Hygric Performance of Shaded and Unshaded Highly Insulated, Lightweight Low-Sloped Roofs

Christoph Buxbaum, PhD **Wolfgang Gallent** **Simon Paulitsch** **Oskar Pankratz**

ABSTRACT

This paper discusses the development of new, well-insulated, lightweight low-sloped roof constructions [<0.15 W/(m^2·K) or <0.026 Btu/(h·ft^2·F)] without conventional vapor barriers but with optimized drying performance. The assemblies consist of timber I-beams faced with different coverings and insulated with cellulose fibers. Their hygric long-term behavior was optimized by improving solar-driven moisture transport to the interior by using darker waterproofing layers.

In Austria, according to standard OENORM B8110-2 (ASI 2003), avoiding interstitial condensation is evaluated using the dew-point method (Glaser scheme). However, this method as applied in the standard only considers very simplified steady-state boundary conditions. Neither solar radiation and undercooling nor wetting processes during construction due to driving rain and hygroscopic sorption nor liquid transport are taken into account. Hence, in the current project, a validated model was used during the design stage to analyze the interaction between waterproofing and vapor-retarding layers as well as the overall hygrothermal response of the roof.

Very often, roof constructions are shaded by other buildings, etc., which is why shaded roof constructions were investigated as well. To verify the simulation results, the assembles were also monitored in a building in Southern Austria.

Simulation as well as in situ measurement results are discussed.

INTRODUCTION

This paper presents first results of a research project on the durability of non-ventilated, highly insulated timber-framed low-sloped roofs in the climate of Central Europe. The primary aim of the work was to investigate the influence of roof membranes and different vapor retarders on their hygrothermal responses. The calculations were performed for partially shaded and unshaded roofs, basically looking to the drying potential when dark-colored roof membranes (short-wave absorptivity > 0.7) are used, that improve solar-driven diffusion and when different code-approved or humidity-adaptive vapor retarders are installed or lacking. It is important to note that usually in Austria, according to standard OENORM B8110-2 (ASI 2003), avoiding interstitial condensation is evaluated using the dew-point method (Glaser scheme). However, the method as applied in the standard only considers very simplified steady-state boundary conditions. Neither solar radiation and undercooling nor wetting processes and hygroscopic sorption nor liquid transport are taken into account. Therefore, the scope of this study is to predict the long-term durability as realistically as possible using transient hygrothermal calculations (WTA 2004).

INVESTIGATED CASES

In the frame of the research, the drying potential of prefabricated timber low-sloped roof constructions, which are used more and more for larger commercial and production buildings in Austria, was analyzed. These roofs typically consist of 400 mm (16 in.) high timber beams faced with oriented strand board (OSB) at both sides. The space between the beams is filled with blown-in cellulose insulation. Based on this base case, eight variants with combinations of foils

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Table 1. Investigated Roof Assemblies, Cases 1 to 8

Cases (Layers from Outside to Inside)							
Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**
unshaded	**shaded**	**unshaded**	**shaded**	**unshaded**	**shaded**	**unshaded**	**shaded**
Roof membrane; Type: plastic (polyolefin); Color: dark-grey Permeance = 0.1426 perm; (s_d-value = 23 m)							
Oriented strand board (OSB) 15 mm (5/8 in.)							
Cellulose blown-in insulation 400 mm (~16 in.)							
Oriented strand board (OSB) 15 mm (5/8 in.)		Humidity-adaptive vapor retarder; Permeance = 13.12/0.328 perm (s_d-value = 0.25/10 m)		Vapor retarder, Permeance = 0.0252 perm (s_d-value = 130 m)		Formwork made of spruce Humidity-adaptive vapor retarder; Permeance = 13.12/0.328 perm (s_d-value = 0.25/10 m)	
		Oriented Strand Board (OSB) 15mm (5/8")					
Acoustic panel; Mineralwool with woodwool covering 75 mm (3 in.)							

(vapor retarders) and OSB boards were analyzed, as were variants consisting of only inside OSB boards (without vapor retarders (Table 1 and Figure 1). All variants were assumed to be unshaded (cases 1, 3, 5, and 7) and shaded (cases 2, 4, 6, and 8).

