Moisture robustness of eaves solutions for ventilated roofs: Experimental studies

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Ventilated pitched wooden roofs with eaves (roof overhangs) is a common building practice in Scandinavian countries. The eaves construction should be designed such that the least possible amounts of rainwater and snow enter the ventilation aperture between the roof cladding and the underlayment. Additionally, ventilation of the roof must be ensured to promote the proper drying-out capabilities of the roof and avoid snow melt and ice formation at eaves and gutters. Small or almost nonexisting eaves are a trend in modern architecture. It is a common perception that such solutions are more vulnerable to moisture damages. The aim of the study is to experimentally investigate the moisture robustness and to find answers to how the design of eaves influences the amount of rain that is driven into the apertures in ventilated roofs. This study observed that the amount of collected water is determined by the water droplet size and wind velocity inside the air cavity. This study simulates a rain event with heavy rain intensity and strong winds. The test represents an example of a storm event with a given droplet size distribution. The results indicate that an increased pressure drop decreases the water ingress.

Introduction

Moisture related damage poses significant challenges to the Norwegian built environment. Indoor moisture, damp building structures, and precipitation contribute to the stress on a building envelope and can produce significant damages (Lisø 2006; Lisø et al. 2006; Gullbrekken et al. 2016). Climate change has been proven to increase the amount and intensity of precipitation. On average, an increase of more than 20% has been registered over the last 100 years, and an increase of an additional 20% is expected before the year 2100 according to the Intergovernmental Panel on Climate Change (IPCC) (Pachauri and Meyer 2014). This will have a large impact on the built environment of the future. Changes in temperature lead to an increase in conditions where wood materials are susceptible to degradation (Lisø and Kvande 2007) as more winter precipitation falls in the form of rain. All these changes lead to higher demands to the entire building and the building envelope parts.

Ventilated pitched wooden roofs with eaves (roof overhangs) are a common building practice in the Scandinavian countries. The eaves protect the façade from rain, wind driven rain (WDR), and snow, as well as forms the inlet for the roof ventilation aperture. The horizontal part of the eave construction should be designed such that the least possible amount of rainwater and snow enters the ventilation aperture. The horizontal part of the eave construction should be designed such that the least possible amount of rainwater and snow enters the ventilation aperture. At the same time, adequate ventilation of the roof must be ensured to promote proper drying-out capabilities of the roof, as well as avoiding snow melt and ice formation at the eaves and gutters.

The development of eave solutions in Norway is primarily based on historical building traditions, practical experience, and field investigations of unfortunate or ill-advised solutions where damages have occurred. Thus, there is a clear need to obtain further and more fundamental knowledge on the performance and durability of commonly used solutions. Small or almost nonexisting eaves are a trend in modern architecture. It is a common perception that such solutions are more vulnerable to moisture damages due to possible increase of water penetration into the roof apertures. First, the façade will be less protected against weathering from wind-driven rain (WDR). Second, the weather resilience of the detail might be impaired in a way that leads to accumulation of precipitation in the ventilation aperture (cavity system) of the roof and increased risks of leaks. Further knowledge regarding the precipitation accumulation is needed. By performing laboratory experiments, the WDR performance can be studied for different eave solutions and, hence, provide a basis for design and future recommendations.
The need for development of well-functioning building solutions for the building envelope and other parts, with respect to both strategies and solutions, was demonstrated by Lisø (2006) who found that 75% of all damages and defects in the Norwegian building stock are caused by moisture-related problems. Furthermore, they found that two-thirds of the investigated defects were related to defects in the building envelope. The study of Gullbrekken et al. (2016) added to the study of Lisø (2006) and focused on pitched roof construction. In pitched wooden roofs, 67% of the defects are caused by precipitation or indoor moisture. Use of balanced ventilation systems and airtight vapor barriers were found to be effective means to prevent moisture damage from indoor air.

