensitive external walls. Information on the driving rain tightness of new façades or the driving rain tightness of connections between façade and windows etc. is not widely available. Moreover, there is currently a lack of knowledge as to how water leakage occurs, so realistic moisture calculations and reliable risk analyses for new façades have not been feasible. This means that there are major risks in moisture safety that could lead to insufficient energy efficiency and durability which could lead to a rise in costs and environmental impact. Today, however, climate data and calculation programs are available for modelling rain load, run-off water, water absorption on façades etc. Based on this, the aim of this research is to improve knowledge and generate more data on driving rain tightness, and water leakage flow through the outer layer of the external wall. In addition, the aim has also been to develop a new algorithm in order to calculate water leakage flows more accurately. As defects and water leakages are usually pointwise present, moisture calculations need to be made using two or three dimensions in order to make them relevant.

This thesis is based on:

- field measurements of moisture and temperatures in different external walls in seven buildings located at different sites in Sweden,
- a compilation of over 100 driving rain trials on a range of façades and systems with façades details,
- focused experiments for four different commercial façades, partly with the best possible assembly and partly with commonly occurring imperfections,
- measurements of water leakage flow for seven different defects at the façade details,
- measurements of water leakage flow in a large number of well-defined holes and slits with different dams (protruding details),
- theoretical description of the behavior of the water on material, in holes, along with an analysis of measurement results with linear regression and validation.

The results show water leakage in more than 90 % of all the façades studied, and in more than 60 % of all window-wall interfaces. Consequently, it can be deduced that today's façade solutions are difficult or impossible to make rain tight, in other words the outermost layer of the external wall is normally not rain resistant due to defects at façade details. One reason why there was no major difference in the results between unventilated and ventilated pressure-equalized façades is probably due to the presence of defects at protruding details

(dams) and hydrostatic pressure due to difference in height level between holes inlet and outlet. Many holes slope downwards which generates increased hydrostatic pressure in the hole. Additionally, results from field measurements show water leakage in timber frame walls from driving rain in 5 of 7 new buildings. This is regardless of whether they are ventilated or not, and consequently confirms that façades are not usually raintight. The results show that during the tests and experimental trials, the water leakage through each point leakage corresponds to 0.5-2% of the vertical water flow cross a unit width of the façade at the given height width for carefully assembled façades. This indicates that even though an assembly is conducted carefully, there are still small, concealed or invisible defects. As a result, point water leakage through the outermost layer should be included in the moisture dimensioning of external walls.

A new algorithm for calculating water leakage has been developed based on empirical values. In many cases, linear regression analysis indicates an acceptable correlation. The factors that had the greatest importance for the water leakage flow in experimental trials were:

- façade materials
- the size of the hole/slot,
- the size of the dams,
- hydrostatic pressure (gravity) over the hole,
- pressure difference across the façade layer
- the water flow on the façade

For four of the factors; façade material, the size of the hole, the size of the dams and hydrostatic pressure, are derived from the building, while the other two factors derive mainly from the prevailing weather conditions. In order to use the algorithm, a table has been prepared with the constituent constants. The constants are selected depending on the type of material, holes and protrusion as well as heavy or light driving rain load.

Protruding details (dams) can increase the water leakage flow through the holes, as compared to holes without dams. The hydrostatic pressure can lead to equally strong pressure forces such as wind pressure, which means that significant water leakage can also be expected in pressure-equalized façades. All the water that flows to a hole with a diameter of more than 1 mm can easily penetrate which is why the maximum water leakage flow is directly linked to the water flow on the façade. If water dams up and is directed to the hole, all of the water collected could also penetrate. The reason for this is that the inflow capacity through the hole can be greater than the water flow that usually occurs on façades.

Sammanfattning

Denna avhandling redogör för regntätheten hos fasader med fasaddetaljer och vilka inläckageflöden som kan förväntas. Vidare redogör den för de väsentligaste mekanismerna för inläckage i otätheter i det yttersta skiktet i ytterväggar. En ny algoritm har tagits fram baserad på empiriska mätningar av inläckage. För att kunna göra noggranna beräkningar av inläckage behöver otätheternas geometri och mått kunna definieras exakt. Det finns omfattande data i denna avhandling som möjliggör att relativt rimliga antaganden av inläckageflöde kan göras, trots att otätheternas geometri och mått är okända.

Skador har på senare år uppkommit på fasader och de är orsakade av inläckage. Bakgrunden är att fasader och anslutningsdetaljers regnskyddande funktion har varit otillräcklig, vilket bidragit till fuktskadeproblem inuti fuktkänsliga ytterväggar. Uppgifter om nya fasaders regntäthet eller regntäthet hos anslutningar mellan fasad och fönster etc har varit relativt sällsynt. Vidare har det saknats kunskap om hur inläckage sker, varför realistiska fuktberäkningar och pålitliga riskanalyser av nya fasader inte varit möjliga att göra. Det innebär att det finns stora risker i fuktsäkerheten som kan leda till att inte tillräcklig energieffektivitet och livslängd uppnås och föranleder till ökade kostnader och miljöbelastning. Idag finns det dock klimatdata och beräkningsprogram för att modellera regnbelastning, avrinningsvatten, vattenabsorption på fasader etc. Med utgångspunkt i detta så är målet med denna forskning att öka kunskapen och ta fram mer data om regntäthet och inläckageflöde genom det yttersta skiktet i ytterväggen. Vidare har målet också varit att utveckla en ny algoritm för att mer exakt kunna beräkna inläckageflöden. Eftersom otätheter och inläckage vanligtvis finns punktvis behöver fuktberäkningar göras i två eller tre dimensioner för att de ska bli relevanta.

Denna avhandling är baserad på:

- fältmätningar av fukt- och temperatur i olika ytterväggar i sju byggnader lokaliserade på olika platser i Sverige,
- en sammanställning av över 100 kommersiella slagregnsprovningar av olika typer av fasader och fasadsystem,
- riktade experiment av fyra olika kommersiella fasader dels med bästa möjliga montage dels med vanligt förekommande brister,
- mätning av inläckageflöde i sju olika otätheter vid fasaddetaljer,
- mätning av inläckageflöde i ett stort antal väldefinierade hål och slitsar med olika utstickande detaljer (dämmen),
- teoretisk beskrivning av vattnets beteende på material, i hål samt analyser av mätresultat med linjär regression och validering av modell.

Resultaten visar på inläckage i mer än 90% av alla studerade testväggar och i mer än 60 % av alla anslutningar mellan fasad och fönster. Därmed kan konstateras att dagens fasadlösningar är svåra eller omöjliga att göra regntäta, det vill säga det yttersta skiktet i ytterväggen är oftast inte regntätt på grund av otätheter vid fasaddetaljer. En anledning till varför det inte framkommit någon markant skillnad i resultat mellan oventilerade och ventilerade tryckutjämnade fasader är förmodligen på grund av att många otätheter återfinns vid utstickande detaljer, oberoende av fasadsystem, som ger upphov till att vatten däms upp och

ger ett betydligt hydrostatiskt tryck. Många hål lutar nedåt vilket ger ett ökat hydrostatiskt tryck i hålet. Vidare visar resultat från fältmätningar på inläckage till träregelstommen av slagregnsinträngning i 5 av 7 nya byggnader. Detta oberoende av om de är ventilerade eller inte, och bekräftar således att fasader vanligtvis är otäta. Resultaten visar att vid provningar och experimentella försök ligger ofta punktinläckageflödet omkring 0,5 till 2 procent av vattenbelastningen per meter fasadbredd för noggrant monterade fasader. Det tyder på att även om montaget görs noggrant så finns det ändå små, dolda eller osynliga otätheter. Därför bör punktinläckage genom det yttersta skiktet beaktas vid fuktdimensionering av ytterväggar.

En ny algoritm för beräkning av inläckage har tagits fram baserad på empiriska värden. Analys med linjär regression visar i många fall på relativt god korrelation. De faktorer som hade störst betydelse för inläckageflödet vid experimentella försök var:

- fasadmaterial
- hålets/slitsens storlek,
- dämmets storlek,
- hydrostatiskt tryck (gravitation) över hålet,
- tryckskillnad över fasadskiktet
- vattenbelastning på fasaden.

För fyra av faktorerna; fasadmaterial, hålets storlek, dämmets storlek samt hydrostatiskt tryck så härrör de till byggnaden, medan de två andra faktorerna härrör framförallt till väderförhållande. För att kunna använda algoritmen har en tabell tagits fram med ingående konstanter. Konstanterna väljs beroende på typ av material, hål och dämme samt hög eller låg regnbelastning.

Utstickande detaljer, dämmen, kan öka inläckaget genom hål, jämfört med hål utan dämme. Det hydrostatiska trycket kan ge upphov till lika stora tryckkrafter som vindtryck varför betydande inläckage också kan förväntas i tryckutjämnade fasader. Allt det vatten som rinner mot ett hål med diameter över 1 mm kan tränga in varför det maximala inläckageflödet är direkt kopplat till vattenflödet på fasaden. Om vatten däms upp och leds mot hålet kan även allt det vatten som samlats upp tränga in. Anledningen är att inflödeskapaciteten genom hålet kan vara större än den vattenbelastning som vanligtvis uppkommer på fasader.

Nyckelord: slagregn, vattenläckage, regninträngning. regntäthet, hål, dämme, utstickande detaljer, otätheter, vattenbelastning, läckageflöde, fasaddetaljer, fönsteranslutning, EN 12865

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Preface

This thesis summarizes the studies carried out in the research project *Risk Analysis of New Innovative Facade Systems for Energy Efficiency of the Million Program Buildings, Step 1*. The project was initiated by Professor Carl-Eric Hagentoft, Chalmers, when he was operating agent for a program in the International Energy Agency (IEA/ECBCS) with the title: *Annex 55, Reliability of Energy Efficient Retrofitting- Probability Assessment of Performance and Cost (RAP-RETRO)*. The aim of the program was to answer the question: How do we design and realize robust retrofitting with low energy demand and life cycle costs, while controlling risk levels for performance failure?

The main financiers are the Construction Industry's Organisation for Research and Development in Sweden (SBUF), The Swedish Energy Agency (within E2B2) and RISE Research Institutes of Sweden. In addition, participating partners are; NCC, Weber, STO, Paroc, Soleed, Boxmodul, WSP, PEAB and Wästbygg. Furthermore, financing has been provided by several travel contributions from the Maj and Hilding Brosenius Research Foundation. I am very grateful to you all.

I would like to thank my colleagues at RISE, my colleagues at the laboratory for driving rain simulations at RISE and my colleagues within the research project and financier for their contributions and collaboration.

My penultimate thanks go to main supervisor Professor Carl-Eric Hagentoft and assistant supervisor Associate Professor Paula Wahlgren, both Chalmers, and to assistant supervisor Adjunct Professor Kristina Mjörnell, RISE and LTH, for all your encouragement and support in all studies and in the final step in summarizing them for this thesis.

Finally, I am grateful for my wonderful and beloved wife Christel´s support and for my brilliant and beloved children Ville and Hollie´s understanding through the years.

Lars Olsson

Gothenburg, November 2018

List of publications

This thesis is based on the work contained in the following papers, referred to by boldfaced roman numerals in the text:

Leakage occurrence and leakage position

I. OLSSON, L. 2014, Results from laboratory tests of wind driven rain tightness in more than 100 façades and weather barriers, 10^{th} Nordic Symposium on Building Physics, 15-19 June, 2014, Lund, Sweden: Lund University.