Cases 7 and 8 had no inside OSB sheathing but were finished with a humidity-adaptive vapor-retarding foil providing diffusion resistance and airtightness. This variant was chosen to show the drying improvement by using humidity-adaptive vapor retarders. In practice, such construction is rarely used for larger roof systems. In fact, use of an inside OSB sheathing is more cost-efficiently manufactured (use of mounting apparatus, etc.) and provides more resistance against mechanical impacts and stresses than a thin foil. Besides, long-term performance of an airtight OSB layer is easier to achieve (e.g., connection areas, etc.).

All analyses assumed the roof structure cases 1 to 8 to be absolutely airtight and the insulation to be correctly installed, so no convective vapor flow could develop, affecting moisture buildup.

SIMULATIONS

The simulations were carried out with the WUFI® software developed at the Fraunhofer Institute for Building Physics (IBP 2000) in Holzkirchen, Germany, and validated against outdoor measurements and laboratory tests (Kuenzel 1994).

The analysis was conducted under the assumption that the roof structures had good airtightness and insulation installation and thus was without convective vapor flow affecting moisture buildup.

DEFAULT PROGRAM SETTINGS

The surface film coefficient at the exterior surface was taken as wind dependent, whereas the one at the inside surface was set equal to 8 W/(m^2·K). A shortwave absorptivity of 0.7 was chosen for the dark-grey colored plastic roof membrane.

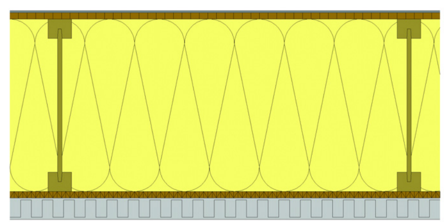

Figure 1 *Schematic draft of investigated roof assemblies, cases 1 to 8.*

The roof's slope is 2° eastwards. For the exterior climate, weather data measured at the current research project location (Greifenburg, Southern Austria) and computed data generated with the software METEONORM® (METEOTEST 2007) were used. The room climate varied as a sine curve between 13°C and 22% RH in winter and 26°C and 60% RH in summer. These indoor conditions with lower temperatures during wintertime were monitored during the first year after the erection of the production building. Asinitial conditions for the materials 20°C and 80% RH were chosen (Karagiozis 1998). Such higher moisture content (i.e., 80%) may be due to rain during transport and mounting of large roof structures or even due to flank diffusion over adjacent masonry (Kuenzel 1996). The material parameters required for each material were taken from the WUFI® material database or measured in the laboratory (Table 2). The hygrothermal behavior was simulated over a period of five years, starting on October 1.

RESULTS

The results concern the hygric behavior of the assemblies. Moisture control is in fact a critical part in building envelope design. Hence, the total water content of the whole constructions was calculated to analyze the drying potential of the

Table 2. Material Properties

Material	Bulk Density, kg/m^3	Porosity, m^3/m^3	Heat Capacity, kJ/kg·K	Heat Conductivity Dry, W/m·K	Diffusion Resistance Factor Dry μ, —
Mineral-bound woodwool covering	320	0,40	2000	0,09	1,9
Mineral wool	60	0,95	850	0,04	1,3
Oriented strand board (OSB)	555	0,6	1880	0,101	287
Cellulose	50	0,95	2000	0,038	1,8

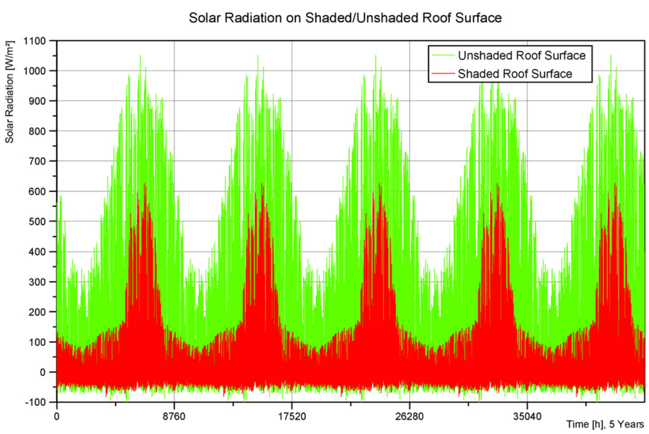

Figure 2 *Solar radiation (starting with October 1st) on roof surface, calculated with METEONORM.*