Robustness and moisture resilience of building envelopes have been the focus of several previous Norwegian studies. Different wooden wall builds was studied by, for example, Gullbrekken et al. (2015) and Rüther and Time (2015). State-of-the-art in modeling of mold failure in timber facades was thoroughly investigated by Gradeci et al. (2016), and building defects and damages caused by moisture in pitched wooden roofs was investigated by Gullbrekken et al. (2016). Weather resilience of specific construction details (e.g., detailing around the eaves and other wall-roof connections) are more rarely studied and numerical simulations and failure assessments are more difficult to perform. However, they are still important to include when assessing the robustness of the building envelope as a whole.

WDR is one of the most important moisture sources with potential negative effects on the hygrothermal performance and durability of building envelopes. In order to perform an analysis of building components, knowledge regarding WDR loads is important. In this study, the performance of eave solutions exposed to WDR will be investigated and characterized using laboratory experiments.

**Background: Literature review**

A large number of studies investigated WDR and the use of experimental, semi-empirical, and numerical methods to determine how WDR affects building envelopes. Many parameters influence the amount of WDR hitting building facades such as building geometry, environment topology, wind speed, wind direction, turbulence intensity, rainfall intensity, raindrop size, and distribution, as well as rain event duration. The large number of parameters and their variability make the quantification of WDR a highly complex task. A substantial amount of research has been performed that realistically quantifies the amount of WDR impinging on building facades. A detailed (and comprehensive) review of WDR research is provided in Blocken and Carmelite (2004). The authors point out that appropriate
quantitative design data for WDR are lacking and that both numerical and semi-empirical studies could be important tools in WDR-assessments. In Blocken et al. (2011), three different models for calculation of WDR are applied to calculate WDR on the facade of a low-rise test building and a tower building for actual rain events. The models are compared with each other and with full-scale measurements. Furthermore, Kubilay et al. (2014) found good agreement between numerical results from CFD simulations and actual measurements on existing buildings. However, the study does not touch upon themes related to protruding elements such as eaves, which points to the need for more extensive laboratory testing.

However, testing methods for WDR effects on building components are often limited to a simplified application of water with a uniform and cyclic static pressure. Fasana and Nelva (2011) performed WDR experimental tests on traditional stone roofs by means of a closed wind tunnel. The performance of traditional roof coverings were measured, and the best building techniques used in the past were investigated in order to improve the efficiency and to satisfy the modern demands of architects, designers, and house owners. In Boardman and Glass (2013) a new laboratory facility is introduced that can create controlled outdoor and indoor conditions and thus help investigate the water management performance and moisture dynamics of exterior wall assemblies. The test chamber was designed to provide realistic WDR under typical conditions and supply measured data to better inform the modeling suggestion that 1% of WDR gets through the cladding. Bitsuamlak et al. (2009) introduces a full-scale testing apparatus that can be adopted for assessing WDR intrusion through the building envelope of full-scale single story building models. An assessment of six roof underlayments as a water barrier was conducted to demonstrate the application of the testing facility.

The traditional construction technique for ventilated wooden roofs uses relatively large roof overhangs. An illustrative example of such a detail is shown in Figure 1. These overhangs have two main functions related to moisture robustness: first, to reduce the amount of wind-driven rain hitting the facade and, second, to reduce the amount of wind-driven precipitation entering the ventilated air cavity between the roof underlayment and the roof cladding. The second function is the matter of investigation in this work. New trends in architecture require solutions with minimal roof overhangs and correspondingly slender design of the eaves. It is an established correlation with the design of deposition chambers in the eaves and the amount of precipitation, falling as snow, entering the ventilation cavity (Thiis et al. 2007).

Large deposition chambers, where the airflow velocity is reduced, according to the correlation given in Equations 1 and 2, have traditionally been recommended for ventilated wooden roofs. If one doubles the cross-section of a cavity, air-speed in the cavity is reduced by half, following the continuity equation (Equation 2). In theory, this will reduce the amount of precipitation transported in the airflow by reducing air-speed.

\[
q_v = \frac{V}{t} = \frac{A \cdot \Delta x}{\Delta t} \tag{1}
\]

where:
- \(q_v\) = flow per unit of time (m\(^3\)/s)
- \(V\) = volume (m\(^3\))
- \(t\) = time (s)
- \(A\) = area of cross-section (m\(^2\))
- \(\Delta x\) = difference in distance (m)
- \(\Delta t\) = difference in time (s)

\[
v_1 \cdot A_1 = v_2 \cdot A_2 \tag{2}
\]

