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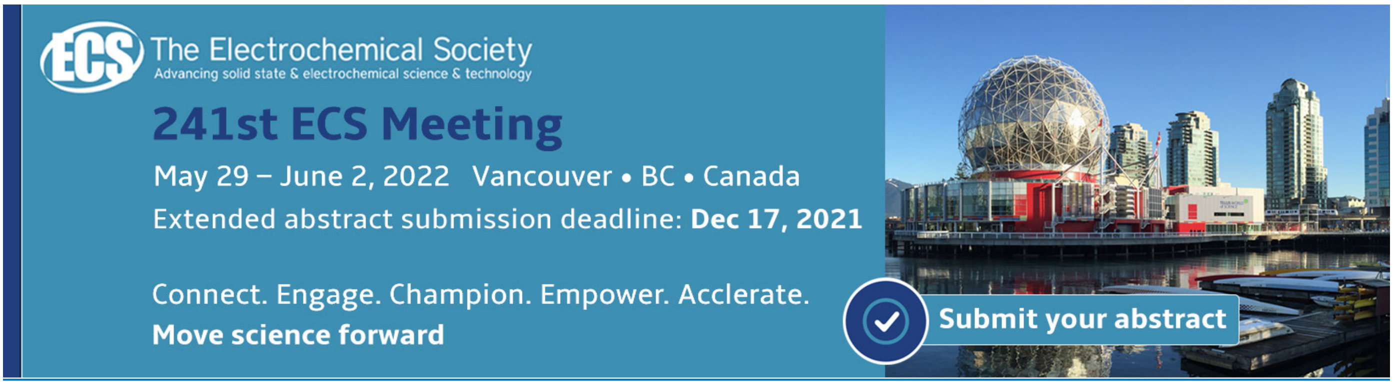

Pitched unventilated wood frame roof with smart vapour barrier – field measurements

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Abstract. Unventilated wood-frame roofs may provide smaller roof thickness and less material use compared to conventional unventilated roofs with all the thermal insulation above the load bearing structure. Unventilated roofs are, however, normally built without wooden materials between the vapour barrier and roof membrane due to moisture safety. Field measurements on the pitched unventilated wood-frame roof of an office building in Norway is performed to demonstrate and document the performance of this type of roof construction. Through monitoring of moisture and temperature, the study aims to contribute to verification of simulations and laboratory measurements showing that unventilated wood-frame roofs may be built with wooden materials if a smart vapour barrier is used. The results show moisture levels below 15 weight-% on the warm side of the rafters throughout the first 15 months of measurements. On the cold side of the rafters, the moisture content increased during winter due to built-in moisture in the construction and reached levels close to 25 weight-%. The moisture content decreased to around 15 weight-% when summer arrived, which shows an expected redistribution of moisture and indicates possible drying of the construction. The measurements underline the importance of limiting built-in moisture to reduce the risk of mould growth, but the study also implies that for some given premises an unventilated pitched wood-frame roof may have acceptable moisture risk.

1. Introduction

With increased demands on energy efficiency of building envelopes, larger insulation thickness of constructions is required. In conventional unventilated (compact) roofs (roofs where the material layers are placed as closed to each other as possible), the insulation layer is typically positioned above the structural part of the construction. To avoid a large increase in construction thickness in order to meet stricter performance criteria, choosing an unventilated wood frame roof construction, where the insulation is placed between the wooden rafters, may give a more slender construction. In addition to lower roof height, unventilated wood frame roofs may provide reduced material needs and positive economic effects compared to conventional unventilated roofs. Unventilated wood frame roofs with thermal insulation between the rafters may also give the possibility of wooden roofs with long spans and low inclinations. However, unventilated roofs are normally built without organic materials because of hygrothermal risks.

Unventilated roofs typically require a vapour barrier at the interior warm face of the thermal insulation to prevent convective moisture transfer and vapour diffusion from the interior. Conventional vapour barriers, such as polyethylene foils (PE-foils), prevents drying of the structure towards the interior. Consequently, as unventilated roofs are built with a vapour tight roof membrane on the exterior side of the thermal insulation, unventilated roofs with wooden materials are particularly vulnerable to leakages or high levels of built-in moisture. High moisture levels in such constructions may lead to biological degradation (rot) and may impact the durability of the roof. Wooden materials between the vapour barrier and the roofing are therefore generally not recommended.

