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Moisture robustness of eaves solutions for ventilated roofs – experimental studies

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ABSTRACT
Ventilated pitched wooden roofs with eaves (roof overhangs) is a common building practice in the Scandinavian countries. The eaves are protecting the façade from rain, wind driven rain (WDR) and snow, and it covers the roof ventilation aperture. The eaves should be designed so that the least possible amounts of rainwater and snow enters the ventilation aperture between the roof cladding- and underlayer roofing. At the same time, adequate ventilation of the roof must be ensured to promote proper drying-out capabilities of the roof and to avoid problems of snow melt and ice formation at eaves and gutters during winter season. Small or almost non-existing eaves is 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 aperture.

The aim of the study is to experimentally investigate the moisture robustness of the described risk area and to find answers to how the design of eaves influence the amount of rain that is driven on to the underlayer roofing under the aperture in ventilated roofs.

It was found that the amount of collected water in the different test series to a large extent are given by the water droplet size as well as the wind velocity inside the air cavity. The results from this study simulates an example of a rain event with heavy rain intensity and strong winds (storm). 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. Comparative tests showed that installation of a wire mesh largely decreases the measured water collection and the dynamic pressures inside the air cavity.

KEYWORDS
Roof design; eaves; robustness; precipitation, water ingress

INTRODUCTION
Moisture related damages pose significant challenges to the Norwegian built environment. Indoor moisture, damp building structures and precipitation stresses the building envelope and can provoke significant damages. 75 % of all damages and defects in the Norwegian building stock are caused by moisture related problems and 2/3 of defects are related to the building envelope (Lisø 2006). In pitched wooden roofs 67 % of the defects are caused by precipitation or indoor moisture (Gullbrekken, Kvande, 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 (Pachauri and Meyer 2014). Changes in temperature leads to an increase in conditions where wood materials are susceptible to degradation (Lisø and Kvande 2007). These changes lead to higher demands on the entire building and the building envelope parts, where mould and other biological growth is critical. A state-of-the-art in modelling of mould failure is thoroughly investigated by Gradeci et al. (Gradeci, Labonnote et al. 2016).

Ventilated pitched wooden roofs with eaves (roof overhangs) is a common building practice in the Scandinavian countries. The traditional construction technique for ventilated wooden roofs uses relatively large roof overhangs. These overhangs have two main functions related to moisture robustness; Firstly, to reduce the amount of wind-driven rain (WDR) hitting the facade and secondly to reduce the amount of wind-driven precipitation entering the ventilated air cavity between the roof underlayer and the roof cladding. WDR is one of the largest moisture sources with potential negative effects on the hygrothermal performance and durability of building envelopes. A detailed (and comprehensive) review of WDR research is given in (Blocken and Carmeliet 2004, Blocken, Abuku et al. 2011, Kubilay, Derome et al. 2014). Large deposition chambers where the air-flow velocity is reduced, have traditionally been recommended for ventilated wooden roofs (Thiis, Barfoed et al. 2007). However, new trends in architecture calls for solutions with minimal roof overhangs and slender design of the eaves. It is a common perception that such solutions are more vulnerable to moisture damages. Quantifying the amount of precipitation is important to provide a basis for future design-recommendations of moisture robust eave solutions. The design of roofs and eaves (roof overhangs) and how they influence the quantity of WDR impinging on building facades are studied in several publications (Hersels 1996, Ge and Krpan 2009, Chiu, Ge et al. 2015). However, there is a need to obtain further and more fundamental knowledge on the performance and durability of commonly used solutions, especially through experimental studies (Fasana and Nelva 2011, Boardman and Glass 2013). Some experimental studies have been carried out (Inculet and Surry 1995, Inculet 2001, Blocken and Carmeliet 2005, Kvande and Lisø 2009). To the authors' knowledge, few studies have quantified the amount of precipitation accumulation in the apertures and eaves of sloped ventilated wooden roofs caused by WDR.

The aim of the study is to experimentally investigate the moisture robustness of eaves solutions and how the design of eaves influence the amount of rain which is driven inside the ventilated air cavity of the roof aperture. Influencing factors that will be studied are; the length of the roof overhang and the ventilation aperture opening size and position.

METHODS

Test series are described in Table 1 and 2 and Figure 1. The measurements were carried out in a *Rain and Wind apparatus* in accordance with principles in NS-EN 12865:2001 (ISO 2001) method B. Smaller quantities of rain than advised in the standard were used due to limitations in the equipment. The facility is described in (Kvande and Lisø 2009). The sample exposed to WDR had an area of 2.45 m x 2.45 m. The width of the roof surface was 1.8 m. Transparent acrylic boards were used as wind-barrier in the wall and as underlying roof and roof cladding to make visual inspection easier. The front of the roof cladding was covered with a 200 x 19 mm weatherboard, with a steel gutter in front to promote realistic air-flow vectors. An expansion chamber was used to adjust wind-speeds in the roof aperture. Ten eaves-solutions with three different overhang lengths and various closure-solutions of the eaves were tested. Table 1 and 2 shows illustrations and description of the different sample configurations. Test series B4 is identical to B3 apart from a wire mesh covering the ventilation opening in the eave. A mesh like this is used to prevent insects and birds from entering the eave in real buildings. It was chosen to add this for the series with the largest amount of water collected in the aperture (B3).