Where:
- \(v_1\) = flow speed in cross-section 1
- \(A_1\) = area of cross-section 1
- \(v_2\) = flow speed in cross-section 2
- \(A_2\) = area of cross-section 2

The design of roofs and eaves (roof overhangs) and how they influence the quantity of WDR impinging on building facades has also been widely studied. Hershfield (1996) performed a survey of building envelope failures in the coastal climate of British Columbia. Walls with roof overhangs were shown to have fewer problems than those without overhangs. The influence of overhang size on WDR exposure of the building facade is also studied in a large scale experimental study on various buildings in the same climate (Ge and Krpan 2009). It was found that low-rise and high-rise buildings with roof overhangs reduced the WDR exposure by about 4 and 1.5 times, respectively. The influence of building geometry and architectural details such as balconies, cornices, pitched roofs, and inset corners on the wetting pattern of scaled down building models placed in a wind tunnel was studied by Inculet and Surry (1995) and Inculet (2001). Results showed that building height had a minimal influence on the wetting pattern although the intensity on the top edge likely increased with increasing height. The cornice was successful in protecting the top of a building facade just below the cornice. For a gabled roof, the rain impact on the front face was also reduced. In Blocken and Carmeliet (2005), WDR measurements on a low-rise building with a combination of a flat-roof and a sloped-roof with varying overhang widths were performed. It was found that the flat roof with a smaller overhang width caught significantly more rain than the sloped roof with a slightly larger overhang. Also, it was noticed that a mere 2-cm increase in overhang width significantly decreased the amount of WDR below it. Furthermore, the effect of eaves of various sizes on the WDR wetting of a low-rise building was investigated numerically by Foroushani et al. (2014). Various wind and rain conditions were considered using CFD-based simulations and validated against experimental and numerical data in the literature. The simulations showed that performance of the overhang was highly dependent on its size, wind-speed, and angle, while the influence of rainfall intensity was small. The effectiveness of overhangs in protecting the building façade was further investigated in Chiu et al. (2015) in an analysis of the spatial distribution.
of WDR on a building façade before and after the installation of a temporary retractable roof overhang. The building is a six-story mid-rise building with a flat roof located in Vancouver, British Columbia, Canada. The amount of WDR deposition on the façade was significantly reduced with a 1.2-m overhang, especially in the areas directly below the overhang.

Many studies investigate the exposure of walls and roofs to WDR, but few studies have investigated the exposure and theoretical performance of the designs of the eaves details as such. Thiis et al. (2007) tested the snow penetration in a ventilated roof or attic for several different eave solutions. The testing was performed in a wind tunnel in an environment of cold air and with production of artificial snow. It was found that the rate of snow penetration was largely dependent on the design of the eaves and the ventilated air-cavity in the roof. An experimental study was performed by Kvande and Lisø (2009) on various types of parapet flashing. The tests were performed in a RAWI-box (as shown in Figure 2) in accordance with principles given in NS-EN 12865:2001 (ISO 2001). The results provided a basis for the ranking different flashing designs according to their performance under WDR loads.

Thiis et al. (2007) studied different eave designs and their inlets to specify the ability to reduce snow penetration into the roof. The position and design of the ventilation openings were found to be the most important factors in reducing snow penetration. An inlet position close to the wall was found to provide approximately five times more snow concentration of the air entering the roof cavity compared to a position close to the end of the eave. Issues related to the accumulation of snow in the ventilation aperture are not addressed in this current study.

To the authors' knowledge, few studies have quantified the amount of precipitation accumulation in the ventilation apertures and eave solutions of sloped ventilated wooden roofs caused by WDR. Quantifying the amount of precipitation is important in order to provide a basis for future recommendations and design of eave solutions in general and more specific design of slender eaves. Experiments with various sizes and various designs of ventilation aperture have been provided in this study. In order to improve existing building practice and develop robust solutions for the roof-wall-connection, laboratory experiments were performed.