Calculations and laboratory measurements [1-6] indicate that the abovementioned challenge may be solved if a moisture adaptive ("smart") vapour barrier is applied instead of a conventional vapour barrier at the interior side of the roof construction. A smart vapour barrier has a moisture dependent vapour permeability, meaning the vapour resistance depends on the moisture conditions in the surroundings. Given low relative air humidity (RH), the water vapour permeability of the material is low, while the permeability increases as RH increases. In general, this type of vapour barrier allows for drying of the construction towards the interior during summer, while it prevents condensation in the construction during winter. Using a smart vapour barrier may therefore be a cost-effective measure to improve the climatic robustness of unventilated wood frame roofs and reduce the related damage risks.

An important issue is whether the smart vapour barrier provides sufficient drying capacity during summer to avoid mould or rot in the construction. The capacity of dry-out may be affected by several factors: outdoor- and indoor climate, temperature on the roofing, colour of the roofing, orientation of the roof, inclination, shadowing, any construction above the underlayer roof (e.g. green roofs, tempered insulation or PV panels), the vapour resistance of the interior ceiling and the actual vapour resistance of the smart vapour barrier during summer conditions. Several factors also affect the risk of humidification during winter and mould growth in general, for example the interior air humidity and the vapour resistance of the smart vapour barrier during winter conditions, the built-in moisture level, the temperature level in the construction and the type of materials used. Many of these factors have been investigated through research on unventilated wood frame roofs with smart vapour barriers, both numerically [2, 5-7], experimentally [1-4] and through field investigations [5, 6, 8]. Earlier research has indicated that unventilated wood frame roofs may have acceptable moisture risk, but that the moisture level in the construction before applying the smart vapour barrier is important [8]. It is also concluded that a moisture variable barrier is favourable, and that early and durable air tightness of the construction reduces evaporation and high starting moisture content [9]. Hence, prefabrication may ensure a moisture safe solution. Furthermore, it has been shown that the colour of the roofing may have a significant impact on the moisture level in the roof and that the use of a smart vapour retarder instead of a conventional vapour barrier may reduce the moisture content in the rafters [10]. However, little research seems to have been carried out on the subject of pitched unventilated wood frame roofs. The study presented in this paper aims at contributing to the field by investigating the significance of roof pitch and orientation on redistribution of moisture, as well as the functionality of unventilated wood frame roofs when applying a ventilated BIPV roofing on top of the roof construction.

The present paper investigates the hygrothermal behaviour of a pitched unventilated wood frame roof with smart vapour barrier through field measurements. The study is carried out on the roof of an office and educational laboratory building (The ZEB Laboratory) located in Norway. The main goal of the pilot project is to demonstrate and document the performance of the roof under real climatic conditions. Through monitoring of moisture and temperature, the study will aim to contribute to verification of simulations and laboratory measurements showing that for some given premises, unventilated roofs may be built with organic materials if an interior smart vapour barrier is. This paper presents premises for construction of the given roof and provides initial results from the monitoring of moisture conditions in the roof. Measurements are to be continued in order to control and study the hygrothermal conditions over a longer period of time.

2. Field measurements

To improve the knowledge on hygrothermal conditions in unventilated wood frame roofs, a field study is carried out on the ZEB Laboratory, a full-scale zero emission office and educational laboratory building located in Norway (Trondheim), see Figure 1. The building was constructed during 2019–2020. The ZEB Laboratory is a ZEB-COM building [11] supposed to work as a research tool in development of climate-friendly and climate adapted buildings. Hence, renewable energy production on the building must account for emissions linked to construction (C), operation (O) and materials (M) of the building.

Figure 1. The ZEB Laboratory in Trondheim, Norway. Photo: m.c.herzog / visualis-images.