II. OLSSON, L. 2015, Long-term Field Measurements of Moisture in Wooden Walls with Different Types of Façades: Focus on Driving Rain Tightness, Energy Procedia, Vol. 78, pp. 2518-2523.

III. OLSSON, L. 2016, Laboratory study of driving rain resistance of four façade systems with window fittings - Experimental results of leakage flows, CESB 2016 - Central Europe Towards Sustainable Building 2016: Innovations for Sustainable Future, pp. 1233-1240.

Magnitude of leakage flows

IV. OLSSON, L. 2016, Laboratory study of rates of inward leakage in seven different gaps in a façade exposed to driving rain or water splash, Buildings XIII – Thermal Performance of the Exterior Envelope of Whole Buildings Conference, Clearwater Beach, Florida, US: ASHRAE.

V. OLSSON, L. 2017, Rain resistance of façades with façade details: A summary of three field and laboratory studies, Journal of Building Physics, 2018, Vol. 41(6) pp.521–532.

VI. OLSSON, L. 2017, Rain intrusion rates at façade details - a summary of results from four laboratory studies, Energy Procedia,132, pp. 387-392.

Conceptual model of leakage flows

VII. OLSSON, L, Hagentoft, C-E. 2018, Driving rain induced water leakage through defects in façades - A new algorithm, Scientific Journal, Submitted.

VIII. OLSSON, L, Hagentoft, C-E. 2018, New algorithm for water leakages flow through rain screen deficiencies, 7^{th} International Building Physics Conference, 23-26 Sep, 2018, Syracuse, NY, USA.

My work input in **Paper VII and VIII** was as main author, where I performed the experiments, did the analysis and wrote the papers, apart from equations and linear regression.

Other related publications by the author:

- OLSSON, L. 2014. Moisture Conditions in Exterior Wooden Walls and Timber During Production and Use. Licentiate thesis, Gothenburg, Sweden: Chalmers University of Technology.
- OLSSON, L. 2016. Regninläckage och dess mekanismer i fasader (SP Rapport 2016:82), [In Swedish], Borås, Sweden: SP Technical Research Institute of Sweden.
- Hagentoft, C-E, Olsson, L. 2017. Rain Intrusion behind Insulated Modules Attached to Façades of Old Buildings: A Probabilistic Modelling Approach, Australasian, Building Simulation, November 2017, Melbourne, Australia.

1 Introduction

One of the primary functions of external walls and façades is to protect the indoor environment and moisture sensitive parts of the building from the outside climate such as driving rain. The driving rain tightness function has been inadequate and extensive moisture damage problems have occurred due to water leakage in new, well-insulated rendered façades, called faced sealed or ETICS (External Thermal Insulation Composite System) in Sweden, North America and New Zealand (Morrison Hershfield Limited, 1996, Williams & Williams, 1998, Lawton, 1999, CMHC, 2000, Building-Industry-Authority, 2003, Samuelson et al., 2008, Woodbury, 2009, Gibson, 2009, Jansson, 2014). The reason is the water leakage at defects, particularly at the façade details, such as connections between façade and windows, at balconies, ventilation and cable penetrations where rain water has leaked in. Significant water leakage has occurred despite the defects being concealed or invisible. Water leakage is also common in other types of façades with damage to a greater or lesser extent to moisture sensitive external walls, (Sandin, 1993b, Nevander & Elmarsson, 1994, Waltz & Nelson, 1999, CMHC, 2003, Geving, 2011). Furthermore, it is generally established that driving rain can leak through masonry façades as they have cracks, often small and invisible cracks, thin cracks with a thickness in parity with the diameter of a strand of hair (Sandin, 1993a, Straube, 2010, Van Den Bossche et al., 2011).

On the other hand, there are many other types of façade materials, such as painted wooden panels, plaster, concrete elements, metal panels, etc. that may well be waterproof, and more or less water repellent, free from cracks, and for these reasons can be considered as impermeable to rain. In these cases, it is not the material in the cross section of the wall or in the middle of a seamless surface on the external wall, which is the critical section. Instead, there are joints, seals and attachments in the façade that are impermeable (Straube, 1998, Waltz & Nelson, 1999, Lacasse et al., 2009) as well as connections between façade materials and windows, doors, balconies, electrical and ventilation penetrations (Scott, 1984, Tsongas et al., 1998, Kudder & Erdly, 1998, Carll, 2000, Beaulieu et al., 2002, Lacasse, 2003a, Teasdale-St-Hilaire & Derome, 2005, Bassett & Overton, 2015). The risk of rain penetration is greater if there are façade details than it would be in a seamless façade. Many of the façade details protrude from the façade, which means that water can change direction or flow together (Garden, 1963) and in both cases can lead to increased water load. In addition to rain you have condensation, melt water from snow, etc. which can cause water exposure to façades and façade details, and this can also be in the form of water splashes (Garg et al., 2007). Water splashing alone can cause an increased water load, especially if water is directed together at the details and then falls on underlying details generating splashes. In addition, water splashing means that surfaces that are relatively well protected from driving rain may be exposed to water splashes.

Driving rain is the most extreme moisture load that façades and external walls are regularly exposed to. Nevertheless, relatively little research has been conducted on driving rain tightness and water leakage flows in façades and external walls with commonly used façade details such as windows, balconies, electrical and ventilation penetrations, etc. (Teasdale-St-Hilaire & Derome, 2005, Hens, 2010, TenWolde, 2011).

The way in which façades are exposed to driving rain, with different rain intensities, frequencies and the degree of water absorption on the façade surface, and modelling with calculation programs, has been studied considerably more (Lacy, 1965, Beijer & Johansson, 1976, Sandin, 1987, Zhu et al., 1995, Straube, 1998, Choi, 1999, Adl-Zarrabi & Högberg, 2001, Högberg, 2002, Hall & Hoff, 2002, Cornick & Lacasse, 2005, Geving et al., 2006, Hens, 2010, Straube, 2010, Blocken et al., 2013, Kubilay et al., 2014, Johansson et al., 2014, Künzel, 2015, Finken et al., 2016, Tariku et al., 2016) and there are standardized methods (ISO, 2009) in place for calculating driving rain on façades. Furthermore, there are standard test methods for simulating driving rain under pulsating air pressure (SIS, 2001) on façades.

Overall, data is available to be able to take into account the amount of driving rain that reaches the façade surface, but insufficient data and knowledge about water leakage amounts that passes the façade layer (Hens, 2010, TenWolde, 2011). However, there are certain studies that focused on water leakage flow and developed an empirical function with regard to water load and air pressure difference (Lacasse, 2003b, Sahal & Lacasse, 2005, Lacasse et al., 2009, Van Den Bossche et al., 2012). Several are conducted under static air pressure difference. The issue is that these are restricted to few defects and it does not appear to indicate how representative they are in reality. Consequently, there is a need for more knowledge about driving rain tightness, the leakage rate, water leakage process and more data to be really able to produce reliable theoretical calculations (Hens, 2010, Ngudjiharto et al., 2014) and produce risk analyses for both new production and renovation with new façades (Bednar & Hagentoft, 2015). In addition, there has been no tradition or claim in Sweden or within EOTA (European Organisation for Technical Approvals) to show the driving rain tightness for façades, external walls and layers in the wall with frequently used façade details (EOTA, 2013). This could also be a further explanation as to why specific data and performance have been generally lacking. In recent times, however, the Swedish National Board of Housing, Building and Planning has set (Boverket, 2014) more clearly defined requirements for external walls and connection details than previously, and a new guideline, ETAG 034, has been issued (EOTA, 2012) for façade systems with air gaps behind which includes some trials of driving rain tightness depending on the façade system. In the long run, this would lead to more data on driving rain tightness in these systems. If we continue to lack the knowledge, data, and performance statements, there are risks in terms of moisture-related damage, indoor environmental problems, increased renovation and action initiatives, and not achieving energy efficiency. All in all, this results in an increased environmental impact and a rise in costs.

1.1 Hypothesis

The hypothesis is that all façades with façade details has driving rain intrusion, even if they have been assembled in a proper way. If the hypothesis is true, then the water leakage amount is a factor that need to be included in moisture calculation and there is a need to estimate the amount of leaking water.

1.2 Aim

The goal is to improve knowledge and generate more data on driving rain tightness, water leakage flow and on developing a new calculation algorithm for water leakage flow. This increases the ability to produce more accurate predictions and calculations on water leakage through façades. Questions to answer are: How common are leakages, where do they occur, why are window-wall interfaces so problematic, how large are the leakage flows and how can the leakage flows be mathematically described.

1.3 Scope

This thesis investigated driving rain tightness and water leakage flow through façades exposed to driving rain, including façade layers with frequently used façade details. The research addresses façades with protruding details (such as connections between façade and windows, balconies, electrical and ventilation penetrations), as well as joints and attachments. Long term field measurements are made to determine the extent of leakages in real buildings. Large-scale laboratory tests are performed to study the leakages more in detail and to quantify the leakages. An algorithm is designed so that more accurate calculations of expected leakage flows through façades can be made. Small scale laboratory measurements are performed for phenomenological studies that forms a base for the conceptual model.

The long-term field measurements include seven buildings with different types of façades, most during seven years, in different locations, see **Paper II and V**.

The large-scale laboratory measurements include a compilation of over 100 commercial tests, covering tightness to driving rain and water leakage flow for different types of façades and external walls, which have been installed by suppliers, see **Paper I, V and VI**. In addition, four different commercial façade solutions, covering a total of 29 window-wall interfaces, were tested with or without conscious imperfections by the façade suppliers, see **Paper III, V** and **VI**. The final large-scale laboratory tests were performed on seven different and common façade details, such as windows, part of balcony, ventilation pipe, metal flashing, see **Paper IV** and **VI**.

The small-scale measurements were made to increase the knowledge on water flow in leakages and to create and validate the algorithm and included leakage factor, see **Paper VII** and **VIII**.

1.4 Limitations

The thesis does not cover the functions, performance or robustness of the façade or critical moisture conditions within the wall construction, only rain intrusion in the interface between façade details and façade, either through the outermost layer or all the way into the load-bearing structure. Nor does it cover data of wind driven rain intensity, runoff patterns, runoff rate or calculation of moisture conditions.

Regarding rain and wind loads in the field measurements, it is the actual stresses that the façades have been exposed to that are studied and these are described by data from nearby measurement stations during the field measurement period.

The algorithm is based on to empirical results from measurements with well-defined holes, and it is assumed that water flows vertically down the façade, and the façade is saturated or non-moisture-absorbing.

2 Theoretical framework

The investigations on driving rain tightness and rain leakage in this thesis requires a theoretical framework to understand the leakages and to create a leakage algorithm (see Chapter 5). In the following, a theoretical description of the most dominating factors and forces involved, that are of high practical significance to the inward leakage process, are described. These include, the path and behaviour of the water that falls onto the façade with descriptions of water flow, leakage factor and transport through leakages. This is more thoroughly described in **Paper VII and VIII**,

2.1 Theory of waters behaviour on materials

Whether or not water is attracted or discharged from material or air depends on the surface energy (surface tension) (De Gennes et al., 2004). If the surface energy is greater than the water, the water is attracted to the material or the reverse if the surface energy of the material is lower than that of the water (Hall & Hoff, 2002). This explains why water can behave differently for different materials, why the water likes to flows along material and that the water is more likely to dissipate, known as wettable, on the surface of the material (Garden, 1963, De Gennes et al., 2004). If there are capillaries, holes or similar in the material that causes capillary forces to form, the water is drawn or absorbed into the material even more (Garden, 1963) but not if the material is saturated (Hall & Hoff, 2002). A prerequisite for capillary forces to form is that the surface energy of the material must be higher that of water. Mineral and metallic materials generally have very high surface energy, but on the other hand, many plastics have an equal or lower surface energy than water.