**Objective and scope**

The aim of the study is to experimentally investigate the moisture robustness of eave solutions and to answer the following research questions:

- How will the design of eaves influence the amount of rain that is driven into the roof underlayment and inside the ventilated air cavity of the roof aperture?
- Is the length of the roof overhang influencing the amount of rain?
- Will the ventilation aperture opening size and position affect the amount of rain entering the ventilation aperture?

The effect of critical parameters related to the design of the eaves were investigated through an experimental study. Emphasis is placed on mechanisms related to precipitation accumulation in the ventilation aperture under the roofing caused by wind and WDR.

The scope of this study is limited to the accumulation of rain in the ventilated air cavity between the roofing and underlayment roof in relation to the design of the roof eaves. Other issues, such as the accumulation of snow in the ventilation aperture, are not addressed in this current study.

**Methodology**

**Sample description**

Figure 3 shows a schematic of the test sample, which was planned, built, and mounted in the surround-template of the test apparatus (the RAWI-box is described in the test procedure section). The area of the sample exposed to the WDR had an area of 2.45 m x 2.45 m. The load bearing structure was made using a 148 x 48 mm wooden framework. The width of the roof surface was 1.8 m. Transparent acrylic boards (made of Lexan) were used as wind-barrier in the wall and to represent both the underlying roof and roof cladding. The ventilation aperture in the roof had a total height of 72 mm, as shown in Figure 3. This was achieved using 36 x 36 mm counter battens running parallel to the load bearing construction. This separated the roof surface into three chambers divided by the battens. The 36 x 36 mm tile battens were orientated perpendicular to the load bearing construction representing the furring strips for mounting of...
the roof cladding. The rain screen of the wall was made of 19 mm thick wooden cladding. The front end of the roof cladding was covered with a 200 x 19 mm wooden board (weatherboard). A standard steel gutter was placed in front of this to promote realistic airflow vectors to ensure visual inspection of any rain hitting the layers of the roof and wall. Joints between boards and other movable parts were made air-tight using adhesive tape. A de-pressurization chamber was constructed in the rear of the ventilation aperture. This chamber was used to adjust wind-speeds in the ventilation aperture of the roof and to prevent any rain not deposited on the roof surfaces from exiting the aperture. The sample was subject to pressure differences as described in Table 1.

Ten different eave-solutions were tested, as described and shown in Figure 4, Table 1, and Table 2. Detailing of the eaves was carried out in accordance with the illustrations shown in Table 1. Three different overhang lengths, d = 36, 100, and 200 mm, as shown in Figure 4 and Table 1, were tested. Various solutions for the closure of the eaves for each of the overhang lengths were also tested. Table 1 and Table 2 show illustrations and descriptions of the different sample configurations.

**Air velocity in the air cavity of the ventilation aperture**

The accumulation of water inside the air cavity will increase with increased air velocity in the ventilation aperture between the roof cladding and the underlayment.

In order to calculate the airflow $V (m^3/s)$ and corresponding air velocity inside the air cavity, we have used a calculation model of the air cavity system, as presented in Gullbrekken et al. (2017), as shown in Equations 3–11.

$$\dot{V} = \sum \Delta p \cdot \frac{1}{R}$$

$$\sum \Delta p = \Delta p_e + \Delta p_w$$

$$\Delta p_e = (\rho_{cavity} - \rho_{exterior}) \cdot g \cdot h$$

$$\Delta p_w = \frac{\Delta c_p \cdot \rho \cdot v^2}{2}$$

where $\Delta p$ is the driving pressure difference in Pa, which consists of driving forces caused by buoyancy ($\Delta p_e$) and wind ($\Delta p_w$). The driving forces from the buoyancy are provided by the temperature difference and, thereby, the difference in density, $\rho$ (kg/m$^3$) between the air inside the air cavity and the exterior air, the gravity, $g$ (m$^2$/s), and the height between the inlet and outlet of the air cavity, $h$. The driving force from buoyancy was not investigated in the study, since there is no temperature difference. The driving forces from wind are provided by the wind velocity, $v$ (m/s), density, $\rho$, and the wind pressure coefficient, $\Delta c_p$.