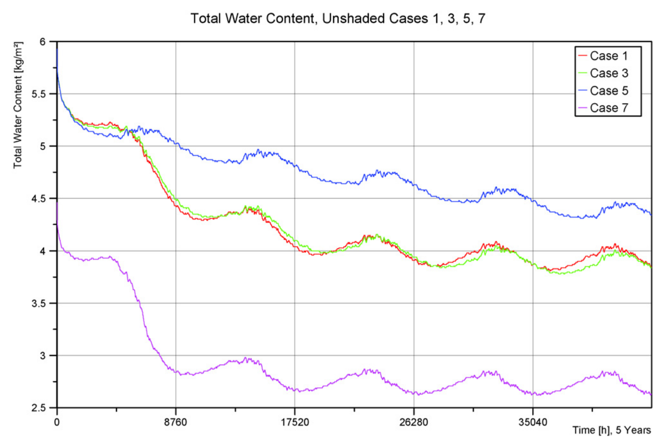

Figure 3 *Total water content (TWC) of unshaded cases 1, 3, 5, 7.*

chosen constructions. Further, the water content in different layers and especially timber-based materials was analyzed to assess the possibility of wood decay. It is noted that according to Austrian codes, the critical limit regarding the moisture content in timber was chosen with >20 mass percent (M%), although it is well known that wood deterioration only occurs at higher moisture levels and long exposure times. In addition, the relative humidities and temperatures, due to the impacting solar radiation (Figure 2) on the interfaces between the cellulose and the exterior OSB decking and the interior vapor retarder and the OSB decking, respectively, were calculated to assess the risk of mold growth based on the exposure time. In Figures 2–12 of this paper, results for the whole period of five years are shown.

UNSHADED ROOF SYSTEMS

Total Water Content (TWC)

First, simulations were carried out on the unshaded roof systems of cases 1, 3, 5, and 7. Figure 3 shows total water content (TWC) found during the five-year period. All cases were dry. The humidity-adaptive vapor retarder applied in case 7 has the most significant influence on remaining moisture in the roof. Inward drying in fact is fastest, as it is not hindered by a quite vapor-tight inside OSB sheathing. Humidity-adaptive vapor retarders have reduced vapor resistance at higher relative humidities, a fact promoting inward vapor flow in summer. TWC in case 1, the roof with inside OSB sheathing only, levels off at a seasonal maximum of ~4 kg/m^2 after about 5 years. Case 3, with an additional humidity-adaptive foil, behaves similarly. The code-approved roof construction of case 5, with the tightest vapor retarder foil, shows the slowest drying. In general, the dark plastic membrane affords a higher drying rate in all variants. Higher temperatures at the exterior, due to a higher shortwave absorptivity of the membrane, in fact increase the inward vapor pressure gradient, accelerating drying. Clearly, inward drying capacity should be considered as an important design factor (Powell and Robinson 1971; Straube 2001; Desjarlais 1995).

Water Content (WC), Exterior OSB Decking

The next step in this parametric study was to predict the moisture response of the wooden components and especially the exterior OSB decking. In Figure 4, one can observe that the moisture content of the OSB for all cases exceeds 20 M% during the first wintertime and then decreases over the years. In cases 1, 3, and 7 it levels off at about ~90 kg/m^3 during the wintertime in the fifth year and is therefore below the critical limit of 20 M%.

