Eva Armstrong Støver and Marte Haugen Sundsøy

Rain Intrusion Through Horizontal Joints in Façade Panel Systems - Experimental Investigation

Master's thesis in Civil and Environmental Engineering
Supervisor: Tore Kvande
June 2022

Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

NTNU
Norwegian University of
Science and Technology

Eva Armstrong Støver and Marte Haugen Sundsøy

Rain Intrusion Through Horizontal Joints in Façade Panel Systems - Experimental Investigation

Master's thesis in Civil and Environmental Engineering
Supervisor: Tore Kvande
June 2022

Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

NTNU
Norwegian University of
Science and Technology

Preface

This master thesis is written as the final project of the five-year Master of Science program in Civil and Environmental Engineering at the Norwegian University of Science and Technology (NTNU) during the spring of 2022. The thesis is written under the auspices of NTNU and SINTEF's research program Klima 2050. Klima 2050 aims to reduce the societal risk associated with climate changes and improve buildings' resistance to precipitation.

It has been challenging and very instructive to transfer the theoretical knowledge we have acquired during our studies to such a practical assignment. It has been exciting to gain insight into an issue that has a relevance outside of our academic endeavors. In addition, we have learned how to plan and conduct laboratory experiments.

We would like to thank everyone who has contributed with help and guidance of the thesis. A special thanks to our main supervisor Tore Kvande for good inputs, feedback and a close follow-up. He has been a great help in understanding the problems the thesis is investigating and how to structure the laboratory experiments. In addition, Stig Geving has assisted with his knowledge during the preparation of the thesis and laboratory experiments. We would also like to thank Erlend Andenæs who has been a great help during the writing of the scientific paper and for helping us understand other problems within building physics. Additionally, Remy Eik from SINTEF has contributed by turning our words into illustrations. Furthermore, we would like to thank SINTEF and NTNU for the opportunity to use the laboratory and equipment to carry out the experiments. The implementation of the laboratory experiments would also not have been possible without the help and guidance of departmental engineer Ole Aunrønning at NTNU and senior technician Øystein Holmberget at SINTEF. Øystein has provided a tremendous help by showing us how to use equipment, discussing and solving problems, and sharing his knowledge from previous experiments. We would also like to thank suppliers who have agreed to contribute with their products and input.

We would furthermore like to thank our friends and families for all of their support and encouragement during our work with this thesis. Likewise the thesis would not have been the same without the tremendous help of Claire Armstrong and her exquisite proofreading.

June 10th, 2022

Eva Armstrong Støver and Marte Haugen Sundsøy

Abstract

Façade panels are commonly used as cladding on larger buildings in Nordic countries. It is recommended to mount the façade panels with horizontal and vertical joints to allow for temperature and moisture movements. The vertical joints are assumed to be sufficiently watertight due to the use of gaskets combined with vertical battens. The horizontal joints are more prone to substantial water intrusion since they are usually kept open. SINTEF therefore recommends the use of joint profiles but due to esthetic reasons they are often not used. Few studies on water intrusion through horizontal joints in façade panel systems exist. However, the handful have previously investigated the following parameters: Different façade panels, joint widths, joint profiles, joint designs, air pressure, joint depth, and air cavity depth. The results of the studies vary greatly and the results are often inconsistent. All studies have, however, measured a substantial amount of water intrusion through horizontal joints.

The purpose of the master's thesis is to investigate the water intrusion through horizontal joints in façade panel systems. The main goal is to find joint solutions for horizontal joints that reduce water intrusion. Five façade panels with different surface characteristics were tested in SINTEF and NTNU's driving rain apparatus in accordance with NS-EN 1027:2016 without applied pressure. Different combinations of joint widths (3, 5 and 8 mm), joint profiles (T1-profile, T2-profile, h-profile, U-batten and gasket) and bevelled joints (15°, 30° and 45°) were tested. A total of 72 unique experiments were conducted.

The laboratory tests show a substantial amount of water intrusion through horizontal joints. Water intrusion to the wind barrier and the interior side of the panels, with 5 mm and 8 mm joint widths, constitute 0.5-1.7% and 18.6-20.2%, respectively, of the total amount of applied water, 6000 mL/min. Panels with a surface characteristic that ensures an evenly distributed water runoff generally experience less water intrusion than panels with an uneven water runoff. A joint width of 3 mm in an open joint led to the least amount of water intrusion to both the wind barrier and the interior side of the panels. Uncertainty related to whether a 3 mm joint width can be used due to temperature and moisture movements in the panels, implies that the solution cannot, however, be recommended without further ado. A joint width of 5 mm in an open joint led to the most water intrusion compared to the other joint widths. The protected joints had discrepancy in water intrusion. The use of joint profiles usually leads to reduced water intrusion, of which the h-profile is the only solution that is completely watertight. The T-shaped profiles provide a reduction in water intrusion, but the performance is highly dependent on the mounting and placement in the joint. The T2-profile is more watertight than the T1-profile due to the design of the profile protruding parts. The T1-profile's protruding part points straightforward, while the T2-profile's protruding part is downward sloping. U-battens, ventilated horizontal battens in the joints, are not recommended due to the high risk of splashing to the wind barrier. A protected joint with a gasket led to more water intrusion than without. Bevelled joints are a good solution. The experiments indicate a positive correlation between the angle of inclination and watertightness. Furthermore, a top-and-bottom-bevelled joint will be more watertight than a top-bevelled joint.

The study indicates that few joint solutions are watertight, whereas some protective measures leads in more water than an open joint. In addition, it is not sufficient to only have an open joint, as this can lead to large water intrusions to both the wind barrier and the interior side of the panels, while not protecting the wind barrier against UV radiation. The efficiency of joint solutions should be evaluated through testing, before implementing them in façades.

Sammendrag

Plane plater er vanlig å bruke som fasadekledning på store bygninger i Norden. Fasadeplatene anbefales å monteres med horisontale og vertikale fuger for å tillate temperatur- og fuktbevegelser. De vertikale fugene antas å være tilstrekkelig tette grunnet bruk av tetteremse sammen med vertikal lekt. De horisontale fugene mangler denne understøttingen. Mye regnvann kan trenge inn bak fasadeplatene gjennom de horisontale fugene på grunn av denne utførelsen. SINTEF anbefaler bruk av fugeprofiler, men dette blir ofte ikke benyttet av estetiske årsaker. Få tidligere studier er gjennomført for vanninntrenging gjennom horisontale fuger for plane fasadeplater. Studiene har testet ulike fasadeplater, fugebredder, fugeprofiler, fugegeometrier, lufttrykk, påført vannmengde, fugedybde og tykkelse på luftespalten. Resultatene fra studiene varierer, men konkluderer at det er mye vanninntrenging gjennom de horisontale fugene.

Hensikten med masteroppgaven er å teste vanninntrengingen gjennom horisontale fuger i fasadekledning av plane plater. Ulike løsninger ble testet som mulige barrierer mot vanninntrenging gjennom fugen, deriblant ulike fugeprofiler og -geometrier. Hovedmålet er å finne løsninger for åpne horisontale fuger som reduserer vanninntrengingen til et minimum. Fem fasadeplater med ulike overflatekarakteristikker ble testet i slagregnskapet til SINTEF og NTNU i henhold til NS-EN 1027:2016, men uten trykkforskjeller. Ulike kombinasjoner av fugebredder (3, 5 og 8 mm), fugeprofiler (T1-profil, T2-profil, h-profil, U-lekt og tetteremse) og skråskjæringer (15°, 30° og 45°) ble testet. Totalt ble 72 unike forsøk gjennomført.

Laboratorieforsøkene viser at det er stor vanninntrenging gjennom åpne horisontale fuger. Vanninntrengingen til vindsperren og baksiden av platene, med 5 mm og 8 mm fugebredde, er henholdsvis 0,5-1,7% og 18,6-20,2% av totalt påført vannmengde, 6000 mL/min. Plater som har en overflatekarakteristikk som sikrer en jevnt fordelt vannavrenning (vannfilm) får generelt mindre vanninntrenging gjennom fugene enn plater som opplever ujevn vannavrenning (konsentrerte vannstrømmer). En fugebredde på 3 mm ved åpne horisontale fuger førte til minst vanninntrenging til både vindsperre og bakside av platene. Usikkerhet knyttet til om 3 mm kan brukes på grunn av temperatur- og fuktbevegelser i platene, gjør at den løsningen ikke kan anbefales uten videre. En fugebredde på 5 mm ved åpne horisontale fuger førte til mest vanninntrenging sammenlignet med de andre fugebreddene. Bruk av profiler fører i de fleste tilfeller til redusert vanninntrenging, hvorav h-profil er den eneste løsningen som gir en vanntett fuge. T-formede fugeprofiler gir en reduksjon i vanninntrenging, men ytelsen er svært avhengig av monteringen og plasseringen i fugen. T2-profilet er mer vanntett enn T1-profilet på grunn av utforming av profilutstikkene. T2-profilets utstikk har en helning mens T1-profilets utstikk peker rett frem. U-lekter, ventilerte horisontale lekter i fugen, som barriere anbefales ikke grunnet stor risiko for vannsprut til vindsperre. Tetteremse som barriere førte til mer vanninntrenging, enn uten. Skråskjærte fuger er en god løsning. Forsøkene indikerer en positiv korrelasjon mellom vinkel på skråskjæring og vanntetthet. Videre vil en topp og bunn skråskjært fug være mer vanntett enn en fug med kun skråskjært topp.

Studien indikerer at få løsninger er vanntette. Enkelte løsninger kan lede mer vann inn bak kledningen enn hvis ingen form for barriere hadde vært benyttet. I tillegg er det ikke tilstrekkelig å kun ha en åpen fug med ingen form for barriere, da dette kan føre til stor vanninntrenging til både vindsperren og baksiden av fasadeplatene. Derav er det viktig å benytte testede fugeløsninger som barriere i plane plater med horisontal fug.

Contents

1 Introduction

1.1 Background

In human history there has seldom been warmer temperatures than now (Miljødirektoratet, 2021). The last time it was as warm as today Greenland was green and there were hippopotamuses in England. The Intergovernmental Panel on Climate Change (IPCC) published its sixth assessment report on the physical science basis for climate change in the autumn of 2021. The report confirms that global warming is caused by human activity, and that climate change is faster than ever (Masson-Delmotte et al., 2021). The updated climate-situation is that the global mean temperature has increased with 1.1 ℃ since pre-industrial times. This implies that extreme weather occurs more often now than before. This trend will increase in the future, if the world continues as before and does not take necessary measures. According to Masson-Delmotte et al. (2021), Nordic countries will see longer summers and shorter winters, a wetter and warmer climate, with more intense and frequent extreme weather, such as heavy rainfall.

Climate change is expected to cause an increase in precipitation by 18% in Norway within the end of the century compared to present precipitation rates (Hanssen-Bauer et al., 2015). Moisture is either partly or wholly responsible for 75% of building damages in Norway (Bøhlerengen, 2018). Subsequently, an increase in precipitation load and intensity could lead to increased damage to the built environment. Klima 2050 is a Centre for Research-based Innovation (SFI). Their goal is to reduce the societal risks associated with climate changes by carrying out long-term research in close collaboration with the industry (Klima2050, n.d.). One approach is to reduce the risks through climate adaption of buildings and infrastructure. This thesis works within Klima 2050's first work package: *WP1: Climate exposure and moisture-resilient buildings*.

The purpose of a façade is to protect the users of the building and the building itself against the climatic and mechanical stresses of the outdoor environment (Edvardsen & Ramstad, 2017; Kvande, 2013). To reduce the dangers of precipitation and moisture, it is recommended to build façades according to the principle of two-stage weatherproofing (Ingebretsen et al., 2022). Exterior walls in Norway are often designed and built according to this principle. There should be a separate wind and rain screen with a ventilated air cavity in between which ensures that the pressure is evened out, the cavity is drained, and moisture in the interior part of the wall can dry out (Thue, 2016). In an outer wall, built according to the principle of two-stage weatherproofing, the function of the wind barrier and cladding is to act as a wind and rain screen, respectively. The main task of the cladding is to protect the rest of the wall from precipitation, but it often also has the task of being architecturally pleasing and protecting the wind barrier from UV radiation.

A type of façade cladding that is often used, partly because of its esthetic appearance, is façade panel systems. It is recommended to mount them according to the principle of two-stage weatherproofing (Gaarder, 2019). The main challenge related to façade panel systems are that they are mainly mounted with horizontal open joints between the panels, which makes the cladding one of the least watertight claddings available (Geving, 2021). Therefore it is recommended to use joint profiles as a protection measure in the joints, thus building according to the principle of two-stage weatherproofing. This is however not a common practice, and the horizontal joints are often kept open. Façade panel systems are thereby exposed to substantial water intrusion, especially in areas prone to driving rain. Rain with a horizontal force component, wind, is called driving rain (Thue, 2016). Both the wind barrier and the lath system can sustain some water intrusion, however larger amounts can cause problems (Bøhlerengen, 2018; Geving, 2022). Water intrusion to the wind barrier is the most concerning, as the wind barrier is raintight and vapor permeable to allow outwards drying of moisture (Geving, 2022). Additionally, if water infiltrates to the wind barrier, water can then infiltrate to the inner wall through weaker spots in the barrier, like for instance screw holes that fasten the lath system. Furthermore, water can cause rot in the lath system and consequently weaken it. Figure 1.1 shows a possible consequence of water intrusion through joints. In this case vertical open joints and a horizontal batten with a joint profile were used. This example shows that the façade panel systems experience problems in today's climate. Since heavier and more intense rainfall is expected in the future, it is particularly important to enhance the knowledge regarding water intrusion through horizontal open joints.

Figure 1.1: Large amounts of water intrusion through both vertical and horizontal joints in an apartment block in Bergen. One consequence is a decomposing wind barrier (Geving, 2022).

1.2 Purpose

This master thesis is written in cooperation with Klima 2050. The purpose of the thesis is to empirically test the water intrusion through horizontal joints with different joint solutions. The main target is to find solutions that reduce water intrusion to a minimum. An additional aim is to verify laboratory measurements conducted in relation to a master thesis at NTNU from 2020 conducted by Mo and Lid (Mo & Lid, 2020). In such the goal is to enhance the knowledge about water intrusion through horizontal joints, and how water intrusion can be prevented. The thesis is structured around answering the following three research questions:

1. What is known from existing scientific literature about the raintightness of horizontal joints in façade panel systems?

2. How can the raintightness of horizontal joints in façade panel systems be determined through laboratory experiments?

3. How do different joint solutions affect water intrusion through horizontal joints in façade panel systems?

The first research question is answered in the scientific paper in Appendix A. The laboratory methodology in Chapter 3 is seen as the main answer to the second research question. In addition, the main challenges and uncertainties regarding the laboratory measurements that are presented and discussed in Section 4.2 and 4.10. The main emphasis of this thesis is related to the last research question. The third research question is answered in the scientific paper in Appendix A, and also in more detail in Chapter 4.

1.3 Limitations

The master thesis is limited to façade panel systems with horizontal joints. The laboratory measurements were limited by several factors. The tests were limited to the panel selection already available at the SINTEF and NTNU laboratory, as the ordered panels for the master thesis have still not arrived. Therefore the tested panels are made of glass fiber, fiber cement and high pressured laminate. The tests only look at water intrusion through horizontal joints, not vertical ones. In addition, the testing was performed according to NS-EN 1027:2016 in the driving rain apparatus in SINTEF and NTNU's laboratory. Pressure is not a parameter in the tests, and was not applied at any occasion. Several of the results are expressed with line graphs, however, no assumptions are made about what occurs between graph points. The lines are used for easier readability.

1.4 Defining Terms and Concepts

In this thesis a lot of terms and concepts are used. In the following a discussion regarding the most important terms and concepts is presented. There are two main challenges: Firstly, different terms have been used in the literature to explain the same concepts. Secondly, a substantial part of the literature is written in Norwegian. For the latter, it is important to find the correct corresponding term in English. The diverging use of terms and concepts may also be due to geographical variation, and thereby climatic differences. The discussion is limited to terms and concepts used in studies found through the literature review.

The Principle of Two-Stage Weatherproofing

Mas et al. (2011) uses the term *Pressure Equalised Rainscreen walls.* This term entails that there is no pressure difference between the exterior and interior side of the cladding. The pressure difference is equalized by openings such as open joints. A different term that is used is *ventilated façades* and *cross-ventilated façades* (Dordá et al., 2010; Recatala et al., 2018). Dordá et al. (2010) states that this requires at least two openings: One air inlet and one air outlet, in addition to a *chamber* on the inside of the façade. The chamber is likely a term that corresponds to the term *air cavity* used in several other studies (Herbert & Harrison, 1974; Mas et al., 2011). Isaksen (1964, 1966) uses the Norwegian term "luftet kledning" which is commonly translated to *ventilated façades* (Bunkholt et al., 2021). Bassett and Overton (2015) calls the same concept for *cavity wall.* In the study by Recatala et al. (2018) it is stated that, in an European context, ventilated façades are an adaptation of the rainscreen concept on a multilayered building envelope. The rainscreen concept is a principle of designing the cladding to prevent rain intrusion. This differentiates between the rainscreen which is the outer layer and cladding, and the backwall.

All of the previously mentioned studies focus on the pressure equalization across the cladding. Pressure equalization is used as a mean to reduce water intrusion through open joints. However, in Norway, the term is "totrinnstetting" which roughly translates to *two-stage weatherproofing,* or *two-step weatherproofing*, where the focus is not on the equalization of pressure, but what hinders air, water and moisture from infiltrating the exterior part of a façade or building part. Ingebretsen et al. (2022) uses *two-stage weatherproofing*, but emphasizes that it is unclear what is the best translation for the term. A differentiation between the Norwegian and English terms could be that the Norwegian term explains what elements are included in the concept, while the English terms explains the function of the concept.

Façade Panels

In the literature there is a differentiation between the terms that are used to describe the outer wall in general and the type of cladding that is used.

The English translation of the title of Isaksen's study from 1966 is "Open joints in exterior claddings?" (Isaksen, 1966). In both of his studies the Norwegian term "kledning" has been used. This would correspond to the term cladding, which means a covering or coating on a structure or material (Ayo et al., 2022). Several studies have used the term *Rainscreen Wall* or *Façade* for the outer wall (Bassett & Overton, 2015; Dordá et al., 2010; Fernández, 2010; Mas et al., 2011). Cladding is also commonly used (Bassett & Overton, 2015; Isaksen, 1966; Mo & Lid, 2020). In this thesis the term *façade* or *cladding* will be used to describe the exterior wall and cladding.

To describe the products that are used in experiments conducted by Mas et al. (2011) both the terms *stone coverings*, *stone panels* and *panels* have been used. Dordá et al. (2010) calls the cladding products for *slabs.* Isaksen (1964, 1966) and Mo and Lid (2020) calls the cladding products for "paneler" or "fasadepaneler", which corresponds to *panels* or *façade panels* in English. Mo and Lid also used Fernández (2010) also uses the term *panels.* Bassett and Overton (2015) called the products *direct fixed sheet cladding* or just *sheet cladding.* In this thesis the terms *façade panel* or *panels* will be used.

Joint Width

In this thesis the term *joint width* is defined as the vertical distance between two façade panels in the horizontal joint, as shown in Figure 1.2. Several studies have also used this term in the same manner (Dordá et al., 2010; Mas et al., 2011). In the study conducted by Dordá et al. (2010) *joint width*, *thickness* and *size* is used to describe the concept defined as joint width in this thesis. However, Mas et al. only use the term *joint width* in the methodology and discussion of their experimental study, while the other terms are used in the introduction. Herbert and Harrison (1974) also use the term *joint size*, however they do not define the term. Other terms used are *joint openings* and *gaps.* Gap might be used to describe the air cavity depth by Herbert and Harrison (1974), while Bassett and Overton (2015) use it to describe the joint width. In Norwegian "fugebredde" is used for joint width (Gaarder, 2019).

Joint Depth

Mas et al. (2011) used the term *thickness* in relation to the panels that have been used. In this study the thickness of the panel is equal to the depth of the joint, as is illustrated in Figure 1.2. However, Mas et al. (2011) uses the term *depth* when describing the air cavity between the panels and back wall. Dordá et al. (2010) uses the term *thickness* both for the joint width and depth.

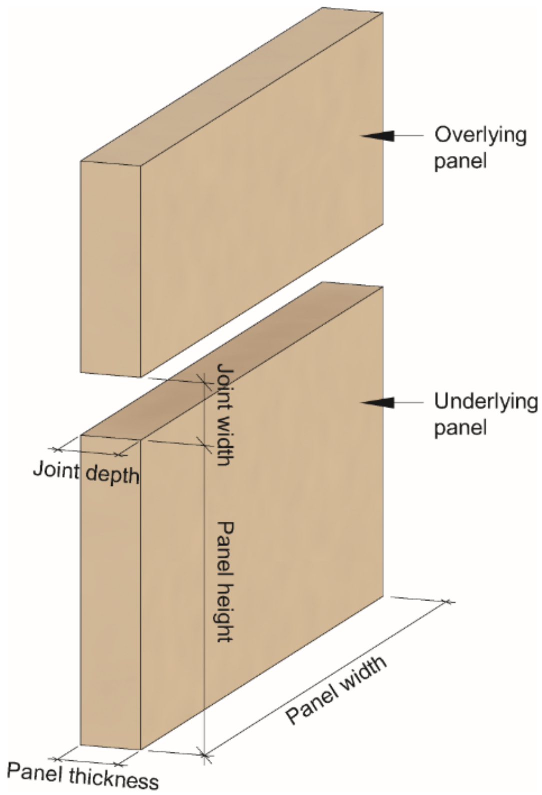


Figure 1.2: Definition of terms used to describe dimensions of the joint and panels.

However, in the description of the experimental study thickness is used for joint depth. Isaksen (1964, 1966) uses the term "dybde" which is translated to depth. Depth is used when discussing the joint, while thickness is used to describe the façade panels. In a lot of the studies only the thickness of the façade panels are used to describe the joint depth (Dordá et al., 2010; Mas et al., 2011).

Joint Profiles

Bassett and Overton (2015) used the term *flashing* for joint profiles. The definition of flashing, which is the commonly used term in New Zealand, is a component formed from a rigid or flexible waterproof material that drains or deflects water back outside the cladding system (NZBC, 2021). This is the same definition as joint profiles. An example of a profile is given in Figure 1.3. Herbert and Harrison (1974) used *labyrinth joint* for their suggested sealing of the joint. These are drastically different from profiles used in Norway, since they are formed as labyrinths which provide a tortuous path to help prevent leakage. Mo and Lid (2020) called the joint profiles for (among other): "profilløsning", "fugeprofil", "beskyttelsesprofil", "horisontalprofil", or just "profil". The Norwegian terms translated are: *profile solutions*, *joint profile*, *protecting profile*, *horizontal profile*, and *profile*. In this thesis the term used will either be *joint profiles* or just *profiles* for short.

Figure 1.3: A h-profile in a joint. Photo taken during test no. 26 with Glass Fiber Rough and a h-profile.

1.5 Structure of the Thesis

The thesis is mainly structured around the scientific paper in Appendix A. The scientific paper presents both the methodology and results from the literature review of previous studies. Furthermore, the results compared with previous studies are presented. The thesis includes more details than the scientific paper. Additionally, an article published in Byggeindustrien gives a short summary of some of the main findings, given in Appendix B.

Chapter 2: Theoretical framework
The theoretical framework presents relevant theory that was excluded from the scientific paper. The framework includes theory related to water, rain intrusion through horizontal open joints, two-stage weatherproofing, and current recommendations from SINTEF regarding the mounting of façade panels systems on buildings.

Chapter 3: Methodology for the Laboratory Testing
This chapter presents the method of the laboratory experiment. The chapter is a supplement to the method presented in the scientific paper, and elaborates more in detail.

Chapter 4: Results and Discussion
In this chapter the results from the laboratory experiments that were conducted are presented and discussed more in detail than in the scientific paper. In addition, a presentation and short discussion of the most prominent errors and uncertainties that may have affected the results are presented.

Chapter 6: Conclusion

The conclusion summarizes what has emerged from the results and discussion. The conclusions from the scientific paper are somewhat elaborated in this chapter.

Chapter 7: Further Work

In this chapter some recommendations regarding further work and suggestions to different laboratory experiments are presented.

2 Theoretical Framework

In this chapter the theoretical framework related to the laboratory testing and results is presented. The chapter is divided into the following sections; water, rain intrusion through horizontal open joints, the principle of two-stage weatherproofing and recommendations regarding façade panels. Additionally, the results from the literature review of existing scientific literature, presented in the scientific paper, see Appendix A, is used as theoretical framework.

2.1 Water - A Brief Description

To describe how water behaves two basic principles need to be understood, cohesion and adhesion. Cohesion is the ability of similar molecules to stick to each other due to attraction (Pedersen, 2018). Solid substances have high cohesive properties and do not stick to surfaces they come in contact with, and gases have low cohesive properties and stick to surfaces they come in contact with. Adhesion is the ability of dissimilar molecules to stick to each other due to attraction (Grøn, 2020). Water has both cohesive and adhesive properties. Water molecules will attract each other and stick to one another, due to the the cohesion properties. Water will also be attracted to other surfaces, this is due to the adhesive force between the water molecules and molecules of the surface.

Surface tension is a force that causes the surface of a fluid to contract and form a droplet (Hofstad, 2019). The tension arises due to cohesive forces between adjacent water molecules (Aarnes, 2020). The water molecules are pulled equally in all directions by adjacent water molecules. Since the molecules at the water surface do not have adjacent water molecules on all sides, they are pulled inward, and hence causing a spherical droplet. Water molecules form droplets on wax paper because the surface tension is much greater than the adhesive forces between the paper and the water molecules. When water, or a liquid, flows through a narrow space, the adhesive and cohesive forces act together to lift the water against the natural force of gravity (Helseth, 2020). This occurrence is called capillary suction. One of the purposes of the air cavity in the outer wall is to prevent capillary transport between the façade cladding and wind barrier (Thue, 2019).

The contact angle, θ, as illustrated in Figure 2.1, is a way of categorizing how water reacts in contact with a substance (Helseth, 2021). The contact angle can be measured by taking a picture of a water droplet on a surface, thereupon measuring the angle, θ. This will indicate whether the water droplet is more attracted to itself or to the surface it is on. A substance with a contact angle less than 90° is categorized as hydrophilic, and the adhesive forces between the substance and the water droplet are stronger than the water's surface tension. If the angle is greater than 90° it is categorized as hydrophobic, and the adhesive forces between the substance and the water droplet is weaker than the water's surface tension.

When rain hits the façade cladding the water will either splash off, flow down the façade, evaporate, be absorbed or remain on the cladding (Blocken et al., 2013). The proportion of rain that splashes off, flows off, or remains on the façade will be affected by parameters such as surface tension, wind forces and the size of the water droplets (Blocken & Carmeliet, 2006). A previous study concluded that 49.7% of rain on façade panels would splash off (Recatala et al., 2018) Increased surface tension and roughness will affect the velocity of the water flow (Park et al., 2018). There are several factors that affect water movement on a wall surface, such as: Exposure to driving rain, evenly distributed water runoff, horizontal wind, the materials of the cladding, surface roughness,

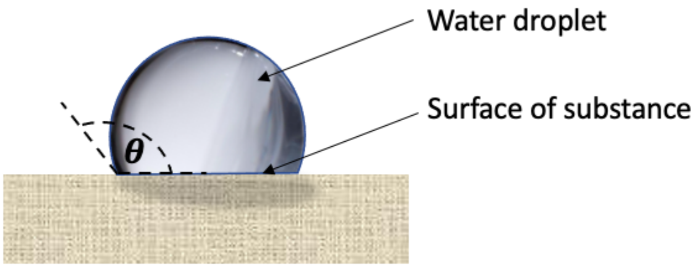


Figure 2.1: Contact angle, θ, for a water droplet on a substance.

degree of wet condition, protruding wall elements, and dirt on the cladding (Bielek, 1977). Surface tension is not a force that works between different substances, it explains how molecules in a liquid, or a solid, act with each other (Marmur, 2021). It is therefore believed that some of the authors confused surface energy with surface tension. Surface energy can explain how a liquid reacts with a solid (Parsons & Jefferson, 2006). Theoretically, water will stream linearly down a smooth surface (Bielek, 1977). Contrarily, when there is an inertia in the water streams, the water movement becomes irregular and very complicated. For a rough surface the water flows in an evenly distributed layer, also known as a water film. Additionally, the water flow velocity will be lower than for a smooth surface, due to increased friction between the water and the surface. The velocity of the water flow can affect the amount of rain intrusion (Recatala et al., 2018).

2.2 Rain Intrusion Through Horizontal Open Joints

Rain intrusion through horizontal open joints have several driving forces. According to Birkeland (1966) and Bunkholt et al. (2021) there are five different ways rain infiltrates horizontal open joints. These are presented in Figure 2.2.

In cases with driving rain can infiltrate the joint directly due to gravity (Birkeland, 1966). Driving rain is rain that has a horizontal velocity component, wind (Thue, 2016). The amount of driving rain on a façade will be a function of the topography and geographical location. Buildings located at wind-exposed areas along the coast are more prone to experience driving rain. The amount of driving rain on a façade can be calculated by using Computational Fluid Dynamics (CFD) software. The rain intrusion due to gravity will depend on the joint depth and width, and occurs for joint widths greater than 0.5 mm, as presented in Figure 2.2a (Birkeland, 1966; Bunkholt et al., 2021).

At joint widths < 0.5 mm capillary suction might occur due to surface tension and small joint widths, see Figure 2.2b (Birkeland, 1966). Capillary suction will be affected by the surface of the materials and the joint width (Aarnes, 2020). In some cases smaller joint widths can lead to an increase in water intrusion (Mo & Lid, 2020). This can be the case when using joint profiles that are not properly tightened to the façade panels.

SINTEF recommends a joint width of ≥ 5 mm (Bunkholt et al., 2021; Gaarder, 2019). Joint widths between 0.01 and 4-5 mm can likely lead to rain intrusion due to wind pressure from the outside (Birkeland, 1966), as presented in Figure 2.2c.

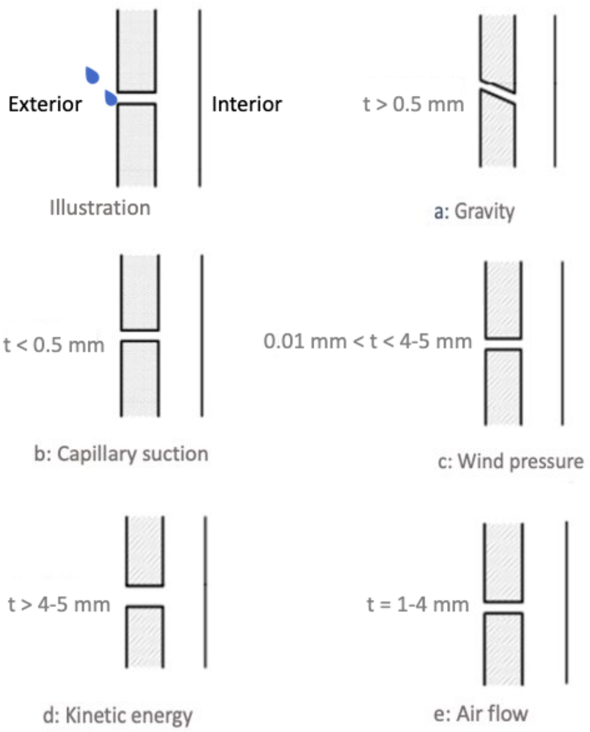


Figure 2.2: Five different mechanisms for water intrusion through open horizontal joints. Based on a figure by Bunkholt et al. (2021).

For joint widths > 4-5 mm the water droplets' kinetic energy might also be a driving force for rain intrusion (Bunkholt et al., 2021), see Figure 2.2d. On impact with the underlying panel, parts of the water droplet may splash to the interior side of the façade. This can be the case for water flowing down the exterior and the interior side of the façade panels, driving rain that directly hits the joint, or water droplets hanging on the overlying panel. The latter will often have a lower kinetic energy due to the size of the joint widths.

When the joint widths are varying between 1-4 mm, as presented in Figure 2.2e, local air flows can carry the water droplets through the joints (Birkeland, 1966; Bunkholt et al., 2021). The local air flows are a result of the ventilated façade, where air will flow from higher to lower pressure.

2.3 The Principle of Two-Stage Weatherproofing

To ensure effective protection against precipitation, it is recommended that the building envelope is built according to the principle of two-stage weatherproofing (Bunkholt et al., 2021). The first step in the principle is a rain screen, and the second step is a wind barrier combined with an air cavity, as illustrated in Figure 2.3. The wind barrier is raintight and vapor permeable to allow outwards drying. Between the rain screen and the wind barrier there must be a ventilated air cavity with adequate drainage possibilities (Kvande, 2013). Otherwise there is a risk that water will be led directly from the cladding to the wind barrier or that water will intrude by capillary suction (Bunkholt et al., 2021). Water intrusion can also occur if there is inadequate pressure equalization over the cladding, the air cavity prevents this (Bunkholt et al., 2021). If there is excessive ventilation in the cavity, there is a risk of condensation on the interior side of the cladding due to low surface temperatures.

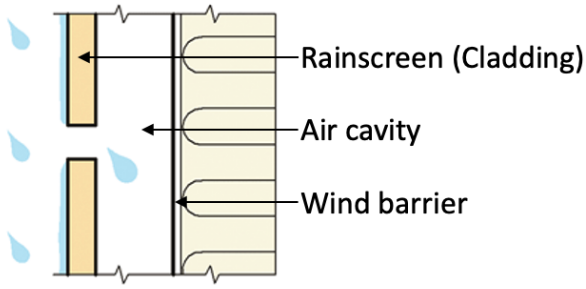


Figure 2.3: Principle of two-stage weatherproofing for an exterior wall with façade panels. The principle is not used for the horizontal open joint. Figure adapted from (Kvande, 2013).

The purpose of the rain screen is to minimize the intrusion of precipitation through the cladding. Additionally, it has to protect the back wall from mechanical stresses (Kvande, 2013). The rain screen itself must withstand the mechanical and climatic stresses to which it is exposed (Bunkholt et al., 2021). The rain screen should be as raintight as possible. The protection will vary depending on which façade cladding is chosen.

2.4 Recommendations Regarding Façade Panel Systems

Façade panel systems are often used as cladding on larger buildings in Nordic countries (Gaarder, 2019). The panels are low-maintenance, moisture resistant, and are not sensitive to UV radiation, air pollution, or temperature variations. However, if damages occur to the panels they cannot be repaired, but have to be replaced by new ones. It is common to distinguish between panels composed of polymer composite, high pressure laminate (HPL) and fiber cement. An overview of typical dimensions for some panels are given in Table 2.1. Additionally, panels of metal and natural stone can be used.

Table 2.1: Overview of typical dimensions of panels, given by Gaarder (2019).

Panel	Panel height	Panel width
Polymer Composite	0.8-3.5 m	0.6-1.2 m
Fiber Cement	0.6-3.0 m	0.6-1.2 m
High Pressure Laminate	2.0-4.1 m	0.9-1.9 m

Mounting of the panels should follow the supplier's instructions regarding maximum distance between the fastening points, the minimum distance from the fastening points to the corner and edge, and the batten distances (Gaarder, 2019). This is due to varying strength and stiffness of the panels. The panels should be mounted as a ventilated façade system, and should also act as a rain screen in the principle of two-stage weatherproofing (Bunkholt et al., 2021). To allow for moisture and temperature movements in the panels and the substrate, the panels must be mounted with vertical and horizontal joints (Gaarder, 2019). The fastening points must also be able to absorb temperature and moisture movements from the façade panels, as well as battens. Thus, the panels must be pre-drilled to ensure that the holes have a greater diameter than the screw stem.

Although the panels should be mounted with vertical and horizontal joints, the joints should not be open without a protection measure, as this can lead to rain intrusion and UV radiation to the wind barrier (Gaarder, 2019). SINTEF recommends joint widths of at least 5 mm, but less than 10 mm (Bunkholt et al., 2021). In addition, recommends using joint profiles on horizontal joints. In Figure 2.4 the three illustrated profiles are the Norwegian recommendations. Joint profiles are often made from extruded aluminium. They are inserted longitudinally into joints. The maximum length of the profiles are 3 m.

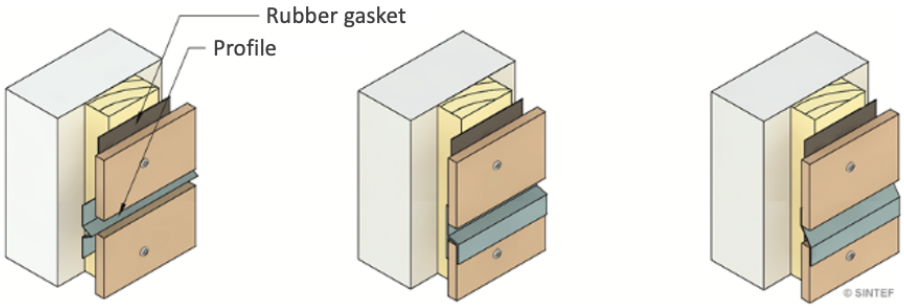


Figure 2.4: Joint profiles recommended by SINTEF (Gaarder, 2019). From the left: T1-profile, h-profile, and Z-profile.