$$\sum R = \sum \Delta P_{friction} + \sum \Delta P_{local-losses}$$

$$\Delta P_{friction} = \frac{\lambda \cdot P_d}{D_h}$$

$$P_d = \frac{1}{2} \cdot \rho \cdot u_w^2$$

$$D_h = \frac{2 \cdot a \cdot b}{a + b}$$

**Fig. 3.** Left: Cross-section of the test sample. Top right: 3D-rendering of the sample showing the sample front. Bottom right: 3D-rendering showing the sample from the rear.
$\Delta P = \frac{\xi \cdot \rho \cdot u_m^2}{2}$ (11)

where $\Delta P$ is the sum of the pressure losses through the air cavity system consisting of friction losses and local losses. The pressure loss gradient (Pa/m), $\Delta P_{\text{friction}}$, inside a channel is dependent on the dynamic pressure $p_d$ (Pa), the hydraulic diameter $D_h$ (m), and the friction number $\lambda$ ($\cdot$).

Regarding the pressure loss by local losses $\Delta P_{\text{local-losses}}$ (Pa), $\xi$ is the minor loss coefficient ($\cdot$), $\rho$ is the density of the air (kg/m$^3$), and $u_m$ is the average velocity (m/s) in the channel. The $u_m$ is the airflow $Q$ (m$^3$/s) divided by the area of the smallest cross-section of the flow path $A$ (m$^2$). The hydraulic diameter $D_h$ (m) is shown in Equation 8 where $a$ and $b$ are the side lengths of the rectangular air channel (m).

Fig. 4. Different eaves’ overhang lengths (denoted d) will be studied.
By use of Equations 3–11, the pressure loss of the two counter battens and opening gap in the expansion room of the constructed test sample of Figure 3 was designed to correspond to a sloped (lean-too) roof with a length of 10 m, counter batten height of 30 mm, tile batten height of 36 mm with a center to center distance of 350 mm, and an inlet and outlet area of 0.050 m²/m.

In the experiments, the dynamic pressure in the aperture was measured using a pitot-tube (PT). The PT was placed toward the rear of the aperture in order to measure the area where laminar flow was most likely to occur. However, the pressure readings were highly irregular, indicating turbulent flow in this part of the aperture.

Test procedure

The measurements were carried out in the Rain and Wind apparatus (RaWi-box) in the laboratory of SINTEF and NTNU in Trondheim. Introductory calibration studies were performed in accordance with the principles provided by the standard NS-EN 12865:2001 (ISO 2001). Smaller quantities of rain than those advised in the method description were used due to limitations in the equipment. The modified procedure according to Method B, which is intended for quantitative testing, was carried out according to the procedure in Table 1 and Table 2. Test series B4 is identical to B3 except that a wire mesh covering the ventilation opening in the eave was installed. A mesh like this is usually used in real buildings to prevent insects and birds from entering the eave and roof aperture. It was added only to series B3 as it had the largest amount of water collected in the ventilation aperture.

Water was only applied in the form of driving-rain during the first calibration tests I1 and I2. For the remaining test series, both driving rain and a water mist spray was used. The total volume flow of water for the driving rain nozzles was measured at 660 l/h and 550 l/h after turning on the water-mist nozzles, for example, 110 l/h was the volume-flow applied by the water mist nozzles.

The driving rain nozzles were positioned 37 cm from and 3 cm below the outer lower edge of the weatherboard behind the rain gutter. The position was chosen such that the applied water should hit the area just over and below the edge of the weatherboard and, thus, creating the maximum moisture load possible.

Water accumulated in the ventilation aperture was collected by drilling holes next to the wind-barrier and roof underlayment joint as depicted in Figure 5. There were 3-mm high self-adhesive gaskets placed on the roof underlayment that lead the water into the drilled holes. Plastic tubing was then used to lead the water into the collection vials. The amount collected was then measured using a high precision scale. This was performed separately for each of the three chambers divided by the 36 x 36 mm counter battens.