2.1. Roof construction

The building is constructed with a 20 m long pitched unventilated wood frame roof facing south with an inclination of 32°. On top of the roof construction, building integrated photovoltaics (BIPV) are installed as a ventilated roofing with an air cavity of 126 mm between the PV panels and the underlayer roof. The roof inclination is optimized to harvest as much solar energy as possible. The roof cross section is shown in Figure 2 and Figure 3. The roof consists of 450 mm glulam beams (glued laminated timber beams) and I-beams with mineral wool (loose fill glass wool) thermal insulation between the beams. 18 mm wooden roof boards (plywood) with black asphalt underlayer roof (watertight membrane) is installed on the exterior side of the rafters. On the interior side of the rafters a smart vapour barrier is utilized. The technical properties of the smart vapour barrier are presented in [12]. The roof has gypsum interior lining with a vapour open acrylic painting.

2.2. Premises for the use of smart vapour barrier

To obtain satisfactory functionality when applying a smart vapour barrier in the roof construction, some given premises should be fulfilled. To increase the drying capacity of the roof during summer, a dark underlayer roof is used as it allows higher surface temperatures when subjected to solar radiation. However, the ventilated BIPV roofing may decrease heating from the sun on the underlayer roof and consequently reduce the drying of the roof construction. Laboratory measurements [4] show, however, than even a shaded roof will dry out eventually, although less heating from the sun will slow down the process. This is assumed to be acceptable as long as the moisture conditions in the roof is controlled prior to installation of the thermal insulation and smart vapour barrier. Furthermore, the drying capacity of the roof is increased by choosing a ridge construction with no ridge beam (or similar) and a very vapour open exterior air barrier in the wall construction. The ridge construction is shown in Figure 3.

The moisture content in the rafters has been measured during construction of the building to inspect the moisture conditions at different stages in the process. It was presupposed that the moisture content should not exceed 15 weight-% at the time of installation of thermal insulation and smart vapour barrier. In addition to built-in moisture, unventilated wood frame roofs are very vulnerable to air leakages from the interior. Therefore, it was ensured that the vapour barrier was mounted as a continuous layer.

The moisture resistance of the interior ceiling is of major concern when applying a smart vapour barrier. The ceiling must be vapour open to make it possible for moisture that diffuses through the barrier to reach the indoor air. Therefore, the ceiling in the ZEB Laboratory is constructed with gypsum boards with a vapour open painting and an air cavity between the vapour barrier and the gypsum. The air cavity is also reducing the risk of penetration of the smart vapour barrier due to fixing of lighting and ventilation channels.

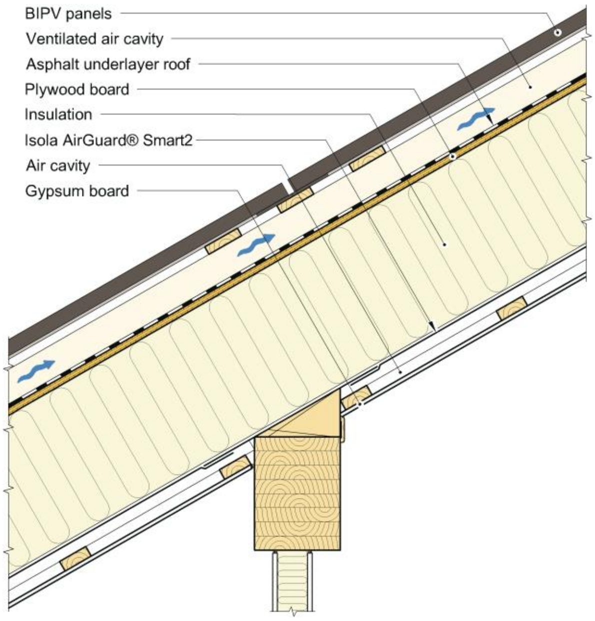

Figure 2. The unventilated wood frame roof construction.