3 Methodology for Laboratory Testing

The purpose of the methodology chapter is to present the work in a way that enables reproduction. In addition, the purpose is to ensure openness regarding how information is gathered and results are produced. This chapter is supplemented by the method chapter in the scientific paper, presented in Appendix A, where the literature review methodology and a more concise version of the laboratory testing methodology is given. The method for the laboratory test presents a detailed description of the construction of the test rig, drainage system, and adaptions of the test rig for testing different parameters.

3.1 Test Rig Set-Up

The construction of the test rig is shown in Figure 3.1, which shows the test rig from the interior side. The figure gives a summary of the dimensions of the test rig. Figure 3.2 and 3.3 give a better illustration of what the test rig looks like from the exterior and interior side, respectively.

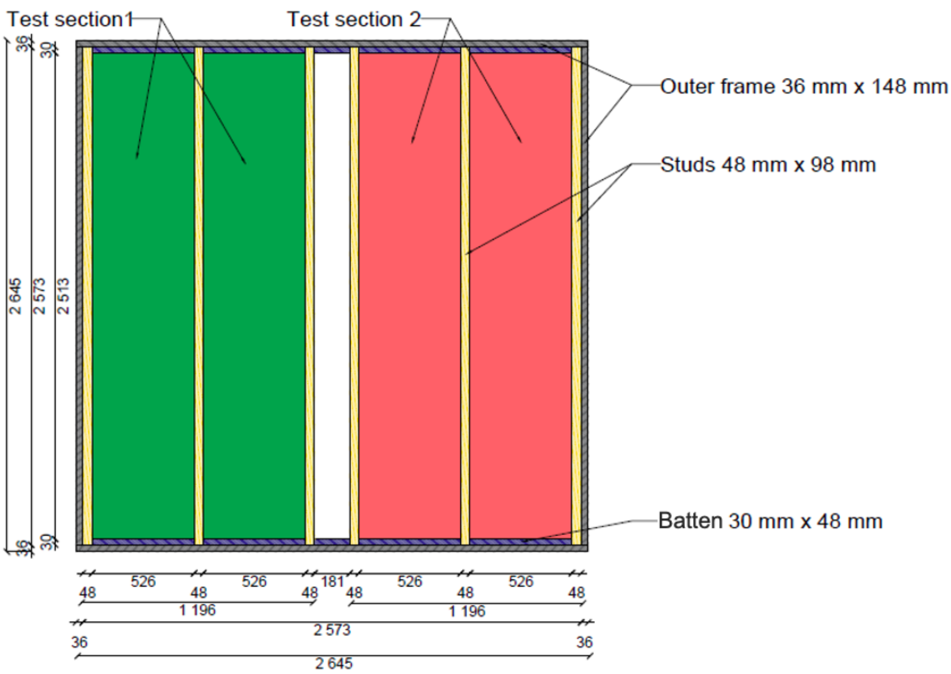


Figure 3.1: The test rig seen from the interior side. The outer frame, battens and studs are all made of wood. All dimensions are given in millimeter.

The test rig was mounted to a metal frame that was used to lift and fasten the test rig in the driving rain apparatus. Thus, the size of the test rig was restricted by the metal frame. The outer wooden frame was attached to the metal frame. The gap between the metal and outer wooden frame was sealed by an elastic sealant, then taped in order to avoid unwanted water leakage that can compromise the results.

The outer wooden frame had an outer dimension of 2645 mm x 2645 mm, consisting of 36 mm x 148 mm studs. These studs were already fastened to the metal frame. On the inside of the top and bottom of the outer wooden frame a horizontal 30 x 48 mm batten was mounted. These battens simplifed aligning the studs and the outer frame. In addition, the studs could be mounted to both

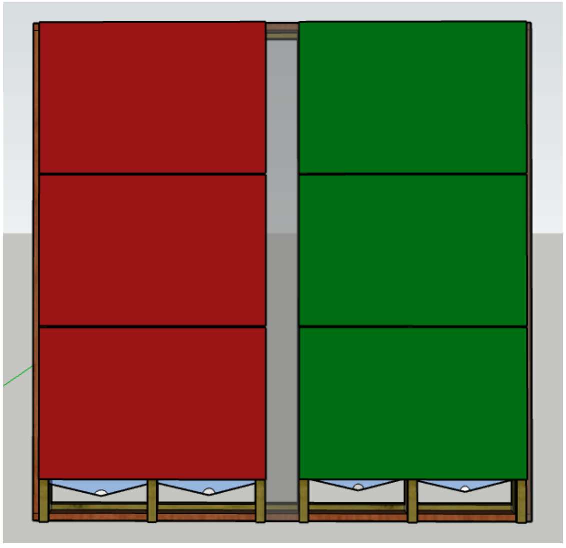


Figure 3.2: Test rig from the exterior side. Green panels represent test section 1 and red panels test section 2. Plastic gutters can be seen hanging below the panels.

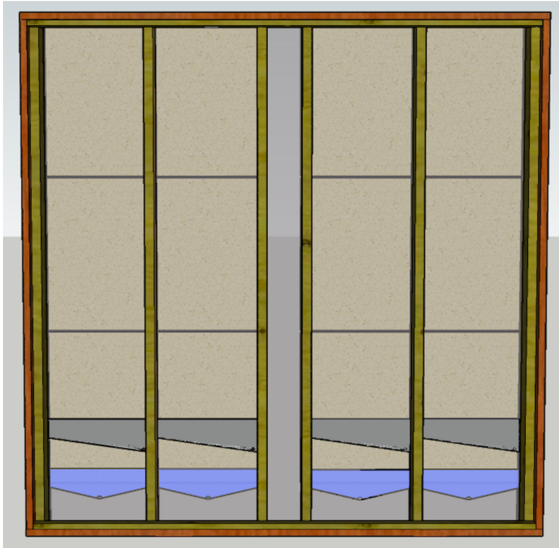


Figure 3.3: Test rig from the interior side. Left side is test section 1, and right side is test section 2. Both the aluminium and plastic gutters can be seen.

the outer wooden frame and battens, making them more solidly fastened. The test rig could be built without the horizontal top and bottom battens, but they are recommended. The battens were fastened by using ϕ5.5 70 mm screws with a distance of approximately 300 mm.

On the exterior side of the battens and within the outer wooden frame, 48 mm x 198 mm studs were mounted. The studs were fastened by using three ϕ5.5 80 mm screws on the top and bottom to the outer wooden frame. The studs were mounted as shown in Figure 3.1, and were placed so that there are two test sections with a distance of 181 mm between them. The studs in the test section were mounted with a center distance of 550 mm, thus following the mounting instructions from the façade panel suppliers. The space in between the two test sections were there to avoid water flow between them.

On the exterior side of the studs and outer wooden frame a transparent 12 mm thick polycarbonate board (Lexan) was mounted in the place of a wind barrier. This consisted of two boards. The outer dimensions of each of the two boards were 1330 mm x 2650 mm. The transparent board enables observation of the interior side of the test rig. Holes were pre-drilled and recessed, before the Lexan boards were fastened to the studs. The holes were pre-drilled in order for the screws to be aligned with the exterior side of the Lexan board. The pre-drilled holes had a cone shape and ϕ3.5 50 mm screws were used. Transparent tape was fastened over the screws and between the two boards, thus ensuring watertightness of the screw holes and between the two Lexan Board. Furthermore, duct tape was used to tape between the edges of the Lexan board and the outer frame. The duct tape was fastened in a four-step procedure. First the duct tape was placed on the metal frame and the elastic sealant, to ensure enough adhesion between the metal frame and tape on the Lexan board. Secondly, tape was placed on the edge of the Lexan board and fastened tightly to the tape on the metal frame. Third, tape was placed on the Lexan board above the existing tape, to tighten any gaps. Finally, the corners and other places where the duct tape was not properly tight were sealed. All the steps started from the bottom, then the sides and the top. This was done to counteract the water flow. The principle of taping from the bottom to the top is used for sealing the two test sections as well, without sealing the bottom.

After the frame and Lexan board were sealed six 30 mm x 48 mm vertical battens was mounted to the studs through the Lexan board by using ϕ5.5 80 mm long screws with a distance of approximately 600 mm. This gave a 30 mm air cavity depth. At first only the top of the battens were fastened in order to mount the drainage system on the Lexan board, and seal the system beneath the battens. An ethylene propylene diene monomer (EPDM) gasket was stapled to the battens. Two types of EPDM gaskets were used according to recommendations from the façade panel suppliers. For the fiber cement panels an EPDM with grooves was used, see Figure 3.4, and for the rest of the panels a plain gasket was used, see Figure 3.5. The gaskets were 70 mm wide.

Figure 3.4: EPDM with grooves, used with fiber cement panels.

Figure 3.5: Plain EPDM used with Glass Fiacksier and High Pressure Laminate panels.

3.2 Drainage System

The drainage system consists of two gutters placed in between the vertical battens: One on the Lexan board, and one on the lowest façade panel, as illustrated in Figure 3.6. The gutters on the Lexan board were used to collect water that flows on the wind barrier. The gutters on the façade panels were used to collect water flowing on the interior side of the façade panels. Details regarding the drainage system are given in Appendix C. Two different kinds of gutters were used in the laboratory tests. This was done in order to test which kind of geometric shape and layout for the gutters would be the most preferable. In addition, delays in shipment of the aluminium foil required a different solution for the gutters on the façade panels. Figure 3.6 shows the geometric shape of both gutters.

The drainage system on the Lexan board was mounted first. A hole with diameter of 16 mm was drilled through the Lexan board, approximately 40 mm from the vertical battens. The gutter system was constructed with a 0.2 mm x 600 mm, soft, aluminium foil, and taped with double-sided tape to the Lexan board. The foil was cut in order to fit within the battens and have an extra edge for folding. 600 mm of foil was cut out as a square. After the gutters were fastened to the board, they were also drilled through. The top of the foil was fastened to the Lexan board with aluminium tape, to ensure watertightness in the transition between the board and gutter. The plastic tubes, with a diameter of 16 mm, were then connected to the gutter system with sleeves and pulled through the Lexan board. The tubes were pulled through the predrilled holes in the Lexan board to minimise the length of the tubes. Therefore, eliminating the possibility for water to lay stagnant in the tube. The tubes were approximately 1 m long. Sleeves were mounted on the inside of the gutter, and the perimeter was sealed with aluminium tape. After the sleeves and

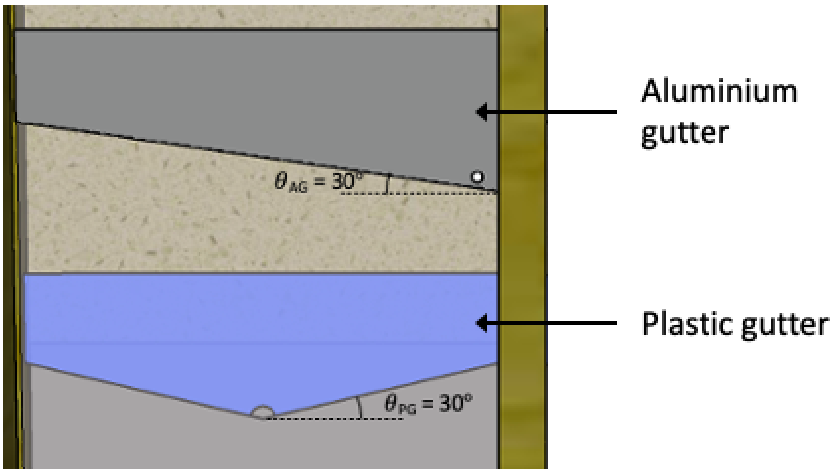


Figure 3.6: Aluminium and plastic gutter geometry. θ_{AG} and θ_{PG} give the inclination of the aluminium and plastic gutter, respectively.

tubes were properly fastened, the foil was folded with a 30° angle. The folding was done by placing a 300 mm metal stick at the bottom of the gutter, that was used as a stencil for the folding to get an even edge in the gutter. The side edges were sealed with aluminium tape. The gutter was placed underneath the battens, and after the battens were properly mounted a waterproof elastic sealant was used between the battens and foil. Before the lowest façade panel was mounted the gutter was evened out using a roll. After a test run the gutters were cut additionally in order to avoid contact between the interior side of the panels and the gutters.

After the drainage system was mounted for the Lexan board, the drainage system on the façade panels were constructed. A 0.2 mm thick vapor barrier was used. This was cut into rectangles measuring 600 mm x 400 mm. A triangle was cut from the edge to the center of the gutter, in order to create an inclination that could lead the water to the tubes. Thereafter a hole was cut at the gutters' lowest point, and a sleeve fastened. The tube with a diameter of 16 mm was fitted into the sleeve and sealed with tape. The tubes were approximately 4 m long, in order to reach the measuring buckets placed outside the driving rain apparatus. Consequently, the tubes from the plastic gutters were approximately four times longer than the tubes from the aluminium gutters. Finally, the perimeter of the gutter was sealed and fastened with aluminium tape. The plastic gutters were fastened to the interior side of the façade panels with aluminium tape. They were placed so that the gutters would be suspended under the bottom panel, this ensured easier access for adjustments. Additionally, aluminium tape was fastened around the perimeter of the gutter in order to make it more rigid and easily shaped. After the panels were mounted and the test rig was hoisted into the driving rain apparatus, three pieces of double sided tape were placed on each gutter. The gutter could then be fastened, by tape, to the Lexan board. Thus, ensuring that the plastic gutters would not collapse and that the edges of the gutter were in contact with the vertical battens.

3.3 Testing in the Driving Rain Apparatus

The testing was conducted by using a driving rain apparatus set up and adapted to testing of watertightness in accordance to NS-EN 1027:2016 " *Windows and doors - Watertightness - Test* *method*". The standard for testing was chosen since the SINTEF and NTNU laboratory had calibrated their driving rain apparatus according to NS-EN 1027:2016, in addition the study conducted by Mo and Lid (2020) was based on the same standard. The apparatus is equipped with a row of nozzles, that could be adjusted both vertically and horizontally. The row consists of six nozzles placed 400 mm from each other. The nozzles could be angled either 24 or 84° to the azimuth. The row of nozzles were placed 100 mm above the top joint, and between 250-260 mm from the exterior side of the façade panels. Each nozzle was set up to spray 2 L/min water, and distributed the water as a circular spray pattern on the façade panels. The row of nozzles were not centered according to the test rig, but the amount of water applied to each test section was approximately the same, as this was measured. A spray rate of 2 L/min per nozzle is equivalent to 5 L/min per meter, or 6 L/min per test section. During the testing there was no pressure difference to the test rig. Since there was an opening in the bottom of the test rig and some opening on the top, in addition to the joints, the test rig was considered to be ventilated. Therefore it was expected that the air cavity between the panels and Lexan board would be pressure equalized. Additionally, it was assumed that the there was no pressure over the cladding. Even though the main focus of NS-EN 1027:2016 is testing watertightness with applied pressure, this was excluded from the testing conducted in the present study. The reason for this was that each test would be more time consuming if pressure was applied, thus fewer parameters would have been included in the test program. Additionally, since the test rig was built as a ventilated façade, it was assumed that the applied pressure differences would be equalized across the joints. However, in reality façades may experience pressure differences due to wind, or at corners of the building, therefore the testing method would be a simplification of real conditions.

After the test rig was lifted into the driving rain apparatus, the following test procedure was conducted for all the tests:

- Water was applied for 10 minutes. This was done to ensure normalized conditions before the measurements commenced. In addition, it enabled time to observe, take notes, pictures and video recordings of the test sections.
- Subsequently, water was applied for 2 minutes, and a measuring jug was used to measure water collected from the interior side of the panels and from the wind barrier. This segment was repeated at least three times for each tested parameter. If one of the three measurements varied largely from the others, another measurement was taken.
- Lastly, the measurements were processed in Excel. The three measurements per parameter were averaged to get a single amount that represents the water intrusion for each parameter. If more than three measurements were taken, the outlier was not included when averaging. The results were divided by 2 minutes to get the results in mL/min.

Three measurements were conducted to ensure the validity of the results, thus ensuring that outliers were not used in the presentation and comparison with other results. However, the water runoff and distribution, and thereby water intrusion, was expected to be somewhat unpredictable, thus meaning replication of a tested parameter could yield different water intrusion results. If more replications were performed one could calculate whether differences in the results were statistically significant. However, a broader set of indicative results, parameters, were deemed to be of greater interest than fewer and statistically comparable results.

An overview of the test program and the testing order is presented in Appendix D. The test program can be simplified to seven smaller stages:

1. The glass fiber panels were tested with the following parameters; 3 mm, 5 mm, 8 mm, T1-profile, T2-profile, h-profile, and sealed top joint. All these tests were conducted with a non-bevelled joint. The panels were mounted while the test rig was in a horizontal position and then lifted into the driving rain apparatus by qualified SINTEF personnel. Glass Fiber Smooth was mounted on test section 1, and Glass Fiber Rough was mounted on test section 2. The adjustments performed to change test parameters were carried out while the test rig was still in the driving rain apparatus. The test rig was then hoisted down into a horizontal position on the floor, thereupon the panels were disassembled.

2. The same procedure was executed on the fiber cement panels, with the exception of the h-profile which did not fit these slightly thicker panels. Additionally, a test with a plain gasket placed on the interior side of the joints was conducted. Fiber Cement Grey was mounted on test section 1, and Fiber Cement White was mounted on test section 2. The test rig was then hoisted down into a horizontal position on the floor, thereupon the panels were disassembled.

3. The U-battens were fastened and the fiber cement panels were screwed to the U-battens. The test rig was then hoisted into the driving rain apparatus again. Subsequently the four different parameters that include the U-batten were tested. The adjustments were carried out while the test rig was still placed in the driving rain apparatus. The test rig was then hoisted down into a horizontal position on the floor and dismantled.

4. The same procedure as stage 3 was then repeated for the glass fiber panels.

5. The Glass Fiber Smooth panels were then bevelled by SINTEF personnel, starting with a 30° top-bevelled joint, and fastened to the test rig. The HPL panels were mounted as they were with a 45° top-and-bottom-bevelled joint. Glass Fiber Smooth was mounted on test section 1, and HPL were mounted on test section 2. The test rig was then hoisted into the driving rain apparatus, tested, and hoisted out again. The two different façade panels were bevelled and tested repeatedly until the Glass Fiber Smooth panels had been tested for all the bevelled joint designs.

6. The HPL panels were then bevelled to a 90° (rectangular) joint. The same procedure as performed in stage 1 and 2 was followed, except the panels were not tested with a gasket or h-profile.

7. The HPL panels were then hoisted in and out of the driving rain apparatus to test the remaining bevelled joint designs.

The different parameters that were tested are: Façade panels, joint widths, bevelled joint designs, joint profiles, and sealed top joint. The different test combinations are presented in Table 3.1. There was a different method for every different parameter. The different profiles, sealed top joint, and bevelled joint designs were all tested with the panels' respective recommended joint widths. The only exception was HPL, which was tested with both a 5 and 8 mm joint width for the different parameters. It is, however, chosen to focus on the recommended joint width (8 mm) when presenting the results of the HPL panels.

Table 3.1: Overview of the complete test program. An "X" means that the combination has been tested in the laboratory measurements. (FP is an abbreviation for fastening points).

	HPL			Glass Fiber Smooth			Glass Fiber Rough			Fiber Cement Grey			Fiber Cement White		
	3mm	5mm	8mm	3mm	5mm	8mm	3mm	5mm	8mm	3mm	5mm	8mm	3mm	5mm	8mm
Open joint		**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
T1-profile		**X**	**X**		**X**			**X**			**X**			**X**	
T2-profile		**X**	**X**		**X**			**X**			**X**			**X**	
h-profile					**X**			**X**							
Sealed top joint		**X**	**X**		**X**			**X**			**X**			**X**	
Gasket											**X**			**X**	
U-batten					**X**			**X**			**X**			**X**	
U-batten with extra fastening points					**X**			**X**			**X**			**X**	
U with gasket					**X**			**X**			**X**			**X**	
U with gasket and extra fastening points					**X**			**X**			**X**			**X**	
Bevelled top 15°		**X**	**X**		**X**			**X**							
Bevelled top 30°		**X**	**X**		**X**			**X**							
Bevelled top 45°		**X**	**X**												
Bevelled both 15°		**X**	**X**		**X**			**X**							
Bevelled both 30°		**X**	**X**		**X**			**X**							
Bevelled both 45°		**X**	**X**												

Façade Panels

Five different panels were tested, consisting of different materials, as presented in Table 3.2. The dimensions presented in the table were measured before the panels were bevelled. The panels are representative for products that are used in Norway today, and originate from three different suppliers. The supplier's recommendations regarding mounting of the different panels are given in Appendix E. The panels were reused from a previous laboratory measurement conducted by Mo and Lid (2020). Thus, the recommended joint widths presented in Table 3.2 are based on information from suppliers given to Mo and Lid. The panels were fastened to the vertical battens, and each panel was fastened with four $\phi 4$ 28 mm long screws to each batten, in accordance with supplier recommendations.

To more easily categorize and explain how the panels react to water and water runoff, the contact angle was measured. A water droplet was dropped on each panel with a pipette, and subsequently a picture was taken and later analyzed to measure the contact angle. The different panels were then categorized by how hydrophobic or hydrophilic they are.

Table 3.2: Overview of the tested façade panels with their respective dimensions, recommended joint widths, and surface characteristics.

Material	Dimensions [mm]	Recommended joint width [mm]	Surface characteristics
Glass Fiber Smooth	1195x840x6	5	Painted and very smooth
Glass Fiber Rough	1195x840x6	5	Crushed stone and very rough
Fiber Cement Grey	1192x800x8	5	Painted and smooth
Fiber Cement White	1192x800x8	5	Sandblasted and rough
HPL	1200x800x8	8	Painted and very smooth

Joint Width

Three different joint widths were tested: 3, 5 and 8 mm. The joint width was measured as the distance between the over- and underlying panel on the exterior side of the joint. Two spacers with a desired thickness corresponding with the joint widths were used. The thickness of the spacers were measured with a digital caliper. The test rig was positioned horizontally when new façade panels were mounted. It was kept in a vertical position in the driving rain apparatus when the joint width was changed between tests. The façade panels were mounted from top to bottom. The top panel was fastened first, then the spacers were placed in between the panels and the lower panel was pushed against the spacers. After the middle panel was fastened, the procedure was repeated for the bottom panel and joint.

Joint Profiles

In total eight joint solutions with joint profiles were tested. Three of the joint profiles had parts that protruded within the joint, and are hereby referred to as *joint profiles within the joint*. The other joint profiles did not have protruding parts within the joint. To make a clear distinction between the two types of joint profiles, the joint profiles without protruding parts are hereby referred to as *joint profiles behind the joint*. The three joint profiles within the joint, T1-, T2-, and h-profile, are shown in Figure 3.7. The T1- and h-profile are recommended by SINTEF (Gaarder, 2019). A Z-profile is also recommended, but was not tested since it could not be acquired. All the profiles were made of aluminium and were approximately 1 mm thick, their dimensions are given in Figure 3.8. The profiles were mounted by loosening screws for easier access, thereby pressing the profile into the joint longitudinally. The two T-profiles were pushed downward so their protruding parts were pressed to the bottom edge of the joint. This was done to reduce the risk of water infiltrating underneath the profile. The h-profile was only tested for the glass fiber panels, since the profiles only fit panels with joint widths ≤ 6 mm. The two T-profiles were tested for all the façade panels.

The joint profiles behind the joint consisted of different combinations with a plain 70 mm wide EPDM-gasket and ventilated steel U-batten. The U-batten had a depth of 15 mm and a height of 70 mm. The gasket was equivalent to the one used between the vertical battens and façade panels for the glass fiber and HPL panels. A gasket as a protection measure was tested since similar joint

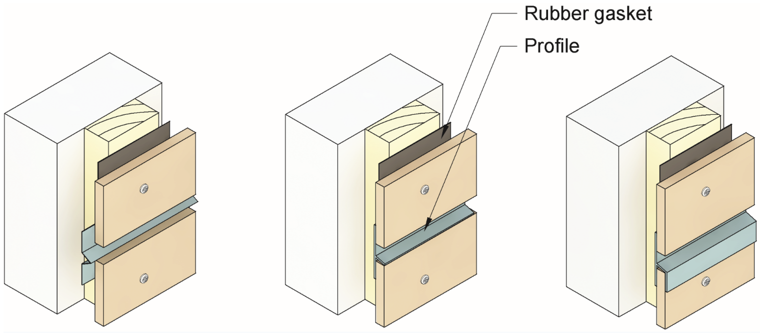


Figure 3.7: Joint profiles. From the left: T1-profile, T2-profile and h-profile. Normally a vertical batten is not used in combination with an U-batten.

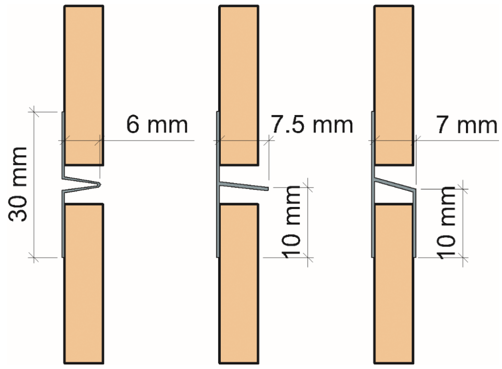


Figure 3.8: Joint profile dimensions. From the left: T1-profile, T2-profile and h-profile. Left side of panels is the interior side, and right side is the exterior. Altered from Geving (2022).

solutions have been observed on several buildings in Trondheim. Extra fastening points were used to test if a tighter fit would lead to less water intrusion, as was suggested as further work by Mo and Lid (Mo & Lid, 2020). The HPL panels were not tested with any of the profiles used behind the joints. The combinations are presented in Table 3.1 and Figure 3.9.

The U-batten was fastened to the vertical battens and positioned so that the joints were centered on the U-battens, as shown in Figure 3.9. The mounting deviates from common practice, since vertical battens are typically replaced by the U-battens. The U-batten had a depth of 15 mm, thus increased the air cavity from 30 to 45 mm, and reducing the distance from the nozzles to the panels by 15 mm. Additionally, the panels could only be fastened at the bottom and top of the panels to the U-battens. Therefore the panels are only mounted with six fastening points, instead of the usual 12. The tests with extra fastening points have a total of ten fastening points. Thus, the distance between fastening points were reduced from c/c 550 mm to c/c 275 mm. The U-battens were fastened by using $\phi4$ 35 mm self-drilling screws for metal. The gasket was pulled through in a similar manner to the other profiles (pushed in and pulled through the joint). The gasket was fastened with screws.

Bevelled Joint Designs

One of the test parameters was how the geometric design of the joint could affect the water intrusion. Most of the façade panels that are used in Norway have a horizontal flat edge. They can however be altered. A bevelling of the overlying panel create a dripping edge that could lead

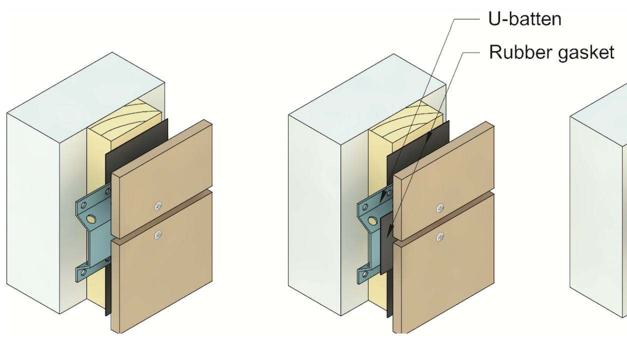


Figure 3.9: Joint profiles behind the joint. From the left: U-battens without a gasket, U-batten with a gasket, and with only a gasket.

to less water intrusion, as was shown by Mo and Lid (2020). The HPL panels and the Glass Fiber Smooth panels were used to test bevelled joint solutions. The other panels were considered unfit for cutting by authorized SINTEF personnel.

Three different bevelled angles were tested: 15°, 30°, and 45°. The Glass Fiber Smooth panels were only tested with 15° and 30° bevelled edges, since 45° was considered too great a crack and break risk. 45° was only tested with the HPL panels, since they were already cut previously to this testing. Each degree was tested with a top-bevelled joint and a top-and-bottom-bevelled joint, as shown by alternative 1 and 2, respectively, in Figure 3.10. The glass fiber panels were tested with an increasing angle size. The HPL panels were already cut to a 45° angle on top and bottom and were therefore cut and tested with decreasing angle sizes. The order of testing was chosen to minimize the cutting of the panels.

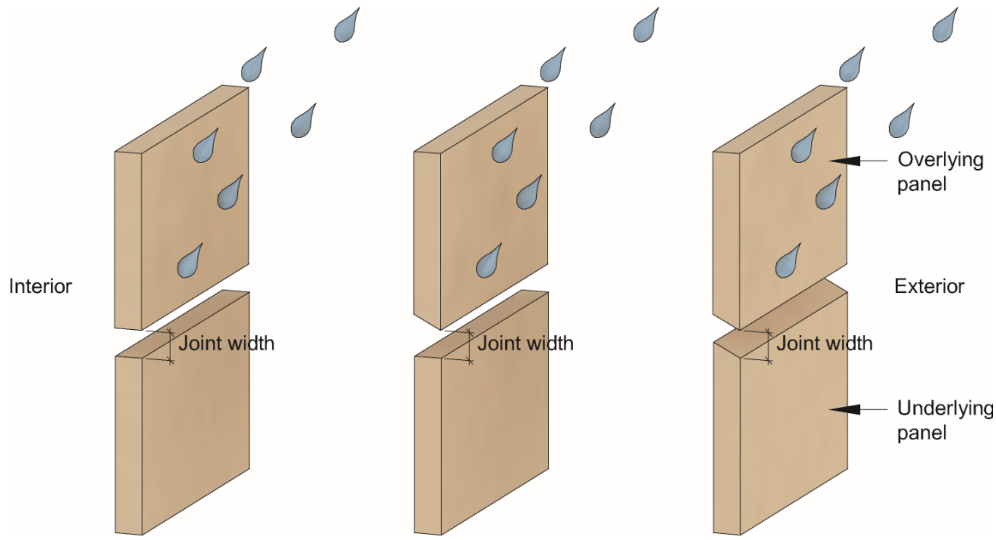


Figure 3.10: Different bevelled joint designs. Alternative 1 shows a rectangular joint. Alternative 2 shows a top-bevelled joint. Alternative 3 shows a top-and-bottom-bevelled joint.

The panels were cut using diamond blades to achieve the bevelled joint designs. The cutting was conducted by authorized SINTEF personnel. The blades were used according to the supplier's recommendations. The panels were tested with a joint width of 5 mm. The HPL panels were also tested with a joint width of 8 mm, according to mounting recommendations for these panels, see Table 3.2. To ensure the correct joint width, the same method as for rectangular, non-bevelled, joints was used. The joint width is measured on the exterior side of the joint, as can be seen in

Figure 3.10.

Sealed Top Joint

To test for water intrusion without direct spray into the top joint and with an increased amount of water runoff on the lower joint, the top joint was sealed. All panel types were tested. A plastic film was taped to the top of the panels and fastened so that it covered the top joint. The testing with a sealed top joint was conducted after the testing of T2-profiles, therefore only the profile in the lower joint was removed to ensure the watertightness of the top joint. The plastic film was patted down, so it stuck to the panels. This was difficult to accomplish on the Glass Fiber Rough panels due to the surface structure. The plastic film was equivalent to the vapor barrier used to construct the gutters placed on the façade panels.

Testing of the Test Sections

When all the previously mentioned joint solutions had been tested, the runoff on each test section was measured. The test was conducted to check how much water hits and flows down the panels, or in this specific case the wind barrier. The panels and gaskets were removed during this test. The aluminium gutters were slightly folded out to gather more water. Furthermore, the plastic gutters were used to collect any possibly water escaping from the aluminium gutters. They were fastened to the Lexan board and stapled to the vertical battens so that they would keep their shape and not collapse due to the water's weight.

4 Results and Discussion

In this chapter the results from the laboratory experiments will be presented. The results are presented both in a qualitative and quantitative measure. The water intrusion through the joints are measured quantitatively, while the description of water runoff and intrusion is presented qualitatively. The results are presented based on the different parameters that are tested: Joint width, joint profiles, bevelled joint design, and sealed top joint. All measurements and their test numbers, before they are averaged, can be seen in Appendix D. At the end of the chapter sources for error and uncertainties are presented. In the scientific paper, Appendix A, the results and their correlation with current knowledge from previous experiments are presented and discussed.

4.1 Observed Water Behaviours

In the presentation and discussion of the results and observations, several terms and concepts of water behavior will be used. The terms used to describe water behavior both relating to water intrusion and runoff, will be the following:

Droplets

Droplet means a small drop of water and is used to describe water hanging or running down a surface. *Hanging droplets* often occured on the edges of open joints if the joint width was sufficient, or as for instance shown in Figure 4.1 hanging off protruding elements. The term *running droplets* is used in relation to low water flow. The water trickles slowly and a clear droplet could be seen running down the panel or Lexan board, as shown in Figure 4.2.

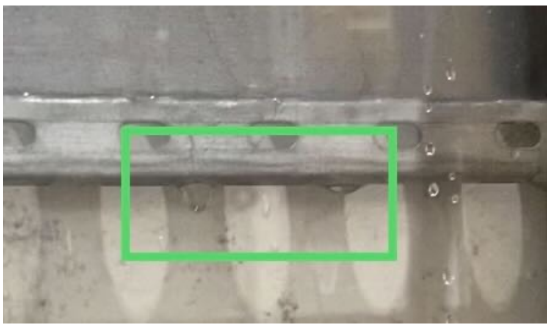


Figure 4.1: Water hanging in droplets on the interior side of the U-batten in the lower joint. Photo taken during test no. 99 with Fiber Cement Grey panels and an U-batten.

Figure 4.2: Water trickling down a surface, running droplets. Photo: Anatoli Weingart.
.

Dripping

Dripping occurred when water was hanging in droplets as shown in Figure 4.1. When the object with hanging droplets was sufficiently wet, the water droplets would start dripping. This could typically be seen in joint widths of 5 and 8 mm, and protruding elements. Figure 4.3 shows droplets in a 8 mm joint dripping to the underlying panel edge.

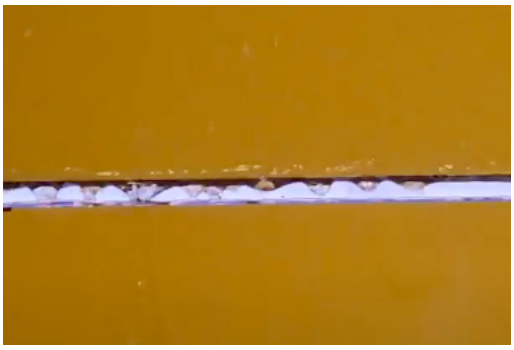


Figure 4.3: Dripping in the lower joint. Photo taken during test no. 183 with HPL panels and an 8 mm joint width.

Splashing

Splashing often occurred due to dripping. When the droplets hit a surface this creates a splash. Such behaviour is observed both on the wind barrier, in the joints and in the gutters. Splashing caused by direct spray through the top joint onto the wind barrier will be referred to as direct spray, as it is difficult to see the difference. It is, however, assumed that splashing always occurred in a joint when there is direct spray.

Water Bridges

Water bridges occurred in the joints when the water flow creating water droplets was high enough to create a connecting bridge between the top and bottom edge of the joint. Furthermore the joint had to be at least < 8 mm for water bridges to occur. Figure 4.4 shows a *partial water bridge*, as there are air gaps in between the water bridges. Partial water bridges were usually observed in 5 mm joint. A *continuous water bridge*, as shown in Figure 4.5, had no air gaps and was continuous. In almost every test a continuous water bridge could be observed in the top joint, if the joint was open. Likewise it was often observed in a 3 mm joint.

Figure 4.4: A partial water bridge in the lower joint. Photo taken during test no. 58 with Fiber Cement White panels and a 5 mm joint width.

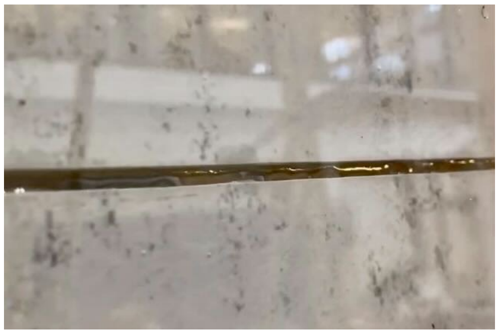


Figure 4.5: Water bridge that is continuous throughout the lower joint. Photo taken during test no. 43 with Fiber Cement Grey panels and a 3 mm joint width.

Direct Spray

The water flow had a horizontal component when it was sprayed from the nozzles. When the water intruded the top joint and hit the wind barrier directly due to the horizontal water flow component it is called direct spray. This caused water droplets and running droplets on the wind barrier. This is illustrated in Figure 4.6.