There are formulas for calculating the water surface tension or capillary forces that can transport water in holes and between two tightly spaced surfaces. Additionally, there are formulas in place for determining water flow through holes. These formulas are described in **Paper VII**. As water is liquid, the highest water pressure occurs at the bottom of a water collector due to the forces of gravity. This means that if a hole in a façade is filled with water, it can have relatively large pressures in the bottom, or in the outlet of the hole, in particular if the hole is inclined (reaching magnitudes of 100 Pa for centimetre high holes). The driving force for the water to flow through the hole due to the hydrostatic pressure can therefore be in parity with the wind pressure loads that can arise against façades. Formulas for these forces and pressures are described in **Paper VII**.

2.2 Water leakage process

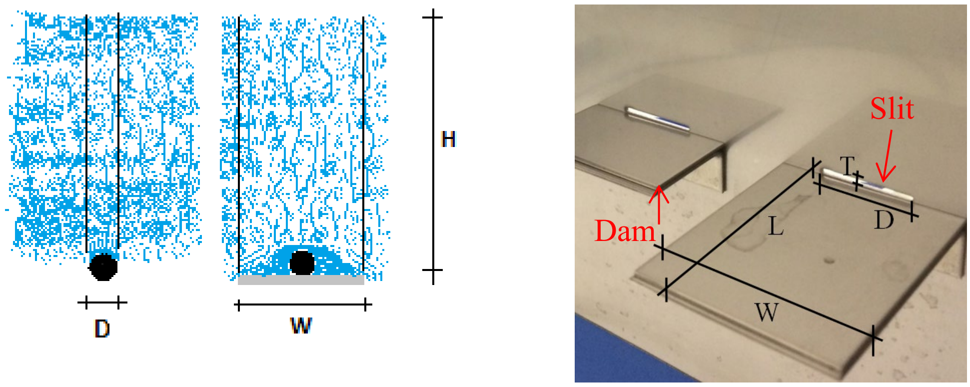
The water leakage process is relatively complicated but can be described with simple relationships.

If the façade is capillary saturated or non-moisture-absorbing, then all of the water that is deposited on the façade surface will run downwards and be added along the vertical façade surface defined as water flow on the façade. The greatest water flow thus occurs at the bottom of the façade provided there are no water-diverting details. The water quantity that loads a water penetration or hole, G_{max} (kg/s), is based on the area (catch area) above the defect, defined by height H, (m) and hole width D (m) (without obstruction/dam), or dam width W (m), see Equation (1) and Figure 1(a). The width of the catch area is made up of either the width of the hole (D) or the width of the dam (W). The dam can redirect water from surfaces next to the hole so that more water reaches the hole. Notations for the geometry of the hole/slit and dam are also provided in Figure 1(b). The driving rain intensity (deposited on the façade) is denoted g_{DR} (kg/(m^{2}s)).

$$G_{max} = H \cdot D \cdot g_{DR} \quad \text{(no dam)} \quad \text{or} \quad H \cdot W \cdot g_{DR} \quad \text{(with dam)} \tag{1}$$

The water leakage rate through the defect is denoted G (kg/s). We define a factor η (-) describing how efficiently the caught water is actually leaking in through the façade layer, see Equation 2.

$$G = \eta \cdot G_{max} \qquad 0 \leq \eta \leq 1 \tag{2}$$



a) *b)*

Figure 1. (a) Catch area as regards hole width (D) or dam width (W) plus façade height (H). The assumed catch area is shown within the two vertical lines. (b) The figure shows a vertical stainless steel sheet with several horizontal stainless steel dams located underneath of defects consisting of horizontal slits. Further descriptions of dimensions are given with notations such as protrusion length (L) and height (T) of slits, as used in Chapter 5.

Under the assumption that there is no resistance for the water to flow through a hole in an infinitely thin vertical layer, the water that hits the hole would then be evenly distributed on each side of the thin layer due to uniformity. A factor describing the resulting distribution of water is then $\eta = 0.5$, which can be termed the water leakage factor. This term is used later to analyse the results in the proposed algorithm, which is also in part with other studies. The reasoning for this is described in more detail in **Paper VII**.

Further, it is assumed that the pressure difference, P_{tot}, will be an important factor to include in a calculation algorithm for estimated leakage flow. The estimated value of the leakage factor can be expressed as:

$$\eta_{est} = f(P_{tot}) \tag{3}$$

The total pressure difference for a non-absorbing surface is obtained through:

$$P_{tot} = P_w + P_h - P_{men} \tag{4}$$

The counter pressure in the meniscus, P_{men}, that forms on the rear surface, due to surface tension, counteracts leakage, while the pressure from the water column, P_h, and the wind, P_w, helps to increase the leakage.

For an absorbing material, a counteracting meniscus does not form on the rear of the hole in the same systematic way and can be neglected based on results in experimental results in Chapter 4. Thus,

$$P_{tot} = P_w + P_h \quad (5)$$

For the sake of simplicity, the effect of the pressure in rivulets, P_{riv}, has been excluded from this description. However, it may be of significance for hydrophobic and non-absorbing façade materials with low surface energy such as plastic surfaces and prevailing water flows in rivulets: This is further described in (Hagentoft & Olsson, 2017).

There are physical limitations for water leakage flow. In **Paper VII**, calculations have been made using water leakage formula, Equation 8 in **Paper VII**, which shows that, even for a heavy water flow of 2.9 l/min,m façade width, it is not until the hole begins to be less than 1 mm in diameter that the flow can begin to be restricted by the hole size. If, on the other hand, there is a dam underneath the hole, the dam creates an increased water load on the hole, which requires a somewhat deeper analysis, see further in **Paper VII**.

3 Field measurements and laboratory set-up

In order to determine the driving rain tightness and the water leakage flow in real façades and to obtain input data for the algorithm, a number of experiments in different scales have been performed (field measurements, large-scale laboratory measurement and small-scale laboratory measurements). The initial field measurements were made to study the actual stresses that the façades were subjected to with respect to rain and wind loads. Measurements were performed in seven buildings with different types of façades, most during seven years. The driving rain that reached behind the second line of defence (the weather barrier) was measured using wireless sensors (for temperature, relative humidity and moisture content) in the timber structure near façade details. Weather data were taken from nearby weather stations. Some examples of sensor location in the walls are indicated by red arrows in Figure 2 together with photo of two of the sensors.

Method descriptions for the field study etc. are presented in more detail in **Paper II, V.**

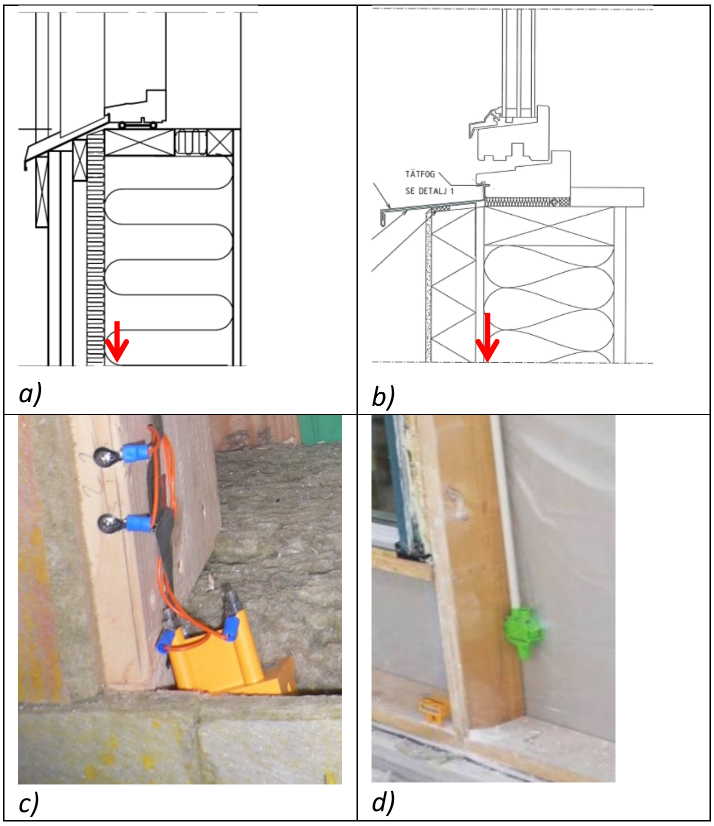


Figure 2. Vertical cross-section of external walls (a–b) with part of window-wall interface. The outdoor area is to the left. The red arrows show the studied positions. Photo (c) shows the position of a sensor in a residential building of seven-storey height. Photo (d) shows the position of a sensor in a residential building of two-storey height.

In order to further understand the results from the field measurements and to quantify the leakages through the façades, large-scale driving rain laboratory measurements on 14 different types of details, such as pipes, balconies and screen roofs, and an additional 29 measurements on window-wall interfaces, have been performed.

For the driving rain tests in the laboratory, a standardised European method has been used; EN 12865 ”Determination of the tightness of external wall systems to driving rain under pulsating air pressure” (SIS, 2001). The reason why the method uses pulsating air pressure is that it is more realistic than static air pressure. The applied pressure differences were 0 Pa, 0-150, 0-300, 0-450 and 0-600 Pa in most cases. A pressure difference of 600 Pa corresponds to storm, approximately 30 m/s in wind speed, and 60 mm in water column as hydrostatic pressure. The method also includes rain load without any air pressure difference at all (0 Pa), which corresponds to pressure-equalized façades. Rain load was made of water spray created with water spray nozzles all across the façade area. The exposed surface is in a rain chamber and the inside of the wall is in a normal laboratory climate about 20ºC and 25-50 % RF. The pulsating air pressure was created in the rain chamber using a fan, which produced differential pressures across the wall. The pressure difference over different layers in the wall, depends on the air leakage rate of each layer in relation to the entire wall and is also somewhat dependent on the flexibility of the air barrier and compressibility of the air volume (Garden, 1963, Rousseau et al., 1998, Van Den Bossche, 2013).

Rain leakage was detected by using indicators that consisted of absorption paper and thin electrodes for resistance measurement, in the study of compilation of over 100 commercial tests. As façades usually consist of multiple façade details, the façade details are important in the testing of commercial façades, see Figure 3 and **Paper I.**

Figure 3. Example of a commercial test wall (size 3 x 3 m) with façade details; windows, balcony, and two fixings (marquis and downpipe fastener).