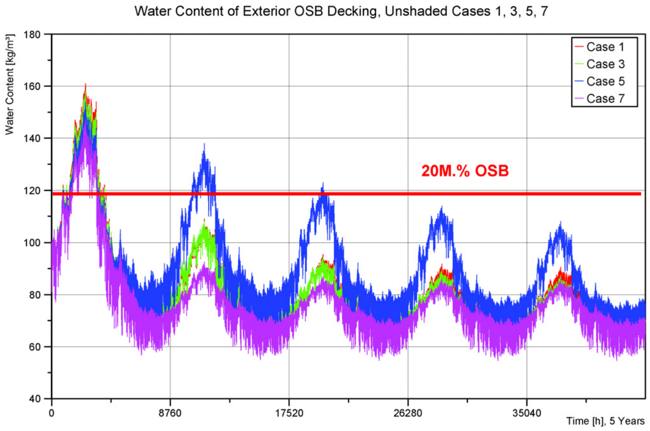

Figure 4 *Moisture content (by mass) of the external OSB, unshaded cases 1, 3, 5, and 7.*

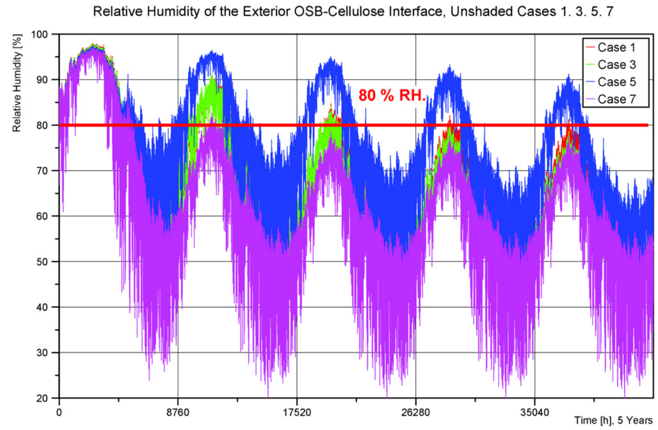

Figure 5 *Relative humidity at the external OSB-cellulose interface, unshaded cases 1, 3, 5, and 7.*

Only the moisture content of the exterior OSB in case 5 remains at a higher humidity level during the first 3 winter periods, increasing beyond 20 M %. This effect is quite crucial for the practical application since the unscheduled moisture within the construction will be trapped between the exterior roof membrane and the interior vapor-tight conventional retarder for a longer time. This potential higher humidity level during long periods would enhance the risk of mold or even wood decay fungi growth and hence cause a potential premature construction failure, although the construction assembly is code-approved!

Relative Humidity on the Interface to the Cellulose

In addition, the relative humidity on the interface between the external OSB decking and the cellulose insulation was calculated to assess the risk of mold growth (Figure 5). The simulations were started with an initial moisture content of 80% RH. This higher moisture content at the start is useful to predict the construction's dryability. The simulation predicts a higher relative humidity of ~95% during the first winter for all constructions, due to the higher initial moisture conditions. In principle, mold growth is possible at relative humidities of >80% and at >5°C. In Figure 5 it is also clear that case 7, with a humidity-adaptive foil on the inside only, shows the best dryability. The relative humidity at the interface of the external OSB-cellulose therefore continuously decreases during the time of investigation and remains below the critical border of 80% RH after the second year.

Cases 1 and 3 also show a decreasing gradient, but nevertheless the 80% RH is exceeded during some weeks within the first three winters when the temperatures (Figure 6) are reduced. It has to be noted that blown-in cellulose is blended with fungicides such as boric acid, boric pentahydrate, etc., by default. In cases of direct contact between wooden surfaces and cellulose, these additives should limit the germination of mold growth under moisture conditions between 80% and

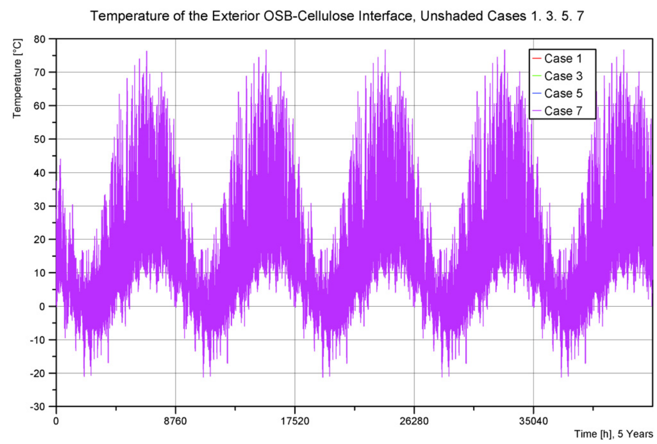

Figure 6 *Temperature at the external OSB-cellulose interface, unshaded cases 1, 3, 5, and 7.*