Water Film

Water films occurred both on the exterior and interior side of the façade panels, in addition to flowing over the entire exterior joints. Usually, when a water film flowed over a joint, less water infiltrated the joint. Figure 4.7 shows an a water film on the exterior side of the panels.

Figure 4.6: Direct spray through the top joint to the wind barrier. Photo taken during test no. 86 with Fiber Cement White and an 8 mm joint.

Figure 4.7: Water film on exterior side of panel. Photo taken during test no. 195 with HPL panels and a sealed top joint.

Streams

Streams describe water runoff as shown in Figure 4.8. This was the most often observed runoff, and was observed to a varying degree. *Concentrated streams* is used to describe streams that usually lead to larger amounts of water intrusion.

Ejection Effect

For highly concentrated streams on the exterior side of the panels, water could infiltrate the joint and hit the wind barrier directly because of a horizontal flow component, this is referred to as the ejection effect. Figure 4.9 shows an example of the ejection effect. When this phenomenon occurred a lot water intrusion to the wind barrier was measured. It was however, a sporadic and unpredictable effect.

Figure 4.8: Water streams down the interior side of a panel. Photo taken during test no. 97 with Fiber Cement Grey panels and an U-batten.

Figure 4.9: Ejection effect from a joint to the wind barrier (Mo & Lid, 2020).

4.2 Problems Relating to the Water Intrusion to the Wind Barrier

Further presentation and discussion of the results will be highly influenced by the problems that are discussed in this chapter. The uncertainties relating to the water intrusion to the wind barrier are the reason why these results are less focused on than the water intrusion to the interior side of the panels.

The water intrusion to the wind barrier was mainly caused by direct spray from the nozzles. The only exception being some instances of splashing and ejection effect. Throughout all the measurements, the results for the water intrusion to the wind barrier are varying. At times there was not enough water on the wind barrier to fill up the gutters, the water would linger on the wind barrier in droplets instead. Additionally, since there were smaller amounts of water, the results are more sensitive to uncertainties and errors. It was also uncovered that the amount of water intrusion was highly dependant on the nozzle placement. The placement of the nozzles was supposed to be 100 mm vertically above the joint and 250 mm horizontally. The procedure for moving the nozzles was manual, and did not have a high degree of accuracy (estimated accuracy of ±15 mm). Since the joint widths varied from 3 to 8 mm, this inaccuracy can have a substantial affect on the direct spray that intruded the joints. The nozzles were never moved horizontally, even though the panels have different thicknesses and the U-batten caused a 15 mm wider air cavity. The distance to the nozzles was thereby reduced by 15 mm when the U-battens were used. This caused the spray radius to decrease, and the joints experienced a more concentrated spray from the nozzles.

After the rig was hoisted in before test 49-54, the nozzles were not adjusted vertically, which was discovered after the testing was completed. The nozzles were placed 60 mm above the top joint, instead of 100 mm. The nozzles were subsequently moved to 100 mm above the top joint and the tests were repeated, test 55-62. The results for these measurements are shown in Figure 4.10. Since a 60 mm distance to the joint gives more water intrusion to the wind barrier and less to the interior side of the panels, it can be assumed that the nozzles were at a better placement for direct spray to enter the top joint. The water intrusion to the wind barrier increased 107% and 61% when the row of nozzles was moved from 100 mm to 60 mm, for the grey and white panels, respectively. The panels have a less dramatic change in water intrusion to the interior side of the panels, -18% and -12% for the grey and white panels, respectively. The data indicates that the nozzle placement, and the inaccuracy related to it, has a bigger influence on the water intrusion to the wind barrier than the interior side of the panels.

The uncertainties relating to the wind barrier have led to the conclusion that the wind barrier results need to be interpreted with caution. Very few results are completely comparable, because with every hoisting in and out of the test rig, the nozzles had to be adjusted vertically. Additionally, the two test sections might not have perfectly aligned top joints, and this would cause differences between the test sections. Therefore comparisons of water intrusions for different panel claddings can not be made with certainty. However, water intrusions for the same panels, as long as the test rig has not been lifted out between tests, can be compared. This is the case, for instance, for different joint widths. The further discussions regarding water intrusion to the wind barrier will focus more on the effect different parameters may have on water intrusion, rather than the actual water amount.

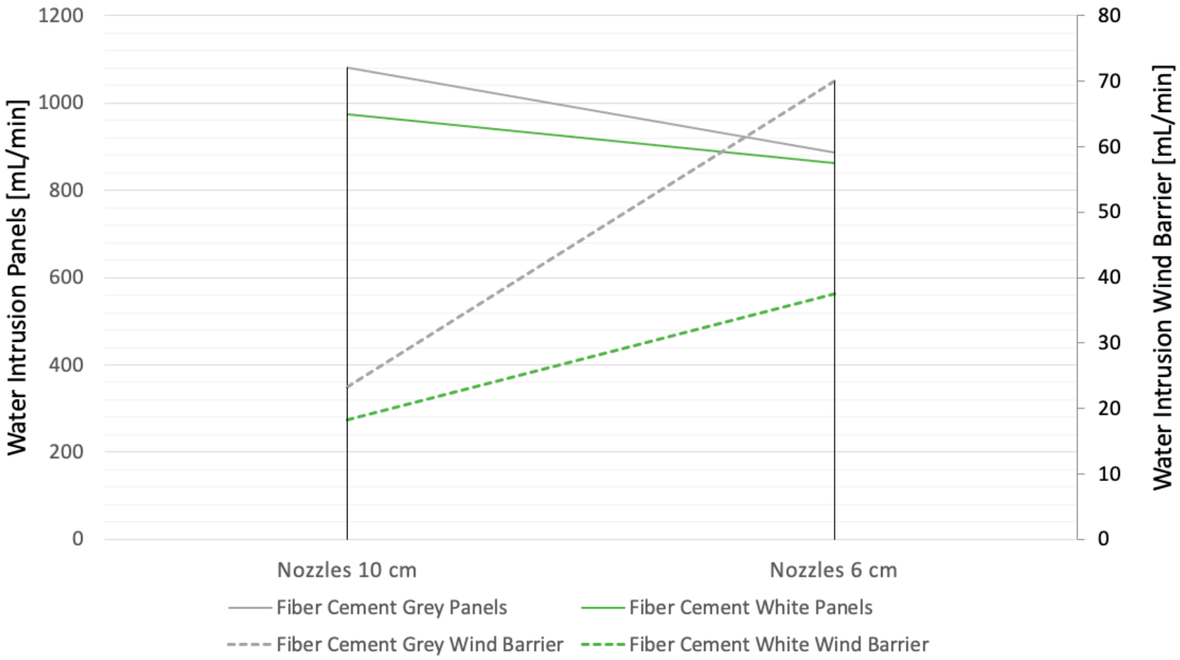


Figure 4.10: Water intrusion with a 5 mm open joint and different nozzle placements. The left vertical axis and solid lines show the water intrusion to the interior side of the panels. The right vertical axis and the dashed lines show the water intrusion to the wind barrier.

4.3 Façade Panels

The different panels are sorted and categorized by their contact angle with a water droplet in Table 4.1. All the panels' exterior sides were hydrophilic, but to different degrees. The contact angle was only measured on the exterior side of the panels. Only the Glass Fiber Rough panels has a completely different surface on the exterior and interior side. For Glass Fiber Smooth, Fiber Cement White and Grey there might be differences between the exterior and interior side. The HPL panels has equivalent surfaces on both sides. The contact angle measurements rough estimates, due to restrictions such as the picture resolution, measurement tools, and since only a single picture was taken of each panel. Furthermore, the dispersing of the water droplets can be affected by other substances on the panels, such as, for instance, dirt or tape remains. Furthermore, since all the panels have been used before, some of them could be more worn than others. These limitations combined with what was known about the surface characteristics, given in Table 3.2, can be used to explain the observed and measured water intrusion. Additionally, observed water runoff on the exterior side of the panels gives a clearer picture. Due to differing water intrusion through the top joint the water runoff on the middle panel varied, but the general observations for the panels are:

- **Glass Fiber Smooth**: Water from the nozzles concentrated from water films directly underneath the nozzles into concentrated streams. Additionally, several smaller streams covered the exterior side of the panels. A lot of water intrusion occurred from the concentrated streams. The streams were smaller and less concentrated on the lower panel. Dripping in the joints and water bridges were a frequent occurrence.
- **Glass Fiber Rough**: The water seemed to be evenly dispersed in a water film. Water often flowed in a film across the joints. The crushed stones on the surface seemed to counteract

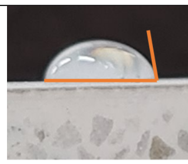
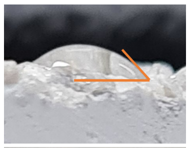
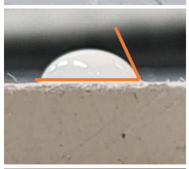
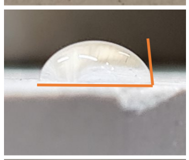
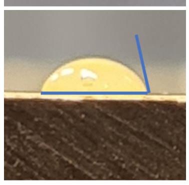
the forming of streams. Water runoff on the exterior side of the panels was more difficult to observe than on the other panel types.

- **Fiber Cement Grey**: Water from the nozzles concentrated from water films directly underneath the nozzles into concentrated streams. There were also several smaller streams. A lot of water intrusion occurred from the concentrated streams. Dripping in the joints and water bridges was a frequent occurrence. The streams were smaller and more concentrated on the lower panel, probably caused by a smaller water amount than on the middle panel. Very similar behaviour as seen on Glass Fiber Smooth.

- **Fiber Cement White**: Most of the water runoff was an evenly dispersed water film, while some water was concentrated in smaller streams. The evenly dispersed water often directed the runoff water across the joints in a water film. Dripping in the joints and water bridges are a frequent occurrence.

- **HPL**: Most of the water runoff is evenly dispersed on the middle panel. A decreasing amount of water increased the runoff in streams, rather than in film. Dripping in the joints and water bridges were an often occurrence.

Table 4.1: Overview of the different façade panels' contact angle. A substance is hydrophilic when the contact angle is ≤ 90°.

Facade Panel	**Contact Angle**	**Classification**	**Figure**
Glass Fiber Smooth	80°	Slightly Hydrophilic	
Glass Fiber Rough	48°	Very Hydrophilic	
Fiber Cement Grey	65°	Hydrophilic	
Fiber Cement White	84°	Slightly Hydrophilic	
High Pressure Laminate	77°	Hydrophilic	

The Glass Fiber Smooth, Fiber Cement White, and HPL panels all have roughly the same contact angle, 80°, 84°, and 77°, respectively. These are all hydrophilic, but not by much. They are less hydrophilic than the other two panels. It is therefore expected that these three panels will have a higher water flow velocity since less adhesion acts between the water molecules and the panels.

Figure 4.11 indicates that these three panels give varying amounts of water intrusion through the joints. The Glass Fiber Smooth and HPL panels are both characterized as very smooth, since they also have similar contact angles it is expected that they have similar amounts of water intrusion. In Appendix F it can be seen that HPL and Glass Fiber Smooth often have a similar and the most water intrusion compared to the other panels. The total water intrusion to the interior side for the Glass Fiber Smooth, Fiber Cement White, and HPL panels were on average 18.5%, 13.9%, and 19.7%, respectively, of the total water sprayed. The somewhat differing results despite similar contact angles indicates that the contact angle is not the only parameter that affects water intrusion.

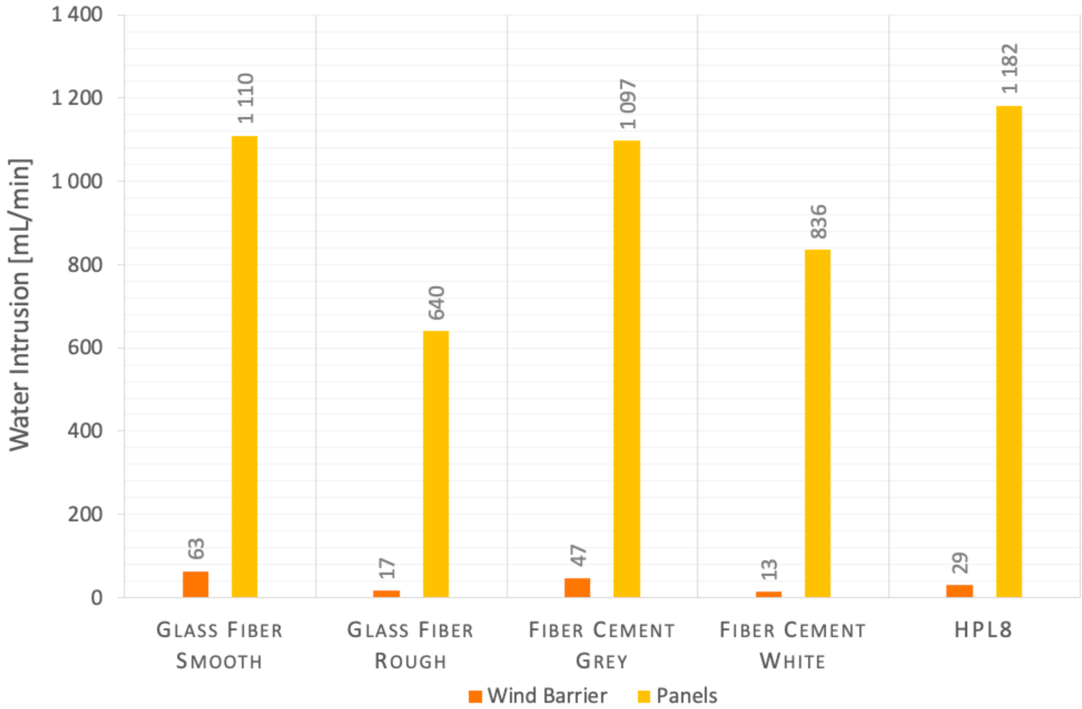


Figure 4.11: Average collected water intrusion on the interior side of the panels and on the wind barrier for the five different façade panels. Averaged over the parameters that are tested with all the panels; 5 mm, 8 mm, T1-profile, T2-profile, and sealed top.

The Glass Fiber Rough and Fiber Cement White have smaller contact angles compared to the other panels. The Glass Fiber Rough panels have a very rough surface with small crushed stones, and therefore it is believed that the roughness of the panel is important for the runoff. Additionally, the contact angle is not easy to measure with accuracy when the surface is as rough as in this instance. The contact angle is measured to be 48°. This indicates that these panels are the most hydrophilic, which would suggest slower water flow and a more dispersed runoff. Observations confirm that the water is more dispersed in a water film seemingly covering the entirety of the panels. As shown in Figure 4.11, the Glass Fiber Rough panels yield the least amount of water on the interior side of the panels with an average water intrusion of 640 mL/min in total, which means 10.7% of the water spayed on the panels infiltrated the joints. The Fiber Cement Grey panels are characterized as hydrophilic and smooth, they can be seen as an intermediate alternative when compared to the other panels. However, according to Figure 4.11, the Fiber Cement Grey panels yield approximately the same amount of water intrusion as the Glass Fiber Smooth and HPL panels. They gave an average water intrusion of 1097 mL/min in total, which means 18.3% of the water sprayed on the panels infiltrated the horizontal joints. However, a closer look at the results, see Appendix F, show that the Fiber Cement Grey panels usually let in substantially less water than the Glass Fiber Smooth and HPL panels. The results in Figure 4.11 are heavily influenced by outlier results with the T2-profile for the Fiber Cement White.

The results are compared to the measured water intrusion with the recommended solutions throughout this chapter. An overview of the standard recommendation results are given in Table 4.2. Every panel type's standard recommended solution if 5 mm, except for HPL. The standard recommendation for HPL is to use an 8 mm joint width, thus when the results for HPL with a 8 mm joint are presented, it is referred to as HPL8, whereas HPL5 represents a 5 mm joint width. The results for the different joint solutions are compared to the recommended solutions by calculating the percentage change.

Table 4.2: Overview of the water intrusion with the standard recommendations; the recommended joint width from suppliers for the panels as presented by Mo and Lid.

Panel name	**Recommended joint width**	**Water intrusion to the wind barrier [mL/min]**	**Water intrusion to the interior side of the panels [mL/min]**
Glass Fiber Smooth	5	43	1767
Glass Fiber Rough	5	22	733
Fiber Cement Grey	5	34	1081
Fiber Cement White	5	23	975
HPL (HPL8)	8	90	1492

It is difficult to make any solid conclusions regarding the influence of the contact angle and surface characteristics on water intrusion and runoff. There are many varying trends as can be seen in Appendix G and F. However, a trend is that smoother panels lead to more water intrusion than rougher panels. It is observed that smoother panels lead to more concentrated streams, and it seems that a dispersed water flow is more desirable to minimize water intrusion. Therefore, it would seem that the roughness of the surface has a greater impact on water runoff and intrusion, than the contact angle. Since the sample pool is quite small, only five panels, the results can be categorized as a trend rather than a solid conclusion.

4.4 Joint Widths

A total of 14 combinations of parameters were conducted on different joint widths for horizontal open joints. Three different joint widths were measured: 3, 5, and 8 mm. The measurements were conducted with every panel. The only exception is HPL, which was not tested with a 3 mm joint width. The standard recommendation is a 5 mm joint width for the all panels except for HPL. The standard recommendation for HPL is a 8 mm joint width.

Water Intrusion to the Wind Barrier

The water intrusion to the wind barrier for joint widths of 3, 5 and 8 mm is shown in Figure 4.12. Water intrusion increases with increasing joint widths. On average 29 mL/min hits the wind barrier when the joint width is 5 mm, and 99 mL/min when the joint width is 8 mm. This corresponds to 0.5% and 1.7%, respectively, of the total water amount sprayed on the panels. Water intrusion occurred with a 3 mm joint width, but the water amount was not sufficient to make the water drip down into the gutters. With a 3 mm joint width, direct spray from the nozzles was the only observed water intrusion. A continuous water bridge was observed in the top joint, and water seemed to be flowing across the exterior part of the joints in a water film. On the other hand, the continuous water bridge might be broken and infiltrate when the façade is exposed to wind. The water amounts measured with a 5 mm joint width are similar, with Glass Fiber Smooth and HPL being the furthest from each other with 43 mL/min and 18 mL/min water intrusion, respectively. The water intrusion is observed from the top joint, and seems to be only direct spray that leads to running droplets and streams for a 5 mm joint width. There is a substantial difference between the infiltration rate at 8 mm for the different panels, with Glass Fiber Smooth being the extreme. This is likely caused by the ejection effect which was observed for every measurement with the Glass Fiber Smooth panels and with a 8 mm joint width. All the other panels had similar water behaviour; running droplets from direct spray in the top joint. However, the water amount hitting the wind barrier is very dependant on the positioning of the nozzles, as discussed in Section 4.2.

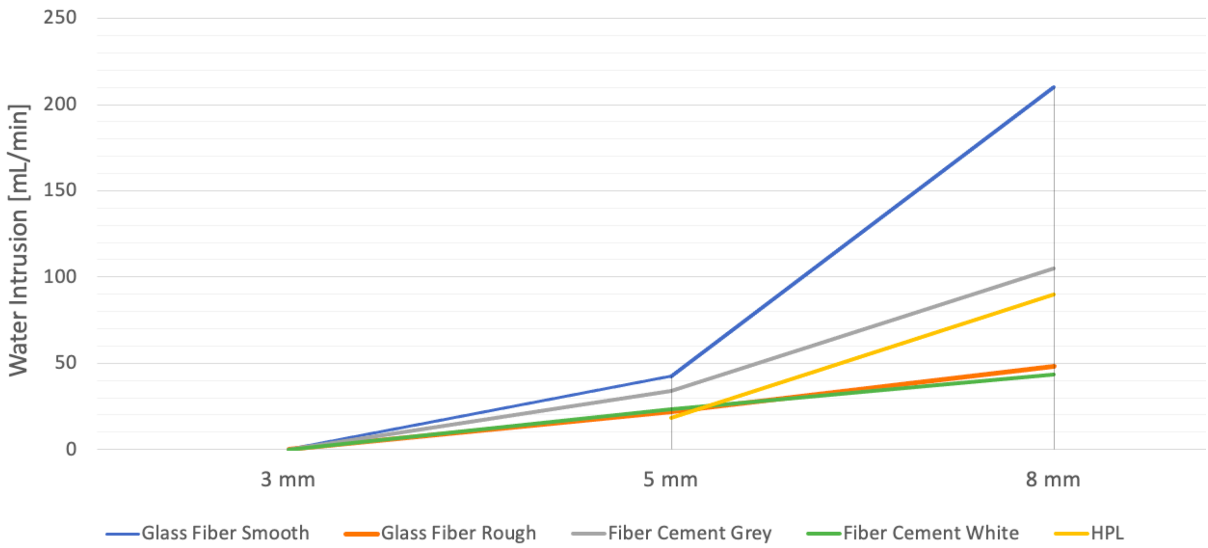


Figure 4.12: Water intrusion to the wind barrier for five different panels with 3, 5, and 8 mm joint widths.

Water Intrusion to the Interior side of the Panels

Water intrusion to the interior side of the panels for a joint width of 3, 5, and 8 mm is shown in Figure 4.13. It was assumed that an increase in joint width would lead to an increase in water intrusion, same as for the wind barrier. This is, however, not found to be the case. All panels except for one, Glass Fiber Rough, experience the most water intrusion with a joint width of 5 mm when compared to the other two joint widths. All the panels lead in the least water with a joint width of 3 mm, while on average the water intrusion is doubled with a joint width of 5 mm and consequently then reduced with a joint width of 8 mm. There are, however, variations to this trend depending on which panel is used.

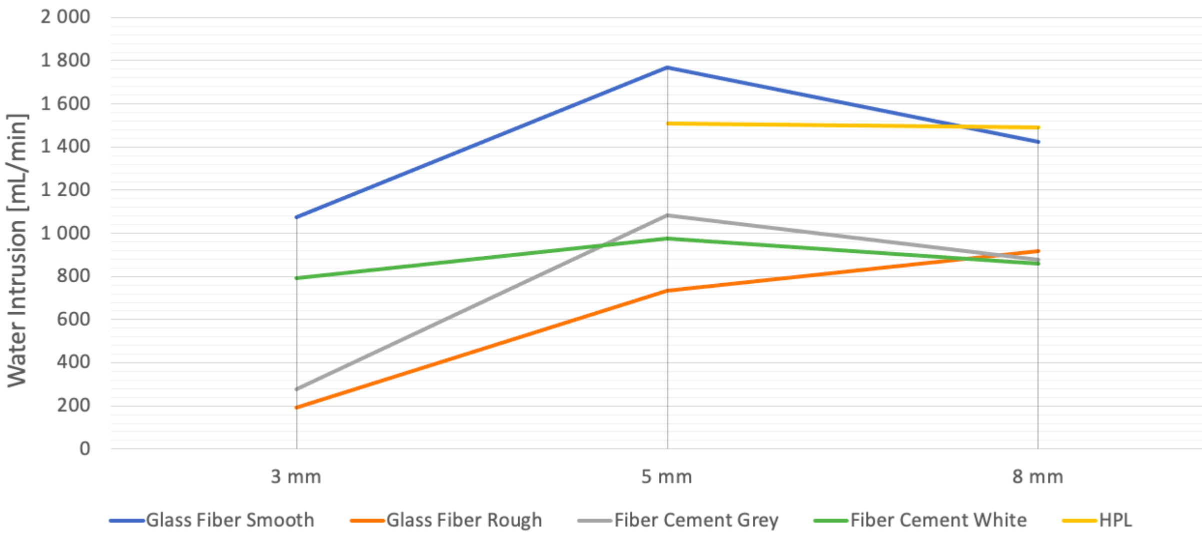


Figure 4.13: Water intrusion to the interior side of the panels for five different panels with 3, 5, and 8 mm joint widths. .

For a 3 mm joint width the water intrusion varied from 3.2% to 17.9% of the total water sprayed on the test sections, the average water intrusion is 9.7%. In every experiment with a 3 mm joint width, a continuous water bridge was observed in the top joint. In the lower joint half of the panels had a continuous water bridge and the other half had partial water bridges. Where the water bridges broke, water would flow down the interior side of the panels in smaller streams. However, the water bridges could also lead water across the joint on the exterior side, acting as a barrier against water intrusion. The panels experiencing a continuous water bridge in the lower joint are the two panels that have the most water intrusion, indicating that more water in the joint leads to more water intrusion. As expected, 3 mm joint width does not lead in a substantial amount of water, however the results differ from panel to panel. The difference between Glass Fiber Rough and Glass Fiber Smooth is almost 900 mL/min. This is not unexpected since, as shown in Section 4.3, Glass Fiber Smooth leads on average substantially more water to the interior than Glass Fiber Rough.

For 5 mm joint widths the water amounts are substantial and vary from 12.2%-29.5% of the total water sprayed on the test sections, with the average being 20.2%. There is a great disparity in water intrusion, varying with 1034 mL/min. This shows that the recommended joint width from the suppliers lead to a substantial water intrusion for all the panels. In the 5 mm joints, partial water bridges and dripping was observed in the lower joint. The only exception was the Glass Fiber Rough where only dripping was observed. This can be explained by the composition of the Glass Fiber Rough panel; the crushed stones are approximately 2 mm of the total panel thickness. Therefore, the even edge were water bridges are formed is smaller than for the other panels. The dripping in the joint will lead to water intrusion due to splashing, but the effect of water bridges are more unsure. On one hand the water bridges might lead the water across the joint, thereby avoiding any water intrusion. On the other hand it can also act as a pathway for water flowing from the exterior to the interior side of the panel. The water in the joints creates water streams, and in the case of Glass Fiber Smooth and HPL, which have the most water intrusion at 5 mm, water films combined with streams were observed on the interior side of the panels. The ejection effect was also observed for every measurement with the Glass Fiber Smooth panels and this likely caused more water intrusion than would occur without the effect.

For the 8 mm joint widths the water intrusion vary from 14.3% to 24.9% of the total sprayed amount, with 18.6% being the average. An 8 mm joint width leads to dripping in the joint for every panel. Compared to the 5 mm joint width the droplets are bigger and seem to have a higher dripping frequency. Similar observations were made for all the panels, with Glass Fiber Smooth and HPL having more concentrated streams and water films that covered a larger share of the panels compared to the other three. Additionally, the ejection effect was observed with the HPL panels, but the horizontal component was not strong enough to lead the water directly to the wind barrier. A reason for this might be that the concentration of water in the joint is not great enough to push the water with enough force for the water to reach the wind barrier. The ejection effect could partly be the reason for HPL having the largest water intrusion (1492 mL/min). The least water intrusion occurred with the Fiber Cement White panels, 858 mL/min. The surprising reduction for the 8 mm joint widths compared to the 5 mm may be explained by the increased water intrusion to the wind barrier.

4.5 Joint Profiles

In total 32 different combinations of parameters were conducted on joint solutions with joint profiles. The different joint profiles are separated in the categories "within the joint" and "behind the joint", as explained in Section 3.3. As profiles cover the joint, they will protect the wind barrier against not only water, but also UV radiation.

4.5.1 Joint Profiles Within the Joints

When the joint profiles within the joints were used there was no water on the wind barrier. However, this was not the case for the interior side of the panels. The results vary, as can be seen in Figure 4.14.

The T1-profile shows disparate results. All panels except for the fiber cement panels experience reduced water intrusion, a 63-70% decrease, when compared to the tests with standard recommendations. Streams on the interior side of the panels were observed for all the measurements. The streams infiltrated underneath the profiles in both the top and bottom joint. Water would run over the profiles on the interior side in the lower joint. Gaps between the profiles and overlying panels could, on the other hand, lead water from the interior to the exterior side of the joint. Yet it was difficult to measure or observe to what extent this occurred. It was more difficult to get the profile tightly fitted with the fiber cement panels because they were generally more worn and more distinct gaps were observed. This is likely why these panels are outliers and lead in slightly more water than the results with standard recommendations. Additionally, the profile dimensions could be an impacting factor. As shown in Figure 3.8, the T1-profile has a 6 mm protruding part, while the fiber cement panels, in this case, are 8 mm thick. It is therefore possible that as long as the profile's protruding part is longer than the panel thickness, the T1-profile is a sufficient joint solution.

The T2-profile also had variable results, but in this case only the Fiber Cement Grey panel is a

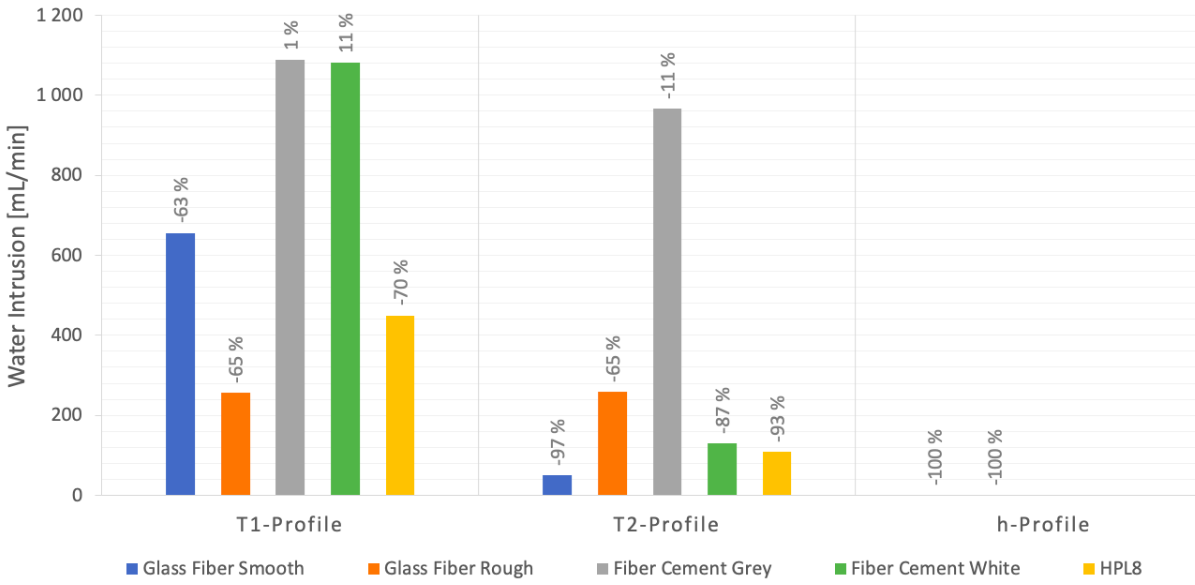


Figure 4.14: Water intrusion to the interior side of the panels using profiles within the joint: T1-, T2-, and h-profiles. The percentage change from the measured water intrusion with the standard recommendations in Table 4.2 is shown.

deviant. All panels except for the Fiber Cement Grey panel experience reduced water intrusion with 65-97% decrease when compared to the standard recommended solutions. Hence, the water intrusion was less than with the T1-profile. The four panels that had less than 300 mL/min had mostly running droplets, and very little water was observed infiltrating through the joints. The Fiber Cement Grey panel's profile was looser on one side, and water could be seen entering though primarily the left side of the section. This indicates that the panel was not sufficiently fastened and therefore the joint and the panel had a larger gap leading to water intrusion. The results for this profile could also have been affected by the dimensions of the protruding part, 7.5 mm in this case. However, since the protruding part could be pressed downward sufficiently to touch the top edge of the panels, it is believed that this is not a vital factor for water intrusion in this case. On the other hand, if the profiles had not been shoved down, but rather for instance centered in the joint, this could be a factor of greater impact. As a whole the T2-profile is a good protection measure, at least compared with the T1-profile and standard recommendations.

The h-profile lets in no water on either the wind barrier or the interior side of the panels. The profiles are, however, only tested for the two glass fiber panels. As Figure 3.8 shows, the h-profile only fits with a panel thickness $\leq$ 6 mm. It is assumed that the reason for this profile's watertightness is due to its tight fit in combination with the protruding part that covers 10 mm of the top of the underlying panel. For water to enter from underneath the profile it is expected that the gap has to allow for capillary suction. In contrast, the problem with the previous two profiles, gaps, is not an issue with the h-profile. However, the profile is not a so called "hidden" profile, and is therefore not a solution that is popular among architects. Additionally, the profile could affect the façades pressure equalization if it is mounted completely tight to the panels. Since the panels are commonly used for larger building façades, the effect of pressure differences on water intrusion will have greater impact than on the test rig used in these experiments.

4.5.2 Joint Profiles Behind the Joints

The joint design solutions under the category profiles behind the joint include different combinations with a gasket and U-batten. The gasket alone was only tested on the two fiber cement panels. The U-batten was tested on the Glass Fiber and fiber cement panels. The U-batten was combined with a gasket and extra Fastening Points (FP) between the existing fastening points.

Water Intrusion to the Wind Barrier

The water intrusion to the wind barrier was varying, as can be seen in Figure 4.15. It may be important to mention that due to the U-batten being fastened to the vertical battens, the air cavity is larger than for the other parameters. Thereby, the water had to travel further horizontally to reach the wind barrier. Since the U-battens are typically mounted directly on the back wall, wind barrier, the infiltrated water would be led along the battens directly to the wind barrier. The gasket, even when used alone, hindered water from hitting the wind barrier very efficiently. However, the water intrusion was not zero for every measurement, as the graph indicates, see Appendix G. The measurements with only a gasket caused water intrusion to the wind barrier by water entering through the top joint and splashing off the gasket in the lower joint, but not enough water to be measured. A similar phenomenon was observed with the U-batten and several of the combinations with an U-batten; water would splash from the lower U-batten and to the wind barrier, but to varying degrees. When only an U-batten was used, see "U" in Figure 4.15, the fiber cement panels had too little water on the wind barrier to be measured. There was also splashing but too little water to be measured for "U + FP" with the fiber cement panels, "U + Gasket" with the Fiber Cement White, and "U + Gasket + FP" with Fiber Cement White and Glass Fiber Smooth. The amount of splashing could be very varying, even from measurement to measurement for the same parameter. The amount of water can therefore not be seen as a direct consequence of what panel is used, but rather more depending on the water runoff that occurs. Additionally, the combination of a gasket and U-batten gives a better protection against water intrusion to the wind barrier. On the other hand, it is believed that if the U-batten is used in taller buildings with many joints, more splashing will occur and thereby not protecting the wind barrier at all. For instance, the "U" with Glass Fiber Rough gives a 777% increase in water intrusion from the standard recommendation. The reason is the splashing in the air cavity from the U-batten. The infiltrated water amount in this case is almost equivalent to the most extreme measured water amount on the wind barrier.

Water Intrusion to the Interior Side of the Panels

As shown in Figure 4.16, the different combinations with an U-batten and a gasket gave varying degrees of water intrusion to the interior side of the panels.

A gasket alone in the joint was only used in combination with two panels. A sufficient amount of water entered to the interior side of the panels. There was 75% more water intrusion for the Fiber Cement White when compared with the standard recommendations. The Fiber Cement Grey panels did not have the same increase, but rather a very similar water intrusion as the test with the standard recommendation. This can indicate that the gasket's watertightness is very dependant on mounting and runoff. It was observed that water would just push through the gasket, and enter the joint with ease. Since the gap between the underlying panel and gasket appears to be small,

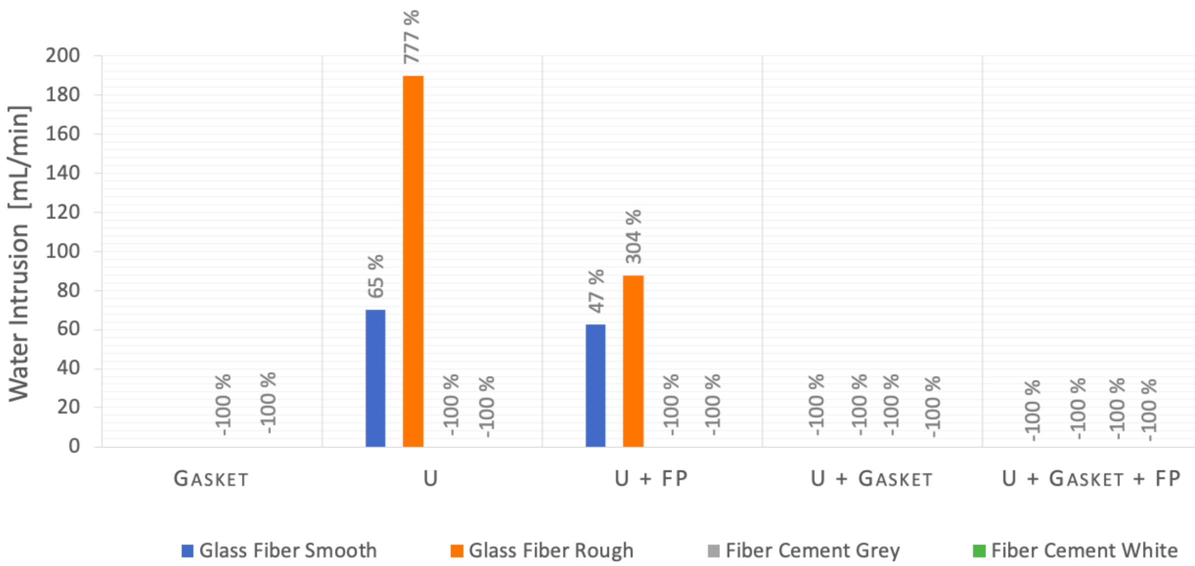


Figure 4.15: Water intrusion to the wind barrier using profiles behind the joint: Gasket, U-batten, U-batten + extra FP (Fastening Point), U-batten + gasket, and U-batten + gasket + extra FP. Vertical axis gives the water intrusion in mL/min. The percentage change from the measured water intrusion with the standard recommendations in Table 4.2 is shown.