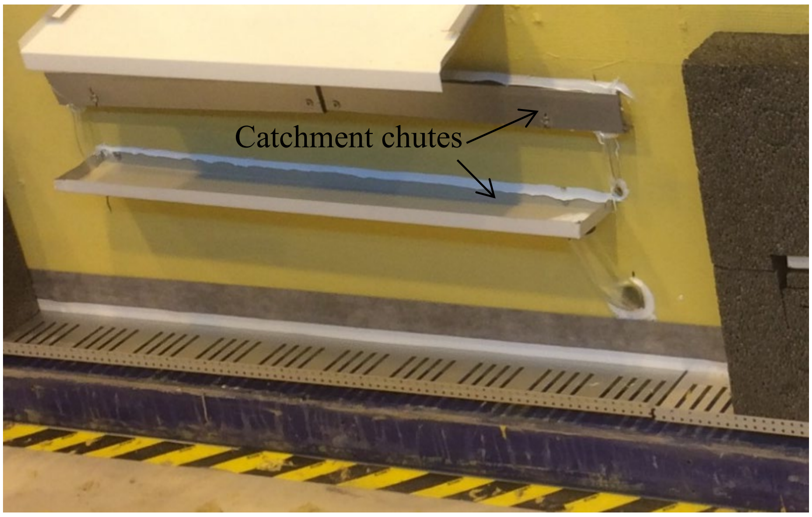
Additional laboratory measurements were performed on windows, a common and problematic detail, where also the leakage flow was measured for various workmanship. Four different façade solutions were evaluated, see Figure 4. All four walls have wall sizes of 3 x 3 meter, and a total of 29 windows were tested, see also **Paper III**. The walls consisted of three horizontal rows of windows to represent a façade of a multi-storey building. The façades were divided into three vertical sections, for three of the four walls, where one section was assembled in the best possible way, and the other two with imperfections based on field experience or assembled by staff who did not undergo any special training on the system.

a) b) c) c)

Figure 4. (a) Ventilated façade with polymer composite boards, (b) 15 mm thin prefabricated high-performance concrete sandwich element with elastic joints, (c) 20 mm plaster façade with 200 mm mineral wool with drainage possibility and weather barrier (second line of defence), (d) 8 mm plaster on 100 mm EPS with drainage possibility and weather barrier. Water spray racks are shown in (c).

Within the walls, under the bottom of window frame, collecting trays were installed for measuring the water leakage amount and a little further down, collecting chutes were installed under the details etc. and led with a hose to a closed collecting container, to measure the water leakage flows, see Figure 5.

a)

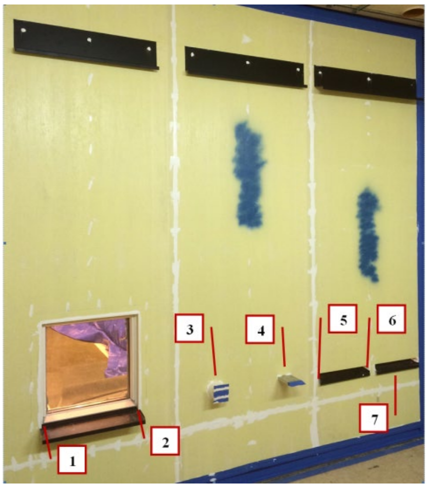


b)

Figure 5. (a) Photo of a collection tray that was placed in the gap under the window frame (the gap was air sealed on inside with transparent tape). (b) Photo of catchment chutes positioned on the outside of the weather barrier, between the façade (to be mounted) and the weather barrier, the smaller just below the exterior window sill and the larger placed approximately 30 cm above the bottom of the wall. To the right of the image, you can see the installation of EPS-insulation in progress.

Based on the field measurements and previous laboratory experiences, seven defects were created in connections to façade details in a full scale 3 x 3 metre experimental wall. The defects were made in or between a water-repellent plaster-based boards and details. The material had a thickness of 10 mm and matching non-absorbing façade layer. In addition to driving rain testing according to EN 12865, splashing is also investigated. For this reason, special external flashings were fitted high up on the façade, as shown in Figure 6a, to create water drip. The applied rain load of 0.55 l/min, m above flashings are not included in given water flow on the façade of 2.9 l/min, and is indicated in the results as splash.

At the rear of the façade layer collecting channels were installed that led to glass bowls, see Figure 6b and **Paper IV**.



a)

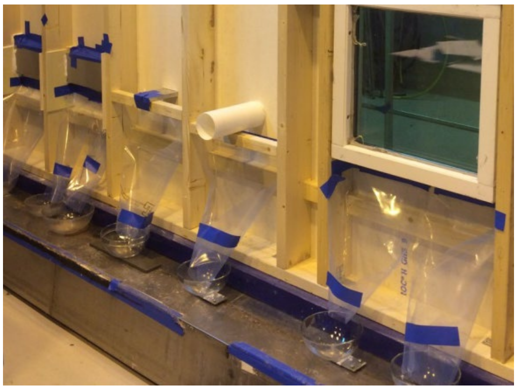

b)

Figure 6. (a) Photo of the front of the wall element with the defects in the details numbered according to Table 1 in Chapter 4.2, (b) Photo of the rear of the experiment wall with collection funnels and bowls.

In order to create a conceptual model that can describe the behaviour of the water, including, the path of the water, the water flow, the transport through leakages as well as dependence of façade material, small-scale experiments were made. The experiments used well-defined holes, slits and dams, see Figure 1 (b) and Figure 7 and **Paper VI** and **VII**, and the façade surface above holes and slits that are exposed to rain was 1 metre high. The façade materials consisted of three different façade materials, including fibre cement board (6 mm in thickness), polycarbonate board (6 mm) and stainless steel sheet (1 mm). The materials are non-moisture absorbing or have been surface saturated with water prior to the measurement of the water leakage flow. The materials are considered representative as many façade materials are non-moisture absorbing or become saturated on the surface relatively quickly when there is a rain load (Garden, 1963, Hens, 2010). At the rear of the façade under holes and slits, collecting channels were installed and the water was led down to the collection containers, see Figure 7.

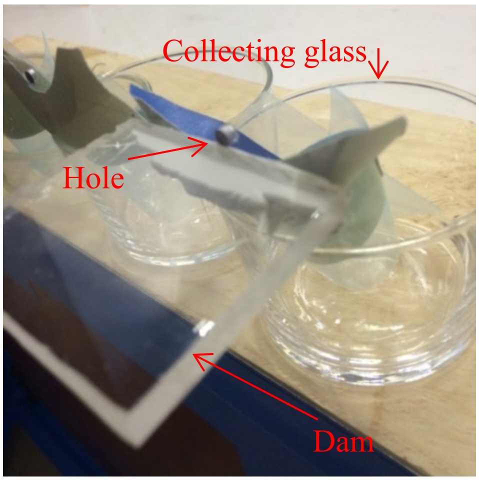


Figure 7. A horizontal dam mounted beneath a hole in a polycarbonate board (note that the polycarbonate board is transparent and located in front of the glasses). Parts of the other cases are also visible further away in the photo as well as collecting channels behind the polycarbonate board. The holes and dams are placed at the bottom of the rain exposed surface. The height of the rain exposed surface was 1 metre.

The measurement uncertainty and standard deviation of the water leakage flow when repeating experimental trials are reported in both **Paper IV** and **VII**. For the measured values of well-defined holes, a linear regression analysis has been conducted for the determination of constants and the determination coefficient R^2. The proposed algorithm is validated and the algorithm is based on empirical values, which are described in more detail in **Paper VII and Paper VIII**.

4 Measurement results

The results are grouped into three categories: 1. Long-term field measurements for determining the extent of leakages in existing buildings, 2. Large-scale laboratory tests to study the leakages more in detail and to quantify the leakages, 3. Small-scale laboratory tests for phenomenological studies that forms a base for the conceptual model.

4.1 Field measurements

In the results from field measurements, water leakage occurred, all the way into the wooden frame, in 5 of 7 buildings which corresponds to 70 %, relatively independent of façade systems (façade wooden panels, fibre cement boards or plaster), and with or without ventilated air gap behind the façade, see **Paper II**. The measurements were taken in the timber frames and timber sill, which means near the rear of the second line of defence/weather barrier and also near to the façade details. In periods of heavy rain, there is often no sign of leakage. The field measurements showed that rainfall alone is not sufficient to get water leakage and that water leakage occurred only when sufficient rainfall, wind speed and wind direction toward the façade occurred, see **Paper II** and **V**. No extreme or unusual wind speeds were detected. The moisture content dropped within one or two weeks to their normal values again, see **Paper V** and Figure 8. Figure 9 shows one of the leakage occasions shown in Figure 8 and includes wind direction, wind speed, horizontal rain load and driving rain index, DRI, which is the product of the three aforementioned factors.

The results from the field measurements show that leakage at windows and other connections and details in façades or external walls is fairly common. Whether the water leakage has continued to other parts, etc. or caused moisture damage was not part of the study.

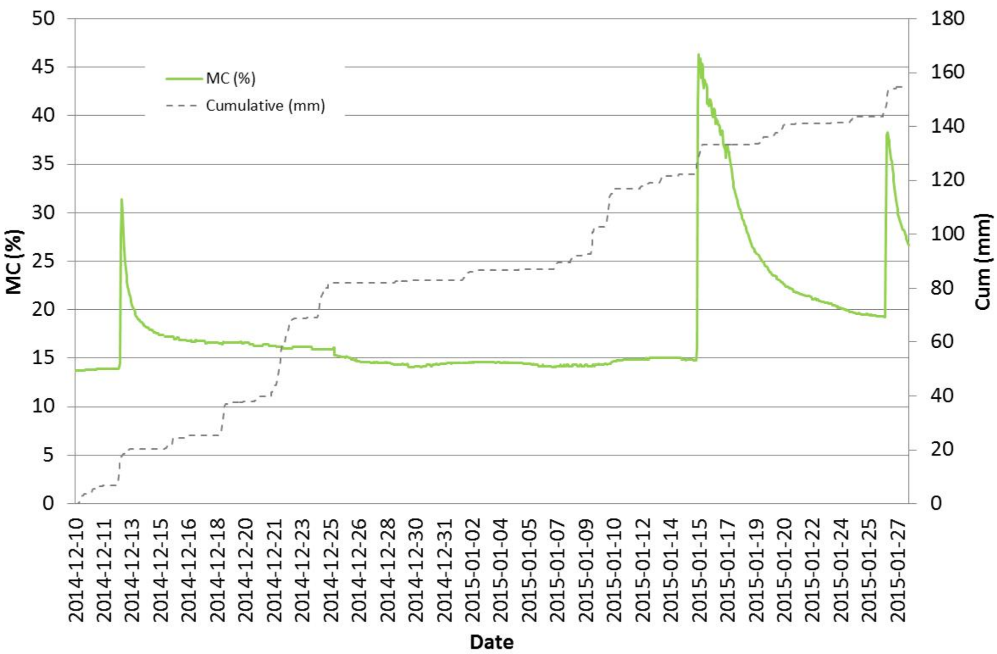


Figure 8. Moisture content (MC) measurements, in one of the houses. Cumulative (mm) represents accumulated rain on horizontal surface at a nearby weather station from 2014-12-10.