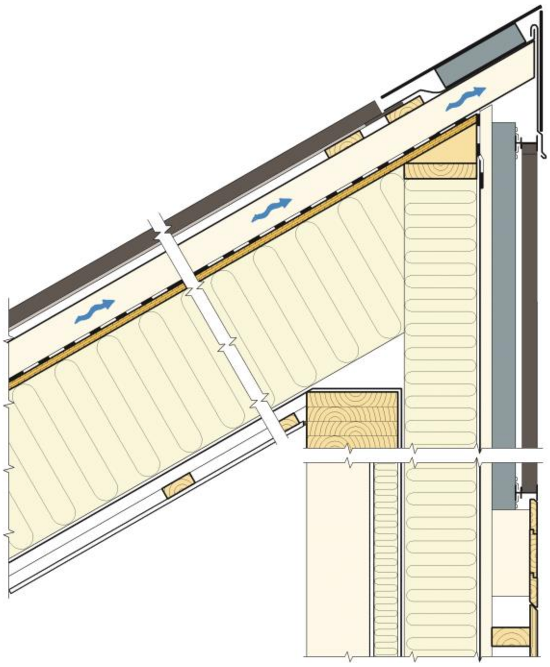

Figure 3. Detail of the roof construction at the ridge of the roof.

2.3. *Instrumentation*

In addition to planning with measures to reduce the risk of moisture problems, the hygrothermal conditions in the roof is monitored through field measurements. Parts of the roof is instrumented with wireless sensors (Hygrotrac S-160-0, Omnisense) installed in different positions in the rafters. The sensors measure wooden moisture content, temperature, and RH. Two of the glulam beams in the roof were instrumented, with four sensors installed in each beam. The most moisture critical position is considered to be the cold side of the rafters or the plywood roof boards below the vapour tight underlayer roof (see Figure 2). It is also of interest to study how moisture redistributes in the construction between summer and winter. Therefore, sensors were positioned both in the top (cold side) and bottom (warm side) of the rafters, 10 mm from the roof boards and 10 mm from the smart vapour barrier, respectively. Sensors were mounted both at the eaves and ridge of the roof, 0.1 m from the beam ends. The position of the sensors in the cross section is shown in Figure 4. All sensors were installed during construction of the roof. Measurements have been conducted throughout the construction period.

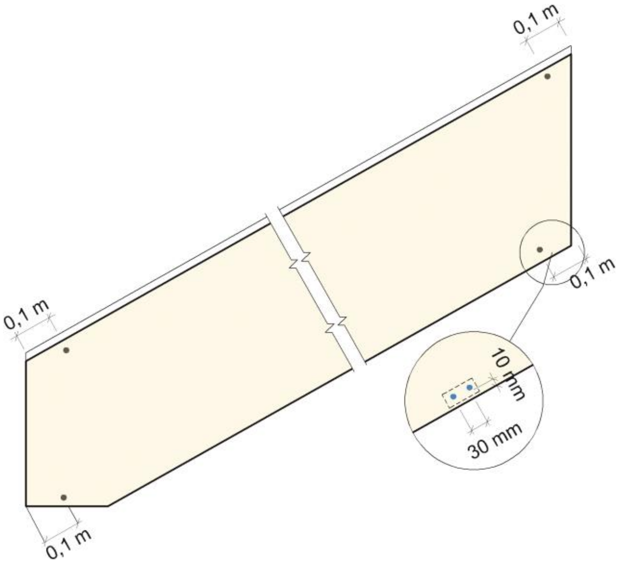

Figure 4. Position of sensors in the rafters indicated by grey dots. Two rafters are instrumented with four sensors in each rafter.

2.4. *Correction of measurements*

The installed sensors are calibrated for measurements in pine, while the rafters in the part of the roof where sensors are installed are glulam beams of spruce. The relation between measured moisture content in samples of the glulam beams from the roof and the true moisture content was investigated by the drying and weighing method [13]. Based on the measurements, Equation 1 is used to correct the moisture measurements given by the sensors.

$$\%MC_{spruce}=11.384 - 0.8737 \times \%MC_{measured} + 0.1226 \times \%MC^2_{measured} - 0.0023 \times \%MC^3_{measured} \quad (1)$$

MC_{spruce} is the corrected moisture content measurement in weight-%, while $MC_{measured}$ is the measured moisture content in weight-%. The measurements are corrected for temperature internally in the measurement system.

3. Results and discussion

Measurements of wooden moisture content, temperature and RH in the unventilated wood frame roof of the ZEB Laboratory have been conducted for 15 months. Measurements are to be continued in order to control and study the hygrothermal conditions over a longer period of time.