When wind was stopped by a surface (in this case a wall), the dynamic pressure of the wind was transformed to force pressure onto the facade, F (N), as described in Equation 12.

\[
F = p_d \cdot A
\]

where \( p_d \) (Pa) is provided by Equation 7 and \( A \) is the surface area. By solving Equation 10 and assuming an air temperature of 20°C, a wind pressure of 400 Pa corresponds to an air velocity of 26 m/s. The wind speed corresponds to storm level (level 10 on the Beaufort scale; Huler 2005).

Results

Introductory and calibration measurements: I1 and I2

Prior to the actual testing, several calibration and optimization tests were carried out in order to achieve the desired water-load on the sample. The first series were conducted

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### Table 2. Test configurations used in the experimental studies.

| Test ID | Overhang length, mm | Opening, mm | dP, Pa | Duration of test, min |
|---------|---------------------|-------------|--------|----------------------|
| I1      | 36                  | 36          | 0–200  | 20                   |
| I2      | 36                  | 36          | 0–300  | 20                   |
| A1      | 36                  | 36          | 0–200  | 40                   |
| A2      | 36                  | 36          | 0–400  | 40                   |
| B1      | 100                 | 100         | 0–400  | 40                   |
| B2      | 100                 | 18          | 0–400  | 40                   |
| B3      | 100                 | 36          | 0–400  | 40                   |
| B4      | 100                 | 36          | 0–400  | 40                   |
| C1      | 200                 | 200         | 0–400  | 40                   |
| C2      | 200                 | 18          | 0–400  | 40                   |
| C3      | 200                 | 36          | 0–400  | 40                   |
| C4      | 200                 | 18          | 0–400  | 40                   |
| C5      | 200                 | 36          | 0–400  | 40                   |

Notes: Calibration test I1 has the same basic configuration as used in A1, but with driving rain application only. I2 is identical as I1, but with 300 Pa pressure difference. Test with ID B4 is identical as B3 apart from the addition of a wire mesh covering the eave-opening.

\(^a\)Identical to B3, but with wire mesh covering the opening; \(^b\)Opening in deposition chamber facing the weatherboard; \(^c\)Opening in deposition chamber facing the cladding.

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Fig. 5. The water collection system used during the experiment showing the black gaskets and the tubes that are led into the water collection vials.
According to NS-EN 12865: 2001 Method B (ISO 2001), but with smaller quantities of rain than those advised in the method description due to limitations of the equipment. Several pressure differences across the sample were tested, ranging from 200 to 400 Pa.

It was determined that the mean droplet-size of the applied water was too large for the droplets to be transported into the construction and onto the roof underlayment. This was independent of the pressure difference. Hence, water application using water-mist nozzles were used in the test series A1–C5.

**Results from test series A1–C5**

Table 3 and Figure 6 show the amounts of water collected during the test cycles. A more qualitative description of the visual observations is shown in Table 4.

**Discussion**

In this paper, the authors set out with the aim of answering the following research questions:

- How will the design of eaves influence the amount of rain that is driven onto the roof barrier under the aperture in ventilated roofs?
- Is the length of the roof overhang influencing the amounts of rain?
- Will the ventilation aperture opening size and placement affect the amounts?

The amounts of collected water in the different test series are to a large extent given by both the water droplet size as well as the wind velocity inside the air cavity. Calculations of wind velocity inside the air cavity of the test sample were carried out to ensure realistic pressure losses of the air cavity system and thereby realistic air velocities. The pressure difference of 400 Pa was necessary to transport water from the water-mist nozzle to the test sample. However, the 400 Pa pressure difference applied to the test sample corresponds to rather extreme conditions as it corresponds to a wind speed of 26 m/s, which is categorized as storm level. The pressure loss inside the air cavity system of the test sample corresponds to the pressure loss inside an air cavity beneath the roofing of a rather long sloped (lean-too) roof with typical dimension of the battens and inlet/outlet areas. Based on both the strains from the applied pressure and the corresponding pressure loss through the system the driving forces from wind can be categorized as “worst case” conditions.

During the first stages of the measurements, it was assessed that the total amount of water applied to the test sample was too low. Furthermore, it was found that the size of the water-droplets created in the driving-rain nozzles were too large to be driven into the ventilation aperture in the airflow created by the pressure difference imposed over the test sample. The situation changed when water was applied using water-mist nozzles. More water was driven into the aperture. However, no measurement of the actual droplet-size distributions was feasible to perform.