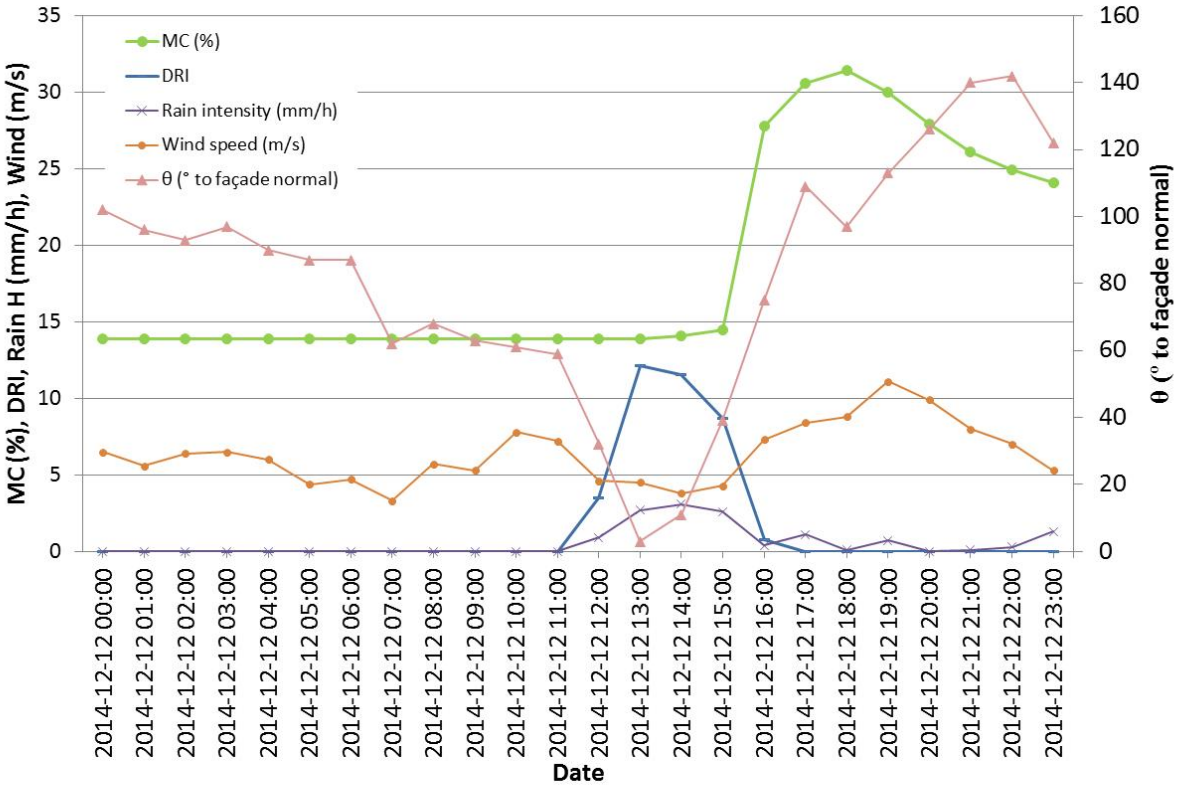


Figure 9. Diagram of one of the days in Figure 8. Driving rain index, DRI (-), rain intensity on horizontal surface (mm/h), wind speed (m/s) and wind direction (θ) are from a nearby weather station. If wind direction is towards the façade, normal vector of the façade, the angel is zero in the diagram.

4.2 Large-scale laboratory measurements

Results from over 100 commercial large-scale laboratory tests demonstrate water leakage in more than 90 % of all test walls and in 50 % of all façade details, see **Paper I.** The fail ratio for driving rain tightness at window connections, for example, was 60-80 %, see Figure 10, almost regardless of façade material, façade systems, ventilated, unventilated and pressure-equalized façades, etc. The water leakage flows were in the range of 0.01-0.1 l/min for the leak with the highest water leakage flow in each test wall (with a water load as set out in EN 12865). The façades lacking pressure equalization tended to produce only slightly higher failed rates.

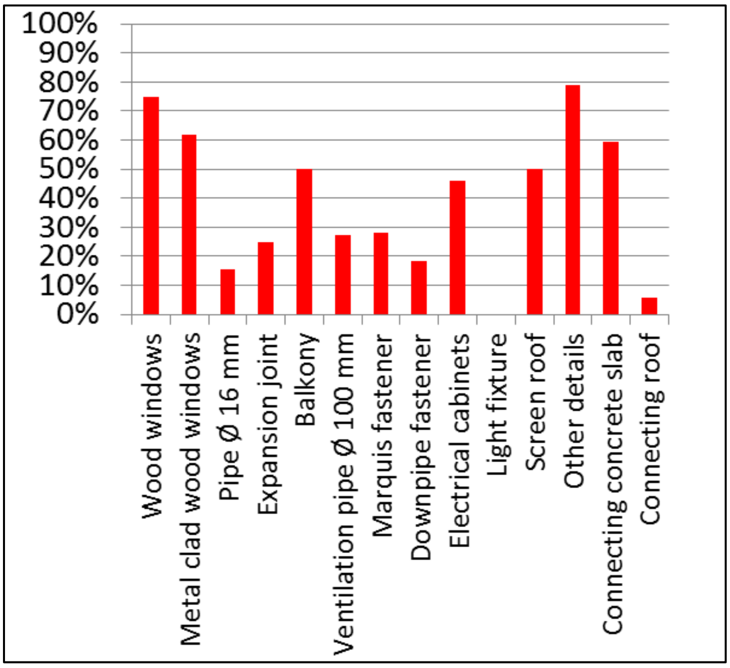


Figure 10. Proportion of details (interface between detail and façade) that leaked water into the wall.

The windows-wall interfaces were particularly difficult to get raintight despite the fact that they are one of the most common details in façades, see Figure 11.

Figure 11. Rain leakage at the corner of the window-wall interfacein an ETICS façade (photo from after the measurements were finished and the wall was opened). The material behind the plaster and insulation board is in this case moisture retaining, which should be avoided.

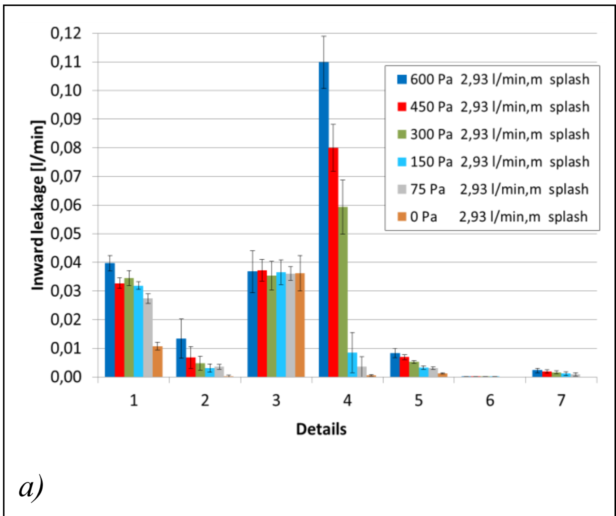
The additional tests on windows in four different types of façades with 29 window connections, see Figure 4, showed similar results. Window-wall interfaces leakage occurred in around 60 % of the windows connections (window-wall interfaces), see **Paper III**. The three largest point water leakages were within 0.01-0.03 l/min, with the water load as set out in EN 12865. No significant difference occurred between the sections that were executed carefully in comparison with the others. In cases where secondary defence or seals were missing at the penetrations and detail connections, water penetrated into the frame of the wall, etc. Many of the water leakages had already been breached at 0 Pa pressure difference across the façade layer.

The seven different type of defects that were investigated concerning leakage flows are shown in Figure 6 and are described in Table 1 and more in detail in **Paper IV**.

Table 1. Description of the defects at the details in terms of deficiency or aperture dimensions, plus remarks as to whether the deficiency is concealed, invisible or visible.

Detail	Deficiency dimension (mm)	Comments
1. Window-wall	(1,5x1,5) + (0,2x9) + (0,1x50)	Concealed position
2. Window-wall	2 x 2	Concealed position
3. Circular duct	0,9 x 35	Visible
4. Rectangular duct	2 x 30	Visible
5. Metal flashing	0,1 x 35	Not visible
6. Metal flashing	Not measurable	Not visible
7. Underneath flashing	0,3 x 120	Concealed, only exposed to water splash from below

Three defects were invisible to the naked eye and the results demonstrated water leakage flow in the range of 0.01-0.04 l/min, and two were visible defects, size of defect: 0.9 x 35 mm and 2 mm x 30 mm, and the results indicated a water leakage flow of between 0.04 to 0.11 l/min, see Figure 12a, with a water flow of 2.93 l/min,m on the façade. Moreover, an example of a comparison of measurements with and without direct rain on the façade surface is shown in Figure 12b. For this case, there were only water splashes that butts up on the façade and that also result in water leakage.



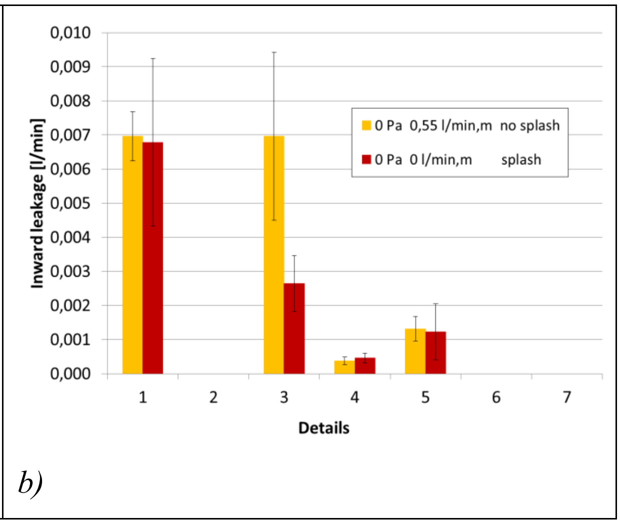


Figure 12. (a) The bars show inward leakage (mean value of 3-7 tests) in seven defects at details with dams beneath holes/slits. Six pressure steps/wind pressure with pulsation were used. The applied water flow was 2.93 l/min,m and water splash. (b) Without any wind pressure and with and without water splash. The standard deviation is also shown.

The above mentioned studies consistently found that water leakage is common in the interface between façades and connection details in new façades built after, or long after, the issues with the water leakage problems of ETICS façades had become widely known, but also other types of façades see **Paper V.** Additionally, it seems normal to have water leakage, despite the fact that no pressure difference was detected across the façade layer, see **Paper III** and **IV**, which means that water is still leaking in due to mechanisms other than wind pressure difference, as has also been demonstrated in other studies (Lacasse, 2003a, Hens, 2010).

4.3 Small-scale laboratory measurements

Thorough measurements have been taken of water leakage flows at well-defined defects (see Figure 6b) with different hole diameter, different slopes, slits with different height and width, with and without dam of varying size. For example, the designation for case 4s10W10L has the following meanings: 4 = hole diameter in mm, s = downward slope, 10W = 10 mm dam width, 10L = 10 mm dam protrusion. No leak was concealed, and the majority of defects were visible to the naked eye within the range from the smallest slots of 0.3 x 3 mm to the largest of 2 x 20 mm, and holes between 1 and 8 mm in diameter, see more detailed description in **Paper VI and, VII**. The results indicated water leakage flow in the range of 0.01-0.09 l/min with a water flow of 2.9 l/min,m on the façade. For holes and slits without dams as well as for smaller dams, water leakage flows occurred in the lower part of the water leakage range, see for example Figure 13 and for larger dams, values were obtained in the upper water leakage range, see **Paper VII**. These measurements are also used in the creation and validation of the conceptual model in Chapter 5.