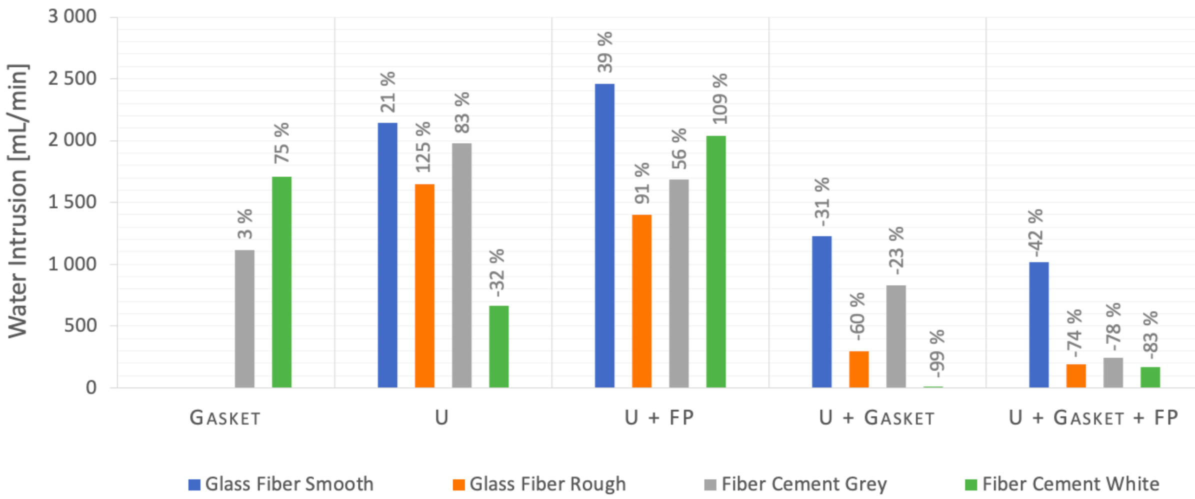


Figure 4.16: Water intrusion to the interior side of the panels using profiles behind the joint: Gasket, U-batten, U-batten + extra FP, U-batten + gasket, and U-batten + gasket + extra FP. Vertical axis gives the water intrusion in mL/min. The percentage change from the measured water intrusion with the standard recommendations in Table 4.2 is shown.

increased water intrusion due to capillary suction may occur. It is believed that the gasket could hinder water in exiting the joint again, and therefore there was more water intrusion.

The U-batten alone led a substantial amount of water to the interior side of the panels, up to 36% of total water sprayed. The only outlier was Fiber Cement White, which saw a decrease of 32% from the standard recommendations. Nothing out of the ordinary was observed for the Fiber Cement White, only that less water entered both the top and bottom joint, when compared to the other panels. It is assumed that the U-batten was more tightly fastened to Fiber Cement White panels, and that was the reason for the decrease. The U-batten as a protective measure against water intrusion appears to be very dependent on the mounting, and therefore sensitive to errors. Additionally, the protruding part of the batten in the air cavity entails a great risk of splashing. It is therefore not recommended as a joint profile.

U-batten combined with extra fastening points gave surprisingly more water on average compared to U-batten alone, largely caused by a substantial increase for Fiber Cement White. The Glass Fiber Rough and Fiber Cement Grey panels had a decrease in water intrusion when compared to the U-batten alone. On the other hand, every panel had a substantial increase from standard recommendations, varying between 56% at the lowest to 109% at the highest. It was believed that extra fastening points would decrease the water intrusion when compared to the U-batten alone, since the gaps were believed to be the greatest in the center between the vertical battens. The assumption was made because previous measurements has shown that an increase in tightness between the profiles and panels have a positive impact on water intrusion. The cause of the increased water intrusion could very likely be the cracks that occurred when the extra fastening points were screwed in, as can be seen in Figure 4.17 and 4.18. Hence, the extra fastening points might have an opposite effect than expected, enlarging the gaps. Conversely, the "U + gasket + FP" tests did not get the same, large amount of water intrusion.

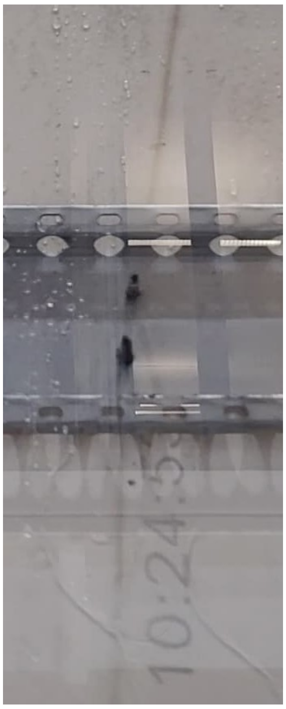


Figure 4.17: Crack in Fiber Cement White caused by extra fastening points, seen from the interior. Caused before testing with "U + FP" in test no. 118.

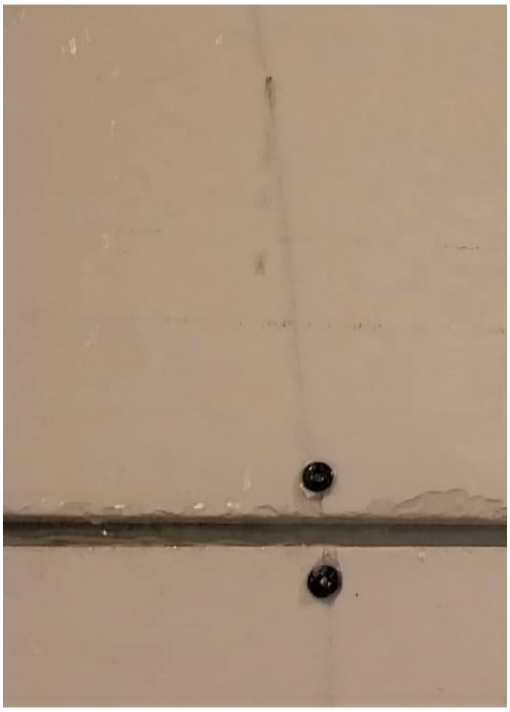


Figure 4.18: Crack in Fiber Cement White caused by extra fastening points, seen from the exterior. Caused before testing with "U + FP" test no. 118.

The U-batten combined with a gasket gave all the panels a decrease in water intrusion compared to the standard recommendations, as can be seen in Figure 4.16. On average the decrease was 48%, but ranging from -23% to -99%, for the Fiber Cement Grey and White panels, respectively. Hardly any water intruded through the U-battens with the Fiber Cement White panels. However, the water streaming in was caused by a fold in the gasket in the lower joint. As a consequence, the results indicates that small errors in mounting of the gasket may not have a great impact on water intrusion. For the other three panels there were water bridges on the exterior which correlated with water streams entering under the U-batten on the interior. Even though this solution minimizes the water intrusion, it is not a recommendable solution due to the risk of splashing to the wind barrier.

The U-batten combined with both extra fastening points and a gasket led in the least amount of water among the profiles behind the joint, as shown in Figure 4.16. The reduction when compared to standard recommendations are between 42% and 83%, with 65% being the average over all reduction. Three of the panels had water intrusion which was $< 4\%$ of the total water sprayed, while Glass Fiber Smooth was the outlier with 17%. Glass Fiber Smooth has a tendency to be the panel with the most water intrusion, though not to the same extent as seen in these measurements. The extra fastening points seem to not have the same effect on the water intrusion as seen with the "U + FP". The negative effect of the extra fastening points seems to be counteracted by the gasket. There is seemingly a limited difference between the U-batten with gasket and U-batten with gasket and extra fastening points.

Neither the U-batten nor the gasket can be recommended for use alone. However, the combination seems to be a better solution. Using extra fastening points can be hazardous for the panels, as can be seen in Figure 4.17 and 4.18. Even though the results indicate that the combination of extra fastening points with an U-batten and gasket is desirable, it is still not recommended. This is due to the risks of defects of the panels and splashing in the air cavity to the wind barrier if water infiltrates the joints.

4.6 Bevelled Joints

A total of 20 combinations of parameters were conducted on joint solutions with bevelled edges. The percentage change from the standard recommendations is given in Appendix H. Only two panels were considered fit for cutting, thus bevelled edges were only tested on HPL and Glass Fiber Smooth. The bevelled edges were hand-cut by authorized SINTEF personnel. Since the panels were hand-cut there may be some uncertainties regarding the accuracy of the angles. The panels were cut shorter for each subsequent bevelment. It is unsure how much this will affect the velocity of the runoff or the water intrusion.

4.6.1 Top-Bevelled Joints

For the top-bevelled joints three different angles were tested; 15°, 30°, and 45°. Generally, top-bevelled joints reduced water intrusion when compared to standard recommendations.

Water Intrusion to the Wind Barrier

The results for the water intrusion to the wind barrier for top-bevelled joints (solid lines) are shown in Figure 4.19. There is a reduction in water intrusion to the wind barrier compared to standard recommendations for a majority of the results. For the HPL8 the reduction is 46-54%, but for HPL5 there is an increase varying between 32-136%. For the Glass Fiber Smooth there is an increase of 76% for a 30° bevelment, and a reduction of 6% for a 15° bevelment. On average the water intrusion increased with 57% from a 15° to 30° bevelment, and decreased with 31% from a 30° to 45° bevelment.

A surprising result is that a 15° bevelled angle led approximately the same or less water to the wind barrier as joints with a 45° angle. Even though it was difficult to observe, a reason may be partial or continuous water bridges which were formed in the top joint. The water bridges could function as barriers against direct spray and could lead water runoff across the top joint instead of in. However, this would not explain the reduction for the HPL8, since water bridges do not form for joint widths of 8 mm. It is surprising that a 30° bevelled joint yields the most water intrusion. However, as mentioned the results are not completely comparable since the rig was hoisted in and out for every bevelment and thereby causing uncertainties regarding the nozzle placement. The two HPL measurements are comparable though. The trend is that a 5 mm joint width leads to less water intrusion than a 8 mm joint width. The trend matches with previous results for other test parameters.

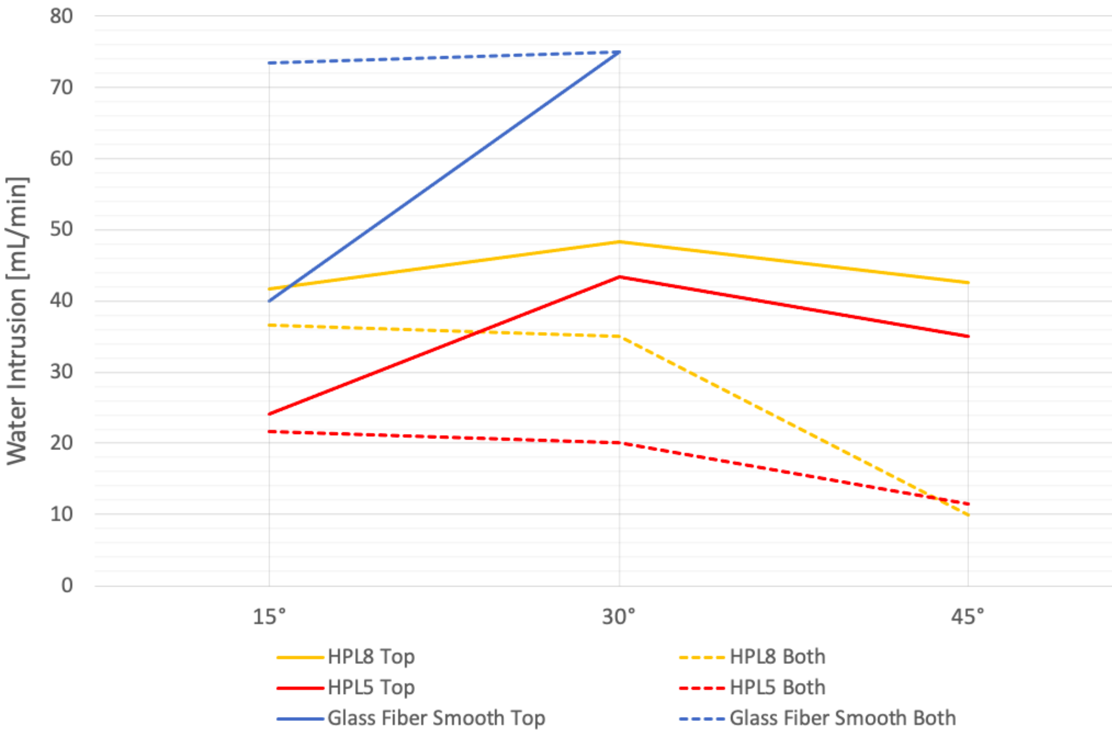


Figure 4.19: Water intrusion to the wind barrier for HPL and Glass Fiber Smooth with different bevelled joint designs. 15°, 30° and 45° represents the degree of bevelment. The solid lines represent the top-bevelled joints. The dashed lines represent the top-and-bottom-bevelled joints.

Water Intrusion to the Interior side of the Panels

The results for the water intrusion to the interior side of the panels for top-bevelled joints (solid lines) are shown in Figure 4.20.

Compared to the measurements with standard recommendations, see Table 4.2, the results indicate that a top-bevelled joint reduces water intrusion to the interior side of the panels. The reduction varies from -12% to -59%. The joint width is measured at the exterior side of the joint. This means that the joint width will be wider at the interior side of the joint. Therefore, it is unlikely that water bridges will form on the interior side of the joint for the bevelled joints. Water that has already infiltrated the joint and is flowing on the interior side of the panels can be led out

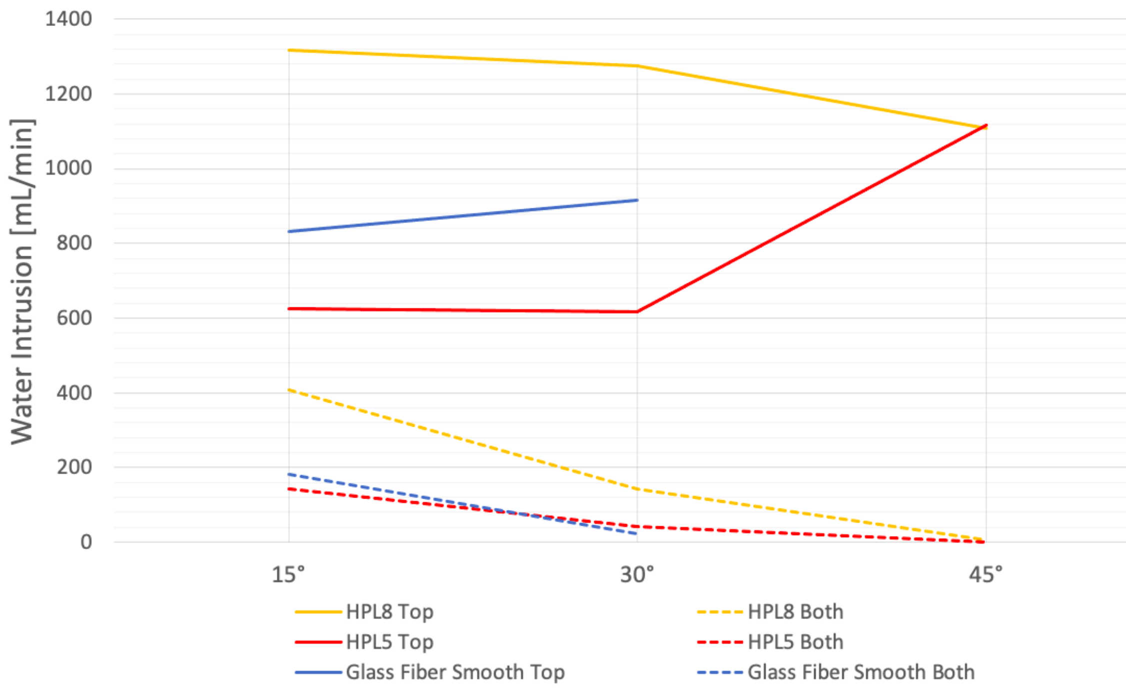


Figure 4.20: Water intrusion to the interior side of the HPL and Glass Fiber Smooth with different bevelled joint designs. 15°, 30° and 45° represents the degree of bevelment. The solid lines represents the top-bevelled joints. The dashed lines represents the top-and-bottom-bevelled joints.

of the lower joint, but it was difficult to observe if this occurred for any of the measurements. Compared to the standard recommendations it is assumed that the top-bevelled joint leads out more infiltrated water, and this may be the reason for the reduction of water intrusion.

The degree of the top-bevelled angle can affect the rate infiltrated water is led out of the joint. On average the water intrusion increased with 1% from a 15° to 30° bevelment, and increased with 19% from a 30° to 45° bevelment. On both the interior and exterior side of the joints a water film can be observed along the edge of the overlying panel. It is assumed that there is also a water film on the underside of the overlying panel. As long as the surface tension and adhesion forces are greater than gravity acting on the water film in the joint, the runoff will probably be led along the water film and out of the joint. This would typically be the case for lower water velocities. Since the joint is bevelled the water along the water film will be lead out to the exterior side of the panels. With an increase in the bevelled angle, water flow will have a greater component along the surface due to gravity, which may cause a greater water flow out of the joint. Interestingly, on average, this was not the case in these measurements, and further investigations are seen as valuable. For more concentrated streams and higher water velocity, the water can drip or flow off the overlying panel. However, due to cohesion forces with the water film on the edge, the drops or streams will probably have a horizontal velocity component that leads the droplets in to the joint. When the underlying panel is non-bevelled the water droplets will splash on impact, and the water may reenter the façade and flow further down the interior side of the panels.

The results indicate that the joint width may have an impact on the water intrusion. For the HPL5 and Glass Fiber Smooth panels there is a decrease in water intrusion to the interior side of the panels with a declining bevelled angle. However, the correlation is the opposite for the HPL8 panels. When the joint width is 8 mm the water droplets that are dripping in the joint appear to be larger and have a higher dripping frequency than for the 5 mm joint. This could lead to a greater water intrusion due to splashing when the joint width is 8 mm. Moreover, in the 8 mm joints there are no partial water bridges or droplets in constant contact with both the top and bottom edge of the joint. As for the 5 mm joint widths and bevelled angles of 15° and 30°, water bridges can form. If the water bridges are located where concentrated streams or water films reach the joint, they can lead the water across the joint. Thus, the water does not infiltrate the joint. When there is a 45° bevelled joint the increase of the joint width due to the bevelment may be too great for water bridges to even occur. The leading of water across the joint may explain why the water intrusion to the interior side of the panels are the greatest for a 45° bevelled joint. In addition, it may be why there is such a considerable increase in water intrusion for the HPL5 panels with a 45° bevelled joint.

Compared to the standard recommendations, the results indicate that a top-bevelled joint reduces water intrusion to the interior side of the façade panel. In contrast to water intrusion to the wind barrier that is both reduced and increased. However, the reduction varies depending on the panel, bevelled angle and joint widths.

4.6.2 Top-and-Bottom-Bevelled Joints

For the top-and-bottom-bevelled joints three different angles were tested; 15°, 30°, and 45°. Compared to the water intrusion for the standard recommendations, see Table 4.2, and the top-bevelled joints with 5 and 8 mm joint widths, the results indicate that a top-and-bottom-bevelled joint reduce water intrusion substantially.

Water Intrusion to the Wind Barrier

An increase in bevelled angle decreases the water intrusion to the wind barrier, as can be seen in Figure 4.19 (dashed lines). HPL8 has a decreased water intrusion for every bevelled angle when compared to the standard recommendation. On average the water intrusion decreased with 1% from a 15° to 30° bevelment, and decreased with 75% from a 30° to 45° bevelment. HPL5, on the other hand, only has a decrease with the 45° bevelled joint. Glass Fiber Smooth has an increase of over 70% in water intrusion compared to the standard recommendations for both a 15° and 30° bevelled joint. The reason for this difference is unclear, but it is assumed that the positioning of the row of nozzles has impacted the results. Nevertheless, for all the top-and-bottom-bevelled joints there are, surprisingly, virtually no difference for a 15° and 30° bevelled joint when it comes to water intrusion to the wind barrier. Even though only the HPL panels have been tested with a 45° bevelled joint, there seems to be a decrease in water intrusion to the wind barrier with an increasing angle.

The observations indicate that the water intrusion to the wind barrier for the top-and-bottom-bevelled joints are more prone to direct spray through the joint than other water behaviors, such as for instance splashing. The only observed water intrusion occurred through the top joint. A decrease in the bevelled angle leads to more water to the wind barrier. With greater bevelled angles, the observed gaps between the panels are smaller, thus creating more of a protective measure against direct spray to the wind barrier. Additionally, this will protect the wind barrier against UV radiation.

A surprising result is that a top-and-bottom-bevelled joint of 45° has a greater water intrusion to the wind barrier than to the interior side of the panels. On the wind barrier the measured water amount is 10 ml/min for HPL8 and 12 ml/min for HPL5, compared with 5 ml/min and too little water to be measured, respectively, on the interior side of the panels. Since the water amounts are minimal, other factors may have an influence on the results. The tubes from the panel gutters are approximately four times longer than the wind barrier tubes. This means that more water is stagnant in the panel tubes at any given time, while there is no stagnant water in the wind barrier tubes. This leads to a larger margin of error for the water gathered from the panels, especially when water amounts are as minimal as in this instance. Hence, there is uncertainty whether water intrusion to the wind barrier will always be greater than to the interior side of the panels for a 45° top-and-bottom-bevelled joint.

Water Intrusion to the Interior Side of the Panels

The results indicate a correlation between an increase in the bevelled angle and a decrease in water intrusion. On average the water intrusion decreased with 72% from a 15° to 30° bevelment, and decreased with 96% from a 30° to 45° bevelment. In comparison to standard recommendations, the water intrusion is reduced by 91% and 73% for the HPL8 panel with bevelled angles of respectively 30° and 15°. The HPL5 panels had a reduction of 97% and 90% with bevelled angles of 30° and 15°, respectively. The Glass Fiber Smooth panels had a reduction of 99% and 90% with bevelled angles of 30° and 15°, respectively. For the HPL panels and a 45° bevelled angle, the reduction is almost 100%. There can be a number of different reasons for these reductions.

Firstly, if splashing occurs to the exterior side of the joint the kinetic energy of the water has to be greater for water to intrude when there is a bottom-bevelled joint. If the bevelled angle is greater, then the kinetic energy must also be greater. Since the joint widths are only varying between 5 mm and 8 mm the difference in kinetic energy of the water droplets should be minimal. However, the results show that for HPL5 and HPL8 there is a considerable difference between the water intrusion for both a bevelled angle of 30° and 15°. In this case, a joint width of 8 mm leads to the most water intrusion. This indicates that the water behavior in the joint seems to have an impact on water intrusion. When the joint width is 8 mm the water is dripping in the joint, and the water droplets appear to be larger than the droplets observed in a 5 mm joint width. In addition, the majority of the droplets in the 5 mm joint are in constant contact with the top and bottom edge of the joint, therefore splashing will be minimal.

Secondly, water that flows down the interior side of the panel can more easily be led out of the lower joint to the exterior. The explanation for this is the same as for the top-bevelled joint. When the water velocity is too great to be led by the water film on the underlying panel, it will drip off the edge. Concentrated streams will probably have a higher water velocity, and therefore drip off the edge. As for the top-bevelled joint, the bottom bevelled edge will be covered by a water film and gravity forces acting on the water will lead it out of the joint. In addition, an increase in the bevelled angle will have a correlating increase in the gravity force component along the surface, which may cause a greater runoff out of the joint. When there is dripping in the joint the droplets will implode after impact with the underlying panel. The water that remains in the joint will be led out of the joint due to gravity forces. The prominent improvement a bottom bevelment makes is likely due to the bevelment creating a channel that leads water out, while also being a protective measure against water infiltrating the joint.

4.7 Sealed Top Joints

In total, 6 different combinations of parameters were conducted with top sealed joints. A test with the top joint sealed was performed with every panel, and with the HPL twice. To investigate the water intrusion without direct spray through the top joint, the top joint was sealed. The results are shown i Figure 4.21. A plastic film was used to seal the top joint. There were some difficulties with the method for Glass Fiber Rough, but this has not caused any apparent impact on the amount of water runoff or water intrusion.

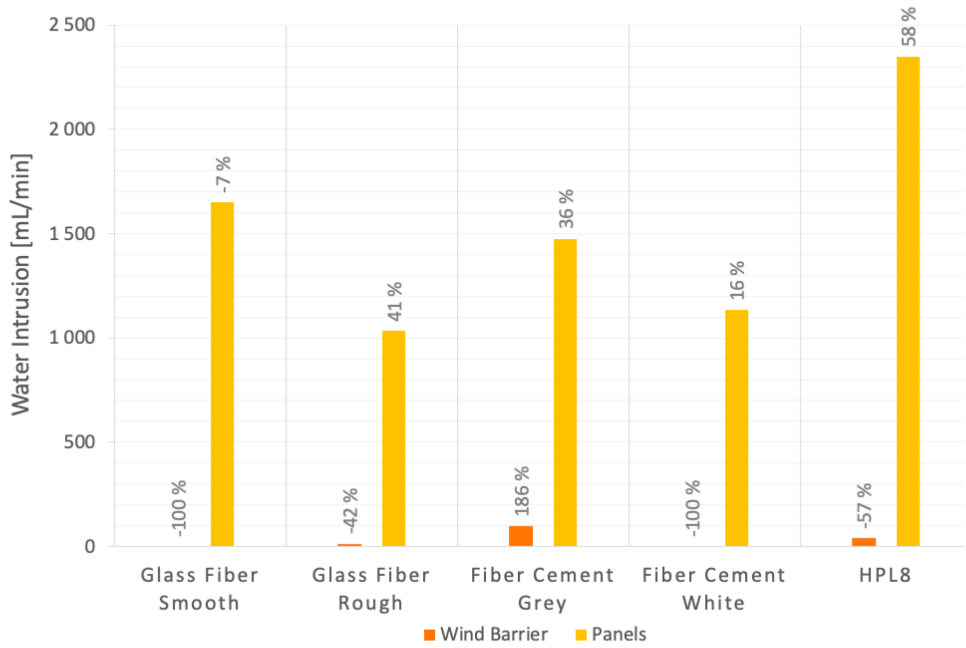


Figure 4.21: Water intrusion to the wind barrier and interior side of the panels with the top joint sealed. The percentage change from the water intrusion measured with the standard recommendations in Table 4.2 is shown.

The water intrusion to the wind barrier varies from panel to panel. Some panels had too little water intrusion to quantify or smaller amounts of water intrusion. Fiber Cement Grey, on the other hand, experienced increased water intrusion, 186%, when compared to the standard recommendations. It has been assumed that the water intrusion to the wind barrier is mostly caused by direct spray. However, as also mentioned there are sporadic instances where other parameters greatly affect the water intrusion to the wind barrier. The increased water amounts with the Fiber Cement Grey can be explained by the ejection effect. The effect was caused by concentrated streams which ended with an ejection to the wind barrier. Additionally, a lot of splashing was observed in the lower joints. This caused water intrusion for all the panels, especially HPL8 which has a 3 mm larger joint width than the other panels, and thereby more dripping and splashing in the joint. The sealing of the top joint has proved that direct spray is not the only reason for water intrusion to the wind barrier, ejection effect and splashing are also forces for water intrusion.

There is an increase in water intrusion to the interior side of the panels for every panel except Glass Fiber Smooth, when compared with the standard recommendations, as is shown in Figure 4.21. However, there is still substantial amounts of water intrusion with the Glass Fiber Smooth panel. The decrease can be explained by water bridges leading the water runoff across the joint. When the top joint was sealed there were more partial water bridges in the lower joint compared to the standard recommendation. As all other panels have received substantial amounts of water intrusion and an increase when compared to the standard recommendations, it is assumed that increased amount of water runoff leads to increased water intrusion. With the top joint sealed there is only one open joint, the lower joint. This means that more water enters through one joint than through two joints with the standard recommendations. This indicates that, when looking at water intrusion to the interior side of the panels, direct spray is not an important factor for water intrusion. Additionally, the results may indicate that façade panel systems should be shorter, therefore increasing the number of horizontal joints, on buildings at geographical locations or orientation that are exposed to a lot of rain. The results also indicate that larger buildings, where the water flow has a high velocity could experience more water intrusion than the panels in the laboratory experience.

4.8 Comparison with Previous Results

The panels used in these laboratory measurements are the same as previous master students Mo and Lid (2020) used in their master thesis. Some of the same parameters they tested were also tested this year. Since the same panels have been used, the present study's results can be directly compared to Mo and Lid (2020) results. Mo and Lid's study will in this section be presented and referred to as the 2020 study. The present study will, in this section and Appendix I and J, be referred to as the 2022 study.

The 2020 study's results are seen as less reliable. Only one measurement was taken, contra the three to four measurements taken this during the present study's laboratory investigations. Therefore it is assumed that the 2020 study's results are more likely to have errors which were not discovered. The gutter systems in 2020 were different from the gutter systems used in the present study. This could affect the amounts measured.

Joint Widths

The trend line from the 2020 study results for water intrusion to the wind barrier tells a different story than the 2022 study's results. The comparison of the results can be seen in Figure 4.22. The 2020 study's results indicate that a 3 mm joint width leads more water on to the wind barrier than a 5 mm joint width. However, a closer inspection of the results, see Appendix I, shows that the results are skewed by an outlier measurement (Fiber Cement Grey 2020). Nevertheless, there was more water intrusion in the 2020 study's measurements, and this could be caused by the placement of the nozzles. The results for a 5 mm joint width are similar. Most of the results for a 8 mm joint width are similar. The trend lines shown in Figure 4.22 are different due to Glass Fiber Smooth 2022 letting in over double the amount of water compared to many of the other panels. Hence, without the two outliers skewing the measurements, the results from both studies would be similar and conclude that a 3 mm joint width leads the least water to the wind barrier.

The trend lines for the 2020 and the 2022 study indicate differing trends when it comes to water intrusion to the interior side of the panels, as shown in Figure 4.23. The 2020 study's results indicate that there is a linear relationship between the joint widths and water intrusion, with 3 mm being the best width to reduce water intrusion and 8 mm being the worst. As earlier mentioned, in the 2022 study the 5 mm joint yields the greatest water intrusion. However, when the results

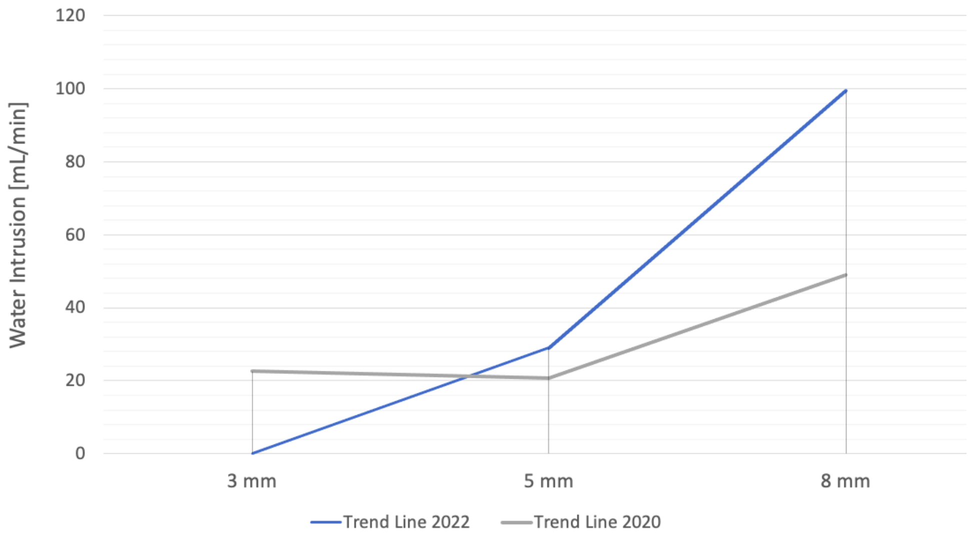


Figure 4.22: Water intrusion to the wind barrier with different joint widths. Comparison between the present study's (2022) laboratory results and Mo and Lid (2020) results. The results for the different panels are averaged to give a trend line.

are more closely scrutinized, see Appendix I, there are few panels with coinciding results. For several of the panels it seems that the 2022 results in general yield more water intrusion. The exception is Glass Fiber Rough which has a similar graph curve, but less water intrusion in the 2022 study, approximately 400 mL for every joint width. It is uncertain why the results are so different. A lot can be explained by the measurements being a rough estimate due to the rough methodology. Additionally, the two experiments do not use exactly the same methodology, though similar. Furthermore, even though the same panels have been used, they are now more worn and this has likely altered the surface characteristics of the panels.

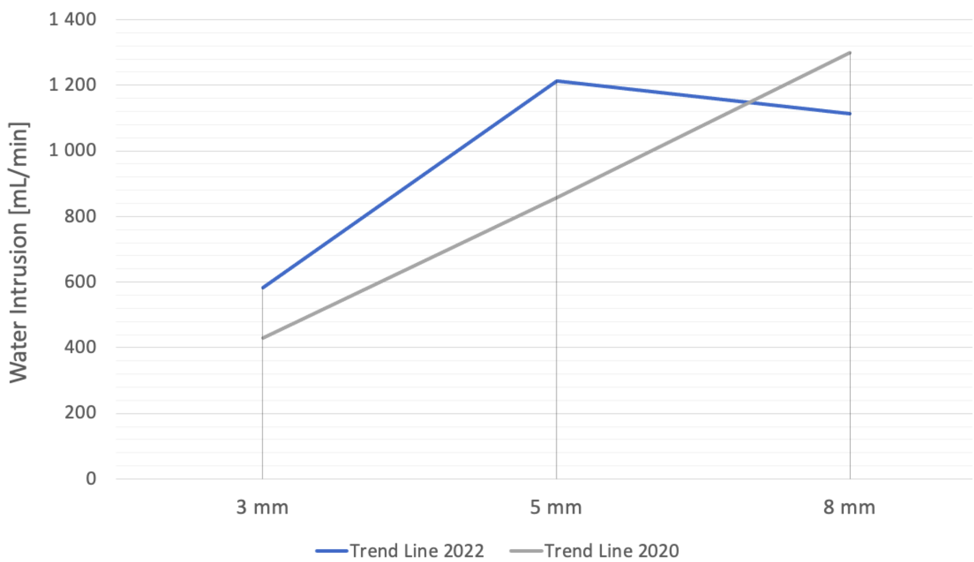


Figure 4.23: Water intrusion to the interior side of the panels with different joint widths. Comparison between the present study's (2022) laboratory results and Mo and Lid (2020) results. The results for the different panels are averaged to give a trend line.

Another interesting comparison can be seen in Figures 4.24 and 4.25. In the 2020 study, because of COVID-19, some tests had to be performed by SINTEF and NTNU personnel. The glass fiber panels were tested by both Mo and Lid, and the SINTEF and NTNU personnel with different joint widths. Figure 4.24 further confirms the uncertainties regarding the row of nozzles. The same panels tested by SINTEF and NTNU personnel gives substantially more water intrusion than the other measurements in 2020 and 2022. Interestingly the SINTEF and NTNU personnel even got a larger amount of water with a 3 mm joint. It is noted that the SINTEF and NTNU personnel used a 3.2 mm joint width, it is however seen as unlikely that a 0.2 mm difference is the cause if the discrepancies. This is underlined by the SINTEF and NTNU personnel getting more water intrusion (to the wind barrier) with a 3.2 mm joint width than the other measurements in 2020 and 2022 with both a 5 and 8 mm joint width. The main takeaway from the disparities in the results are that the measurements are rough and that a small change, for instance the row of nozzles, can effect the water intrusion greatly.