Figure 5 gives an overview of moisture measurements in the roof, including data collected during construction of the building. All results are given in weight-% moisture. Measurements denoted "Cold side of rafters" are measurements 10 mm from the plywood roof board. Measurements denoted "Warm side of rafters" are conducted 10 mm from the smart vapour barrier. The sensors are not able to measure moisture content below 7 weight-%, which equals 10.5 weight-% given correction of the measurements using Equation 1. Hence, the actual minimum moisture content in the roof might be lower than shown in the results. Table 1 shows minimum, maximum and average moisture levels and temperatures measured in the roof. The minimum/maximum value is the lowest/highest value measured among the four sensors on the cold side or warm side of the rafters, while the average value is the mean of measurements from the four sensors through the whole measurement period.

Figure 6 and Figure 7 show the relationship between measured temperatures and RH at the eaves and ridge of the roof, respectively. Measurements on the warm side of the rafters are indicated by red dots, while measurements on the cold side of the rafters are indicated by blue dots.

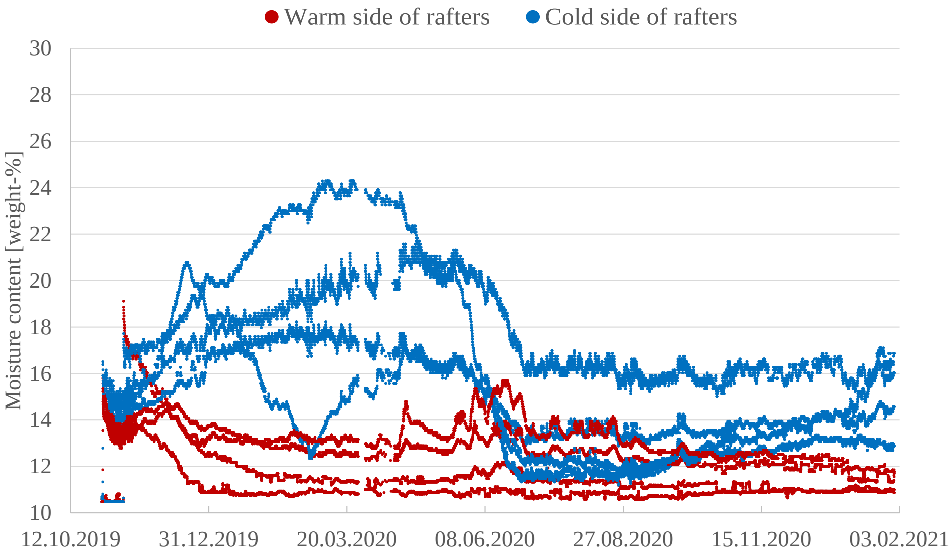

Figure 5. Variation in moisture content [weight-%] in the rafters. Measurements on the warm side of the rafters are measurements 10 mm above the smart vapour barrier, as shown in Figure 2. Measurements on the cold side of the rafters are measurements 10 mm below the plywood boards.

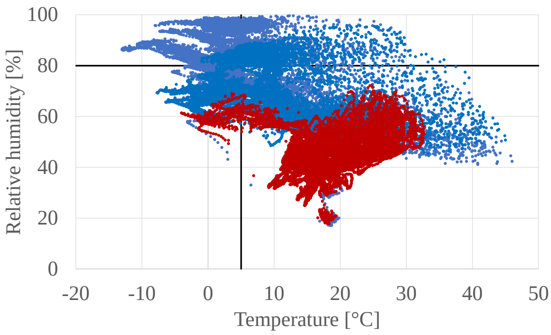

Figure 6. Measurements of temperature and RH on the cold (blue dots) and warm (red dots) side of the rafters at the *eaves* of the roof.

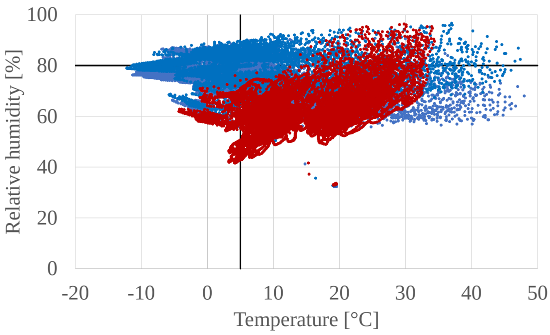

Figure 7. Measurements of temperature and RH on the cold (blue dots) and warm (red dots) side of the rafters (red dots) at the *ridge* of the roof.