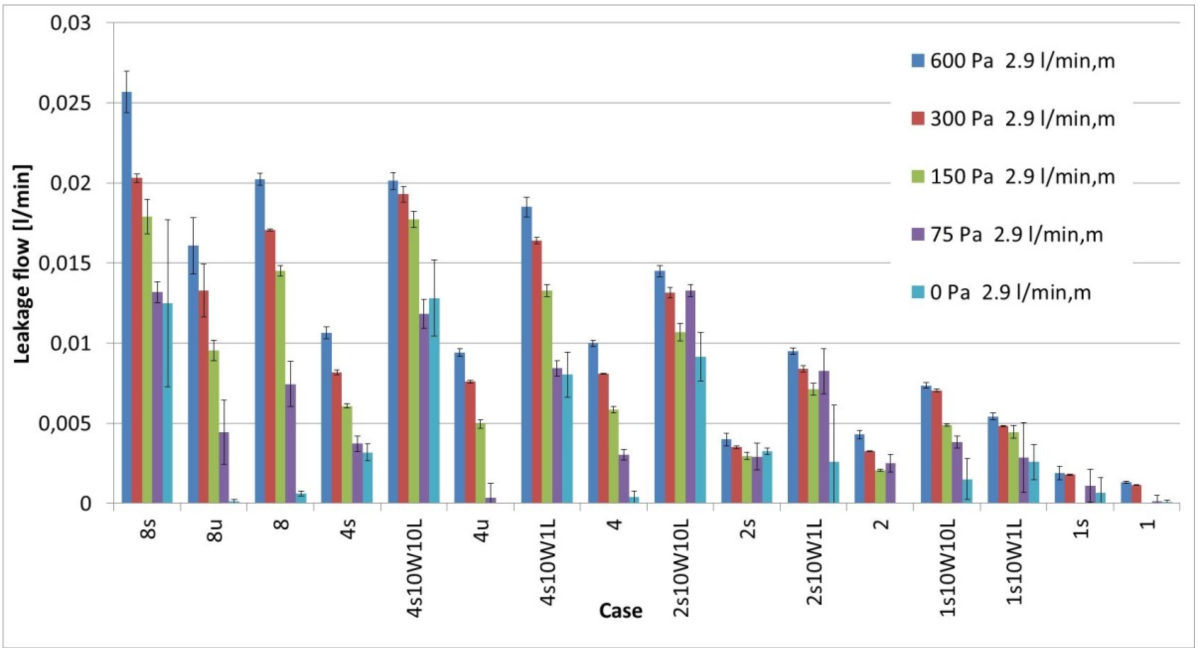


Figure 13. Water leakage flow for different holes with and without dams in a fiber cement board. For example, 4s is a sloping hole with 4 mm in diameter and 10W1L is a dam that is 10mm wide and has a 1 mm protrusion, definitions are further described in Figure 1b. Pulsating wind load from 0 to 600 Pa. Water flow on the façade of 2.9 l/min,m. The standard deviation is also shown.

Leakage occurred already at 0 Pa (i.e. without wind pressure) in most holes, see Figure 13, which was expected based on previous studies. There was leakage in almost all holes at 75 Pa, i.e. even those with a 4 mm hole with an upward slope (case 4u). What differentiates cases 4u and 4 is primarily the level difference between inlet and outlet of approximately 3.5 mm, which corresponds to a P_h of 35 Pa. There is an equivalent difference between case 2 and case 2s with downward slope. Overall, the leakage flow was greatest at 600 Pa wind pressure difference, but there was a relatively small difference in leakage flow at half the pressure difference (300 Pa).

The leakage flow was generally several times greater with a dam than without a dam, and a larger dam led to a larger leakage flow. It can also be noted that dams contribute to a significantly higher leakage flow compared to what an increased wind pressure difference does for a freestanding hole. The downward-sloping holes contribute to the incidence of leakage without pressure difference, even for 2 mm holes.

5 Conceptual model and validation

In order to assess for example the moisture safety of façades and to be able to perform moisture risk assessment, there is a need to determine leakage amount for new and renovated façades (Bednar & Hagentoft, 2015). If you rely solely on today's theoretical analyses, you end up underestimating water intrusion with consequences such as moisture-related damage, interior environment problems, and failure to meet energy efficiency requirements. Therefore, the theory needs to be upgraded with factors that more realistically can predict the behaviour of water leakages on façades.

A common way theoretical to deal with rain leakage is to adopt 1%, as a default value according to ASHRAE Standard160 (ASHRAE, 2016) and apply it on the layer within the wall that is expected to be exposed to water leakage. The water leakage is usually applied per square meter wall, which actually differ from reality where leakages are pointwise.

To make more accurate prediction, a conceptual model has been created based on phenomenological studies, including measurements. The conceptual model consists of the leakage factor, as introduced in Chapter 2.2, Equation 2, and a number of constants and variables that describe the behaviour for different geometries, dams, materials and pressure situations are included in Equation 6. The set-up of the model is based on, and compared to, measurements that are described in **Paper VII, VIII.** Initially the leakage factor from measurements and calculations are compared as follows. The theory of uniformity, as described in Chapter 2, appears to be consistent, which means that many cases with holes with downwards slope (8s, 2s) have a water leakage factor of about 0.5, also shown in **Paper VII** for fibre cement boards. When exposed to heavy wind pressure, the water leakage factor rises to 1 for holes, and consequently all the water that hits the hole is pressed through it, see **Paper VII** Figure with measurements of fibre cement board and in Figure 14. Same principle about uniformity are seen for holes with wide dams, consequently half of the water that hits the dam goes through the hole and half of the water continues down the wall, during high pressure difference which also give a leakage factor of about 0.5, see Figure 14.

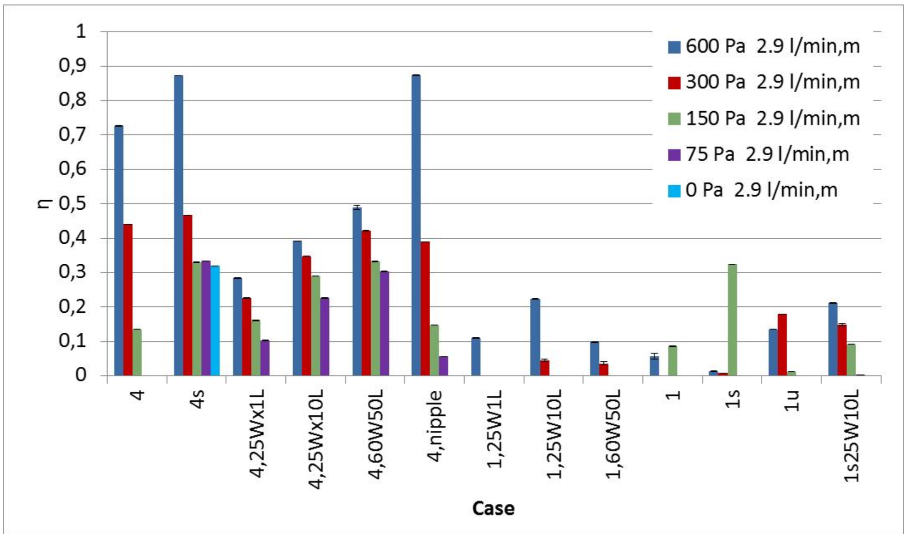


Figure 14. The η-factor of the measured values. Holes with and without dam in polycarbonate board. Water flow on the façade of 2.9 l/min,m.

There are several parameters that have an impact on the leakage factor, such as material, hole size, dam dimension, water flow on the façade, hydrostatic and wind pressure difference. These parameters are key for the algorithm which is assumed as follows.

The following formula for leakage factor η_{est} was adopted:

$$\eta_{est} = \eta_0 + \alpha \cdot P_{tot} + \beta \cdot \frac{D}{W} + \gamma \cdot \frac{D}{L} \qquad (6)$$

The geometrical variables are shown in Figure 1b and for cases without dams η_0 represent the fraction that would enter without applied pressure. A large number of measurements were performed, see **Paper VII,** and the constants above in Equation 6 were determined using linear regression, see Table 2. For each case, a determination coefficient, R^2, is estimated, see Table 2. This represents a measure of how well the measurements are replicated and a value of 1 indicates a perfect fit.

The wind pressure used in Equations 4 and 5 relates to the maximum pressure that occurs under each wind pressure cycle. According to method EN 12865, the wind pressure during one-third of each cycle is zero, $P_w/2$ respectively P_w. The average pressure over the cycle period is thus $P_w/2$. The pressure steps (P_w) in the experiments were 0, 150, 300, 450 and 600 Pa.

Table 2. Constants determined for Equation 6 for a number of experimental cases. The table applies for different water flow on the façades, materials, different size of holes and slits, and dimension of horizontal dams. More details about how to use the table is shown in ***Paper VII*** *especially if other cases will be used.*

Case	Water flow (l/min,m)	η_0	α	β	γ	R^2
Fiber cement- holes (diam. 2/4/8 mm)	2.9	0.19	0.0011	-	-	0.71
	1.1	0.16	0.0010	-	-	0.69
Fiber cement- holes (diam. 1/4 mm) with dams up to 10(W) x 10(L) mm	2.9	-0.039	0.00035	1.36	-0.044	0.85
	1.1	0.012	0.00044	0.92	-0.055	0,71
Fiber cement- slits 0.3(T) x 3(D) to 1.5(T) x 7(D) mm) with dams up to 10(W) x 10(L) mm	2.9	0.42	0.0014	-0.14	-0.014	0.45
Polycarbonate- hole (diam. 4 mm)	2.9	0.065	0.0013	-	-	0.88
	1.1	0.19	0.0014	-	-	0.36
Polycarbonate- holes (diam. 1/4 mm) with dams up to 60(W) x 50(L) mm	2.9	-0.011	0.00054	1.30	0.040	0.73
	1.1	0.029	0.00042	0.77	-0.043	0.47
Stainless steel- slits 1(T) x 5(D) to 2(T) x 20(D) mm	2.9	0.17	0.00077	-	-	0.77
Stainless steel- slits 1(T) x 5(D) to 2(T) x 20(D) mm with dams up to 40(W) x 50(L) mm	2.9	0.017	0.00045	0.57	0.010	0.63

A comparison has been made between the calculated water leakage factor and the measured water leakage factor, see Figure 15. The optimal line has been drawn, which corresponds to the estimated value exactly corresponding to the measured value and indicates how the line is surrounded by the obtained values. For this measurement case, the determination coefficient for the measurement values is $R^2 = 0.71$. Most cases, see Table 2, demonstrated about the same or better determination coefficient. This indicates a more or less clear correlation in most measurement cases.

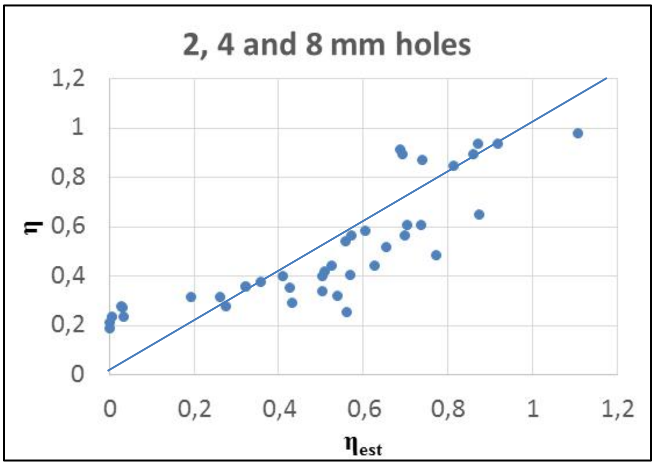


Figure 15. Factor η (measured) is shown on the vertical axis and η_{est} (estimated) on the horizontal axis for 2, 4 and 8 mm holes in fiber cement board without dams, and comparison to the optimal line. The line corresponds to when estimated values exactly correspond to measured values. The water flow on the façade of 2.9 l/min,m.