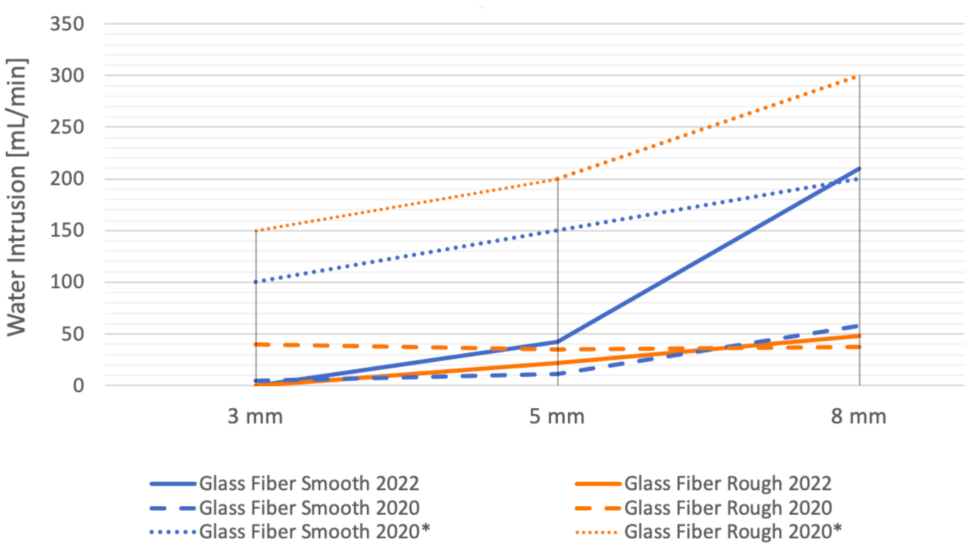


Figure 4.24: Water intrusion to the wind barrier with different joint widths using the glass fiber panels. Comparison between the present study's (2022) laboratory results and Mo and Lid (2020) results, also including tests performed by SINTEF and NTNU personnel. Solid lines are the 2022 results, dashed lines are the 2020 results performed by Mo and Lid, and the dotted lines are the 2020 results performed by the SINTEF and NTNU personnel.

Figure 4.25 also shows differing results for the same parameters. Looking at each joint width separately there is approximately 1000 mL/min difference between the minimum and maximum measurement. The differences in results further confirm that the results should be seen as rough measurements of water intrusion, and that the water runoff can vary unpredictably. This is amplified by Mo and Lid, and SINTEF and NTNU personnel's differing results, even though they used exactly the same method for testings. However, as previously mentioned, the 2020 results are based on only one repetition of each measurement. Therefore, the reliability of the measurements are more uncertain.

Joint Profiles

The same profiles were tested in the 2020 and the 2022 study: T1-, T2-, and h-profiles. Figure 4.26 shows the different water intrusions to the interior side of the panels for the 2020 and 2022 with a T1- and T2-profile. Since both the 2020 and 2022 studies' measurements with a h-profile gave no

Figure 4.25: Water intrusion to the interior side of the panels with different joint widths using the glass fiber panels. Comparison between the present study's (2022) laboratory results and Mo and Lid (2020) results, also including tests performed by SINTEF and NTNU personnel. Solid lines are the 2022 results, dashed lines are the 2020 results performed by Mo and Lid, and the dotted lines are the 2020 results performed by the SINTEF and NTNU personnel.

water intrusion to both the wind barrier and the interior side of the panels, it is not included in the graph. The results for h-profile indicate that it is a reliable protective measure against water intrusion, as it gave no water intrusion both studies. The water intrusion with profiles and for every panel individually is shown in Appendix J. Interestingly, the 2020 study measured water intrusion to the wind barrier, while the 2022 study's measurements saw no water intrusion to the wind barrier. It is unclear why there was water intrusion to the wind barrier in the 2020 study. A possible explanation is that water flowing on the interior side the panels splashed off the lower joint's profile.

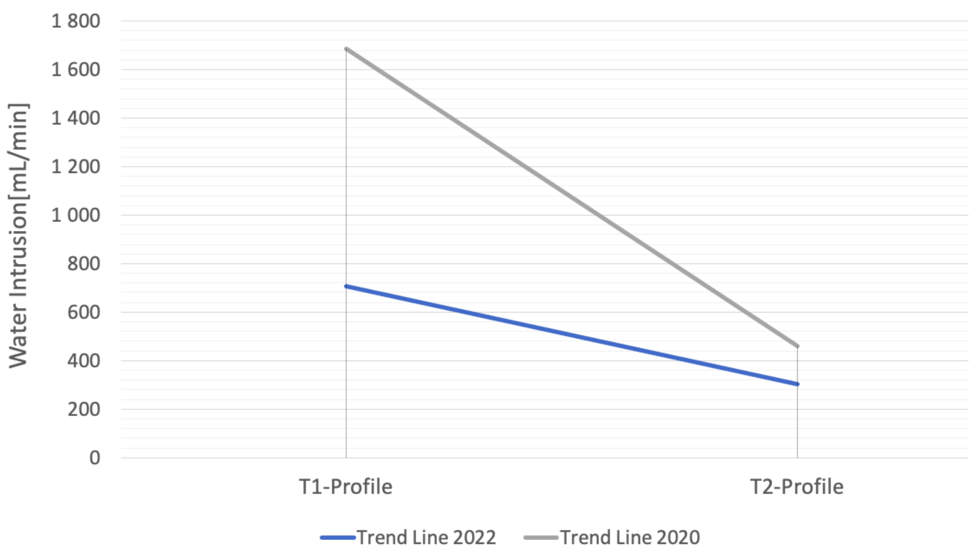


Figure 4.26: Water intrusion to both the wind barrier and interior side of the panels with a T1- and T2-profile. Comparison between the present study's (2022) results and Mo and Lid (2020) results. The results for the different panels are averaged to give a trend line.

The placement of the profiles were a little different in the two studies. In the 2020 study the joints were centered in the joint, as illustrated in Figure 4.27, while in the 2022 study the profiles were pushed downward towards the underlying panel, as illustrated in Figure 4.28. It is assumed that when the profiles are centered in the joints, water on the protruding parts will easier be led via the protruding parts to the interior side. When the protruding parts are pushed down toward the underlying panel the water is not as easily led in through the joint. Instead the water is more easily led over the joint to the underlying exterior panel's surface. It is believed that since the T2-profile's protruding part is pointed downward, that the profile's protruding part was almost as close to the underlying panel in 2020 as in 2022. The T1-profile's protruding part points straight forward, therefore it can not be completely pushed down on the underlying panel. The results indicate that the profile placement in the joint is more crucial for water intrusion with the T1-profile than the T2-profile. Additionally, in Appendix J, no clear similarities between panels' measurements can be seen. This further affirms that the mounting of the profile is a larger factor for water intrusion than the panels used.

Figure 4.27: Water intrusion roughly illustrated when the profiles are centered in the joint.

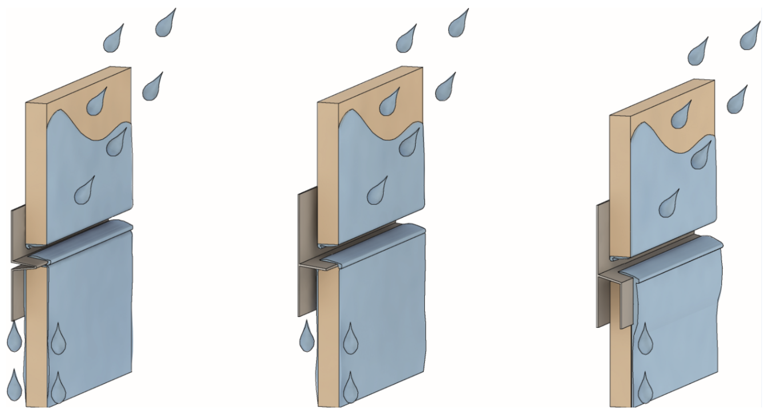


Figure 4.28: Water intrusion roughly illustrated when the profiles are pressed downward in the joint.

Of the two T-profiles, the T2-profile is superior in both the 2020 and the 2022 study. This indicates that the T2-profile should be preferred to the T1-profile, and that the T2-profile is less sensitive to different mounting methods.

Bevelled Joints

The 2020 study's measurements of bevelled joint designs were limited to the HPL panels and only a 45° bevelled angle. The comparison of the results can be seen in Figure 4.29. With a 45° top-and-bottom bevelled joint the results for both the 2020 and the 2022 study yielded no and close to no water intrusion to the wind barrier and the interior side of the panels. They are the most consistent results, and this indicates that this solution is both sound and reliable. The 45° top-bevelled joint, on the other hand, gave varying results. Even though the results for the wind barrier seem similar, there is a difference between no water intrusion and approximately 50 mL/min, though not substantial. This indicates that the a 45° top-bevelled joint does not stop water intrusion to the wind barrier, as it was assumed in the 2020 study. The water intrusion to the interior side of the panels more than doubled for the top-bevelled joint in this study compared to the 2020 results. This indicates that the top-bevelled joint does not give the same reliability as the top-and-bottom bevelled joint. The runoff of the water probably has a larger influence on the water intrusion than direct spray. Additionally, another factor is the cutting of the panels. The 2020 and 2022 studies' measurements for top-bevelled joints were not performed on panels with the exact same length, since they had been cut twice in between the measurements. This could also have an impact on the water runoff and thus the water intrusion.

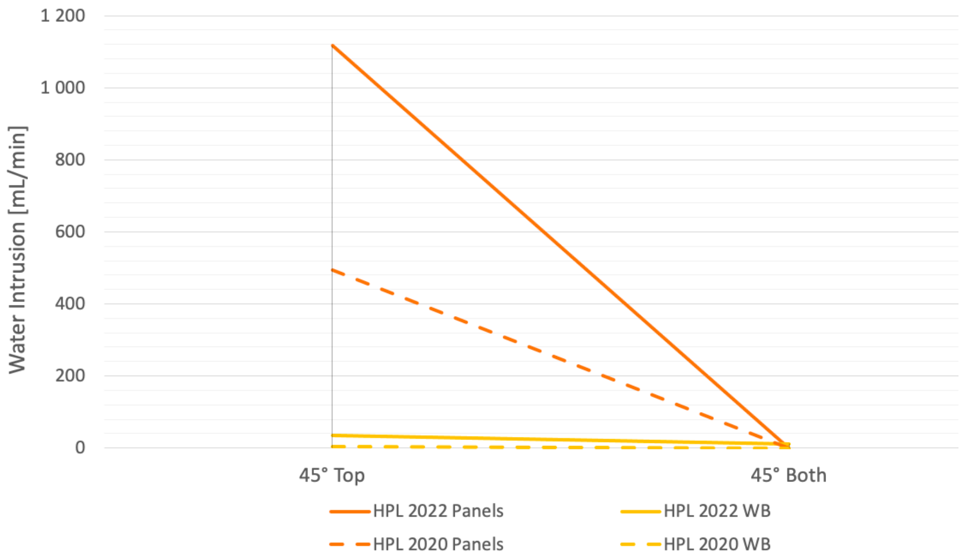


Figure 4.29: Water intrusion to both the wind barrier and interior side of the panels with bevelled HPL panels. Comparison between the present study's (2022) laboratory tests and Mo and Lid (2020) tests on a top 45° and top-and-bottom 45° bevelled joint.

4.9 Testing of the Test Sections

During the testing in the laboratory it was discovered that the row of nozzles was not centred on the test rig, with the nozzles being places differently and thereby also spraying differently on the test sections. On test section 2 the three nozzles were more centred compared to the other test section. The nozzles sprayed more between the vertical battens on test section 1, whereas the middle nozzle on test section 2 hit the vertical batten directly. The direct spray on the vertical batten may cause more splashing off the test section. Furthermore, the observed spray radius differed for the nozzles. The reason for this is unknown, but it is unclear when the nozzles were last cleaned. There could be growths or dirt in the nozzles that affect the spray and distribution of water. Because of these errors and uncertainties the water amount on the test sections without panels was tested. The average collected and measured water on test section 1 and 2 was 3883 ml/min and 3808 ml/min, respectively, equating to 64.7% and 63.5% of the total amount sprayed. Surprisingly the water amounts on the two test sections are approximately the same despite the uncertainties. This means that the tests performed on the two test sections are considered comparable.

The water amounts measured on the test sections are only approximately 60-65% of the total applied water amount. This does not necessarily mean that the total sprayed water of 6000 mL/min is wrong. A previous study claimed that 49.7% of the water sprayed on the panels would splash back (Recatala et al., 2018). This could also be observed, as substantial amounts of water splashed off the wind barrier. Therefore it is reasonable to accept 6000 mL/min as a correct estimate of total water sprayed on each test section.

4.10 Errors and Uncertainties

During testing several sources of errors and uncertainties are observed. Measures to amend for the errors and uncertainties have been implemented throughout the entire duration of the test program. In the following the most relevant sources for errors and uncertainties are presented, and their impact briefly discussed.

Drainage System

Two different kinds of gutters were constructed, detailed pictures are shown in Appendix C. Figure 4.30 is used to help understand the different topics discussed in the section. The plastic gutters collected water from the interior side of the panels, while the aluminium gutters collected water from the wind barrier. Although the original reason for the different gutters was a delayed delivery of materials, it has later been seen as an opportunity to evaluate different gutter systems. No direct testing of the gutters was performed, but the gutters were observed throughout the testing procedure for the whole test program.

Figure 4.30: Gutter system seen from the interior side. Aluminium gutters above the blue plastic gutters.

The aluminium foil was more difficult to work with than the plastic, as it was thicker and more rigid. On the other hand the aluminium kept its shape, while the plastic gutters had to be adjusted continuously and were therefore more time consuming than the aluminium gutters. To ensure that the plastic gutter did not collapse it had to be fastened with double-sided tape to the Lexan board. Consequently, there were slight variations of the plastic gutters for different tests. On the other hand, if the aluminium gutters had been used on the panels, a new gutter would probably have to be made for every panel. This is because they were very well fastened, and got ruffled or ripped when removed. This would not only be time consuming, but also give more uncertainties relating to the comparability of the results, since different gutters would be used for every panel. Consequently, a lot more aluminium foil would also have been used. The plastic gutters were easily reused, and additional gutters were unnecessary.

A single slope was used on the aluminium gutters, while a double slope was used on the plastic gutters. A double slope is better in regards to gathering water runoff, since it is easier to place the tube at the gutter's lowest point. The use of a single slope on the aluminium gutters was chosen because it is easier to construct, due to the previously mentioned rigid nature of the material. In addition, the single slope was recommended by SINTEF personnel, since it had successfully been used in previous experiments conducted in the SINTEF and NTNU laboratory. However, the vertical battens hindered the tubes from being placed at the gutter's lowest point. It is assumed that the tubes connected to the plastic gutters are filled up with water during the 10 minutes the driving rain apparatus is on before measurements commenced. By filling the aluminium gutters with water before testing, it is assumed that the water will be led out of the tubes rather than staying in the gutters. Yet, since the material is opaque, observations regarding the efficiency of the gutters were difficult. Furthermore, no problems due to having single slope were observed. No issue directly related to the gutters being double slope can be ascertained for the plastic gutters.

The watertightness of the gutters is important, but somewhat difficult to ascertain. The plastic gutters' watertightness was tested once in the early stages of the experiments by filling them up with water. They were completely watertight. However, since this was early in the process and the same gutters were used frequently throughout a months duration, they were likely more worn towards the end. It is therefore uncertain if the plastic gutters were completely watertight for the last measurements. Since the plastic gutters were hanging underneath the lowest façade panel, water streaming down the exterior side of the lowest panel would drip or stream on to the plastic gutter. As a result water could have infiltrate or exit the plastic gutter without being discovered. The aluminium gutters could not be tested in the same way due to them being constructed while fastened to the Lexan board. The side edges were also technically open, and only sealed by the vertical battens. On several occasions water leaking from the aluminium gutters under the battens was observed. However, not a substantial amount of water. Furthermore water could run out of the gutter in between the sleeve and the plastic or aluminium foil, or between the tube and sleeve. However, the occurrence of this could not be observed.

The aluminium gutter's tubes were much shorter than the plastic gutter's tubes. The aluminium gutter's tubes led straight out through holes drilled through the Lexan board. Little to no water could be observed lying stagnant in these tubes. The plastic gutter's tubes were very long as to reach the outside of the driving rain apparatus. A lot of water could be observed in the tubes at all times. It was assumed that approximately the same amount of water would be in the tubes at all times, and in that way the measurements would not be too inaccurate. Shorter tubes are the favourable solution because it gives more certainty. Therefore it would have been preferable to drill extra holes through the Lexan board to fit the tubes connected to the plastic gutters through, and thereby eliminate the need for longer tubes. However, the panels used in this study were to big, and it would not be practically feasible to accomplish since the gutters hung below the lower edge of the Lexan board.

An issue observed with the plastic gutters was that water would at times splash from the gutter to the wind barrier, below the aluminium gutters, and thereby not be included in any measurements. This was caused by ruffles in the gutters. The water amounts "lost" due to splashing are considered small and negligible. The plastic gutters also experienced issues with the drainage hole being slightly clogged. This caused more water to splash onto the wind barrier because of the abundance of water lying in the gutter. Tubes with a greater diameter would have a higher rate of runoff, and could therefore be a preferable solution.

To minimize the uncertainties related to the drainage system, a double slope seems to be favourable for gutters. Preferably the gutter's material would be both transparent and stiff, thus enabling observations and avoid continuous adjustment of the gutter. In addition, the tubes should be kept at a minimum length, and lead the tubes through a drilled hole in the Lexan board. The plastic gutter is seen as a favourable choice for the panels, and the aluminium gutters are seen as favourable for the wind barrier.

Row of Nozzles

The placement of the nozzles was supposed to be 100 mm vertically above the joint according to NS-EN 1027:2016. 100 mm was measured from the edge of the overlying panel and the bottom of the nozzle. The procedure for moving the nozzles were done manually. The moving did not have a high degree of accuracy, and was estimated to be ± 15 mm. The impact this uncertainty has on water intrusion is discussed thoroughly in Section 4.2. This is considered to be the greatest uncertainty and error regarding the measured water intrusion to the wind barrier.

Measurement Precision

To measure the infiltrated and collected water, measuring jugs and cups were used. For water amounts ≤ 100 ml a measuring cup with 10 ml intervals was used, whereas for greater water amounts a measuring jug with intervals of 50 ml was used. When the measuring cup was used the amount was rounded to the nearest 5 ml, while the amount in the measuring jug was measured to the nearest 50 ml. As a consequence the measurements are not very precise. However, the measuring method was the same for all the tests.

Deviations From Mounting Instructions

The mounting of the façade panels was conducted according to mounting instructions from the suppliers. However, the screws that were used for all the panels were provided by the supplier of the glass fiber panels. This did not seem to affect the mounting of the panels, since the dimensions of the recommended screws were the same.

Absorption of Water in the Panels

For the fiber cement panels the edges of the panels are supposed to be sealed with an acrylic paint after they are cut, to avoid water absorption of the panels. The panels were not cut during testing. Since the panels have been reused from previous laboratory experiments, it is unknown if they have been previously cut. However, the panels were cracked along some of the edges and increased water absorption was observed along these edges. It is unclear if the absorption impacted the results. Additionally, during testing of the U-battens, the fiber cement panels cracked along the panels height, and absorption was observed along the sides of the crack, although water infiltration was not observed through the cracks. The testing program did not leave time for drying of the panels. This could lead to different degrees of water absorption in the panels, and thereby affect the measured water intrusion.

Drying of Test Rig Between the Measurements
At the end of the test program the setup of the test rig and different parameters were more efficiently executed than at the beginning. Consequently, this gave less time for drying in between measurements and thereby allowing for water to remain on the wind barrier before a new parameter were tested. Therefore, observations of smaller amounts of water intrusion to the wind barrier may have been impacted.

Joint Width
During mounting of the façade panels, a digital caliper and spacers were used to achieve the correct joint width. The same spacers were used for all the tests with the same joint width. Additionally, the same battens were used during the entire test program which sometimes caused the screws to hit previously drilled screw holes, and consequently some screws were pulled downwards during mounting of the panels. An error margin of ± 0.3 mm was accepted.

Cutting of the Panels
To test the bevelled joint solutions the panels were cut. As a consequence the panels were a little shorter after each test with a different bevelled joint. The test program was configured to reduce the amount and number of cuttings. However, the panels were approximately 90 mm shorter at the end of the test program. This would have the largest impact on the velocity of the runoff on the exterior side of the panels. The dripping frequency was, however, observed to be similar for the tests before the panels were cut and for the last tests. The panels were hand-cut, therefore there are some uncertainties regarding the exact angle and the evenness of the edge.

Reuse of Panels from Previous Laboratory Experiments
The panels were reused from laboratory measurements conducted in relation to Mo and Lid's master thesis at NTNU in 2020. The panels have been stacked on top of each other and stored in a cooling room at NTNU and SINTEF's laboratory. This means that there will be some scratches on the surface that might have an impact on the runoff patterns on the exterior and interior side of the panels. However, cardboard was placed in between the panels to reduce damage on the surface. During observation of the runoff on the exterior side of panels, impact of scratches on the surface could not be observed. Additionally, the predrilled holes had been widened, since the panels had been mounted several times. As a consequence of this it was more difficult to properly tighten the panels to the battens. Therefore, it was difficult to press the joint profiles against the panels, which could have allowed for water to infiltrate between the panels and profiles.

5 Conclusion

In the present study 72 unique tests were conducted in a driving rain apparatus with water amounts following NS-EN 1027:2016, without applied pressure. Out of 6000 mL/min sprayed on the test sections, the water intrusion to the wind barrier and interior side of the panels (with a 5 mm and 8 mm joint width) is 0.5-2% and 19-20%, respectively. The water distribution between the wind barrier and interior side of the panels is approximately the same as previous studies' findings. Panels with smooth surfaces, in general experience more water intrusion than rougher panels.

The results and comparisons related to the water intrusion to the wind barrier are highly influenced by the positioning of the row of nozzles, which had an estimated accuracy of ±15 mm. Therefore there are limitations to what conclusions can be drawn regarding the water intrusion to the wind barrier. However, the results indicate that a smaller joint leads less water in than a larger joint, in accordance with previous studies. Additionally, having a protected joint largely prohibits water from reaching the wind barrier. From the test with an U-batten it is evident that protruding parts in the air cavity can lead to large amounts of water on the wind barrier due to splashing. The ejection effect leads the most water to the wind barrier when the horizontal joints are open, but is however sporadic and unpredictable.

The h-profile is completely watertight, the T-profiles on the other hand are not, in accordance with previous studies. The use of profiles reduces water intrusion to the wind barrier. The results indicate that the size of the protruding part compared to the thickness of the panel is an impacting factor on the water intrusion. If the protruding part is shorter than the panel thickness water is more likely to infiltrate the joint. The placement of the profiles in the joint is also important, and they should be pushed down toward the underlying panel to achieve minimal water intrusion. Additionally, the shape of the protruding part is also of importance, with the T2-profile being better than the T1-profile, since its protruding part can be pressed against the underlying panel.

Joint solutions with a gasket or U-batten are not recommended to be used as a protective measure in horizontal joints. The use of either a gasket or an U-batten separately leads in substantial amounts of water. The combination of the two led to less water intrusion and seems like a good protection measure. However, because of the mentioned risk for splashing to the wind barrier, the use of an U-batten in any combination is not a desirable solution.

Bevelled joint solutions reduce the water intrusion compared to standard recommendations, in accordance with previous studies. An increase in bevelment reduces water intrusion for a top-and-bottom bevelled joint, whereas the results for top-bevelled joints are inconclusive. Moreover, a top-and-bottom bevelled joint design is preferable, since it has the greatest reduction in water intrusion.

In conclusion this study finds there should always be a protection measure in horizontal joints. Both to avoid water intrusion and to protect the wind barrier against UV-radiation. However, as the effectiveness of different solutions as a protection measure varies, the joint solutions should be tested as to ensure robustness before they are implemented in buildings.

6 Further work

To increase the knowledge about water intrusion through horizontal open joints, further investigation should be conducted. This study has been limited to investigating a few parameters, thus other parameter should be further explored. Additionally, some of the parameters tested in this study could be further investigated. Variations of bevelled joint designs should be further tested, preferably with more façade panels to get more statistically reliable results. A bottom-bevelled joint could be tested to investigate the impact this joint geometry has on water intrusion. In addition, designing and testing joint profiles with a protruding part that exceeds the joint while still being "hidden" should be further investigated. Different panel types could also be further tested, for instance metal panel and panels with tongue and groove joints.

Further work on testing the difference between old and new façade panels would be interesting. These panels are not recommended for reuse, and if they are damaged it is recommended to replace them. In regards to the environment, an investigation into the possibilities of recycling or reusing the panels are interesting. To which degree wear and tear affects the water intrusion is unknown, and it is therefore also interesting in regards to how water intrusion will vary throughout the panels' lifetime.

A study investigating what the actual practice is in construction work with panel façade systems could be interesting. A brief investigation in Trondheim showed several different solutions, like for instance only a gasket in the joint, used on buildings with panel façade systems. Additionally, by interviewing members in the construction industry, new ideas for joint protection measures could be uncovered.

Additionally, a more in depth investigation of factors leading to water intrusion could be of interesting. The mounting of panels are limited by suppliers recommended joint widths. These are presumably decided due to moisture and temperature movements in the panels. It would therefore be interesting to test how much panels actually expand due to moisture and temperature. This could affect the recommendations about joint width, and thereby the water intrusion through the joints. It is assumed through this thesis that the runoff is an important factor that affects the water intrusion. Therefore it would be interesting to do further testing that focuses on the runoff and how different surface characteristics and properties affect the runoff, and thereby how different runoff patterns affects the water intrusion.

References

Aarnes, H. (2020). Kapillært vann. *Store norske leksikon.* Retrieved November 12, 2021, from snl.no

Ayo, A. W., Opeyemi, O. O., & Ayodeji, A. S. (2022). Physical properties of wall clads produced From Mixture of saw dust and pure water sachet. *World Journal of Innovative Research*, *12*(3). https://doi.org/10.31871/WJIR.12.3.4

Bassett, M., & Overton, G. (2015). Measuring the weathertight performance of flashings. *Buildings*, *5*(1), 130–148. https://doi.org/10.3390/buildings5010130

Bielek, M. (1977). The main principles of water movement on the wall surfaces of building of various roughness. *RILEM/ASTM/CIB symposium on evaluation of the performance of external vertical surfaces of buildings* (pp. 77–96).

Birkeland, Ø. (1966). General report on rain penetration. *Norwegian Building Research Institute*, 14.

Blocken, B., & Carmeliet, J. (2006). On the accuracy of wind-driven rain measurements on buildings. *Building and Environment*, *41*(12), 1798–1810. https://doi.org/10.1016/j.buildenv.2005.07.022

Blocken, B., Derome, D., & Carmeliet, J. (2013). Rainwater runoff from building facades: A review. *Building and Environment*, *60*, 339–361. https://doi.org/10.1016/j.buildenv.2012.10.008

Bøhlerengen, T. (2018). Byggforskserien 421.132 Fukt i bygninger. Teorigrunnlag.

Bunkholt, N. S., Time, B., & Kvande, T. (2021). Luftede kledninger. Anbefalinger for klimatilpasning. *SINTEF*, *23*(23).

Dordá, P. H., Roig, A. M. P., Escrig, A. C., & Gurrea, L. M. (2010). Water penetration into ventilated façade joints, 13.

Edvardsen, K. I., & Ramstad, T. Ø. (2017). *Trehus* (5th ed.). Oslo: SINTEF Akademisk forlag. ISBN:978-82-536-1391-8.

Fernández, M. J. (2010). Study of influence of wind pressure and rain conditions in rain screen walls. *Structural Survey*, *28*(1). https://doi.org/10.1108/02630801011040851

Gaarder, J. E. (2019). Byggforskserien 542.502 Utvendig kledning med plane plater.

Geving, S. (2021). *Praktisk bygningsfysikk* (1st ed.). Bergen: Fagbokforlaget. ISBN: 978-82-450-2801-0.

Geving, S. (2022). *Unngå klimaskader på kledningsplater med åpne fuger.* Retrieved May 10, 2022, from sintef.no

Grøn, Ø. (2020). Adhesjon. *Store norske leksikon.* Retrieved November 12, 2021, from snl.no

Hanssen-Bauer, I., Førland, E., Haddeland, I., Hisdal, H., Mayer, S., Nesje, A., Nilsen, J. E., Sandven, S., Sandø, A. B., Sorteberg, A., & Åndlandsvik, B. (2015). *Klima i Norge 2100 - Miljødirektoratet* [Oppdragsrapport M-406, Norsk klimaservicesenter].

Helseth, L. E. (2020). Kapillaritet. *Store norske leksikon.* Retrieved November 12, 2021, from snl.no

Helseth, L. E. (2021). Kontaktvinkel. *Store norske leksikon.* Retrieved November 12, 2021, from snl.no

Herbert, M. R. M., & Harrison, H. W. (1974). New ways with weatherproof joints. *Watford: Building Research Establishment*, 14.

Hofstad, K. (2019). Overflatespenning – enhet. *Store norske leksikon.* Retrieved November 12, 2021, from snl.no

Ingebretsen, S. B., Andenæs, E., & Kvande, T. (2022). Microclimate of air cavities in ventilated roof and façade systems in nordic climates. *Buildings*, *12*(5), 683. https://doi.org/10.3390/buildings12050683

Isaksen, T. (1964). Fugeutforming og slagreng-gjennongang. *Norges Byggforskinstitutt.*

Isaksen, T. (1966). Åpne fuger i utvendige kledninger? *Norges Byggforskinstitutt.*

Klima2050. (n.d.). *Klima 2050.* Retrieved March 13, 2022, from klima2050.no

Kvande, T. (2013). *Byggforskserien 542.003 Totrinnstetning mot slagregn på fasader. Luftede kledninger og fuger.*

Marmur, A. (2021). Surface tension of an ideal solid: What does it mean? *Current Opinion in Colloid & Interface Science*, *51*, 101388. https://doi.org/10.1016/j.cocis.2020.09.001

Mas, A., Gutiérrez, J., Gil, E., Gil, A., & Galvañ, V. (2011). Design and construction recommendations to improve impermeability in rainscreen walls built with natural stone coverings. *Construction and Building Materials*, *25*(4), 1753–1761. https://doi.org/10.1016/j.conbuildmat.2010.11.091

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, Ö., Yu, R., & Zhou, B. (Eds.). (2021). *Climate change 2021: The physical science basis. contribution of working group i to the sixth assessment report of the intergovernmental panel on climate change.* Cambridge University Press.

Miljødirektoratet. (2021). *FNs nye klimarapport – enkelt forklart.* Retrieved February 17, 2022, from miljodirektoratet.no

Mo, B. H., & Lid, H. S. (2020). Slagregninntrenging i horisontale fuger på fasader med plane plater [Master thesis. NTNU in Trondheim.].

NZBC. (2021). *E2 external moisture - Building Performance.* Retrieved March 28, 2022, from building.govt.nz

Park, C. W., Park, J., Kim, N., & Kim, Y. (2018). Modeling water flow on façade. *Automation in Construction*, *93*, 265–279. https://doi.org/10.1016/j.autcon.2018.05.021

Parsons, S. A., & Jefferson, B. (2006). Chapter 15 - Adhesion analysis of scaling systems. *Interface science and technology* (pp. 257–277). Elsevier. https://doi.org/10.1016/S1573-4285(06)80084-0

Pedersen, B. (2018). Kohesjon. *Store norske leksikon.* Retrieved November 12, 2021, from snl.no

Recatala, M. A., Morales, S. G., & van den Bossche, N. (2018). Experimental assessment of rainwater management of a ventilated façade. *Journal of Building Physics*, *42*(1), 38–67. https://doi.org/10.1177/1744259117719077

Standard Norge. (2016). *NS-EN 1027:2016 windows and doors - Water tightness - Test method.* Retrieved January 27, 2022, from standard.no

Thue, J. V. (2016). *Bygningsfysikk grunnlag.* Bergen: Fagforlaget. ISBN: 978-82-450-1994-0.

Thue, J. V. (2019, July 27). Kapillærbrytende lag. *Store norske leksikon.* Retrieved November 12, 2021, from snl.no

Appendices

A Scientific Paper

In this appendix the article ”Rain Intrusion Through Horizontal Joints in Façade Claddings - Experimental Investigation” presented as it will be submitted to the journal Buildings. Appendix D will also be an appendix to the scientific paper.

Author contributions are as followed: Conceptualization, S.G. and T.K.; methodology, E.A.S., M.H.S., S.G., and T.K.; validation, T.K.; formal analysis, E.A.S. and M.H.S.; investigation, E.A.S. and M.H.S.; resources, T.K.; data curation, E.A.S. and M.H.S.; writing—original draft preparation, E.A.S. and M.H.S.; writing—review and editing, E.A.S., M.H.S., and E.A.; visualization, E.A.S. and M.H.S.; supervision, E.A. and T.K.; project administration, T.K.; funding acquisition, T.K. All authors have read and agreed to the published version of the manuscript.

Article

Rain Intrusion Through Horizontal Joints in Façade Panel Systems - Experimental Investigation

Eva Armstrong Støver [1,‡], Marte Haugen Sundsøy [1,‡], Erlend Andenæs [1*], Stig Geving[2], and Tore Kvande [1]

[1] Norwegian University of Science and Technology (NTNU), Department of Civil and Environmental Engineering, NO, 7491, Trondheim, Norway;
[2] SINTEF Community, Department of Architecture, Materials and Structures, NO, 7465, Trondheim, Norway;
* Correspondence: erlend.andenas@ntnu.no
‡ These authors contributed equally to this work.

Abstract: Façade panel systems with horizontal open joints are commonly used on larger buildings in Nordic countries. Excessive water intrusion through open joints may lead to building defects. Previous studies have shown that current open joint recommendations may not be optimal to prevent water intrusion. It is therefore of interest to investigate the watertightness of different design solutions for horizontal joints. Large-scale measurements are conducted in a driving rain apparatus in the SINTEF and NTNU laboratory in Trondheim. Façade panel systems with different joint solutions are tested according to NS-EN 1027:2016. In total 72 unique tests are conducted, investigating the impact of the four parameters: panel types, joint widths, joint profiles, and bevelled joint designs. The most watertight among the investigated solutions involves a h-shaped aluminium joint profile. Bevelled joints also improve watertightness. For open joints, a narrower joint width was found to decrease water intrusion to the wind barrier. In general, a barrier is needed to protect the joints against water intrusion. However, the effectiveness of protection measures depend on their design and mounting. Some protection measures led to greater water intrusion than no barrier at all.

Keywords: Water intrusion; Rain intrusion; Open joint; Laboratory measurements; Façade panel systems; Watertightness

Citation: Lastname, F.; Lastname, F.; Lastname, F. Title. *Buildings* **2022**, *1*, 0. https://doi.org/

Received:
Accepted:
Published:

1. Introduction

The main objective of a building façade is to shield the building envelope from the exterior climate and ensure the longtime integrity of the building [1]. Façades serve as the primary weather barrier for buildings, and therefore need to withstand climatic loads for many years without requiring excessive maintenance or repairs [2]. Following decades of carbon emissions, the climate is now changing globally [3,4]. Among the predicted consequences of climate change in the Nordic countries are more extreme weather, including more frequent and intense precipitation [5]. Climate change requires buildings and infrastructure to be adapted for future climatic stresses [6,7]. Notably, building façades will be subjected to increased moisture loads which may cause moisture defects [8]. A façade typically consists of several layers, with a ventilated cladding forming the exterior layer. Claddings are in many cases not entirely air- or watertight. Water intrusion through the façade cladding may cause moisture damage to the interior layers [9–11]. The consequences of water intrusion are an issue for façades today, with several defects occurring in wood materials [12,13]. Therefore, it is important to know how much water infiltrates the façade cladding to understand the moisture loads imposed on the interior layers and ensure the long-term integrity of the façade.

In Nordic countries, façades are typically designed according to the principle of two-stage weatherproofing [1]. The principle is thoroughly presented in [16]. An outer layer, the cladding, acts as a weather barrier while a wind barrier is located behind an air cavity, as illustrated in Figure 1. The wind barrier is raintight and vapor permeable to allow outwards drying. The principle of two-stage weatherproofing is used to reduce the risk of moisture damage in joints, roof or outer walls [1,15]. However, while the principle is considered to provide adequate weatherproofing, it is unknown to what degree its performance is affected by the intrusion of rain water through joints or gaps in the cladding [16].

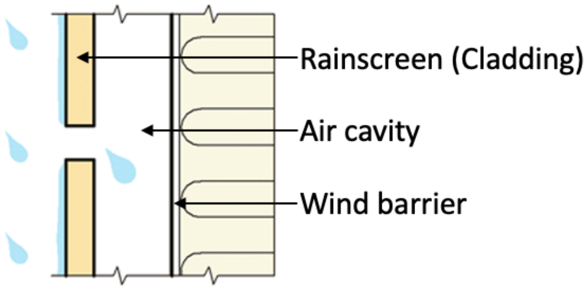


Figure 1. Principle of two-stage weatherproofing for an exterior wall with façade panels. The principle is not used for the horizontal open joint. Figure adapted from [15].

Façade panel systems are commonly used as exterior cladding on larger buildings in Norway [17]. The façade panels are often made of polymer composite, fiber cement, or high-pressure-laminate (HPL) [18,19]. The panels are typically mounted, following the principle of two-stage weatherproofing, to vertical wood or metal battens creating a ventilated air cavity between the interior side of the panels and the wall's wind barrier. It is recommended to mount façade panels with a joint width ranging between 5 and 10 mm to account for expansion of the panels due to moisture and heat. For definitions of the dimensions of joints and façade panels, see Figure 2. The vertical joints are kept relatively watertight by mounting a rubber gasket between the panels and vertical battens. The horizontal joints are on the other hand often kept open, thus deviating from the principle of two-stage weatherproofing . Laboratory experiments show that more than 98% of water infiltration through façade panel systems with open horizontal and vertical joints occurs through the horizontal joint [9].