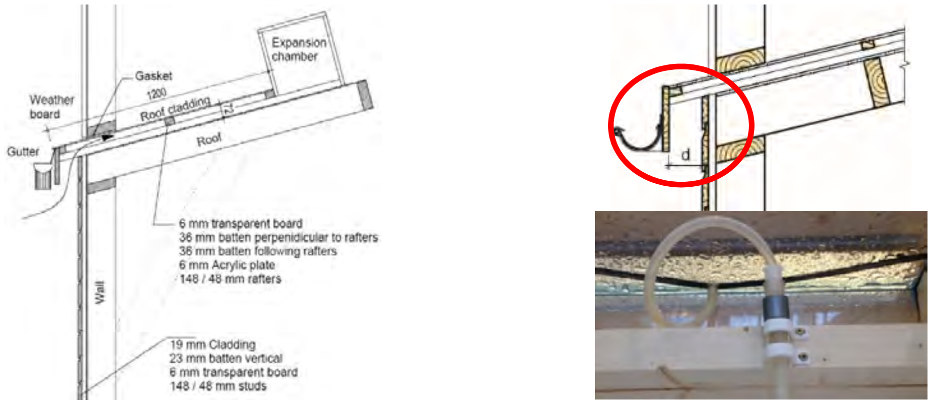


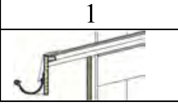
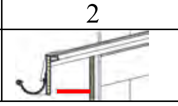
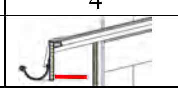
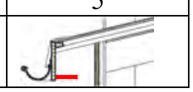
Figure 1. (left) Cross-section of the test sample. (top right) Different eaves overhang lengths (denoted d and circled in red). (bottom right) Water collection system used in the experiment.

Table 1. Test configurations. Test ID's A has 36 mm roof overhang, B has 100 mm and C has 200 mm. d = overhang length, Opening = opening size. I1 is the same as A1, but with driving rain application only. I2 is identical to I1, but w/ 300 Pa pressure difference. The Test ID numbers (1-5) aligns with weatherboard configurations presented in Table 2.

Test ID	I1	I2	A1	A2	B1	B2	B3	B4	C1	C2	C3	C4	C5
d (mm)	36	36	36	36	100	100	100	100	200	200	200	200	200
Opening (mm)	36	36	36	36	100	18	36	36	200	18*	36*	18**	36**
dP (Pa)	0 - 200	0 - 300	0 - 200	0 - 400	0 - 400	0 - 400	0 - 400	0 - 400	0 - 400	0 - 400	0 - 400	0 - 400	0 - 400
Duration (min)	20	20	40	40	40	40	40	40	40	40	40	40	40

* Opening in deposition chamber facing the weatherboard ** Opening in chamber facing cladding

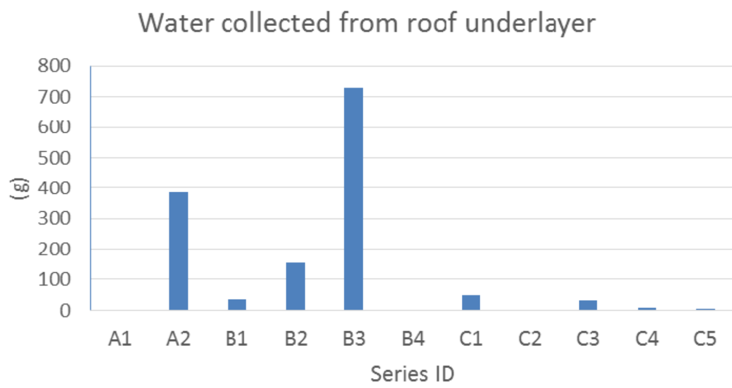
Table 2. Test series A1 to C5 overview. Weatherboard placement and configurations marked in red. Series nr (1-5) relates to the number in the Test ID series presented in Table 1.