After the calibrations of air-speed in the roof aperture and the initial tests applying rain to the sample with different

**Table 3. Test configurations and measured retained amounts of water from roof underlay after 40 min of water application.**

| Test ID | Overhang length, mm | Opening, mm | Pressure difference, Pa | Water collected, mL |
|---------|----------------------|-------------|-------------------------|---------------------|
| A1      | 36                   | 36          | 200                     | –                   |
| A2      | 36                   | 36          | 400                     | 385                 |
| B1      | 100                  | 100         | 400                     | 36                  |
| B2      | 100                  | 18          | 400                     | 156                 |
| B3      | 100                  | 36          | 400                     | 728                 |
| B4\(^a\) | 100             | 36          | 400                     | 0                   |
| C1      | 200                  | 200         | 400                     | 50                  |
| C2      | 200                  | 18\(^b\)    | 400                     | 0                   |
| C3      | 200                  | 36\(^b\)    | 400                     | 32                  |
| C4      | 200                  | 18\(^b\)    | 400                     | 8                   |
| C5      | 200                  | 36\(^c\)    | 400                     | 5                   |

Note:

\(^a\)Identical to B3, but with wire mesh covering the opening;
\(^b\)Opening in deposition chamber facing the waterboard;
\(^c\)Opening in deposition chamber towards the cladding.

**Fig. 6.** Measured accumulated water in the collection system for test series A1 through C5.
methods, the amount of water collected in configurations A2 and B3 was considerably higher than for the remaining configurations. Close to 400 mL of water was collected in A2, which had a 36-mm long overhang and no weather-board covering the underside of the eave. The largest amount of water collected was 728 mL, which occurred in B3, which had a 100-mm overhang and 36-mm opening in the weather-board covering the eaves underneath. Visual observations made during the test suggest that a possible reason was that the position and size of the opening provided a particularly unfavorable airflow direction (vector) for this configuration. Large amounts of water were transported in the airstream and were deposited on the side of the roof cladding facing the ventilation aperture. The deposited water was then “dragged” along the surface until the water droplets became large enough for gravitational forces to impact the cladding with a resulting deposition on the roof underlayment. The Norwegian building design guidelines suggests using a ventilation gap in the roof aperture with a height of 40–50 mm (SINTEF 2005).

Furthermore, it was found that the solutions with a 100-mm roof overhang in general had the highest amounts of water deposition on the roof underlayment, regardless of the opening size under the eave.

A comparison of configurations C3 and C5 shows that the position of the ventilation opening in the roof overhang toward the weather board reduce the collected amount of water. For the 18-mm cavity of configuration C2 and C4, the comparable position produced a small increase in the collected amount of water. However, the measured amount of water for the C4 configuration was low. Thiis et al. (2007) also found that the position of the ventilation opening toward the weather board was effective in reducing snow penetration into the roof compared to a position close to the cladding.

A general observation was that substantial amounts of water were deposited on the roof underlayment without being collected. The slope of the roof was not steep enough for the gravitational forces to be larger than the adhesive forces. Hence, the droplets were not forced off the rear side of the cladding and onto the roof underlayment. Possible future measurements should account for this by applying a hydrophobic treatment to reduce adhesion and be better able to quantify the total amounts of water deposited on the roof underlayment.

As a final configuration, wire-mesh was added to the opening of the B3 configuration. Wire-mesh should always be used for such solutions to prevent insects and birds from entering the ventilation cavity. This configuration showed that the mesh effectively stopped any rain from entering the eave and roof aperture. The droplets were deposited into and onto the fine wire-mesh. This was the case for both the water-mist and larger water droplets. Hence, it can be assumed that a mesh like this will be effective in stopping rain with a large variation of droplet sizes and droplet size-distributions from entering the roof aperture.