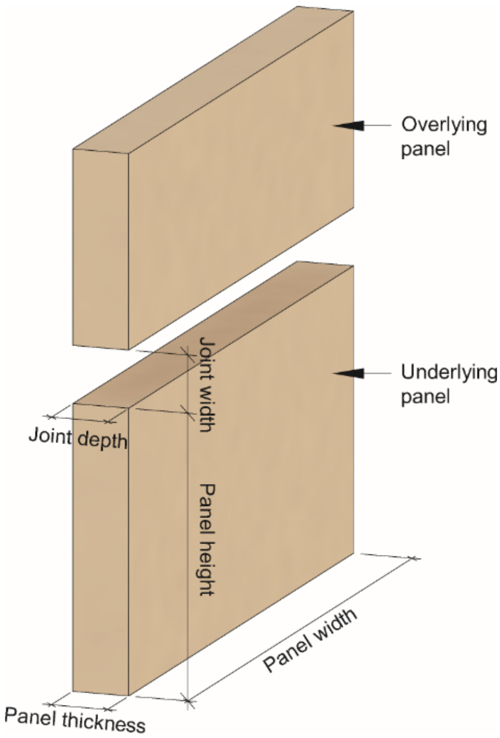


Figure 2. Definition of terms used to describe attributes of the panels and horizontal joints.

In Norway, building design guidelines for outer walls with façade panel systems are issued by SINTEF [18]. The recommendations suggest that horizontal open joints without any form of protection should be avoided [18], since SINTEF's archive of building defects show that moisture damage often occurs behind these types of cladding [20]. However, horizontal open joints are often preferred by architects for esthetic reasons. It is also faster and less expensive to mount façade panels without weatherproofing in the horizontal joints. Consequently, horizontal joints are often left open regardless of Norwegian recommendations. Previous studies show that horizontal open joints facilitate water intrusion both to the interior side of the panels and the wind barrier [21].

On impact with the façade cladding, rain will either splash off, flow down the façade, evaporate, be absorbed, or remain on the cladding [22–24]. Parameters that can affect rain runoff include surface tension, façade roughness, wind forces, the type of cladding material, the degree of wet condition, protruding wall elements, dirt, and the size of droplets, among others [23,25–27]. Water intrusion through joints, or openings, can occur due to kinetic energy, gravity, wind pressure, pressure differences, local air currents, hydrostatic pressure, and capillary forces [20,28–31]. In cases with highly concentrated streams on the exterior side of the panels, the streams can infiltrate the joint and hit the wind barrier directly due to the ejection effect [21]. The ejection effect is a concentrated stream with a horizontal velocity component forming when water flows into a joint, thereby easily leading water to the wind barrier. Water that passes directly through openings without hitting the façade panels is referred to as direct spray.

Joint profiles are extruded elements, often made from aluminium, that are inserted longitudinally into joints to form a protection against water intrusion and UV radiation [18]. It is recommended to use joint profiles to weatherproof horizontal open joints. Common types include the T1-, T2-, and h-profiles illustrated in Figure 3 [18]. The h-profiles have proven to be very effective protection against water intrusion [21,32]. However, profiles that very visibly protrude the joints to the exterior of the panels, like for instance the h-profile, are not popular among architects for esthetic reasons [21]. "Hidden" profiles are preferred, such as the two T-profiles in Figure 3. However, these profiles have been shown to sometimes direct more water behind the façade instead of increasing the watertightness [21]. This is because the profiles do not adhere to the principle of dedicated dripping edges. Furthermore, they are not completely pressed against the panels, creating a sufficient gap to lead water onto the interior side of the panels.

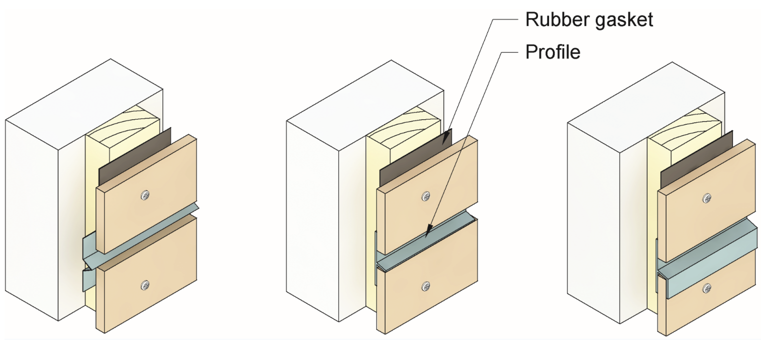


Figure 3. Joint profiles within the joint. From the left: T1-profile, T2-profile, and h-profile.

Joint width recommendations in Norway are based on a study by [33] where 5 mm joint widths were found to be optimal. In general, larger joint widths lead to more water intrusion [21,33–36]. Smaller joint widths increase the risk of static water in the joints, which may foster microbial or algae growth. Joint design that differ from rectangular joints have proven effective against water intrusion [21,36]. For 40 mm joint depths it is very effective to create vertical drainage grooves or quirks [36]. In joints with depths of 6 mm, overhangs and bevelled edges might prevent water intrusion [21].The impact of different joint designs on the water intrusion through horizontal open joints has not yet been sufficiently documented.

The study presented in this article aims to enhance the knowledge about the watertightness of horizontal open joints, and how different joint solutions affect watertightness. Previous studies on rain runoff or -intrusion on façade panel systems have varied in their methodology, including Computational Fluid Dynamics (CFD) simulations [25,37,38], field studies [10,23,34,39] and laboratory studies [10,21,32–34,36,40]. However, few laboratory measurements have been conducted on façade panel systems with horizontal open joints [9,21,33–36,41]. In addition, a previous study shows that some of the current Norwegian recommended solutions involving joint profiles lead to substantial amounts of water infiltrating the façade cladding [21]. However, the parameters of the study were limited, highlighting the need for this follow-up study. To address these general concerns, the following research questions are formulated:

1. What is known from existing scientific literature about the raintightness of horizontal joints in façade panel systems?
2. How do different joint solutions affect rain intrusion through the horizontal joints in façade panel systems?

A scoping literature study and a laboratory study have been conducted. Findings from previous studies will be compared to the laboratory results of the present study, to obtain a more holistic view of the water intrusion through horizontal open joints.

To test the watertightness of horizontal open joints for façade panel systems, laboratory tests are conducted in a driving rain apparatus set up according to NS-EN 1027:2016. The quantity of applied water is determined by NS-EN 1027:2016. Since the test rig is built according to the principle of two-stage weatherproofing, it is considered pressure equalized across the cladding, and air pressure is therefore not of interest.

Certain limitations are acknowledged. Five different types of façade panels are included in this study. The scope of the study is also limited to investigating water intrusion through horizontal open joints in façade panel systems. Additionally, only experimental laboratory studies investigating façade panel systems with similarities to this study are of interest in the literary review.

2. Methods

2.1. Literature review

In order to map the current state of the research field a scoping literature review has been conducted. This method is useful to get an overview of available research within a topic of interest, in addition to uncover knowledge gaps [42]. The research questions determine the premises for relevant keywords and phrases. The scoping method used is based on the five-step procedure described by [43]. These are: Identify and define the research questions; identify relevant research; selecting the most relevant research; map the data; and gather, summarize and report the results.

To identify and collect the most relevant research the scientific databases Scopus, Science Direct, and Oria were used. Oria is a Norwegian research library database. It is used because a large extent of the research within this field is conducted at Norwegian research institutions and published in Norwegian. To widen the search, synonyms to words and phrases used in the research questions were also included. The keywords are primarily English, except some Norwegian searches in Oria. Boolean operators were used to combine keywords and -phrases, as shown in Table 1, thereby excluding irrelevant findings, and narrowing the results. The 50 first results for every search were examined for relevance.

The selection of the most relevant research for further study was carried out using a four-step procedure. The exclusion criteria are based on the articles' relevance in answering the research questions. The first step examined the articles' title. Only titles in English, Norwegian, Swedish, or Danish were considered. The articles considered relevant were gathered in a spreadsheet with information such as author, country, name of journal, year of publishing, keywords and abstract. The second step was to select articles for further study based on relevant keywords. In the third step, the abstract and conclusion of each remaining article were read, subsequently excluding those found irrelevant from further

Table 1. Keywords and -phrases, and Boolean operators used in the literature review.

Keyword or phrase	AND	NOT
Façade OR	”Rain penetration” OR	CFD
”Façade cladding” OR	”Driving rain” OR	
”Panel cladding” OR	”Water penetration” OR	
”Panel façade” OR	”Water intrusion” OR	
Laboratory OR	”Wind-driven rain” OR	
Walls OR	WDR OR	
”Panel frame façade” OR	Laboratory OR	
”Exterior walls” OR	”Laboratory test” OR	
”External cladding" OR	”Open joint” OR	
	Junction	

study. The fourth step included a quick read-through of the entire article. Finally, the references of the remaining articles were reviewed to identify articles that were not found through the database searches. In addition, the ”cited by” function in Google Scholar was used to find literature citing the collected articles. This method is called snowballing or citation chaining [44]. Relevant information gathered outside of the literature review includes Norwegian construction guidelines, and information from textbooks in building physics and encyclopedias.

2.2. Laboratory Measurements

2.2.1. Test Set-up

A vertical test rig, 2645 x 2645 mm, was built with two separate test sections. Each test section was 1196 mm wide and 2573 mm tall, which allowed three panels to be tested in each section, creating two horizontal joints. The test rig was built into a metal frame that was installed in a driving rain apparatus, as shown in Figure 4. The outer wooden frame was fastened to the metal frame, and then the perimeter was sealed with an elastic sealant. The test rig was built by first fastening two battens to the outer frame, and then fastening the studs to both the battens and the outer frame. Instead of a wind barrier, a transparent polycarbonate board (Lexan) was used so that the experiment could be observed.

To measure the amount of water that hits the wind barrier, a gutter system was constructed using aluminum foil, tape, plastic tubes, and sleeves. The aluminium gutter was taped to the Lexan board and not connected to the interior side of the panels. Tubes led the collected water from the aluminium gutter to buckets, as seen in the foreground of Figure 4. A separate gutter system, using plastic foil, was constructed after the panels were mounted to measure the amount of water infiltrating to the interior side of the panels. The plastic gutters were taped to the bottom of the lowest panel. Plastic tubes were used to lead the collected water to buckets placed outside the driving rain apparatus.

Vertical battens were mounted to the Lexan board and underlying studs. The façade panels were mounted on the vertical battens with the plastic gutters fastened. The battens, 30 x 48 mm, created a 30 mm wide air cavity. A 70 mm wide ethylene propylene diene monomer (EPDM) gasket was placed between the vertical battens and façade panels. Two types of EPDM gaskets were used according to recommendations from the façade panel suppliers; one plain and one with grooves. Each panel is approximately 1200 x 800 mm. Three panels were used for each test section, thus creating two horizontal joints in each section.

2.2.2. Rain Testing

The driving rain apparatus was set up according to NS-EN 1027:2016 [45]. The test rig was built as a pressure equalized cladding. The apparatus was equipped with eight nozzles with a distance of 400 mm between them. However, only six nozzles spray water onto the test rig, meaning there are three nozzles spraying on each test section. The nozzles were placed with a horizontal distance of 150 mm from the panels and a vertical distance of 100

Figure 4. The test rig seen from the interior side. The water collecting system consists of buckets and tubes. Left side of the rig is test section 1, and right side is test section 2.

mm above the top joint with an inclination of 24° to the azimuth. An acknowledged source of potential uncertainty is the row of nozzles in the apparatus, which can only be moved manually. The nozzles had to be moved between tests and have a positioning accuracy of approximately ±15 mm. Each nozzle sprays 2 L/min. The majority of the applied water hits above the top horizontal joint, and some water hits the joint directly. The slightly different spray profile for each test may impact the precision and reliability of the wind barrier measurements. The lower horizontal joint will mainly be exposed to runoff water from the overlying panels.

Four different parameters were the focus of the testing: Different façade panels, joint widths, joint profiles, and bevelled joint designs. The different combinations of parameters and an overview of the test program are presented in Table 2. Additionally, tests with the top joint sealed (hindering water intrusion due to direct spray and increased water runoff) and tests without any panels was conducted. All the parameters were tested with open joints. Unless otherwise specified, the joint widths are those given in Table 3. Protection measures are defined as anything used to alter the joint, in this instance different profiles, gasket, and bevelled joint designs. The joints with protection measures are hereby referred to as protected joints. The five panels tested and their characteristics are presented in Table 3. Whenever the present article refers to *the standard recommendation* from the suppliers for the different panels, it is defined as an open joint without any protection measures, and recommended joint widths as stated in Table 3.

Five different panels were tested. The contact angles were obtained by taking pictures of droplets on the panels (lying horizontally), and thereupon measuring the angles of the droplets. Three different joint widths were tested: 3, 5, and 8 mm. The different joint widths were achieved using spacers. The three aluminium joint profiles tested, referred to as profiles within the joint, are shown in Figure 3. The three profiles' dimensions are given in Figure 5. Additionally, a gasket and a ventilated U-batten were tested in different combinations, referred to as profiles behind the joint. Figure 6 illustrates three of the combinations. A 70 mm wide gasket with no grooves was used. The U-batten was made of steel with a depth of 15 mm and a height of 70 mm. The U-batten was mounted to the vertical battens, in common practice vertical battens are not used. Additionally, variants were tested wherein extra fastening points for the panels were placed between the previously existing fastening points in the joint, creating a distance of 275 mm instead of 550 mm. Bevelled joint designs, top-bevelled and top-and-bottom bevelled as shown in Figure 7, with angles 15°, 30°, and 45°, were constructed using a circular saw.

Table 2. Overview of combination of test parameters conducted during the laboratory measurements. (FP is an abbreviation for fastening points).

	HPL			Glass Fiber Smooth			Glass Fiber Rough			Fiber Cement White			Fiber Cement Grey		
	3mm	5mm	8mm	3mm	5mm	8mm	3mm	5mm	8mm	3mm	5mm	8mm	3mm	5mm	8mm
Open joint		X	X	X	X	X	X	X	X	X	X	X	X	X	X
T1-profile		X	X		X			X			X			X	
T2-profile		X	X		X			X			X			X	
h-profile					X			X							
Sealed top joint		X	X		X			X			X			X	
Gasket											X			X	
U-batten					X			X			X			X	
U-batten with extra FP					X			X			X			X	
U-batten with gasket					X			X			X			X	
U with gasket and extra FP					X			X			X			X	
Bevelled top 15°		X	X		X			X							
Bevelled top 30°		X	X		X			X							
Bevelled top 45°		X	X												
Bevelled both 15°		X	X		X			X							
Bevelled both 30°		X	X		X			X							
Bevelled both 45°		X	X												

Table 3. Overview of different panels used in laboratory measurements and the supplier's recommended joint widths (without protection measures)(fourth column), referred to as "standard recommendations" throughout this article.

Material/name	**Surface characteristics**	**Dimensions [mm x mm x mm]**	**Recommended joint width [mm]**
Glass Fiber Smooth	Painted and very smooth	1195x840x6	5
Glass Fiber Rough	Crushed stone and very rough	1195x840x6	5
Fiber Cement Grey	Painted and smooth	1192x800x8	5
Fiber Cement White	Sandblasted and rough	1192x800x8	5
HPL	Painted and very smooth	1200x800x8	8

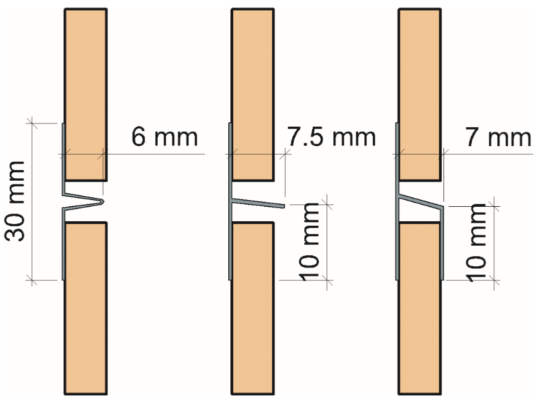


Figure 5. Joint profile dimensions. From the left: T1-profile, T2-profile and h-profile. Left side of panels is the interior side, and right side is the exterior. Altered from [12].

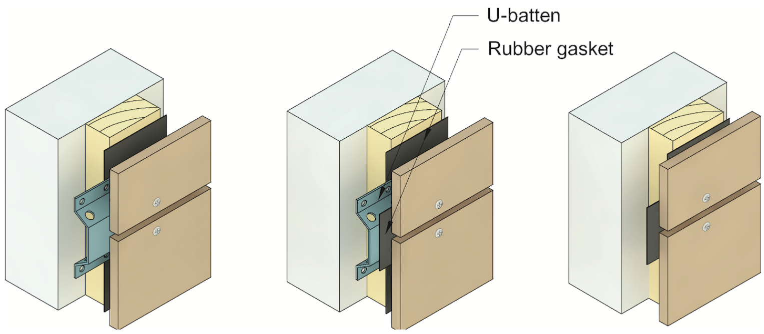


Figure 6. Profiles behind the joint, U-battens. From left: U-batten without a gasket, U-batten with a gasket, and with only a gasket. Normally a vertical batten is not used in combination with an U-batten.

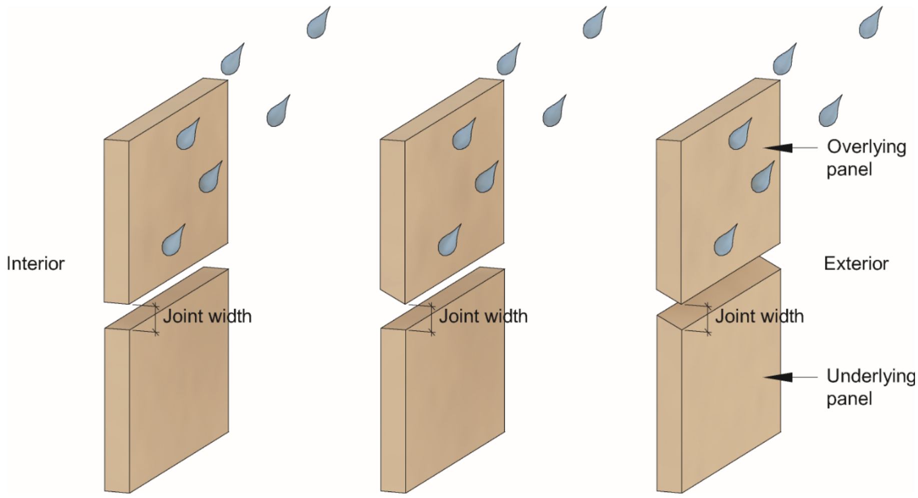


Figure 7. Different bevelled joint designs. From left: A rectangular joint, a top-bevelled joint, and a top-and-bottom bevelled joint.

For every parameter tested, water was applied to the test rig for ten minutes before water collection and measurement commenced. The application of water before the measurements started normalized the water runoff conditions and ensured more consistent results. For each measurement, the water was applied for two minutes. Collected water runoff was measured shortly after the nozzles were turned off, but allowing some time for the water in the gutters to empty into the buckets. The two-minute water application and subsequent measurement was repeated at least three times for every parameter. If a measured result varied considerably from the others, the result was discarded and water applied for an additional two-minute measurement. The water from the gutter systems was collected in buckets and measured using measuring jugs and cups. The three measurements were averaged, with single outliers excluded. The presented output of every parameter test is the averaged collected runoff quantities from the interior side of the panels and from the wind barrier.

3. Results

3.1. Review of Previous Research

A limited number of studies have investigated how rain water distributes between the exterior and interior sides of the panels, and the wind barrier [9,21,33,34]. The majority of studies only investigated the amount of water that infiltrates the open joints. However, it is concluded that most of the water that infiltrates the open joints flows on the interior side of the panels, approximately 25-35% of the total water applied [9,21,34], and only approximately 0.5-2% flows down the wind barrier [9,21]. Isaksen [34] states that with horizontal open joints, there will always be some water intrusion to the wind barrier, however, the quantity is often too small to measure. It is uncertain how much water will flow down the wind barrier, since the quantities are so small that measurement errors will have a large impact [21]. Water will either hit the wind barrier directly through the joint or due to splashing [9]. In laboratory tests, water intrusion due to direct spray from the nozzles will be greater than for runoff on the façade panels. Additionally, the water will often flow down in smaller streams, both on the façade panels and the wind barrier [9,21].

Joint width can have substantial impact on water intrusion through horizontal open joints. Several studies have used joint widths as a test parameter [21,33–35]. Isaksen [34] concluded that joint widths $\geq$ 7 mm will direct too much water to the wind barrier, even with an air cavity width of 40 mm. Isaksen's later experiments came to the same conclusion, while adding that a 5 mm joint width would be satisfactory [33]. The current Norwegian recommendations are based on this conclusion [18]. A joint width $\leq$ 5 mm increases the risk of static water in the joint, which can lead to algae and microbiological growth. Mo and Lid [21] found in their study that there was a positive correlation between the joint width and water intrusion. In addition, they stated that the panels should be mounted with a 5-10 mm joint width to allow for temperature and moisture movement, based on recommendations from product suppliers.

Earlier studies have investigated the effect of joint profiles on water intrusion [21,32,40]. Herbert and Harrison [40] found labyrinth joint profiles to be relatively watertight. The water intrusion in their study was caused by runoff on the exterior side of the panels, being forced through joints by air pressure. However, the studied profiles were quite complex and are not available on the Norwegian market, making the present study unable to replicate the experiment. The Norwegian recommendations advise using joint profiles in open joints to protect the wind barrier from driving rain and UV radiation [18]. Two of the recommended profiles are the T1-profile and the h-profile, illustrated in Figure 3. Earlier studies indicate that the h-profile is a watertight solution [21]. The degree of watertightness will depend on the design of the h-profile [32]. So-called "hidden profiles" have received the greatest industry attention, since they cannot be seen from the exterior [21]. Examples of these are the T1- and T2-profiles. A study by Mo and Lid [21] found neither of the T-profiles to be watertight, and in some cases directing more water to the interior side of the façade panels than when no profile was used. They stated difficulties in tightening the profiles against the panels as a possible explanation for the increased water intrusion.

Studies indicate that non-rectangular joints may reduce water intrusion compared to rectangular joints [21,36]. Mas et al. [36] tested joints with a vertical drainage groove running along the top edge of panels, and joints featuring a quirk edge along the overlying panels. Both designs reduced rainwater intrusion considerably compared to rectangular joints. These results were obtained using panels with a joint depth of 40 mm. Rainwater was drained by the grooves before the water reached the air cavity. However, this drainage design can be difficult to carry out in panels with smaller joint depths and different panel materials. Utilizing quirk-edged joints reduces water intrusion in smaller joints, 4-6 mm. Although no tests were performed on bevelled joint designs, Mas et al. [36] recommended their use. The effectiveness of bevelled joints was confirmed by Mo and Lid [21], where joints bevelled at 45° were proven to be quite watertight.

The size of the air cavity has varied in different experiments. However, few have discussed its impact on rain intrusion. Experiments by Isaksen [33,34] indicated that an increase in the air cavity width led to an increase in the water amount on the interior side of the façade panels. In addition, for greater joint widths, the air cavity width should be made greater correspondingly [33]. An increase in the air cavity width might decrease the amount of water on the wind barrier [33], but this assumption is not backed by any identified studies.

Studies have shown a negative correlation between the joint depth and water intrusion [21,33,35,36,40]. In most of these studies the joint depth has been $\geq$ 20 mm [34–36]. Mas et al. [36] state that it is common to increase the joint depth in order to reduce water intrusion. This conclusion is valid for a number of different façade panels. Conversely, Mas et al claim the influence of joint depth is insignificant for larger joint widths. Admittedly, the panels used in the studies varied in terms of size and texture, which could have an impact on the results. However, all studies conclude that larger joint depths provide better watertightness.

Air pressure on the exterior side of the joints has been used as a parameter in most of the investigated studies [9,21,33,34,40,41]. The studies are in disagreement about the effect of air pressure on water intrusion. Isaksen conducted three experiments with air pressure that indicate that air pressure had no impact on water intrusion [34]. Several other studies came to the same conclusion using static pressure [9,21]. The test rigs in these studies were built as pressure equalized rain screens, which implies that the applied pressure should be equalized across the joints. However, for joint widths ≥ 5 mm, wind gusts are more critical for water intrusion [33]. Later experiments confirmed these results [9]. A study on water intrusion through joints featuring labyrinth profiles, concluded that air pressure, whether dynamic or static, only had an impact after water had infiltrated into the joint profile [40]. The study indicates that an increase in air pressure causes more water intrusion by pressing the water that is lying static in the joint. Earlier studies show the same effect with larger joint widths [33]. Mo and Lid [21] assessed whether applied pressure had an impact on water intrusion, and found no qualitative indication that it did, but conducted no quantitative measurements.

Recatala et al. [9] studied the correlation between spray rate and water intrusion. The study shows that there is a positive logarithmic correlation between spray rate and water intrusion [9]. This correlation is valid for both the interior side of the panels and the wind barrier. The same study concluded that 49.7% of rain on façade panels would splash off.

3.2. Laboratory Results

In total, 72 unique tests of water intrusion were conducted using the test rig. The tests were conducted for the following test parameters: Joint widths, joint profiles, and bevelled joint designs. Additionally, two further tests were performed: one with the top joint sealed, and one test where the panels were removed and water was allowed to spray freely to the wind barrier, measuring the maximum amount of water that could theoretically reach behind the panels. In this section, the performance of the protected joints are expressed as percentage change from the measured runoff for 5 and 8 mm open joints, the standard recommendation for the respective panels (given in Table 3.

3.2.1. Water Distribution Between the Wind Barrier and the Interior Side of the Panels

The results display the water intrusion as measured from the runoff collected at the wind barrier and at the interior side of the panels. There was often too little water on the wind barrier to measure any runoff, for instance with a 3 mm joint width. With joint widths of 5 mm and 8 mm in an open joint, every test yielded measurable runoff. The water distribution can be expressed based on the measured runoff from a 5 and 8 mm joint width for a horizontal open joint. The average water intrusion to the wind barrier and interior side of the panels is 0.5-2% and 19-20%, respectively, of the total water sprayed on the panels (6000 mL/min).

3.2.2. Panel Surfaces

The five different types of panels are categorized by their contact angle and surface roughness. All the panels can be considered hydrophilic, as their contact angles were visually assessed to range from approximately 50° to 85°. As shown in Table 3, the panels are also categorized by how rough or smooth their surfaces are. Observations show that a rough surface causes a disperse water runoff, while the runoff on a smooth surface is primarily in streams.

3.2.3. Joint Widths

For water intrusion to the wind barrier, the same trend is observed for all the panels, as shown in Figure 8. With a 3 mm joint width there was too little water intrusion to create a measurable quantity of runoff. The amount of infiltrated water increased when the joint width was increased from 3 mm to 5 mm, and again up to 8 mm. Glass Fiber Smooth with an 8 mm joint is an outlier, yielding double the water intrusion compared to the other panels. An ejection effect was observed in every measurement with an 8 mm joint width and the Glass Fiber Smooth panels.

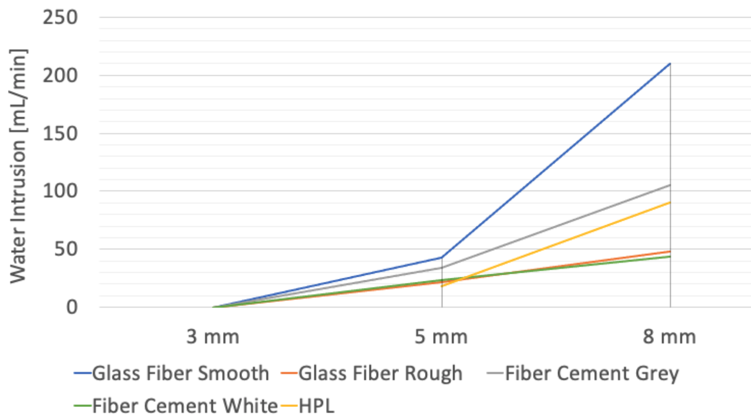


Figure 8. Water intrusion to the wind barrier for five different panels with 3, 5, and 8 mm joint widths.

The water intrusion to the interior side of the panels varies greatly, as shown in Figure 9. The same trend is evident for all the panels, except for Glass Fiber Rough, with an increase in water intrusion when joint widths are increased from 3 mm to 5 mm, and a smaller decrease from 5 mm to 8 mm. Note that there is no measurement combining the HPL panels with a 3 mm joint width, because the recommended joint width for these panels is $\geq$ 8 mm, larger than the others, as shown in Table 3.

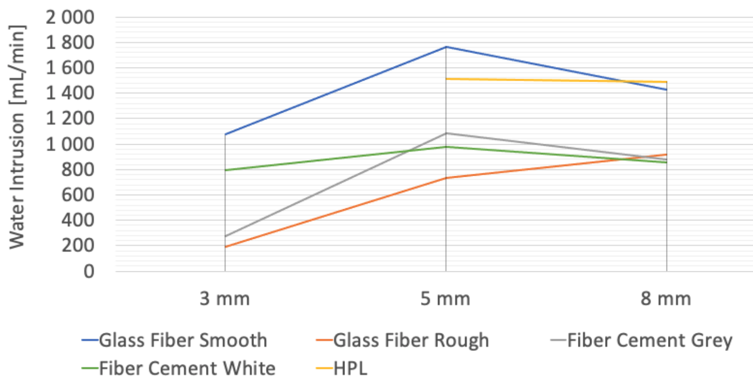


Figure 9. Water intrusion to the the interior side of the panels for five different panels with 3, 5, and 8 mm joint widths.

As the joint width increases, different water behaviours were observed. For the 3 mm joint, a continuous water bridge was formed along the entirety of the joint, whereas only partial water bridges were observed in the 5 mm joint. Dripping occurred in both the 5 and 8 mm joints. However, for greater joint widths the water droplets were larger and had a higher dripping frequency. The horizontal ejection effect was only observed for the smooth panels and 5 and 8 mm joint widths.

3.2.4. Joint Profiles

Figure 10 shows the water intrusion to the interior side of the panels when joint profiles within the joint were used. The amount of water intrusion with both the T1- and T2-profiles varied greatly for the different panels. For the most part, the profiles led in less water than the standard recommended solution did. However, the infiltrated water amounts are still substantial. The h-profile led in the least water with no water intrusion, followed by the T2-profile. All the joint profiles protected the wind barrier from water, hence no water was measured or observed on the wind barrier in any of the tests.

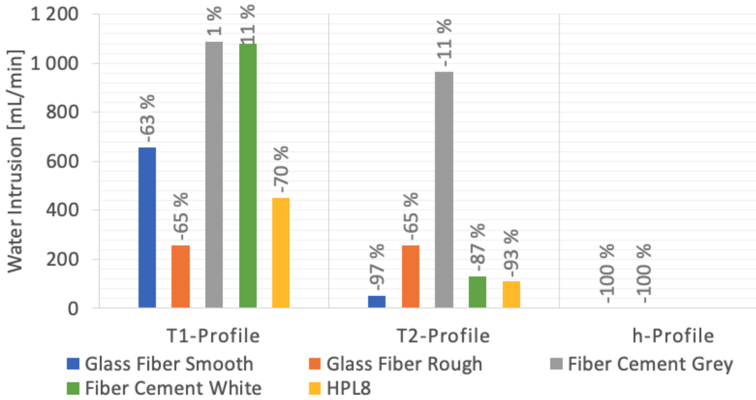


Figure 10. Water intrusion to the interior side of the panels when profiles within the joint were used: T1-, T2-, and h-profiles. The percentage change from the water intrusion measured with the standard recommendations in Table 3 is shown.

Figure 11 shows the water intrusion to the interior side of the panels when joint profiles behind the joint were used. The most effective protected joint solution against water intrusion, in this instance, was an U-batten combined with both a gasket and extra fastening points. An U-batten combined with only a gasket also yielded less water intrusion than the standard recommendations. An U-batten or gasket alone, resulted in increased water intrusion, and measurable amounts of water on the wind barrier in some cases. Similarly, an U-batten combined with extra fastening points resulted in increased water intrusion, even compared to an U-batten alone in several cases. Most tests did not yield measurable amounts of water intrusion on the wind barrier. However, water that had infiltrated the joint would hang on the edges of the U-batten and drip, causing substantial splashing to the wind barrier at the bottom of the air cavity. However, the splashing mostly occurred below the gutters that measured the water intrusion to the wind barrier, rendering quantification impossible. In an instance where water was observed dripping from the top U-batten and splashing off the lower U-batten almost 3.3% of the total water sprayed was measured on the wind barrier.

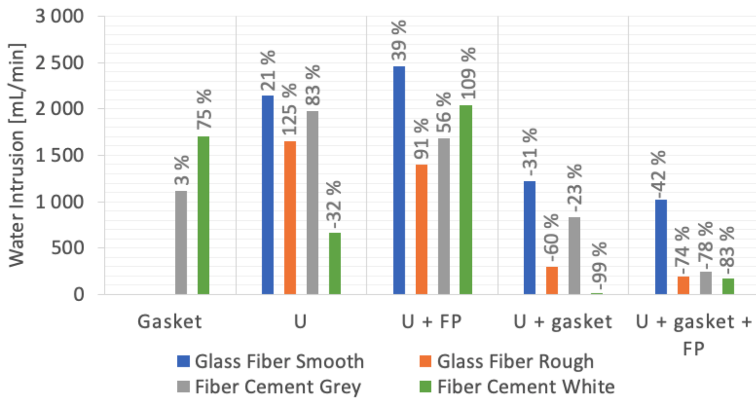


Figure 11. Water intrusion to the the wind barrier when profiles behind the joint were used. Gasket, U-batten, U-batten + extra fastening points, U-batten + gasket, and U-batten + gasket + extra fastening points. The percentage change from the water intrusion measured with the standard recommendations in Table 3 is shown.

3.2.5. Bevelled Joint Designs

Water intrusion to the wind barrier when the joints were bevelled to different angles (see Figure 7) is shown in Figure 12. The peak water intrusion to the wind barrier occurred mostly with a 30° bevelment. Water intrusion increased on average with 58% from a 15° to a 30° top-bevelled joint, and decreased with 1% for a top-and-bottom-bevelled joint. The least water intrusion occurred with a 45° bevelled joint. Water intrusion decreased on average with 30% from a 30° to a 45° top-bevelled joint, and decreased on average with 75% from a 30° to 45° top-and-bottom-bevelled joint. There were large variations in the results, making it unfeasible to draw any general conclusions from this study alone.

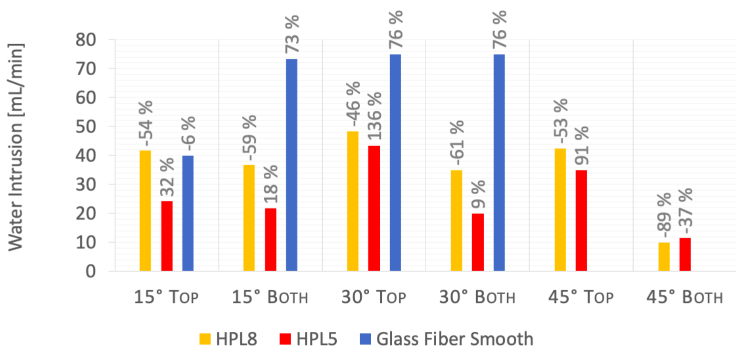


Figure 12. Water intrusion to the wind barrier for HPL and Glass Fiber Smooth with different bevelled joint designs. HPL8 has a joint width of 8 mm, while HPL5 has a joint width of 5 mm. Bevelment degrees are 15°, 30°, and 45°. The percentage change from the water intrusion measured with the standard recommendations in Table 3 is shown.

The amount of water intrusion to the interior side of the panels varied for the top-bevelled and top-and-bottom-bevelled joint designs, as shown in Figure 13. A top-and-bottom-bevelled joint exhibited substantially less water intrusion than a top-bevelled joint. For top-bevelled joints, there was little to no correlation between the bevelment angle and water intrusion. Water intrusion increased on average with 1% from a 15° to a 30° bevelment, and increased on average with 19% from a 30° to 45° top-bevelled joint. The top-and-bottom-bevelled joints exhibited a positive correlation between the degree of bevelment and watertightness. Water intrusion decreased on average with 72% from a 15° to a 30° bevelment, and decreased on average with 96% from a 30° to 45° top-and-bottom-bevelled joint.

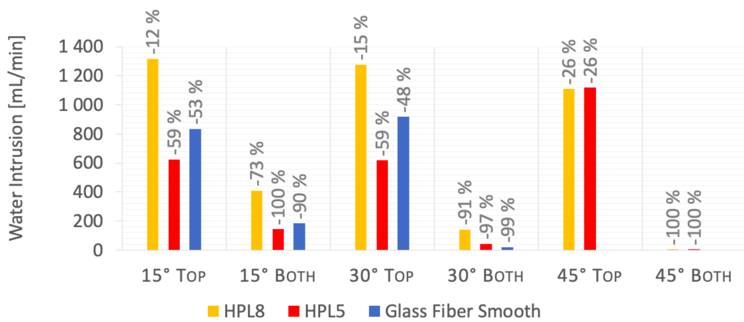


Figure 13. Water intrusion to the interior side of the HPL and Glass Fiber Smooth panels with different bevelled joint designs. HPL8 has a joint width of 8 mm, while HPL5 has a joint width of 5 mm. Bevelment degrees are 15°, 30°, and 45°. The percentage change from the water intrusion measured with the standard recommendations in Table 3 is shown.