90%. The effectiveness of the above-mentioned fungicidal additives in wooden constructions is currently being investigated in a laboratory test at the Carinthia University of Applied Sciences, and first results confirm this theory. Due to the lower temperatures during this time of the year and the fungicidal influence of cellulose, mold germination should be reduced or even limited if cases 1 and 3 are executed with dry materials.

Furthermore, the calculation of the relative humidity at the interface between the OSB board and the cellulose in case 5 indicates a potential risk of mold growth during the whole period of investigation. Figure 5 illustrates that the relative humidity exceeds 80% for several months during the first five years, with a seasonal maximum of 90% to 95% RH. Mold growth is therefore likely to occur.

Provided that good workmanship was done, the developed wall constructions in cases 1, 3, and 7 show relatively good hygric behavior. Under these circumstances, moisture-related problems such as mold and wood-decay fungi growth at the exterior OSB boards should be avoided. It is also noted that in all variants the relative humidity at the interface between the cellulose and internal OSB decking and vapor retarder, respectively (case 7), generally exceeds 80% RH during the first summer due to the assumed higher initial moisture conditions (Figure 7). Cases 1, 3, and 7 show a continuously decreasing gradient and remain below 80% RH after the first year without the risk of mold germination. In addition, the use of code-approved more vapor-tight vapor retarders, such as is used in case 5, traps the moisture inside the roof assembly. Due to the solar-driven inward diffusion, a higher relative humidity at the interface of the foil and the cellulose occurs. The relative humidity gradient exceeds 90% RH during some months in summertime at higher temperatures (Figure 8). Hence, mold germination is possible even in this area of the enclosure.

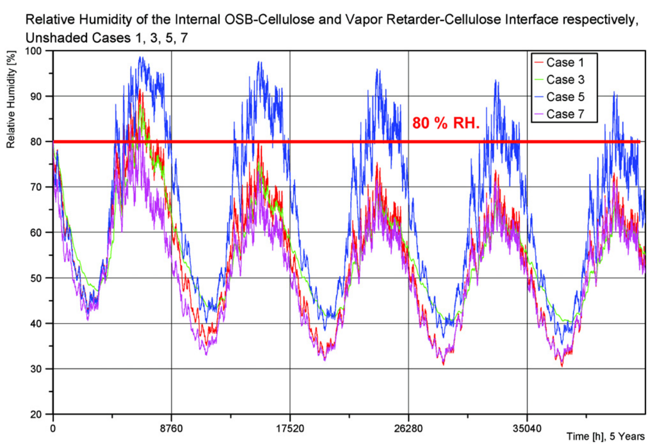

Figure 7 *Relative humidity at the internal OSB-cellulose and vapor retarder-cellulose interface, respectively, unshaded cases 1, 3, 5, 7.*

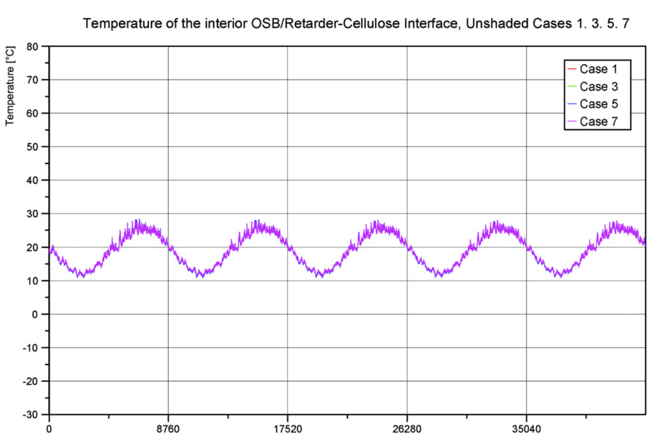

Figure 8 *Temperature at the internal OSB-cellulose and vapor retarder-cellulose interface, respectively, unshaded cases 1, 3, 5, 7.*