Test series	1	2	3	4	5
Configurations A-C					

Water was applied as driving-rain only, in I1 and I2. For the remaining series, both driving rain (large droplets) and a water mist (very small droplets) spray was used. This was done to cover a larger span of droplet-sizes and, thus, to represent a wider span of likely, realistic downpour conditions. No measurement of the actual droplet-size distributions was feasible to carry out. The total volume flow of water for the driving rain nozzles was measured to 660 l/h and 550 l/h after turning on the water-mist nozzles. The nozzles were positioned to create the maximum moisture load possible. Calculations were carried out to ensure the use of realistic air velocities in the aperture. A worst-case scenario of a *storm* (level 10 on the Beaufort scale) was chosen for the experiments. This corresponds to the pressure of 400 Pa used in the experiments. This gives a resulting air velocity of 26 m/s. The dynamic pressure in the aperture was measured using a pitot-tube. The pressure readings were highly irregular, indicating turbulent flow.

RESULTS

Calibration tests were carried out to achieve the desired water-load on the sample. Several pressure differences across the sample was tested, ranging from 200 to 400 Pa. It was found that the mean droplet-size of the applied water was too large for the droplets to be transported into the aperture. This was independent of the pressure difference. Hence, water application using water-mist nozzles were used in A1-C5. Figure 2 show the amounts of water collected during the test cycles. A qualitative description of the visual observations is given in Table 3



Test ID	Water collected (g)
A1	-
A2	385
B1	36
B2	156
B3	728
B4	0
C1	50
C2	0
C3	32
C4	8
C5	5

Figure 2. Test configurations and measured retained amounts of water from roof underlay after 40 min of water application for series A1-C5

Table 3. Visual observations during the test series A1 to C5. Location of water deposition are based on visual inspections and should be treated as qualitative observations.

ID	Observations
A1	No water accumulated on the roof underlayer (RU). No water deposited on the wind barrier (WB) of the wall (e.g. on the vertical board).
A2	Rapid wetting of RU. Small droplets deposited on 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 WB
B1	Rapid accumulation of water on RU (more than for A2). A lot of water running down the WB. Fewer small droplets deposited on RU, deposition length 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 behaviour 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 on RU. Some small droplets in mid-and very little in left section. Some water running down WB.
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 behaviour as B3, but fewer droplets on RU. Some water hitting WB
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.

DISCUSSIONS

The amounts of collected water in the different test series are given by both the water droplet size as well as the air velocity inside the air cavity. The pressure difference of 400 Pa was necessary to transport water from the water-mist nozzles in through the eaves opening. Based on 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". It is not expected that temperatures (above freezing) will affect the deposition of water on roof underlayer or wind-barrier of walls.

Water amounts collected in A2 and B3 was considerably higher than for the remaining. 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.

Visual observations made during the test, suggest that a possible reason was that the position and size of the opening gave a particularly disfavourable air-flow direction (vector) for this configuration. Large amounts of water were transported in the airflow and was 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 force them of the cladding with a resulting deposition on the roof underlayer (RU). Furthermore, it was found that the solutions with a 100 mm roof overhang had the highest amounts of water deposition on the RU regardless of the opening size under the eave. The Norwegian building design guidelines suggests using a ventilation gap in the roof aperture with a height of 40-50 mm (SINTEF 2005).

C3 and C5 indicate that the placement of the ventilation opening in the eave toward the weather board reduce the amount of collected water. For the 18 mm cavity (C2 and C4) the comparable position gave little increase of the collected amount of water. The measured amount of water during C4 was rather low. Thiis, Barfoed et al. (2007) also found that position of the ventilation opening towards the weather board was effective to reduce snow penetration to the roof compared to a position close to the cladding. Thiis, Barfoed et al. (2007) also indicated that the snow concentration of the air entering the air channel decreased by increasing air pressure drop over the eaves construction Hence, the measurements must be seen in connection to snow-indraft which might be a bigger practical issue to solve.

Tests 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 is representing a large pressure drop. Comparing Test B4 and B3 shows that installation of the wire mesh decreases the measured water collection and the dynamic pressures inside the air cavity.

CONCLUSIONS

Measurements of how the design of eaves influence the amount of rain that is driven in to the ventilation aperture roofs have been carried out. The amount of water collected are given by the water droplet size and the wind velocity inside the air cavity. In practice the amount of WDR hitting the facade is dependent of wind speed, wind direction, rainfall intensity, raindrop size and the rain event duration. The results from this study simulates an example of an event with heavy rain intensity and strong winds (storm) with a given droplet size distribution. Hence, the actual amount of water collected in each of the test series are of less interest than the comparison of the amounts of water in the different series.

It can be assumed that a mesh like the one used in B4 will be effective in stopping rain with a large variation of droplet sizes and droplet size-distributions from entering the roof aperture.

There are limitations in the measurements that have been carried out. 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. Substantial amounts of water were deposited on the RU without being collected. Future measurements should take this into account. 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 eaves-design on WDR effects on cladding. Measurements studying real-climate performance should also be carried out.

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