Other comparisons have been made between the calculated water leakage factor and the measured water leakage factor in order to evaluate the conceptual model. These are based on the study in **Paper IV** along with two other studies from the literature (Sahal & Lacasse, 2005, Van Den Bossche, 2013). From Table 2, constants have been selected based on the appropriate material, hole or slit and dam. For a more detailed description see **Paper VII**. Figure 16 (a) represent a slit above a rectangular duct in Table 1 and it shows a comparison of the calculated and measured water leakage factor (from **Paper IV**) where the experiments are based on the same test method as the empirical values in Table 2. An explanation as to why the water leakage factor differs significantly in Figure 16 (a) only at low pressure differences could be down to the fact that the dam continues into the rear of the façade and the water that leaks in remains there to create a crucial point of counter pressure. Figure 16 (b-c) represent slits above a ventilation duct and an electrical outlet and it shows measurements from the literature (Sahal & Lacasse, 2005). The driving rain test method used here applies static pressures and to make the results comparable, double pressure has been applied to the calculated water leakage factor. The reason for doubled pressure in the calculation is that the mean pressure is twice as high for static pressure (P_w) compared to pulsating pressure ($P_w/2$) as previously described. In Figure 16d, the measurements of (Van Den Bossche, 2013) are based on dynamic pressure load with an amplitude of 80 % of mean pressure difference which means that the pressure never drops to zero. This also means that the water leakage could be continuous throughout the experiment.

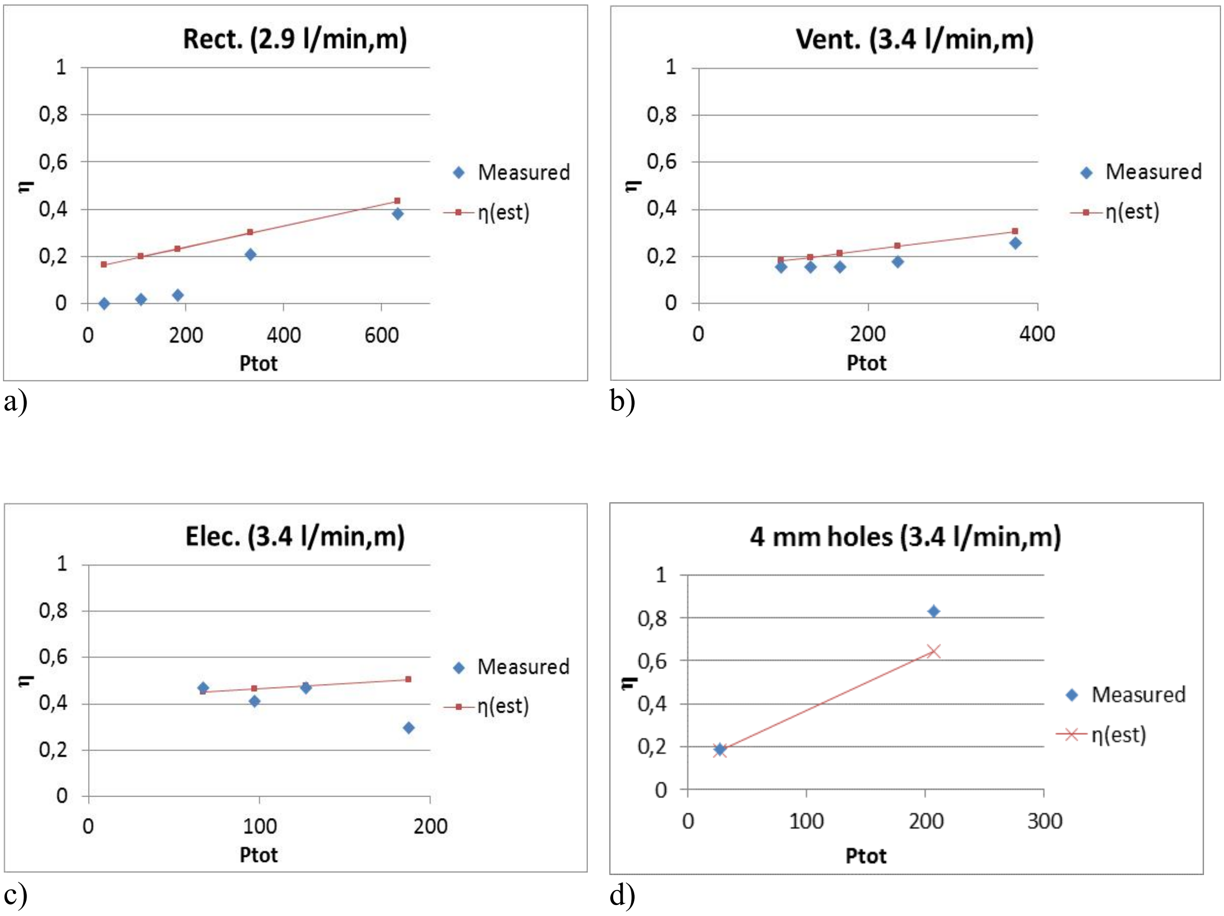


Figure 16. There was a relatively acceptable correlations between the measured water leakage factor, from these three studies, and the calculated water leakage factor, η (-), as per the algorithm. The size of slit and dam is for, Rect: W=100 mm, D=30 mm, L=100 mm T= 2 mm; Vent: W=150 mm, D=50 mm, L=15 mm T= 0.3 mm; Elec: W=50, D=50, L=4 mm, T=0.2 mm; Window: W=800 mm, D=90 mm, L=17 mm, T=0.2 mm and 4 mm holes = is the mean value for a 4 mm hole.

In these comparisons the calculated leakage factors corresponds relatively well with measured leakage factors. The proposed algorithm makes it able to estimate water leakage flow for well-defined holes and slits and horizontal dams. In order to include pointwise water leakage in moisture calculations two- or rather three-dimensional software is required.

6 Conclusions

The conclusion is that driving rain intrusion are almost always expected in small, small concealed or invisible defects in façades with façade details, such as window-wall interfaces etc., regardless of the façade type and façade system, such as face sealed, drained, ventilated and pressure-equalised façades. An explanation as to why there are no obvious differences in driving rain tightness between façades is due to the fact that the defects resemble each other independently of façade and, above all, they are found at façade details protruding details that cause more or less water dams and increase the rate of water leakage. The results indicate more specifically that:

- more than 90 % of all commercial test walls had water leakage,
- more than 60 % of all window-wall interfaces leaked both for commercial test walls and experimental walls,
- field measurements indicate water leakages adjacent to the frame in wooden frame walls in 70 % of the buildings.

One general conclusion is that water leakage can generally always be expected in façades with façade details as long as the opposite is not proven. The defects are often minor, concealed and invisible, and it is hardly possible to determine whether a façade is rain resistant without rain testing. Based on the results, it is therefore difficult or impossible to build rain resistant façades (outermost layer in external walls) using commonly adopted materials and solutions. Based on an assessment of all the results and assuming carefully completed assembly, it is reasonable to assume that the water leakage through each point leakage corresponds to 0.5-2% of the vertical water flow cross a unit width of the façade at the given height. The lower proportion within the range only refers to holes/slits, while the higher proportion refers to holes/slits with dams. If defects and dams are well-defined, the exact water leakage flow can be calculated according to $G = \eta_{est} \cdot G_{max}$. This formula is based on an estimated water leakage factor η_{est}, which is constructed from empirical values, and the water flow that occurs on the façade when it is running towards a hole or slit on a façade exposed to rain. This theoretical relationship correlates relatively well with several other laboratory experiments. The proposed algorithm makes it possible to estimate water leakage flow for well-defined hole and slits. In order to include pointwise water leakage in moisture calculations two- or rather three-dimensional software is required.

The factors that have been proved to be the most important for the water leakage flow are:

- hole/slits size, particularly the width,
- dam size, particularly the width,
- type of surface material,
- hydrostatic pressure between inlet and outlet,
- wind pressure difference across the defect,
- water flow (rain load).

Moreover, it is evident that the hydrostatic pressure can be as important as the wind pressure difference, which means that significant water leakage can also be expected in pressure-equalized façades. The flow capacity of, for example, a small hole with a diameter of more than 1 mm is often significantly greater than the amount of water flowing downwards on a façade. This means that all water running towards the hole could potentially leak in. In the case of moisture-absorbing material, no noticeable counteracting meniscus occurred during the laboratory experiments at the outlet of the water leakage hole. This means that, the water pressure that occurs in a horizontal hole in the façade is sufficient for water leakage to arise. For non-moisture absorbing façades, a little pressure may be required, which could be generated, for example, through hydrostatic pressure from inclined holes or wind pressure.

In addition, measurements have shown that details that are seemingly less exposed to driving rain, such as the underside of window sills, still can be exposed to significant amounts of water due to splashes of water, such as flowing from overhead details, dropping down onto dams etc., and splashing onto the façade, resulting in water leakage.

7 Future research needs

More data is required, for example, for other sizes of holes, slits and dams, as well as other façade materials than in this thesis, in order to conduct accurate moisture calculations in such cases. A dam of more than several millimetres (L), in combination with different inclines, to the protrusion will also need to be studied further.

Studies of driving rain tightness of new types of façades as well as the determination of geometric dimension of defects would improve the capability to make more accurate moisture calculations and complete reliable risk analyses.

As water leakage can be expected through the outermost layer of external walls, regardless of the façade type, a second defence is needed that properly protects the frame and moisture sensitive elements in the wall even in the interface between connections to façade details. The risk of water leakage and water leakage flow through the second defence and combination with different type of façades should be subject to further studies.

In order to describe how water is spreading in the wall, drainage ability and moisture retention behind façades is another area of interest.

8 References

ADL-ZARRABI, B. & HÖGBERG, A. B. 2001. Microclimate:Field Measurements, Driving Rain Analyses. *Performance of the Exterior Envelopes of Whole Buildings VIII.* Clearwater Beach, December 2-7, Florida, USA.

ASHRAE 2016. ASHRAE Standard 160-2016 *Criteria for Moisture-Control Design Analysis in Buildings.* ASHRAE website (www.ashrae.org): ASHRAE.

BASSETT, M. & OVERTON, G. 2015. Measuring the Weathertight Performance of Flashings.

BEAULIEU, P., BOMBERG, M., CORNICK, S., DALGLIESH, A., DESMARAIS, G., DJEBBAR, R., KUMARAN, K., LACASSE, M., LACKEY, J., MAREF, W., MUKHOPADHYAYA, P., NOFAL, M., NORMANDIN, N., NICHOLLS, M., O'CONNOR, T., QUIRT, D., ROUSSEAU, M., SAID, N., SWINTON, M., TARIKU, F. & VAN REENEN, D. 2002. Final Report from Task 8 of MEWS Project (T8-03) - Hygrothermal Response of Exterior Wall Systems to Climate Loading: Methodology and Interpretation of Results for Stucco, EIFS, Masonry and Siding Clad Wood-Frame Walls. Ottawa, Canada: National Research Council Canada.

BEDNAR, T. & HAGENTOFT, C.-E. 2015. Annex 55-Reliability of Energy Efficient Building Retrofitting- Probability Assessment of Performance and Cost (RAP-RETRO), Report 2015:7. *International Energy Agency (IEA) och Energy in Buildings and Communities Programme (EBC).* Gothenburg: Chalmers University of Technology.