Table 1. Minimum, maximum and average temperature and moisture levels measured in the roof. Placement of the sensors on the cold and warm side of the rafters is shown in Figure 4. The average value is the mean of measurements from all the four sensors on the warm or cold side of the rafters.

		Min.	Max.	Avg.
Temperature, cold side	°C	-13.0	48.0	8.7
Temperature, warm side		-4.3	34.4	15.1
Moisture content, cold side	Weight-%	10.5[1)]	24.3	15.7
Moisture content, warm side		10.5[1)]	19.1	12.2

[1)] The sensors are not able to measure moisture content below this level. The actual minimum moisture content may therefore be lower than given in the table

The results in Figure 5 show that the wooden moisture content in the warm part of the rafters (close to the smart vapour barrier) has been relatively low throughout the whole measurement period. In the cold part of the beams, close to the plywood roof boards, the moisture content increased during winter months. This is most likely due to redistribution of built-in moisture in the construction. The roof boards were moistened when the vapour tight bitumen underlayer roof was installed. It was not possible to dry out the plywood before the roof construction was finished. The measured increase in moisture level in the part of the rafters close to the plywood boards is likely a result of the initial moisture level in the plywood, as no major leakages into the roof is suspected. It remains to investigate how the moisture in the roof develops during upcoming winters.

As seen in Table 1 and Figure 5, moisture levels between 15 and 25 weight-% were reached in the top of the rafters during late spring and summer. This implies that there might be a risk of mould growth in the roof if the temperature level is optimal. Viitanen [14] showed that at a temperature of 5°C, a RH of 95% over four weeks was necessary to initiate mould growth. At 90% RH over four weeks, a temperature of 20°C was required to initiate mould growth. If mould growth has first started, mould may develop further at lover temperatures and moisture levels. In the present study, the percentage of measurements with the combination of T>5°C and RH>90% was ≤1.1%, except in one sensor position where this occurred in 5% of the measurements. This means the given conditions have almost never occurred during the first 15 months of measurements, which is also shown in Figure 6 and Figure 7. Hence, the measurements indicate that there is no substantial risk of mould growth in the rafters, as the given temperature and RH levels are not considered critical unless mould growth is already initiated. A similar conclusion was made by [8], based on measurements in two flat unventilated wood-frame roofs with smart vapour barriers. The investigations by [14] showed that a RH of 80% combined with a temperature of 20°C over five months may also initiate mould growth. These conditions have occurred in <4.5% of the measurements in two sensor positions, and in <1% of the measurements in the rest of the sensor positions. The duration of continuous periods with the given temperature and RH levels has not been investigated in the present study. However, as the measurement period is 15 months, it is not possible that a continuous period with the duration and hygrothermal conditions to initiate mould growth given by [14] has been present. It should be noted that the temperature and RH measurements are in a position approximately 10 mm from the warm face of the plywood boards. At the face of the plywood boards, the temperature will be lower, and the RH will be slightly higher, possibly increasing the periods with critical conditions. It should also be added to the discussion that the review performed by [15] showed substantial discrepancies between criteria reported for mould growth in wood-based materials in different studies.

The moisture content in all sensor positions in the top (cold part) of the rafters decreased rapidly to around 15 weight-% when summer arrived. This shows an expected redistribution of moisture inside the construction and indicates drying of the construction. The measurements do not clearly show any difference between the wooden moisture content at the eaves and the ridge of the roof. However, they show that the RH at the warm side of the roof in general is higher at ridge, as shown in Figure 6 and Figure 7.

4. Conclusion

Field measurements have increased the knowledge on unventilated wood frame roofs with smart vapour barriers. Through monitoring of temperature and moisture levels in a roof, the present study implies that for some given premises, a south oriented unventilated pitched wood frame roof may have acceptable moisture risk (≤ 20 weight-% according to [16, 17]). Other orientations may be associated with higher risk as the sun exposure may be lower. The measurements underline the importance of limiting built-in moisture and being concerned with the moisture levels in the roof construction during the building period. However, the study also demonstrated that the roof is able to dry out to a moisture level under a critical level even though the material moisture is high during construction.

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