SHADED ROOF SYSTEMS

Total Water Content (TWC)

Next, the previously discussed roof assemblies were subjected to simulated modeling again, but now with shading of the assemblies. Figure 9 depicts the TWC for cases 2, 4, 6, and 8. Starting again with initial moisture condition of 80%, it is observable that cases 2, 4, and 6, which contain OSB deckings and/or retarder foils, show slightly decreasing gradients varying between approximately 4.8 and 5.3 kg/m^2 during the fifth year, depending on the season. Case 8, consisting only of a humidity-adaptive vapor retarder without internal OSB decking, shows an optimized moisture performance with a lower TWC leveling off at ~3.7 to ~3.9 kg/m^2 in the fifth year.

Although all variants show a continuously decreasing TWC, it is nevertheless important to note that the TWC ratios are much higher than those in the cases without roof shading. The increased TWC ratios accentuate the need for a detailed investigation concerning the moisture content in the exterior OSB.

Water Content (WC), Exterior OSB Decking

Note that according to the literature (Weiß et al. 2000), wood decay fungi growth is normally possible at higher moisture contents, i.e. >20% by mass. The temperature tolerance varies between +3°C and +40°C with an optimum depending on fungi species at about +18°C to +20°C, but usually in building constructions a critical limit of about >5°C should be considered. The calculated results displayed in Figure 10 indicate that the moisture content of the exterior OSB in roof assemblies 2, 4, 6, and 8 remains above 20% and rises up to ~160 and 180 kg/m^3 during every winter within the simulation period. This wetting process, combined with favorable temperatures during late fall and early spring, dramatically assists the possibility of wood fungi growth within a few years. Even in case 8, executed with only a humidity-adaptive retarder foil, the drying potential is also limited, which means

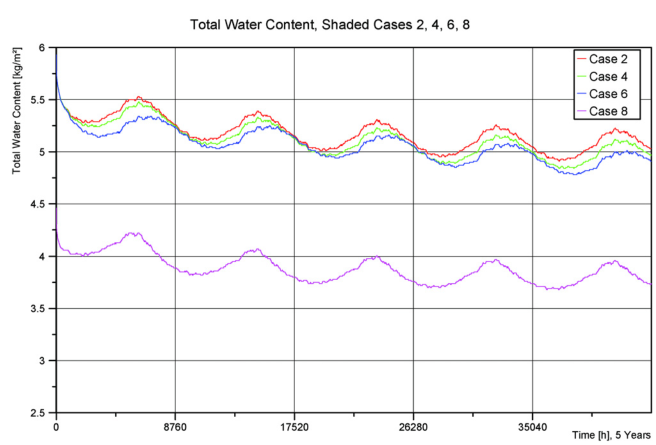

Figure 9 *Total water content (TWC) of shaded cases 2, 4, 6, 8.*

that unforeseen wetting processes will keep higher moisture levels over a longer period—a certain amount of risk can therefore not be excluded.

Relative Humidity at the Interface to Cellulose

To analyze the risk of mold growth inside the construction, the levels of relative humidity (Figure 11) and temperatures (Figure 12) at the interface between the cellulose and the exterior OSB boards were calculated as well. The performance in all cases is similar. The humidity remains above 80% RH mostly all months between fall and spring, with a maximum of more than ~96% RH during the winters without a pronounced drying behavior.

It is also clear in Figure 13 that during summertime, when the exterior OSB board is drying, the vapor drives are gently inwards, causing the relative humidity at the interface to the inside vapor retarders and OSB decking to rise up to ~70% RH, which, from the perspective of mold growth, is negligible. The inward vapor drives are very reduced due to the lower surface temperatures on the waterproofing roof membrane because of the shading influences. The drying potentials to the inside of the roof assemblies are therefore quite limited and a higher amount of moisture still remains within the roof constructions in the course of the years.