### Table 4. Visual observations during the test series A1 to C5.

| Test ID | Observations |
|---------|--------------|
| A1      | - No water accumulated on the roof underlayment (RU)  
          - No water deposited on the wind barrier of the wall (e.g., on the vertical board) |
| A2      | - Rapid wetting of RU  
          - Small droplets of water transported in the airstream and deposited on the RU up to the first furring strip (30–40 cm)  
          - Water deposited on RU in large droplets 15–20 cm from eave  
          - Water running down the wall (acrylic board) |
| B1      | - Rapid accumulation of water on RU (more than for A2)  
          - A lot of water running down the wall/wind barrier  
          - Fewer small droplets deposited on RU, but deposition length the same as for A2 |
| B2      | - More and bigger droplets are transported in the airstream than for A2 and B1  
          - Deposition on cladding, but less than for A2 and B1 |
| B3      | - Similar behavior as B2, but with more rapid wetting of RU  
          - Water retained in vials after 5 minutes  
          - Water driven further along the back-side of the roof cladding than previous series |
| B4      | - Some droplets are deposited on the roof cladding and RU but no water is collected in the vials  
          - Water droplets are deposited in/on the wire mesh |
| C1      | - Some deposition on roof cladding but little is transported on to the RU  
          - Most of the water is collected in the rightmost section, some small droplets in mid-and very little in left section  
          - Some water running down the wall/wind barrier |
| C2      | - Some large droplets are deposited on the RU (8–10 cm from wall/roof joint)  
          - Some small droplets are deposited up to the first furring strip |
| C3      | - Similar behavior as for B3, but fewer droplets on underlay  
          - Some water hitting wall/wind barrier |
| C4      | - Very little water (small droplets) deposited on RU  
          - Some deposition of large droplets on RU up to approximately 5–10 cm from the wall/roof connection |
| C5      | - Similar observations as for C4 |
The measurements should also be coupled to experiments studying challenges related to snow, which might be a bigger issue. The measurements performed by Thiis et al. (2007) indicated that the snow concentration of the air entering the air channel decreased by increasing air pressure drop over the eave construction. Only rain accumulation in the ventilation aperture was studied in this paper. The objective of the project is to facilitate confident design of durable and cost-effective solutions for tall timber facades. Designs will be enabled by taking into account exposure and vulnerability of facade components and systems consistently. The results will be used as input in a risk based design tool and for assessment of building resilience and moisture robustness, which is also part of the Tall Facades project. The authors also acknowledge the Centre for Research-based Innovation “Klima 2050” for providing the necessary funding for the undertaking.

Conclusions and further work

Measurements have been carried out where investigations of how the design of eaves influences the amount of rain that is driven onto the roof barrier under the aperture in ventilated roofs. It was found that the amount of collected water in the different test series are, to a large extent, dependent on both the water droplet size as well as the wind velocity inside the air cavity. In practice, the amount of WDR hitting the facade and more specifically the area directly beneath the roof overhang is dependent on the wind speed, wind direction, rainfall intensity, raindrop size, and the rain event duration. The results from this study simulate an example of a rain event with heavy rain intensity (660 l/h) and strong winds (storm). The test represent an example of a storm event with a given droplet size distribution. Therefore, the actual amount of water collected in each of the test configurations is less interesting. However, a comparison of the amounts of water of the different test-configurations is of interest.

The results from comparing Test B1 by B2 and C2 by C3 indicate that an increased pressure drop decreases the water ingress. This is clearly demonstrated by the introduction of the wire mesh, which represents a large pressure drop. Comparing Test B4 and B3 shows that installation of the wire mesh largely decreases the measured water collection and the dynamic pressures inside the air cavity.

Furthermore, it must be noted that there are some limitations in the measurements that have been performed. There was no feasible way of controlling the droplet size distribution other than that the use of water-mist nozzles created smaller droplets than the driving rain nozzles. The amount of water applied on the sample provided for no possible adjustments. The air velocity inside the ventilation cavity was high. This was, however, necessary to induce rain penetration in the ventilation cavity. The effect of varying wind direction was not accounted for and should be included in future studies. Only rain accumulation in the ventilation aperture was studied in this paper. Future measurements should also be coupled to experiments studying challenges related to snow, which might be a bigger issue. Future studies should also include the combined effects and implications of eave-design on WDR effects on cladding. Future measurements studying real-climate performance should also be performed.

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