3.2.6. Sealed Top Joint and Water Runoff Without Panels

When the top joint was sealed, larger amounts of water entered behind the panels than when both joints were open. Of the total water sprayed on the the panels an average of 27% infiltrated to the interior side of the panels. Additionally, due to splashing, water also hit the wind barrier, an average of 0.4% of the total water sprayed on the panels. The tests where the panels were removed yielded a total water runoff of approximately 64%.

4. Discussion

4.1. Water Distribution Between the Wind Barrier and the Interior Side of the Panels

The measured water distribution to both the wind barrier and interior side of the panels is very similar to earlier studies [9,21,33,34]. The majority of the infiltrated water is observed and measured on the interior side of the panels. If the infiltrated water is not properly drained out of the air cavity, it can facilitate fungal growth on the battens, eventually leading to rot. Water can be led from the interior side of the panels to the wind barrier along the vertical battens. Additionally, in reality, for taller buildings more water will infiltrate to the wind barrier via the vertical battens. The majority of water infiltrating to the wind barrier is due to direct spray, however, by sealing the top joint, it was confirmed that water intrusion also occurred due to splashing and the ejection effect. There is some uncertainty relating to the reliability of the water intrusion measurements on the wind barrier. The row of nozzles is moved manually and with a low degree of accuracy (±15 mm). As direct spray from the nozzles is observed to be the main factor for water intrusion to the wind barrier, the exact placement of the nozzles relative to the joint openings has a substantial impact. By moving the row of nozzles slightly, the amount of direct spray on the wind barrier would vary greatly, while only slightly affecting the water intrusion to the interior side of the panels. Another factor that led to larger amounts of water intrusion to the wind barrier was the ejection effect. This was observed to happen sporadically when concentrated streams of water intersected a joint. The effect caused outlier results, as recorded for Glass Fiber Grey with 8 mm joint width. Due to these inconsistent factors, the measurements of wind barrier runoff are considered more unreliable than water intrusion measurements from the interior side of the panels.

4.2. Panels

With regards to the contact angles and water intrusion, no clear trend could be determined. However, all the panels are categorized as hydrophilic. Therefore, the variation in this parameter is not considered great enough to substantially influence the runoff or water intrusion. On the contrary, the degree of roughness or smoothness was observed to be paramount to the water intrusion. The smoother panels exhibited more concentrated streams which often led to considerable water intrusion where the stream intersected a joint. The rougher panels had a more dispersed runoff, and the water intrusion distributed more evenly over the joint. In earlier studies, the material of the panels have been mentioned, whereas the surfaces' and their impact on water distribution is not as clear. However, for a façade exposed to actual weather, the rain and wind will differ all the time, consequently so will the runoff and distribution of water. The results of this study indicate that panels with a smoother surface are more prone to rain intrusion, there should therefore be stricter regulations when using smoother panels in regards to the robustness of the back wall and the raintightness of the joints.

4.3. Joint Widths

Previous studies have all concluded that there is a positive correlation between joint width and water intrusion [21,33–35]. In the present study, this conclusion only holds for water intrusion to the wind barrier. Water intrusion to the interior side of the panels diverges from this conclusion. On average, peak water intrusion to the interior side of the panels occurred with a 5 mm joint width. From previous research this is the recommended joint width [21,33,34]. Based on the results of the present study, this should not be the recommended joint width, and a joint width of 3 mm seems to be the most desirable as it directs the least amount of water to both the wind barrier and the interior side of the panels. Previous studies have not recommended a 3 mm joint, because microbial growth and algae is considered a risk due to static water remaining in the joint [21,33,34]. However, static water was not observed to be an issue in the present study. As soon as the nozzles were turned off, the water would drain from the joints. In addition, water bridges appear to direct the water runoff across the joints, and thus prevent water intrusion. The conclusion is therefore that a 3 mm joint is the most watertight, but in reality water may still be directed to both the wind barrier and the interior side of the panels due to wind. However, not all panels can be mounted with small joint widths, since the joint must allow for temperature and moisture expansion. On average the water intrusion to the interior side of the panels are less for an 8 mm joint width than a 5 mm. However, the opposite is the case for water intrusion to the wind barrier, which could put a greater strain on the wind barrier.

4.4. Joint Profiles

In general, joint profiles are solutions that decrease water intrusion compared to an open joint. The h-profile is found to be completely watertight, in agreement with a previous study examining the same profile [21]. Contrary to previous results [21], the T-profiles do not (on average) direct more water behind the cladding than the standard recommendations. Additionally, they completely prevent water from entering to the wind barrier. The discrepancy between the present study and earlier studies is likely caused by differences in the placements of the profiles within the joints. In Mo and Lid's [21] study, the profiles were centered in the joints, as illustrated in Figure 14. In the present study, the profiles were pressed down towards the underlying panel as much as possible, as illustrated in Figure 15. The profiles being pressed downward likely caused less water to enter underneath the protruding part, and the water was more easily led across the joints, thereby ensuring a more watertight solution. The T-profiles' watertightness seems to be sensitive to how they are mounted, and to the top edge of the panels being even. Minor unevenness may lead to capillary suction, which could cause increased water intrusion. The results indicate that it is difficult to ensure complete watertightness, especially with the T1-profile. The T1-profile's protruding part can not be completely pressed down to the underlying panel due to its design. Moreover, observations indicate that the majority of water intrusion occurs between the profile and the underlying panel. As a result, profiles should be designed in a way that hinders water from entering underneath them. An idea that needs further investigation is to use a small rubber gasket underneath the protruding part of the T-profiles to make it less sensitive to mounting and more watertight.

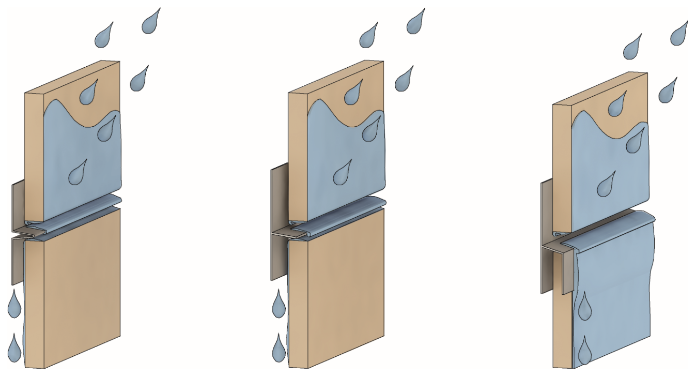


Figure 14. Assumed water intrusion when profiles centered in the joint.

The U-batten reduced water intrusion considerably when combined with a gasket, even more so when this was combined with extra fastening points securing the batten to the panel. Other combinations, surprisingly, directed more water to the interior than an open joint. A reason for this could be capillary suction due to small gaps between the panels and gaskets or battens. Due to the stiffness of both the panels and the U-batten,

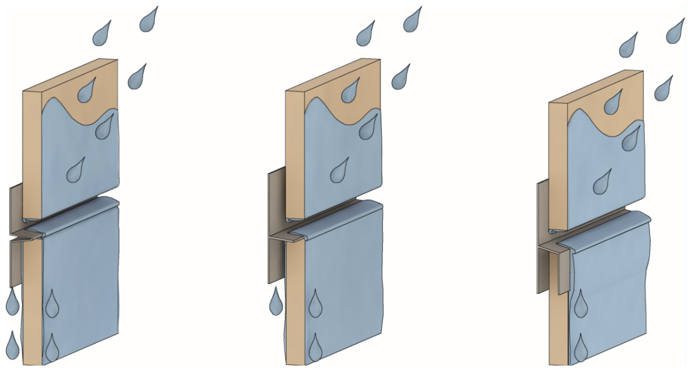


Figure 15. Water intrusion when the profiles are pressed downward in the joint.

the extra fastening points could have increased the gaps between the panels and battens. Additionally, the U-batten causes a risk of water intrusion to the wind barrier. When water drips from the U-batten (which protrudes the air cavity), the droplets impact the underlying U-batten and subsequently splash to the wind barrier. In instances where this happened, a lot of water was observed on the wind barrier. Dripping from the lower U-batten fell below the gutter on the wind barrier, and this effect could therefor not be quantified. Although some of the solutions were efficient protective measures, the risk of large water amounts on the wind barrier may be unacceptably high. The results indicate that protruding parts in the air cavity, for instance horizontal battens, creates an extra risk for water intrusion to the wind barrier if there is water intrusion to the interior side of the panels. Additionally, the U-battens are not supposed to be mounted with vertical battens, as conducted in the present study. Therefore it is likely that the water intrusion to the wind barrier in reality is higher than in the laboratory experiments, since the U-batten and the wind barrier would be in direct contact.

4.5. Bevelled Joint Designs

The tests of different bevelled joint designs yielded similar results to previous experiments: a non-rectangular joint design is better than a rectangular joint [21,36]. A bevelled joint reduces water intrusion through the joint, and also leads infiltrated water out of the façade. The results, with a top-and-bottom-bevelled joint, indicate a positive correlation between the angle of bevelment and reduction in water intrusion to both the interior side of the panels and the wind barrier. With a top-bevelled joint, the increase in angles led to less consistent trend in regards to water intrusion. Angles $\geq 45^\circ$ were not tested, but it is assumed that the positive correlation will uphold for larger angles. However, the handling of the panels could be difficult with larger bevelled angles, and the panels would be more vulnerable to damage. Top-and-bottom-bevelled joints are found to be considerably more watertight than top-bevelled joints. A notable improvement is the reduction in water intrusion due to splashing, since the water is led out of the joint by gravity.

4.6. Sealed Top Joints and Water Runoff Without Panels

By sealing the top joint, water could only infiltrate the cladding through the lower joint. As the water intrusion was substantial, it proves that direct spray is not the only reason for water intrusion. The increase in water intrusion, when compared to open joints, could be due to an increased velocity in water flow. This indicates that panels with larger heights could cause an increase in water intrusion, and thereby more open joints are actually preferable to less. This, however, needs further investigation. Additionally, direct spray is not the only cause of water intrusion to the wind barrier since water infiltrated due to splashing in the joints.

The amount of water measured without any panels coincides with previous results. In the present study less water splashed off compared to earlier studies, however there is still a substantial amount that splashes off. Consequently, the water intrusion, when compared to the theoretically maximum intrusion, would be substantially greater than when compared with the total applied water.

4.7. Other parameters

Previous studies have mentioned certain parameters that may affect water intrusion, but which have not been investigated in the present study. These include: Air cavity depth, joint depth, air pressure, and spray rate.

The air cavity depth is not varied in these tests because the width is determined by the dimensions of the battens. Standard dimensions are used throughout the industry and in practice cavities thus tend to always conform to approximately the same size. The cavity width was increased slightly by the U-battens, but this was not considered to affect the water intrusion.

The joint depth investigation was limited by the available panels which had thicknesses of 6 and 8 mm. Additionally, the effect of joint depth has been thoroughly tested by previous studies and is therefore not as interesting [21,33,35,36,40].

Air pressure was not applied as a driving force due to the test rig being a pressure equalized façade, and therefore pressure differences should not occur. Additionally, the effect of air pressure is not clear from previous studies [9,21,33,34,40,41]. The previous tests by Mo and Lid [21] observed no effect of applied air pressure.

Recatala et al. [9] stated that there is a positive correlation between the spray rate and infiltrated water. The present study did not vary the spray rate, but tested water intrusion with a sealed top joint to increase the amount of water impinging on the bottom joint. The observations are in accordance with those of Recatala et al.

5. Conclusions

The present study carried out an experimental investigation of water intrusion through horizontal joints in façade panel systems. The effectiveness of different joint solutions was tested. Out of a total of 6000 mL/min sprayed on the test sections, the water intrusion to the wind barrier and interior side of the panels with a 5-8 mm joint width is 0.5-2% and 19-20%, respectively. Panels with surface characteristics that ensure a dispersed water runoff, in general exhibit less water intrusion through the joints than smooth panels where concentrated streams occur. Out of the three tested joint widths, a 3 mm joint width yields the least amount of water to both the wind barrier and the interior side of the panels. However, due to uncertainties related to whether a 3 mm joint width can be used due to expansions of the panels, it is not an unconditionally recommended solution. Contrary to both Norwegian recommendations and previous studies, a 5 mm joint is found to lead in the most water to interior side of the panels. The only tested joint solution that yielded no water intrusion is the h-profile, which is therefore suggested to be the optimal solution. The T2-profile yielded less water intrusion than the T1-profile, but the performance of T-profiles is highly dependent on their mounting and placement within the joints. U-battens as a protection measure are not recommended due to the high risk of water intrusion to the wind barrier caused by splashing droplets. Gaskets as a protection measure causes increased water intrusion compared to solutions without a gasket. Bevelled joints are a recommendable solution if profiles cannot be used. The larger the angle, the more watertight the joint, but fragility may become a practical challenge. A top-and-bottom-bevelled joint was found to be the most watertight joint solution, second only to the h-profile.

Acknowledgments: The authors would like to extend special thanks to CAD operator Remy Eik for assisting with illustrations and to Egil Rognvik, Stig Roar Rudolfsen, Øystein Holmberget and Ole Aunrønning for support with the laboratory work. Additionally, a thank you is extended to professor Claire Armstrong at UiT for extensive proofreading.

Author Contributions: Conceptualization, S.G. and T.K.; methodology, E.A.S., M.H.S., S.G., and T.K.; validation, T.K.; formal analysis, E.A.S. and M.H.S.; investigation, E.A.S. and M.H.S.; resources, T.K.; data curation, E.A.S. and M.H.S.; writing—original draft preparation, E.A.S. and M.H.S.; writing—

review and editing, E.A.S., M.H.S., and E.A.; visualization, E.A.S. and M.H.S.; supervision, E.A. and T.K.; project administration, T.K.; funding acquisition, T.K. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the Research Council of Norway (Grant No 237859) and several partners through the Centre for Research-based Innovation "Klima 2050" (see www.klima2050.no).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Edvardsen, I. E.; Ramstad, K. I.: *Trehus*, 4th ed.; SINTEF akademiske forlag: Oslo, Norway, 2018.ISBN: 978-82-536-0919
2. Lisø, K.R. *Building Envelope Performance Assessments in Harsh Climates: Methods for Geographically Dependent Design*. Doctoral Thesis, Norwegian University of Science and Technology: Trondheim, Norway, **2006**:185.
3. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Pachauri, R.K., Mayer, L., Intergovernmental Panel on Climate Change, Eds.; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2015; ISBN 978-92-9169-143-2.
4. IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, **2021** doi:10.1017/9781009157896.
5. Hanssen-Bauer, I.; Drange, H.; Førland, E.J.; Roald, L.A.; Børsheim, K.Y.; Hisdal, H.; Lawrence, D.; Nesje, A.; Sandven, S.; Sorteberg, A. *Klima i Norge 2100—Kunnskapsgrunnlag for klimatilpasning oppdatert i 2015*; Norwegian Environmental Agency/Norwegian Climate Service Center: Oslo, Norway, **2015**.
6. Grynning, S.; Gradeci, K.; Gaarder, J.E.; Time, B.; Lohne, J.; Kvande, T. Climate Adaptation in Maintenance Operation and Management of Buildings. *Buildings* **2020**, *10*, 107, doi:10.3390/buildings10060107.
7. Flæte, O.; Bardalen, A.; Gjærum, I.; Nyeggen, E.; Petkovic, G.; Aanestad, J. *Adapting to a changing climate - Norway's vulnerability and the need to adapt to the impacts of climate change (in Norwegian); Norwegian ministry of the environment.* Official Norwegian Reports NOU 2010:10: Oslo, Norway, 2010.
8. Lisø, K.R.; Kvande, T.; Time, B. Climate Adaptation Framework for Moisture-Resilient Buildings in Norway. *Energy Procedia* **2017**, *132*, 628–633, doi:10.1016/j.egypro.2017.09.698.
9. Recatala, M.A.; Morales, S.G.; Van Den Bossche, N. Experimental Assessment of Rainwater Management of a Ventilated Façade. *J Build Phys* **2018**, *42*, 38–67. doi:10.1177/1744259117719077.
10. Recatala, M.A. ; Morales, S. ; Van den Bossche, N. (2015) Rain infiltration mechanisms in ventilated façades: literature review, case studies, understanding common practice flaws. In: *Proceedings of the 1st international symposium on building pathology (ISBP 2015*), Porto, 24–27 March, p. 659. Porto: FEUP.
11. Bøhlerengen, T.; Rolstad, A.N.; Gustavsen, A.; Einstabland, H.; Meløysund, V. Tightening Against Rain and Wind for Facades—Experience from Practice. In: *Proceedings of the 7th Symposium on Building Physics in the Nordic Countries*: Reykjavik, Iceland, June 13-15, 2008.
12. Geving,S. Kledningsplater til besvær. *Byggfakta* **2022**, *2*,52-54.
13. Ulvnes, K.; Cadamarteri, F. Må fjerne opptil 50 plater etter funn av råte. *adressa.no* 2020. Accessed: 2022-05-27.
14. Thue, J. V. (2016) Bygningsfysikk. 1. red. Trondheim: Fagbokforlaget.
15. Kvande, T., *Totrinnstetning mot slagregn på fasader. Luftede kledninger og fuger.* Byggforskserien 542.003, SINTEF Community, **2013**.

16. Ingebretsen, S.B; Andenæs, E; Kvande, T: Microclimate of Air Cavities in Ventilated Roof and Façade Systems in Nordic Climates. *Buildings* **2022**, *12*, 683; doi.org/10.3390/buildings12050683, ISSN 2075-5309
17. Geving, S. *Praktisk bygningsfysikk*, 1st ed.; Fagbokforlaget: Bergen, Norway, 2021. ISBN: 978-82-450-2801-0
18. Gaarder, J. E., *Utvendig kledning med plane plater*. Byggforskserien 542.502, SINTEF Community, **2019**.
19. Gaarder, J. E., *Fasadekledning av metall.* Byggforskserien 542.201, SINTEF Community, **2019**.
20. Bunkholt, N. S.; Time, B.; Kvande, T. *Luftede kledninger. Anbefalinger for klimatilpasning.* SINTEF Community: Trondheim, Norway, 2021.
21. Mo, B.H.; Lid, H.S. Slagregninntrenging i horisontale fuger på fasader med plane plater. M.Sc. thesis, Norwegian University of Science and Technology: Trondheim, Norway, 2020.
22. Blocken, B.; Derome, D. ; Carmeliet, J. Rainwater runoff from building facades: A review. *Build Environ* **2013** *60*, 339-361. doi:/10.1016/j.buildenv.2012.10.008
23. Blocken, B.; Carmeliet, J. (2006) On the accuracy of wind-driven rain measurements on buildings *Build Environ*, 41 (12), 1798-1810. doi:10.1016/j.buildenv.2005.07.022
24. Abuku, M.; Janssen, H.; Poesen, J.; Roels,S. Impact, absorption and evaporation of raindrops on building facades. *Build Environ* **2009**, *44*, 113–124. doi:/10.1016/j.buildenv.2008.02.001
25. Park, C.; Park, J.; Kim, N.; Kim, Y. Modeling Water Flow on Façade. *Autom. Constr.* **2018**, *93*, 265–279. doi:/10.1016/j.autcon.2018.05.021
26. Bielek, M. (1977) The main principles of water movement on the wall surfaces of building of various roughnesses. *RILEM/ASTM/CIB symposium on evaluation of the performance of external vertical surfaces of buildings. Otaniemi, Espoo, Finland: August 28-31 and September 1-2, 1977*, vol. 1. pp.77-96.
27. Robinson,G.; Baker, M.C. (1975) Wind-driven rain and buildings Technical paper No. 445 Division of Building Research, National Research Council, Ottawa, Canada
28. Birkeland, (1966), 'General Report on Rain Penetration', Norwegian Building Research Institute p. 14
29. Van den Bossche, N *Watertightness of building components: principles, testing and design guidelines.* PhD Thesis, University of Gent, Gent, **2013**.
30. Garden G.K. Rain Penetration and its Control. *Canadian Building Digest*, Division of Building Research, National Research Council of Canada: Ottwawa, Canada, 1963 pp. 401–404. doi:10.4224/40000854
31. Chew, M.Y.L. A modified on-site water chamber tester for masonry walls. *Constr Build Mater 2001 15*, 329–337. doi:/10.1016/S0950-0618(01)00011-3
32. Bassett, M. and Overton, G. Measuring the Weathertight Performance of Flashings. *Buildings* **2015**, *5*, 130-148. doi:/10.3390/buildings5010130
33. Isaksen, T. *Åpne fuger i utvendige kledninger?*. Norges Byggforskningsinstitutt: Oslo, Norway, 1966.
34. Isaksen, T. *Fugeutforming og slagregn-gjennongang*. Norges Byggforskningsinstitutt: Oslo, Norway, 1964.
35. Dordá, P. H.; Pitarch A. M. R.; Escrig, A. C.; Gurrea, L. M. Water penetration into ventilated facade joints. Universitat Jaume I: Castellón, Spain, 2010.
36. Mas, Á.; Gutiérrez, J.; Gil, E.;Gil, A.; Galvañ, V. Design and construction recommendations to improve impermeability in rainscreen walls built with natural stone coverings. *Constr Build Mater* **2011**, *25*, 1753-1761. doi:/10.1016/j.conbuildmat.2010.11.091
37. Blocken,B.; Carmeliet, J. A simplified numerical model for rainwater runoff on building facades: possibilities and limitations *Build. Environ.* **2012**, *53*, 59-73. doi:/10.1016/j.buildenv.2012.01.010
38. Blocken, B.;Carmeliet, J. (2004) A review of wind-driven rain research in building science. *J. Wind Eng. Ind. Aerodyn.* **2004**, *92(13)*, 1079-1130. doi:/10.1016/j.jweia.2004.06.003
39. Bishop, D.; Webster,CJD; Herbert, MRM. (1968) The performance of drained joints. Paper no. 64c, CIB report no. 11 January 1968.
40. Herbert, M.R.M.; Harrison, H.W. New ways with weatherproof joints. Watford: Building Research Establishment, 1974.
41. Fernández, M. J. Study of influence of wind pressure and rain conditions in rain screen walls. *Struct. Surv* **2010**, *28*, 46-52. doi:/10.1108/02630801011040851
42. Stagrum, A.E; Andenæs, E; Kvande, T; Lohne, J: Climate Change Adaptation Measures for Buildings—A Scoping Review. *Sustainability* **2020**, *12*, 1721. doi:10.3390/su12051721

43. Arksey, H.;O'Malley L Scoping studies: Towards a methodological framework. *Int. J. Soc. Res. Methodol.***2005**, *8(1)*, 19–32. doi:/10.1080/1364557032000119616
44. Wohlin, C. Guidelines for Snowballing in Systematic Literature Studies and a Replication in Software Engineering. *In Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering—EASE '14*; ACM Press: London, UK, 2014; pp. 1–10.
45. NS-EN 1027:2016 *Windows and doors - Water tightness - Test method.* Standards Norway, **2016**

B Article to Byggeindustrien

In this appendix the article "Slik gjør vi åpne fuger regntette" is presented. The article is published in Byggeindustriene nr. 09-2022 in the column "Fra ekspertene: NTNU". Author contributions are attached.

Forfatterbidrag

Bekreftelse på forfatterbidrag

Eva Armstrong Støver, Marte Haugen Sundsøy og Erlend Andenæs

Slik gjør vi åpne fuger regntette

«Fra ekspertene: NTNU» i Byggeindustrien nr. 09-2022

Institutt for bygg- og miljøteknikk,
Norges teknisk-naturvitenskapelige universitet (NTNU)

www.ntnu.no

INGRESS: *Fasadekledning med plane plater utføres av estetiske årsaker gjerne med åpne horisontale fuger. Slik utførelse kan føre til at mye regnvann ledes inn bak fasadesplatene. Derfor anbefaler Byggforskserien bruk av fugeprofiler. Våre laboratorieforsøk viser imidlertid at effektiviteten til fugeprofilene er sterkt avhengig av monteringen, samt hvilke profiler som benyttes. En alternativ løsning for å hindre regninntrenging er å skråskjære fasadeplatene.*

Innlegget er skrevet av Eva Armstrong Støver og Marte Haugen Sundsøy en del av deres masteroppgave, med veiledning fra Erlend Andenæs. Innlegget presenterer hovedfunn fra laboratoriestudien.

Eva Armstrong Støver | Marte Haugen Sundsøy | Erlend Andenæs

Slik gjør vi åpne fuger regntette

Fasadekledning med plane plater utføres av estetiske årsaker gjerne med åpne horisontale fuger. Slik utførelse kan føre til at mye regnvann ledes inn bak fasadesplatene. Derfor anbefaler Byggforskserien bruk av fugeprofiler. Våre laboratorieforsøk viser imidlertid at effektiviteten til fugeprofilene er sterkt avhengig av monteringen, samt hvilke profiler som benyttes. En alternativ løsning for å hindre regninntrenging er å skråskjære fasadeplatene.

Eva Armstrong Støver, Marte Haugen Sundsøy og Erlend Andenæs
Institutt for bygg- og miljøteknikk

Eva Armstrong Støver kontrollerer innretningen for oppsamling av vann som renner ned på baksiden av fasadeplatene under regnforsøkene. *Foto: Anne-Line Bakken.*

Plane fasadeplater av polymerkompositt, høytrykkslaminat og fibersement er vanlig utvendig kledning på større bygninger. For å gi rom for temperatur- og fuktbevegelser er det anbefalt at platene monteres med en fugebredde på mellom 5 og 10 mm. De vertikale fugene er relativt vanntette siden de utføres med vertikale lekter og gummipakning, mens de horisontale fugene mangler denne understøttingen og utføres ofte som åpne fuger.

Regnforsøk

En konsekvens av å ha åpne horisontale fuger er at vindsperren får en større påkjenning i form av UV-stråling og regnvann. Byggforskserien anbefaler å benytte fugeprofiler for å tette de horisontale fugene, men disse profilenes effektivitet mot regninntrenging er lite testet. I Klima 2050 har vi derfor regntestet tre ulike fugeprofiler i kombinasjon med fem ulike fasadeplater.

Vi har også sett på hvordan skråskjæring av fasadeplatene kan påvirke regninntrengingen. Tre ulike skråskårede vinkler er testet: 15°, 30° og 45°. Både fugeutforminger med kun skråskåret underkant og med både skråskåret under- og overkant ble testet.

Effekt av horisontale fugeprofiler

I 2020 testet masterstudentene Bendik Haga Mo og Henrik Sindre Lid regninntrenging med fugeprofiler. De monterte fugeprofilene var sentrert i fugen slik vist i figuren. Resultatene fra forsøkene viste at h-profilen gir helt regntett fuge. Begge T-profilene førte til mye regninntrenging. I flere tilfeller ledet de mer vann inn enn når det ikke var benyttet fugeprofiler.

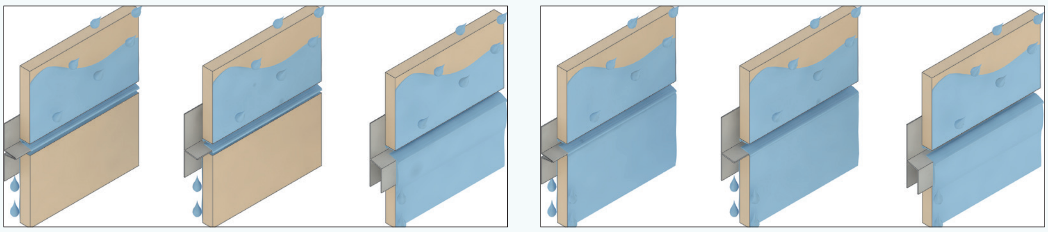
Forsøk utført i våres bekrefter at h-profilene stopper all regninntrenging. I vårt forsøk med T-profilene monterte vi dem med press ned mot underliggende plate, noe som reduserte regninntrengingen betydelig. Effekten var størst for T2-profilen. Ved slik montering av T-profilene er det større sannsynlighet for at vannet renner over utstikkene og ut, i stedet for å bli ledet inn via utstikkene, se figuren.

T2-profilen gav mindre regninntrenging enn T1 fordi T1-profilen ikke har et utstikk som kan presses helt ned mot nedre kant. Resultatene antyder dessuten at lengden på profilutstikket påvirker regninntrengingen. Dersom utstikket er kortere enn platebredden, kan dette føre til mer regninntrenging da vannet enklere blir ledet inn under profilen.

Effekt av skråskjæring

Regnforsøkene viser at skråskjæring hindrer vanninntrenging. For plater med skråskåret underkant gir skråskjæringa en dryppkant for nedsildrende vann. Effekten øker med økende vinkel på skråskjæringen. En ytterligere forbedret beskyttelse får vi ved å skråskjære både under- og overkant av platene siden regnvann som kommer inn i fugen lettere renner ut og fugen blir mindre sårbar for at vann spruter inn til vindsperren.

Ulempene med skråskårede plater er at de blir vanskeligere å håndtere og mer sensitive for brekkasje i kantene. I tillegg er det behov for at skråskjæringen blir utført av plateleverandøren, da det er tidkrevende og utfordrende å skråskjære platekantene på byggeplass.



Sentrisk montering av de T-formede profilene (T1 til venstre og T2 i midten), slik vist øverst, gjør at det meste av regnvannet ledes inn bak fasadeplatene. Montering av profilene med press ned mot underliggende plate, slik vist nederst, hindrer vannet å renne inn. *Illustrasjon: SINTEF*

C Details - Drainage System

Figure C1: Hole with a diameter of 16 mm drilled through the Lexan board. The hole is drilled 40 mm from the left batten and 220 mm from the bottom horizontal batten. This ensures that the gutter is below the second joint. Four holes in total were drilled.

Figure C2: Tape placement for gutter system on Lexan board. Double-sided tape is used.

Figure C3: Closeup of a sleeve placed at the bottom of the gutter with a tube pulled through. The perimeter of the sleeve is sealed with aluminium tape.

Figure C4: To avoid water intrusion behind or on the outside of the gutter system the top of the gutter is taped with aluminium tape and the sides are sealed with a waterproof sealant.

Figure C5: After a test measurement the gutters were improved by cutting them so that the edges did not touch the panels, and thereby get more water than they should.

Figure C6: The water in the gutters were led via tubes to buckets, and then measured with measuring cups.

Figure C7: The foil is cut leaving a rectangle with a triangle cutout.

Figure C8: The foil is folded to get a double slant that leads to the center.

Figure C9: The foil is taped with aluminium tape on the outside and inside.

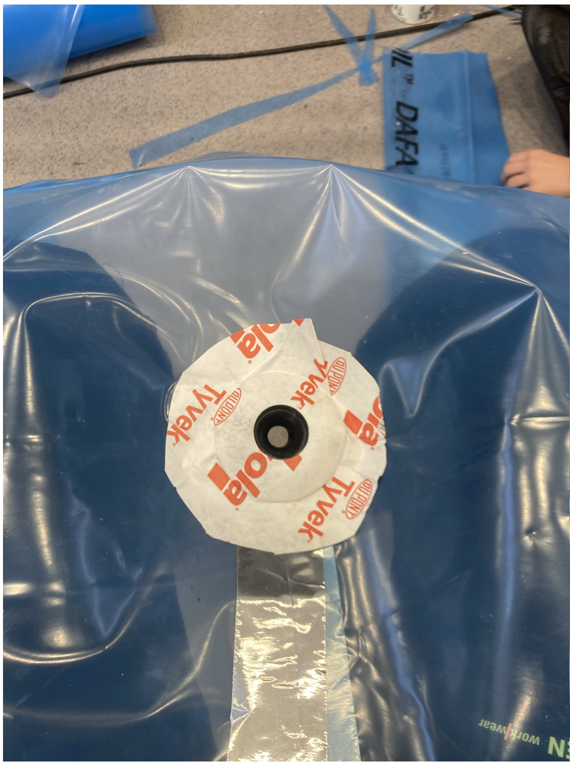


Figure C10: The tape connected to the sleeve was cut into a circular shape, instead of the original square.

Figure C11: Aluminium tape is taped over the sleeve tape to ensure watertightness.

Figure C12: The foils were then cut and trimmed to a fitting shape. The sides of the gutter was ensured watertight by folding them behind and taping with aluminium tape

Figure C13: The edges are taped with aluminium foil to make the edges stiffer.

Figure C14: A tube was pulled through the sleeve and fastened with tape.

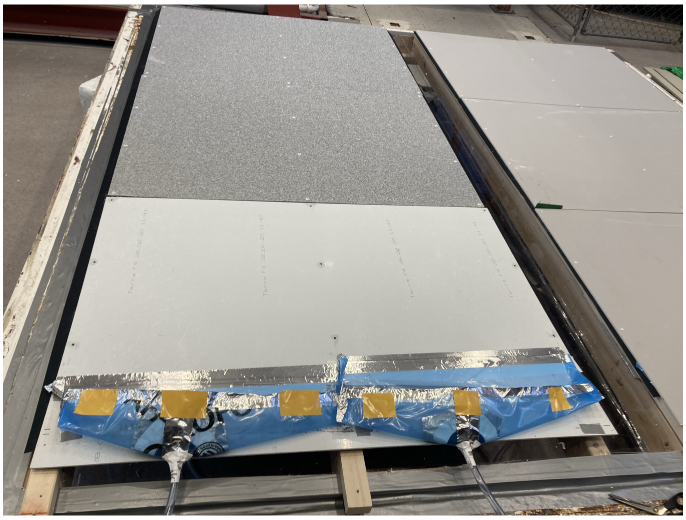


Figure C15: To avoid water intrusion behind the gutter system the top of the gutter is taped with aluminium tape. Double-sided tape is fastened to the "front" of the gutters.

Figure C16: After the test rig is inserted in the driving rain apparatus the double-sided tape is fastened to the Lexan board.

Figure C17: If the gutter had any "ruffles" the water could bounce off and hit the Lexan board instead of going into the gutter.