BEIJER, O. & JOHANSSON, A. 1976. Driving rain against external walls of concrete. *Fasadelement av betong, projektnummer 720444-2/C 1053:2.* Stockholm: Swedish Cement and Concrete Reserach Institute at the Institute of Technology.

BLOCKEN, B., DEROME, D. & CARMELIET, J. 2013. Rainwater runoff from building facades: A review. *Building and Environment,* 60**,** 339-361.

BOVERKET 2014. Building Regulations, BBR 21. Karlskrona: The Swedish National Board of Housing, Building and Planning.

BUILDING-INDUSTRY-AUTHORITY 2003. Report on E2/AS1 Risk Matrix and Weathertight Homes Resolution Service Data. Ministry of Business, Innovation and Employment, New Zealand.

CARLL, C. 2000. Rainwater Intrusion in Light-Frame Building Walls. *2nd Annual Conference on Durability and Disatser Mitigation in Wood-Frame Housing.* Madison, Wisconsin.

CHOI, E. C. C. 1999. Wind-driven rain on building faces and the driving-rain index. *Journal of Wind Engineering and Industrial Aerodynamics,* 79**,** 105-122.

CMHC 2000. Wall Moisture Problems In Alberta Dwellings (Technical series 2000-112). *Research highlight.* Canada Mortgage and Housing Corporation.

CMHC 2003. Water Penetration Resistance of Windows-Study of Manufacturing, Building Design, Installation and Maintenance Factors (Technical Series 03-124). Canada Mortgage and Housing Corporation.

CORNICK, S. & LACASSE, M. 2005. A review of climate loads relevant to assessing the watertightness performance of walls, windows, and wall-window interfaces. *Journal of ASTM International,* 2**,** 1-16.

DE GENNES, P.-G., BROCHARD-WYART, F. & QUÉRÉ, D. 2004. Capillarity and wetting phenomena: drops, bubbles, pearls, waves. New York: Springer Science & Business Media.

EOTA 2012. GUIDELINE FOR EUROPEAN TECHNICAL APPROVAL of KITS FOR EXTERNAL WALL CLADDINGS PART I and II, ETAG 034. Brussel: EOTA European Organisation of Technical Approvals.

EOTA 2013. External Thermal Insulation Composite (ETICS) with Rendering. Brussels: EOTA.

FINKEN, G. R., BJARLOV, S. P. & PEUHKURI, R. H. 2016. Effect of facade impregnation on feasibility of capillary active thermal internal insulation for a historic dormitory- A hygrothermal simulation study. *Construction and Building Materials,* 113**,** 202-214.

GARDEN, G. K. 1963. Rain Penetration and its Control. *CBD-publication 40* [Online]. Available: http://web.mit.edu/parmstr/Public/NRCan/CanBldgDigests/cbd040_e.html.

GARG, K., KRISHNAN, G. & NAYAR, S. K. Material Based Splashing of Water Drops. *In:* KAUTZ, J. & PATTANAIK, S., eds. Eurographics Symposium on Rendering, 2007. The Eurographics Association 2007.

GEVING, S. 2011. *Fuktskader - Årsaker, utredning og tiltak,* Oslo, SINTEF Byggforsk.

GEVING, S., ERICHESEN, T., H., NORE, K. & TIME, B. 2006. Hygrothermal conditions in wooden claddings- Testhouse measurements-Report from the R&D- programme (Climate 2000). Oslo, Norway: Norwegian Building Research Institute 2006.

GIBSON, A. 2009. ´Rotting Homes Bill Tipped to Top $11b. *´NZ Herald, 19 August*.

HAGENTOFT, C.-E. & OLSSON, L. 2017. Rain intrusion behind insulated modules attached to façades of old buildings: A probabilistic modelling approach. *AIRAH and IBPSA´s Australasian Building Simulation 2017 Conference, November 15-16.* Melbourne.

HALL, C. & HOFF, W. D. 2002. *Water transport in brick, stone and concrete,* London, Spon Press.

HENS, H. 2010. Wind-driven rain: from theory to reality. *Proc. Thermal performance of the exterior envelopes of whole buildings XI, Clearwater, Florida*.

HÖGBERG, A. 2002. *Microclimate Load: Transformed Weather Observations for Use in Design of Durable Buildings.* Doctoral thesis, Chalmers University of Technology, Gothenburg, Sweden

ISO 2009. ISO 15927-3:2009 Hygrothermal performance of buildings- Calculation and presentation of climatic data. *Part 3: Calculation of a driving rain index for vertical surfaces from hourly wind and rain data.* Switzerland: ISO The International Organization for Standardization.

JANSSON, A. 2014. Actions against moisture damage in etic walls. *10th Nordic Symposium on Building Physics, 15-19 June.* Lund, Sweden: Lund University.

JOHANSSON, P., GEVING, S., HAGENTOFT, C.-E., JELLE, B. P., ROGNVIK, E., KALAGASIDIS, A. S. & TIME, B. 2014. Interior insulation retrofit of a historical brick wall using vacuum insulation panels: Hygrothermal numerical simulations and laboratory investigations. *Building and Environment,* 79**,** 31-45.

KUBILAY, A., DEROME, D., BLOCKEN, B. & CARMELIET, J. 2014. High-resolution field measurements of wind-driven rain on an array of low-rise cubic buildings. *Building and Environment,* 78**,** 1-13.

KUDDER, R. J. & ERDLY, J. L. 1998. *Water leakage through building facades*, ASTM International.

KÜNZEL, H. Criteria defining rain protecting external rendering systems. IBPC 2015, 6th International Building Physics Conference, 2015 Torino, Italy.

LACASSE, M. 2003a. Recent studies on the control of rain penetration in exterior wood-frame walls. National Research Council Canada.

LACASSE, M. A., MIYAUCHI, H. & HIEMSTRA, J. 2009. Water Penetration of Cladding Components—Results from Laboratory Tests on Simulated Sealed Vertical and Horizontal Joints of Wall Cladding. *Journal of ASTM International,* 6.

LACASSE, M. A., O'CONNOR, T. J., NUNES, S. AND BEAULIEU., P. 2003b. Report from task 6 of MEWS project -- experimental assessment of water penetration and entry into wood-frame wall specimens, - final report. *Research Report, NRC Institute for Research in Construction; Volume 133.* Ottawa, Canada: NRC Institute for Research in Construction; National Research Council Canada.

LACY, R., E. 1965. Driving-Rain Maps on the Onslaught of Rain on Buildings. *Building Researche Station Current Paper 54.* UK, Garston:Building Research Station.

LAWTON, M. 1999. Vancouver's Rotting Condominium Problem—How Did We Get into This Mess? *Journal of Building Physics,* 22**,** 356-363.

MORRISON HERSHFIELD LIMITED 1996. Survey of Building Envelope Failures in the Coastal Climate of British Columbia. Canada Mortgage and Housing Corporation.

NEVANDER, L.-E. & ELMARSSON, B. (eds.) 1994. *Fukthandboken - Praktik och teori "Moisture design manual" 2nd ed,* Stockholm: Svensk Byggtjänst.

NGUDJIHARTO, E., TARIKU, F. & FAZIO, P. Window Sill Defects. 14th Canadian Conference on Building Science and Technology, 2014 Toronto, Canada.

ROUSSEAU, M. Z., POIRIER, G. F. & BROWN, W. C. 1998. Pressure Equalization in Rainscreen Wall Systems. National Research Council of Canada.

SAHAL, N. & LACASSE, M. 2005. Water entry function of a hardboard siding-clad wood stud wall. *Building and Environment,* 40**,** 1479-1491.

SAMUELSON, I., MJÖRNELL, K. & JANSSON, A. Moisture damage in rendered, undrained, well insulated stud walls. *In:* RODE, C., ed. 8th Symposium of Building Physics in the Nordic Countries, 16-18 June, 2008 Copenhagen, Denmark. DTU Denmark, 1253-1260.

SANDIN, K. 1987. The Moisture Condition in Aerated Lightweight Concrete Walls - In situ measurements of the effect of the driving rain and the surface coating. Lund, Sweden: Division of Building Materials Lund Institute of Technology.

SANDIN, K. 1993a. Moisture conditions in cavity walls with wooden framework: Measurements on a test building have been recorded and a number of significant conclusions are presented. *Building Research and Information,* 21**,** 235-238.

SANDIN, K. 1993b. Skalmur med träregelstomme (T10:1993). Stockholm: Byggforskningsrådet.

SCOTT, D. L. 1984. Rain Leakage in Wood Frame Walls: Two Case Histories. National Research Council of Canada.

SIS 2001. SS-EN 12865 Hygrothermal performance of building components and building elements-Determination of the resistance of external wall systems to driving rain under pulsating air pressure. *The European Standard EN 12865:2001 has the status of a Swedish Standard.* Stockholm: SIS, Swedish Standards Institute.

STRAUBE, J. 2010. Simplified prediction of driving rain on buildings: ASHRAE 160P and WUFI 4.0. *Building Science Digest,* 148**,** 1-16.

STRAUBE, J. F. 1998. *Moisture control and enclosure wall systems.* Doctoral thesis, University of Waterloo.

TARIKU, F., SIMPSON, W. & NGUDJIHARTO, E. Analysis of wind driven rain exposure based on long-term monitoring. Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings XIII Conference, Clearwater, FI, USA, 2016.

TEASDALE-ST-HILAIRE, A. & DEROME, D. 2005. State-of-the-Art Review of Simulated Rain Infiltration and Environmental Loading for Large-Scale Building Envelope Testing. *ASHRAE transactions,* 111.

TENWOLDE, A. 2011. A review of ASHRAE standard 160-criteria for moisture control design analysis in buildings. *Journal of Testing and Evaluation,* 39.

TSONGAS, G., GOVAN, D. & MCGILLIS, J. 1998. Field observations and laboratory tests of water migration in walls with shiplap hardboard siding. *Thermal envelopes VII/Moisture-practices***,** 469-483.

WALTZ, M. E. & NELSON, P. E. 1999. Wood Siding Weather Protection: Don't Get Caught in the Rain without It. *Journal of Building Physics,* 22**,** 285-302.

VAN DEN BOSSCHE, N. 2013. *Watertightness of Building Components: Priciples, Testing and Design Guidelines.* Doctoral thesis, University Ghent, Belgium.

VAN DEN BOSSCHE, N., LACASSE, M. & JANSSENS, A. Watertightness of masonry walls: an overview. 12th International conference on Durability of Building Materials and Components (XII DBMC-2011), 2011. FEUP Edições, 49-56.

VAN DEN BOSSCHE, N., LACASSE, M., MOORE, T. & JANSSENS, A. Water infiltration through openings in a vertical plane under static boundary conditions. 5th International Building Physics Conference (IBPC-2012), 2012. Ghent University, Department of Architecture and urban planning, 457-463.

WILLIAMS, M. F. & WILLIAMS, B. L. 1998. An Overview of Water Leakage Problems in Singel-Family Residences Clad with Exterior Insulation and Finish Systems (EIFS). *In:* KUDDER, R. J. & ERDLYAND, J. L. (eds.) *ASTM STP, West Conshohocken, PA*

WOODBURY, C. 2009. Stucco in New Residential Construction - A Position Paper Includes - Updates to Original Information. *In:* DIVISION, B. I. (ed.). Woodbury, Minnesota: City of Woodbury.

ZHU, D., REDDY MALLIDI, S. & FAZIO, P. 1995. Quantitative driving rain exposure on a vertical wall at various Canadian cities. *Building and Environment,* 30**,** 533-544.