IN SITU MEASUREMENTS AT A FULL-SCALE BUILDING

In October 2008, a commercial building with a low sloped roof construction was built in South Austria. One part of the roof construction was used to investigate the hygrothermal performance of the selected roof systems exposed to natural weather conditions and especially to analyze the influence of roof shadings. For the roof assemblies, a construction system similar to the previously calculated case 1 and case 2, with OSB deckings on both sides of the

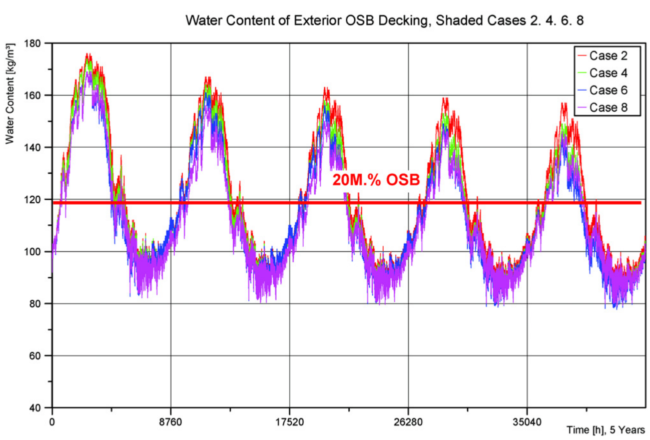

Figure 10 *Moisture content (by mass) of the external OSB, shaded cases 2, 4, 6, and 8.*

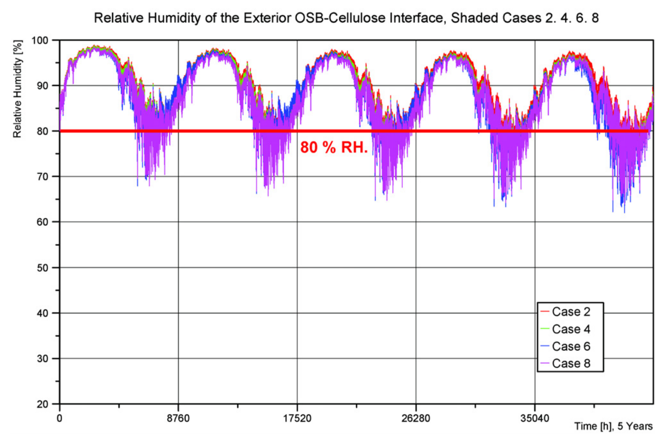

Figure 11 *Relative humidity at the external OSB-cellulose interface, shaded cases 2, 4, 6, and 8.*

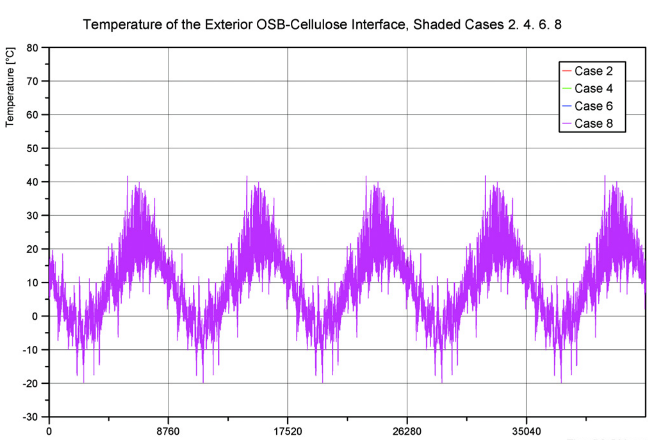

Figure 12 *Temperature at the external OSB-cellulose interface, shaded cases 2, 4, 6, and 8.*