D Test Program and Measurements

Test section number	Test number	Material	Air cavity width [mm]	Joint width [mm]	Joint profile	Other parameters	Bevelled joint	Bevelled angle	Water on interior side of panels [mL]	Percent of total water sprayed (panels) [%]	Water on wind barrier [mL]	Percent of total water sprayed (wind barrier) [%]
1	1	Glass Fiber Smooth	30	3	-	-	-	-	2000	33 %	TLM	-
2	2	Glass Fiber Rough	30	3	-	-	-	-	330	6 %	TLM	-
1	3	Glass Fiber Smooth	30	3	-	-	-	-	2250	38 %	TLM	-
2	4	Glass Fiber Rough	30	3	-	-	-	-	400	7 %	TLM	-
1	5	Glass Fiber Smooth	30	3	-	-	-	-	2200	37 %	TLM	--
2	6	Glass Fiber Rough	30	3	-	-	-	-	430	7 %	TLM	-
1	7	Glass Fiber Smooth	30	5	-	-	-	-	3600	60 %	90	1,50 %
2	8	Glass Fiber Rough	30	5	-	-	-	-	1500	25 %	50	0,80 %
1	9	Glass Fiber Smooth	30	5	-	-	-	-	3500	58 %	75	1,30 %
2	10	Glass Fiber Rough	30	5	-	-	-	-	1500	25 %	40	0,70 %
1	11	Glass Fiber Smooth	30	5	-	-	-	-	3500	58 %	90	1,50 %
2	12	Glass Fiber Rough	30	5	-	-	-	-	1400	23 %	40	0,70 %
1	13	Glass Fiber Smooth	30	8	-	-	-	-	3050	51 %	400	6,70 %
2	14	Glass Fiber Rough	30	8	-	-	-	-	1900	32 %	90	1,50 %
1	15	Glass Fiber Smooth	30	8	-	-	-	-	2800	47 %	360	6,00 %
2	16	Glass Fiber Rough	30	8	-	-	-	-	1800	30 %	100	1,70 %
1	17	Glass Fiber Smooth	30	8	-	-	-	-	2700	45 %	500	8,30 %
2	18	Glass Fiber Rough	30	8	-	-	-	-	1800	30 %	100	1,70 %
1	19	Glass Fiber Smooth	30	5	T1	-	-	-	1800	30 %	0	0,00 %
2	20	Glass Fiber Rough	30	5	T1	-	-	-	700	12 %	TLM	-
1	21	Glass Fiber Smooth	30	5	T1	-	-	-	1700	28 %	0	0,00 %
2	22	Glass Fiber Rough	30	5	T1	-	-	-	650	11 %	0	0,00 %
1	23	Glass Fiber Smooth	30	5	T1	-	-	-	1750	29 %	0	0,00 %
2	24	Glass Fiber Rough	30	5	T1	-	-	-	700	12 %	0	0,00 %
1	25	Glass Fiber Smooth	30	5	h	-	-	-	0	0 %	0	0,00 %
2	26	Glass Fiber Rough	30	5	h	-	-	-	0	0 %	0	0,00 %
1	27	Glass Fiber Smooth	30	5	h	-	-	-	0	0 %	0	0,00 %
2	28	Glass Fiber Rough	30	5	h	-	-	-	0	0 %	0	0,00 %
1	29	Glass Fiber Smooth	30	5	h	-	-	-	0	0 %	0	0,00 %
2	30	Glass Fiber Rough	30	5	h	-	-	-	0	0 %	0	0,00 %
1	31	Glass Fiber Smooth	30	5	T2	-	-	-	110	2 %	0	0,00 %
2	32	Glass Fiber Rough	30	5	T2	-	-	-	550	9 %	0	0,00 %
1	33	Glass Fiber Smooth	30	5	T2	-	-	-	95	2 %	0	0,00 %
2	34	Glass Fiber Rough	30	5	T2	-	-	-	450	8 %	0	0,00 %
1	35	Glass Fiber Smooth	30	5	T2	-	-	-	95	2 %	0	0,00 %
2	36	Glass Fiber Rough	30	5	T2	-	-	-	550	9 %	0	0,00 %
1	37	Glass Fiber Smooth	30	5	-	Sealed Top Joint	-	-	3300	55 %	TLM	-
2	38	Glass Fiber Rough	30	5	-	Sealed Top Joint	-	-	2000	33 %	TLM	-
1	39	Glass Fiber Smooth	30	5	-	Sealed Top Joint	-	-	3250	54 %	TLM	-
2	40	Glass Fiber Rough	30	5	-	Sealed Top Joint	-	-	2100	35 %	20	0,30 %
1	41	Glass Fiber Smooth	30	5	-	Sealed Top Joint	-	-	3350	56 %	TLM	-
2	42	Glass Fiber Rough	30	5	-	Sealed Top Joint	-	-	2100	35 %	30	0,50 %
1	43	Fiber Cement Grey	30	3	-	-	-	-	600	10 %	TLM	-
2	44	Fiber Cement White	30	3	-	-	-	-	1550	26 %	TLM	-
1	45	Fiber Cement Grey	30	3	-	-	-	-	600	10 %	TLM	-
2	46	Fiber Cement White	30	3	-	-	-	-	1600	27 %	TLM	-
1	47	Fiber Cement Grey	30	3	-	-	-	-	450	8 %	TLM	-
2	48	Fiber Cement White	30	3	-	-	-	-	1600	27 %	TLM	-
1	49	Fiber Cement Grey	30	5	-	-	-	-	1750	29 %	120	2,00 %
2	50	Fiber Cement White	30	5	-	-	-	-	1600	27 %	70	1,20 %
1	51	Fiber Cement Grey	30	5	-	-	-	-	1900	32 %	140	2,30 %
2	52	Fiber Cement White	30	5	-	-	-	-	2000	33 %	80	1,30 %
1	53	Fiber Cement Grey	30	5	-	-	-	-	1650	28 %	160	2,70 %
2	54	Fiber Cement White	30	5	-	-	-	-	1700	28 %	80	1,30 %
1	55	Fiber Cement Grey	30	5	-	-	-	-	1800	30 %	90	1,50 %
2	56	Fiber Cement White	30	5	-	-	-	-	1600	27 %	70	1,20 %
1	57	Fiber Cement Grey	30	5	-	-	-	-	2450	41 %	80	1,30 %
2	58	Fiber Cement White	30	5	-	-	-	-	2100	35 %	50	0,80 %
1	59	Fiber Cement Grey	30	5	-	-	-	-	2150	36 %	80	1,30 %
2	60	Fiber Cement White	30	5	-	-	-	-	1800	30 %	50	0,80 %
1	61	Fiber Cement Grey	30	5	-	-	-	-	2000	33 %	60	1,00 %
2	62	Fiber Cement White	30	5	-	-	-	-	2000	33 %	40	0,70 %

1	63	Fiber Cement Grey	30	5	-	-	-	-	2050	34 %	50	0,80 %
2	64	Fiber Cement White	30	5	-	-	-	-	1900	32 %	90	1,50 %
1	65	Fiber Cement Grey	30	5	T1	-	-	-	1950	33 %	0	0,00 %
2	66	Fiber Cement White	30	5	T1	-	-	-	2100	35 %	0	0,00 %
1	67	Fiber Cement Grey	30	5	T1	-	-	-	2250	38 %	0	0,00 %
2	68	Fiber Cement White	30	5	T1	-	-	-	2300	38 %	0	0,00 %
1	69	Fiber Cement Grey	30	5	T1	-	-	-	2350	39 %	0	0,00 %
2	70	Fiber Cement White	30	5	T1	-	-	-	2250	38 %	0	0,00 %
1	71	Fiber Cement Grey	30	5	T1	-	-	-	2150	36 %	0	0,00 %
2	72	Fiber Cement White	30	5	T1	-	-	-	2000	33 %	0	0,00 %
1	73	Fiber Cement Grey	30	5	T2	-	-	-	2050	34 %	0	0,00 %
2	74	Fiber Cement White	30	5	T2	-	-	-	300	5 %	0	0,00 %
1	75	Fiber Cement Grey	30	5	T2	-	-	-	1850	31 %	0	0,00 %
2	76	Fiber Cement White	30	5	T2	-	-	-	180	3 %	0	0,00 %
1	77	Fiber Cement Grey	30	5	T2	-	-	-	1900	32 %	0	0,00 %
2	78	Fiber Cement White	30	5	T2	-	-	-	300	5 %	0	0,00 %
1	79	Fiber Cement Grey	30	5	-	Sealed Top Joint	-	-	2800	47 %	200	3,30 %
2	80	Fiber Cement White	30	5	-	Sealed Top Joint	-	-	2100	35 %	0	0,00 %
1	81	Fiber Cement Grey	30	5	-	Sealed Top Joint	-	-	2950	49 %	230	3,80 %
2	82	Fiber Cement White	30	5	-	Sealed Top Joint	-	-	2300	38 %	0	0,00 %
1	83	Fiber Cement Grey	30	5	-	Sealed Top Joint	-	-	3100	52 %	150	2,50 %
2	84	Fiber Cement White	30	5	-	Sealed Top Joint	-	-	2400	40 %	0	0,00 %
1	85	Fiber Cement Grey	30	8	-	-	-	-	1700	28 %	220	3,70 %
2	86	Fiber Cement White	30	8	-	-	-	-	1750	29 %	80	1,30 %
1	87	Fiber Cement Grey	30	8	-	-	-	-	1600	27 %	220	3,70 %
2	88	Fiber Cement White	30	8	-	-	-	-	1700	28 %	90	1,50 %
1	89	Fiber Cement Grey	30	8	-	-	-	-	1950	33 %	190	3,20 %
2	90	Fiber Cement White	30	8	-	-	-	-	1700	28 %	90	1,50 %
1	91	Fiber Cement Grey	30	5	Gasket	-	-	-	2400	40 %	TLM	-
2	92	Fiber Cement White	30	5	Gasket	-	-	-	3400	57 %	TLM	-
1	93	Fiber Cement Grey	30	5	Gasket	-	-	-	2150	36 %	TLM	-
2	94	Fiber Cement White	30	5	Gasket	-	-	-	3350	56 %	TLM	-
1	95	Fiber Cement Grey	30	5	Gasket	-	-	-	2150	36 %	TLM	-
2	96	Fiber Cement White	30	5	Gasket	-	-	-	3500	58 %	TLM	-
1	97	Fiber Cement Grey	45	5	U	-	-	-	3850	64 %	TLM	-
2	98	Fiber Cement White	45	5	U	-	-	-	1300	22 %	TLM	-
1	99	Fiber Cement Grey	45	5	U	-	-	-	4200	70 %	0	0,00 %
2	100	Fiber Cement White	45	5	U	-	-	-	1300	22 %	0	0,00 %
1	101	Fiber Cement Grey	45	5	U	-	-	-	3800	63 %	0	0,00 %
2	102	Fiber Cement White	45	5	U	-	-	-	1400	23 %	0	0,00 %
1	103	Fiber Cement Grey	45	5	U	Gasket	-	-	1800	30 %	0	0,00 %
2	104	Fiber Cement White	45	5	U	Gasket	-	-	200	3 %	0	0,00 %
1	105	Fiber Cement Grey	45	5	U	Gasket	-	-	1700	28 %	0	0,00 %
2	106	Fiber Cement White	45	5	U	Gasket	-	-	10	0 %	0	0,00 %
1	107	Fiber Cement Grey	45	5	U	Gasket	-	-	1600	27 %	0	0,00 %
2	108	Fiber Cement White	45	5	U	Gasket	-	-	20	0 %	TLM	-
1	109	Fiber Cement Grey	45	5	U	Gasket	-	-	1550	26 %	TLM	-
2	110	Fiber Cement White	45	5	U	Gasket	-	-	30	1 %	TLM	-
1	111	Fiber Cement Grey	45	5	U	Gasket, extra FP	-	-	500	8 %	0	0,00 %
2	112	Fiber Cement White	45	5	U	Gasket, extra FP	-	-	320	5 %	TLM	-
1	113	Fiber Cement Grey	45	5	U	Gasket, extra FP	-	-	450	8 %	0	0,00 %
2	114	Fiber Cement White	45	5	U	Gasket, extra FP	-	-	350	6 %	TLM	-
1	115	Fiber Cement Grey	45	5	U	Gasket, extra FP	-	-	500	8 %	0	0,00 %
2	116	Fiber Cement White	45	5	U	Gasket, extra FP	-	-	340	6 %	TLM	-
1	117	Fiber Cement Grey	45	5	U	Extra FP	-	-	3300	55 %	TLM	-
2	118	Fiber Cement White	45	5	U	Extra FP	-	-	4200	70 %	TLM	-
1	119	Fiber Cement Grey	45	5	U	Extra FP	-	-	3400	57 %	TLM	-
2	120	Fiber Cement White	45	5	U	Extra FP	-	-	3950	66 %	TLM	-
1	121	Fiber Cement Grey	45	5	U	Extra FP	-	-	3400	57 %	TLM	-
2	122	Fiber Cement White	45	5	U	Extra FP	-	-	4100	68 %	TLM	-
1	123	Glass Fiber Smooth	45	5	U	Gasket	-	-	2350	39 %	0	0,00 %
2	124	Glass Fiber Rough	45	5	U	Gasket	-	-	730	12 %	0	0,00 %
1	125	Glass Fiber Smooth	45	5	U	Gasket	-	-	2400	40 %	0	0,00 %
2	126	Glass Fiber Rough	45	5	U	Gasket	-	-	600	10 %	0	0,00 %
1	127	Glass Fiber Smooth	45	5	U	Gasket	-	-	2600	43 %	0	0,00 %
2	128	Glass Fiber Rough	45	5	U	Gasket	-	-	450	8 %	0	0,00 %
1	129	Glass Fiber Smooth	45	5	U	Gasket, extra FP	-	-	2000	33 %	TLM	-
2	130	Glass Fiber Rough	45	5	U	Gasket, extra FP	-	-	350	6 %	0	0,00 %
1	131	Glass Fiber Smooth	45	5	U	Gasket, extra FP	-	-	2000	33 %	TLM	-

2	132	Glass Fiber Rough	45	5	U	Gasket, extra FP	-	-	400	7 %	0	**0,00 %**
1	133	Glass Fiber Smooth	45	5	U	Gasket, extra FP	-	-	2100	35 %	TLM	-
2	134	Glass Fiber Rough	45	5	U	Gasket, extra FP	-	-	375	6 %	0	**0,00 %**
1	135	Glass Fiber Smooth	45	5	U	Extra FP	-	-	4800	80 %	125	2,10 %
2	136	Glass Fiber Rough	45	5	U	Extra FP	-	-	2700	45 %	175	2,90 %
1	137	Glass Fiber Smooth	45	5	U	Extra FP	-	-	5000	83 %	125	2,10 %
2	138	Glass Fiber Rough	45	5	U	Extra FP	-	-	3050	51 %	175	2,90 %
1	139	Glass Fiber Smooth	45	5	U	Extra FP	-	-	4950	83 %	125	2,10 %
2	140	Glass Fiber Rough	45	5	U	Extra FP	-	-	2650	44 %	175	2,90 %
1	141	Glass Fiber Smooth	45	5	U	-	-	-	4150	69 %	140	2,30 %
2	142	Glass Fiber Rough	45	5	U	-	-	-	3400	57 %	380	6,30 %
1	143	Glass Fiber Smooth	45	5	U	-	-	-	4300	72 %	140	2,30 %
2	144	Glass Fiber Rough	45	5	U	-	-	-	3300	55 %	380	6,30 %
1	145	Glass Fiber Smooth	45	5	U	-	-	-	4400	73 %	140	2,30 %
2	146	Glass Fiber Rough	45	5	U	-	-	-	3200	53 %	380	6,30 %
1	147	Glass Fiber Smooth	30	5	-	-	Top Bevelled	15	1750	29 %	80	1,30 %
2	148	HPL	30	8	-	-	Top and Bottom Bevelled	45	10	0 %	20	0,30 %
1	149	Glass Fiber Smooth	30	5	-	-	Top Bevelled	15	1600	27 %	80	1,30 %
2	150	HPL	30	8	-	-	Top and Bottom Bevelled	45	10	0 %	20	0,30 %
1	151	Glass Fiber Smooth	30	5	-	-	Top Bevelled	15	1650	28 %	80	1,30 %
2	152	HPL	30	8	-	-	Top and Bottom Bevelled	45	10	0 %	20	0,30 %
2	153	HPL	30	5	-	-	Top and Bottom Bevelled	45	TLM	-	23	0,40 %
2	154	HPL	30	5	-	-	Top and Bottom Bevelled	45	TLM	-	23	0,40 %
2	155	HPL	30	5	-	-	Top and Bottom Bevelled	45	TLM	-	23	0,40 %
1	156	Glass Fiber Smooth	30	5	-	-	Top Bevelled	30	1800	30 %	150	2,50 %
2	157	HPL	30	8	-	-	Top Bevelled	45	2150	36 %	85	1,40 %
1	158	Glass Fiber Smooth	30	5	-	-	Top Bevelled	30	1900	32 %	150	2,50 %
2	159	HPL	30	8	-	-	Top Bevelled	45	2250	38 %	85	1,40 %
1	160	Glass Fiber Smooth	30	5	-	-	Top Bevelled	30	1800	30 %	150	2,50 %
2	161	HPL	30	8	-	-	Top Bevelled	45	2250	38 %	85	1,40 %
2	162	HPL	30	5	-	-	Top Bevelled	45	2150	36 %	70	1,20 %
2	163	HPL	30	5	-	-	Top Bevelled	45	2250	38 %	70	1,20 %
2	164	HPL	30	5	-	-	Top Bevelled	45	2300	38 %	70	1,20 %
1	165	Glass Fiber Smooth	30	5	-	-	Top and Bottom Bevelled	30	60	1 %	150	2,50 %
2	166	HPL	30	8	-	-	Top Bevelled	30	2800	47 %	100	1,70 %
1	167	Glass Fiber Smooth	30	5	-	-	Top and Bottom Bevelled	30	50	1 %	160	2,70 %
2	168	HPL	30	8	-	-	Top Bevelled	30	2400	40 %	100	1,70 %
1	169	Glass Fiber Smooth	30	5	-	-	Top and Bottom Bevelled	30	20	0 %	140	2,30 %

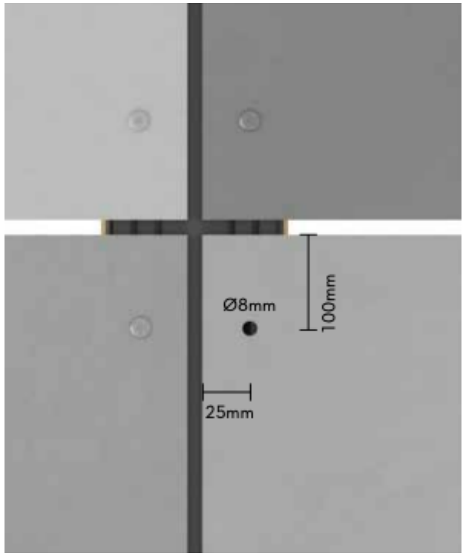
2	170	HPL	30	8	-	-	Top Bevelled	30	2450	41 %	90	1,50 %
2	171	HPL	30	5	-	-	Top Bevelled	30	1300	22 %	60	1,00 %
2	172	HPL	30	5	-	-	Top Bevelled	30	1200	20 %	100	1,70 %
2	173	HPL	30	5	-	-	Top Bevelled	30	1200	20 %	100	1,70 %
1	174	Glass Fiber Smooth	30	5	-	-	Top and Bottom Bevelled	15	350	6 %	150	2,50 %
2	175	HPL	30	8	-	-	Top Bevelled	15	2450	41 %	80	1,30 %
1	176	Glass Fiber Smooth	30	5	-	-	Top and Bottom Bevelled	15	400	7 %	150	2,50 %
2	177	HPL	30	8	-	-	Top Bevelled	15	2800	47 %	90	1,50 %
1	178	Glass Fiber Smooth	30	5	-	-	Top and Bottom Bevelled	15	350	6 %	140	2,30 %
2	179	HPL	30	8	-	-	Top Bevelled	15	2650	44 %	80	1,30 %
2	180	HPL	30	5	-	-	Top Bevelled	15	1350	23 %	50	0,80 %
2	181	HPL	30	5	-	-	Top Bevelled	15	1150		50	0,80 %
2	182	HPL	30	5	-	-	Top Bevelled	15	1250	21 %	45	0,80 %
1	183	Testing of test section									7550	126 %
2	184	HPL	30	8	-	-	-	-	3050	51 %	160	2,70 %
1	185	Testing of test section									7550	126 %
2	186	HPL	30	8	-	-	-	-	2800	47 %	190	3,20 %
1	187	Testing of test section									7750	129 %
2	188	HPL	30	8	-	-	-	-	3100	52 %	190	3,20 %
2	189	HPL	30	8	T1	-	-	-	850	14 %	0	0,00 %
2	190	HPL	30	8	T1	-	-	-	900	15 %	0	0,00 %
2	191	HPL	30	8	T1	-	-	-	950	16 %	0	0,00 %
2	192	HPL	30	8	T2	-	-	-	300	5 %	0	0,00 %
2	193	HPL	30	8	T2	-	-	-	150	3 %	0	0,00 %
2	194	HPL	30	8	T2	-	-	-	200	3 %	0	0,00 %
2	195	HPL	30	8	-	Sealed Top Joint	-	-	5000	83 %	90	1,50 %
2	196	HPL	30	8	-	Sealed Top Joint	-	-	4600	77 %	60	1,00 %
2	197	HPL	30	8	-	Sealed Top Joint	-	-	4500	75 %	80	1,30 %
2	198	HPL	30	5	-	-	-	-	3100	52 %	30	0,50 %
2	199	HPL	30	5	-	-	-	-	3050	51 %	50	0,80 %
2	200	HPL	30	5	-	-	-	-	2900	48 %	30	0,50 %
2	201	HPL	30	5	T1	-	-	-	2500	42 %	0	0,00 %
2	202	HPL	30	5	T1	-	-	-	2400	40 %	0	0,00 %
2	203	HPL	30	5	T1	-	-	-	2300	38 %	0	0,00 %
2	204	HPL	30	5	T2	-	-	-	80	1 %	0	0,00 %
2	205	HPL	30	5	T2	-	-	-	80	1 %	0	0,00 %
2	206	HPL	30	5	T2	-	-	-	50	1 %	0	0,00 %
2	207	HPL	30	5	-	Sealed Top Joint	-	-	4450	74 %	10	0,20 %
2	208	HPL	30	5	-	Sealed Top Joint	-	-	4350	73 %	10	0,20 %
2	209	HPL	30	5	-	Sealed Top Joint	-	-	4300	72 %	10	0,20 %
2	210	HPL	30	8	-	-	Top and Bottom Bevelled	15	850	14 %	70	1,20 %
2	211	HPL	30	8	-	-	Top and Bottom Bevelled	15	800	13 %	80	1,30 %
2	212	HPL	30	8	-	-	Top and Bottom Bevelled	15	800	13 %	70	1,20 %
2	213	HPL	30	5	-	-	Top and Bottom Bevelled	15	175	3 %	40	0,70 %

2	214	HPL	30	5	-	-	Top and Bottom Bevelled	15	500	8 %	50	0,80 %
2	215	HPL	30	5	-	-	Top and Bottom Bevelled	15	300	5 %	40	0,70 %
2	216	HPL	30	5			Top and Bottom Bevelled	15	350	6 %	50	0,80 %
2	217	HPL	30	8	-	-	Top and Bottom Bevelled	30	250	4 %	70	1,20 %
2	218	HPL	30	8	-	-	Top and Bottom Bevelled	30	300	5 %	70	1,20 %
2	219	HPL	30	8	-	-	Top and Bottom Bevelled	30	300	5 %	70	1,20 %
2	220	HPL	30	5	-	-	Top and Bottom Bevelled	30	90	2 %	40	0,70 %
2	221	HPL	30	5	-	-	Top and Bottom Bevelled	30	70	1 %	40	0,70 %
2	222	HPL	30	5	-	-	Top and Bottom Bevelled	30	90	2 %	40	0,70 %
2	223	Testing of test section									7900	131,70 %
2	224	Testing of test section									7650	127,50 %
2	225	Testing of test section									7750	129,20 %
2	226	Testing of test section									8050	134,20 %

E Information Regarding the Panels and Their Mounting Instructions

Figure E1: Information about the different panels and the most important information related to the mounting of the panels

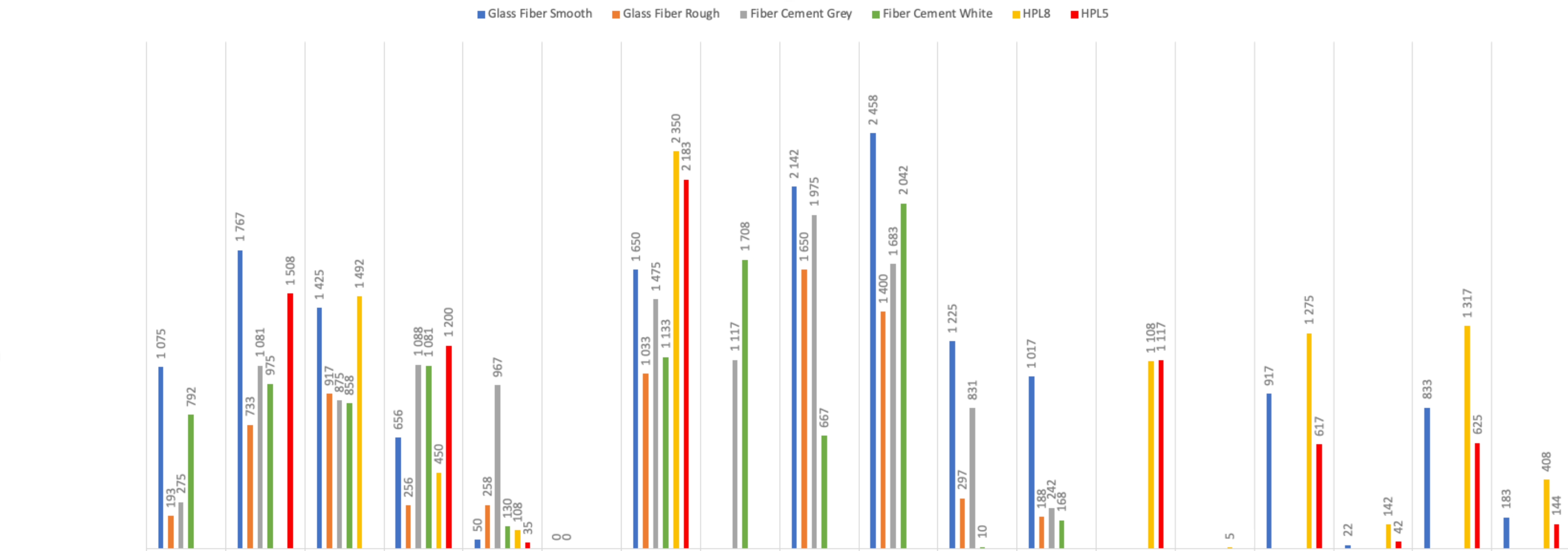
Material/Name	Supplier	Product	Surface	Dimensions [mm]	Recommended Joint Width [mm]	Type of Gasket	Predrilled holes?	Maximum Batten Distance [mm]	Maximum Screw Distance [mm]	Recommended Batten Dimension [mm]	Corner Screw Distance [mm]	Edge Screw Distance [mm]
Glass Fiber Smooth	Steni	Colour	Painted and very smooth	1195x840x6	5	Plain	Yes,Ø7mm	600	570	23x98	15-50	15-50
Glass Fiber Rough	Steni	Terra	Crushed stone and very rough	1195x840x5	4-6	Plain	Yes,Ø7mm	400	300	23x98	15	15
Fiber Cement Grey	Cembrit	Cover	Painted and smooth	1192x800x8	5	Grooves	Yes, Ø8mm	629	600	23x98	25	100
Fiber Cement White	Cembrit	Patina Original	Sandblasted and rough	1192x800x8	5	Grooves	Yes, Ø8mm	629	600	23x98	25	100
HPL	Tepo	Max Compact Exterior	Painted and very smooth	1200x800x8	8	Plain	Yes, Ø6mm	770	770	25x98	20	50-80



Example of mounting instructions and minimum distance between the predrilled holes and the edge and corner.

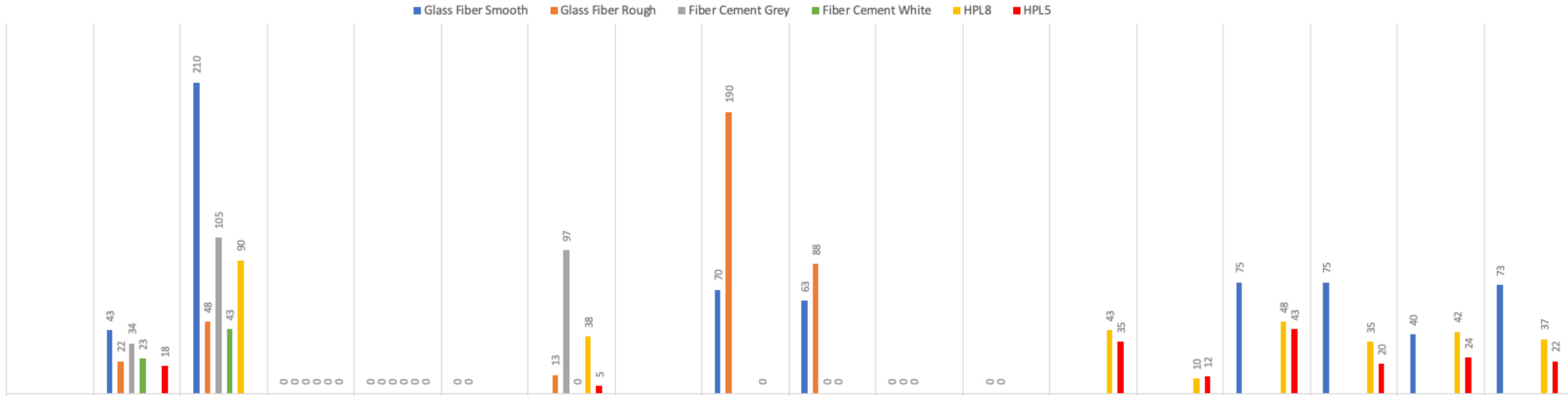
100 mm = Edge Screw Distance [mm]
Ø8mm = Predrilled Hole
25 mm = Corner Screw Distance [mm]

F Results - Water Intrusion to the Interior Side of the Panels



	3 mm	5 mm	8 mm	T1	T2	h	Sealed Top Joint	Gasket	U	U + FP	U + Gasket	U + Gasket + FP	45	Both 45	30	Both 30	15	Both 15
Glass Fiber Smooth	1 075	1 767	1 425	656	50	0	1 650		2 142	2 458	1 225	1 017			917	22	833	183
Glass Fiber Rough	193	733	917	256	258	0	1 033		1 650	1 400	297	188						
Fiber Cement Grey	275	1 081	875	1 088	967		1 475	1 117	1 975	1 683	831	242						
Fiber Cement White	792	975	858	1 081	130		1 133	1 708	667	2 042	10	168						
HPL8			1 492	450	108		2 350						1 108	5	1 275	142	1 317	408
HPL5		1 508		1 200	35		2 183						1 117	TLM	617	42	625	144

G Results - Water Intrusion to the Wind Barrier



	3 mm	5 mm	8 mm	T1	T2	h	Sealed Top Joint	Gasket	U	U + FP	U + Gasket	U + Gasket + FP	45	Both 45	30	Both 30	15	Both 15
Glass Fiber Smooth	TLM	43	210	0	0	0	TLM		70	63	0	TLM			75	75	40	73
Glass Fiber Rough	TLM	22	48	0	0	0	13		190	88	0	0						
Fiber Cement Grey	TLM	34	105	0	0		97	TLM	TLM	TLM	0	0						
Fiber Cement White	TLM	23	43	0	0		0	TLM	TLM	TLM	TLM	TLM						
HPL8			90	0	0		38		0				43	10	48	35	42	37
HPL5		18		0	0		5						35	12	43	20	24	22

H Overview of Percentage Change with Different Bevelled Joint Designs

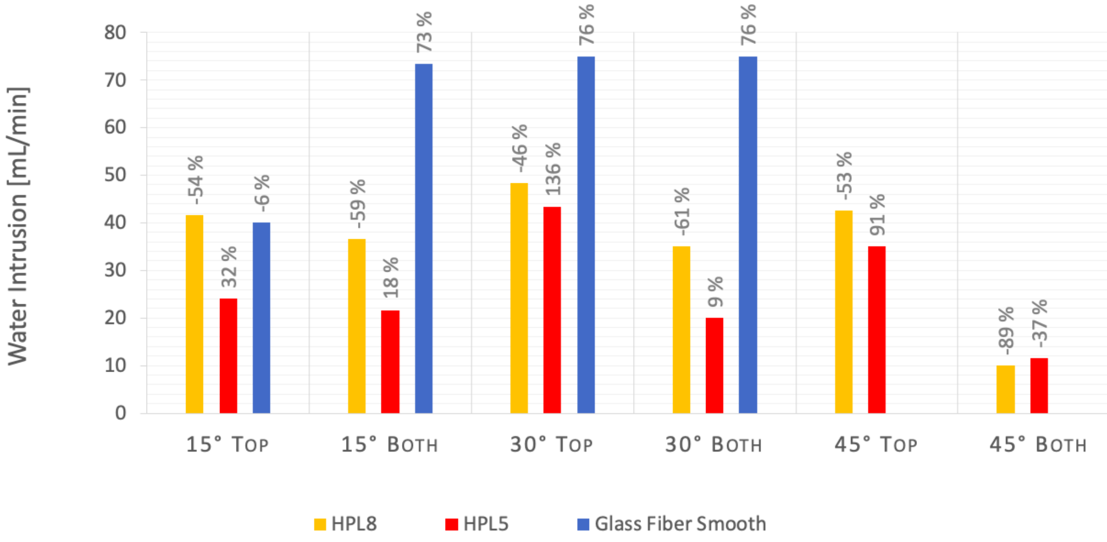


Figure H1: Water intrusion to the wind barrier for HPL and Glass Fiber Smooth with different bevelled joint designs. HPL8 has a joint width of 8 mm, while HPL5 has a joint width of 5 mm. 45 top represents a top-bevelled joint of 45°, and so forth. While 45 both represents a top-and-bottom-bevelled joint of 45°, and so forth.

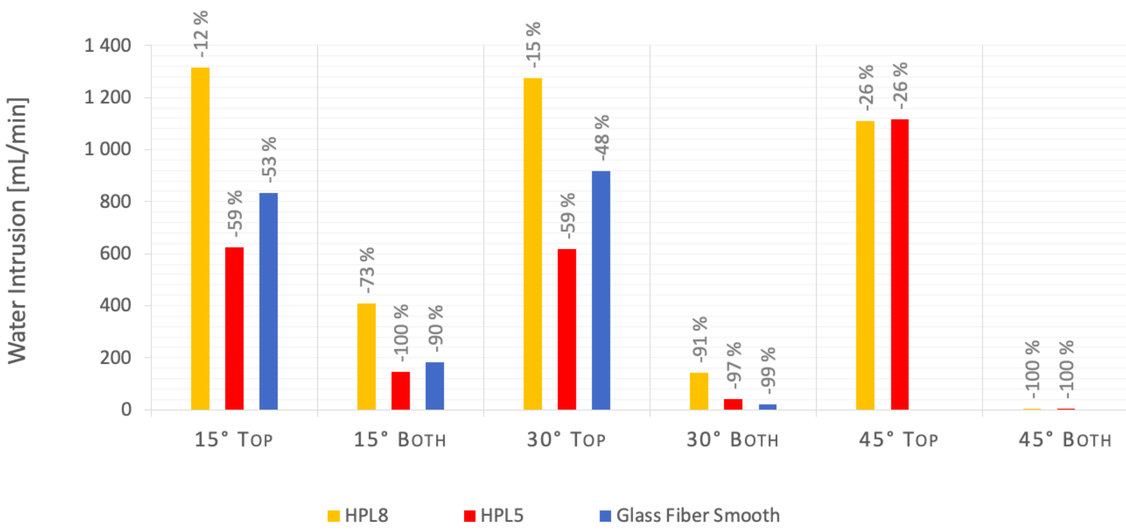


Figure H2: Water intrusion to the interior side of the HPL and Glass Fiber Smooth with different bevelled joint designs. HPL8 has a joint width of 8 mm, while HPL5 has a joint width of 5 mm. 45 top represents a top-bevelled joint of 45°, and so forth. While 45 both represents a top-and-bottom-bevelled joint of 45°, and so forth.

I Comparison of Water Intrusion with Different Joint Widths - The Mo and Lid Study (2020) and the Present Study (2022)

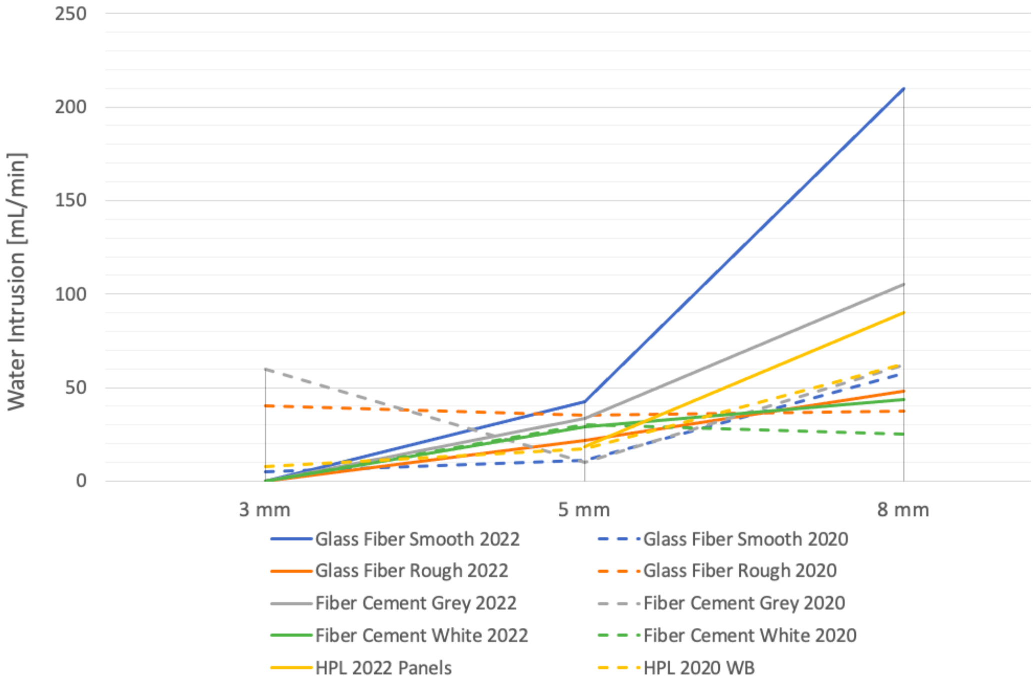


Figure I1: Water intrusion to the wind barrier for different joint widths. Compilation of this years laboratory results (2022) and Mo and Lid (2020) results (2020).

Figure I2: Water intrusion to the interior side of the panels for different joint widths. Compilation of this years laboratory results (2022) and Mo and Lid (2020) results (2020).

J Comparison of Water Intrusion with Different Joint Profiles - The Mo and Lid Study (2020) and Our Study (2022)

Figure J1: Water intrusion to the wind barrier with the two T-profiles. Comparison between this years laboratory results (2022) and Mo and Lid (2020) results (2020).

Figure J2: Water intrusion to the interior side of panels with the two T-profiles. Comparison between this years laboratory results (2022) and Mo and Lid (2020) results (2020).

Støver and Sundsøy

Rain Intrusion Through Horizontal Joints in Façade Panel Systems - Experimental Investigation

NTNU
Norwegian University of
Science and Technology