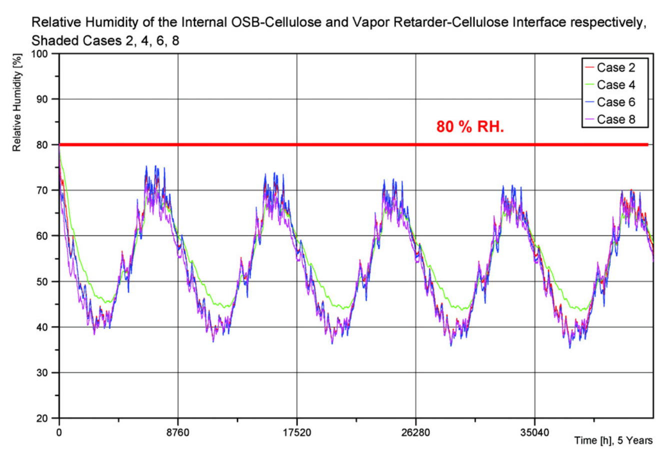

Figure 13 *Relative humidity on the internal OSB-cellulose and vapor retarder-cellulose interface, shaded cases 2, 4, 6, and 8.*

timber I-beams and without vapor retarder foils, was chosen. All roof components are equipped with special measurement equipment. The measurements started on December 30, 2008, and are ongoing. Based on these measurements, further simulation comparisons with the actual weather data will be carried out. These weather data are recorded with a separate weather station located at the building site, and the indoor conditions are monitored continuously. The slope of the investigated roof sections is 2° eastwards.

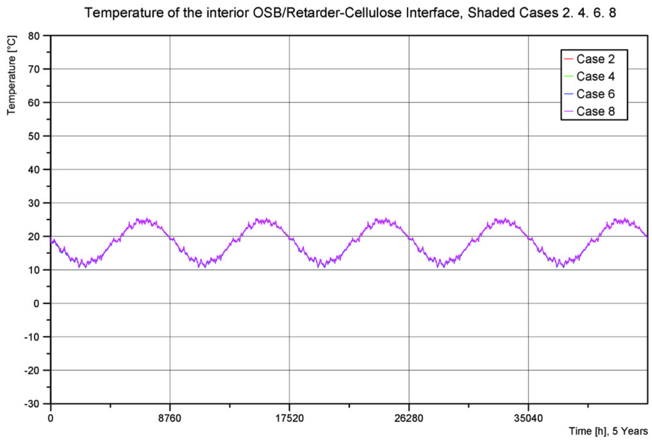

Figure 14 *Temperature on the internal OSB-cellulose and vapor retarder-cellulose interface, shaded cases 2, 4, 6, and 8.*

Results—In Situ Measurements

In this section, measured results for the period January 2009 (after completion of measurement datalogger installation, etc.) to January 2010 are presented. On the interfaces between the external and internal OSB deckings to the cellulose insulation layer, capacitive humidity and temperature sensors were installed to measure the hourly values for relative humidity and temperature (Figure 17). On the internal and external roof surfaces, additional temperature sensors were applied and the climate data inside and outside the building were monitored continuously. In addition, optical radiation sensors were installed above the shaded and unshaded roof partitions to verify the climate data computed with METEONORM® (METEOTEST 2007).

Figures 18, 19, and 20 provide an overview of the measured data concerning inside and outside climate, solar radiation on shaded and unshaded roof constructions, and measured inside and outside roof surface temperatures.

The measured relative humidity values within the roof constructions are presented in Figure 21. In the case of the unshaded roof construction (Element 2), the relative humidity at the interface of the external OSB and the cellulose varies between ~25% RH in summer and ~79% RH during winter. In

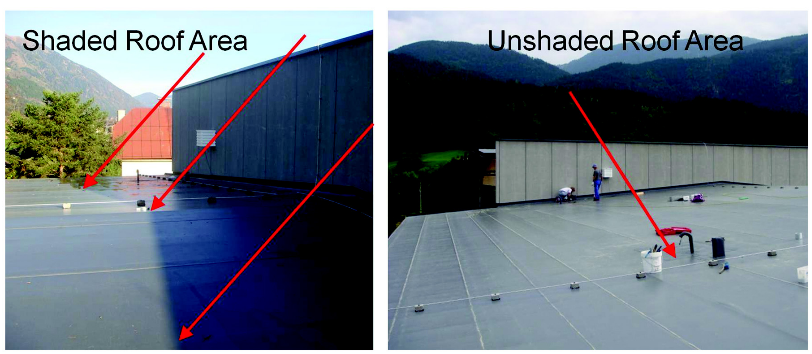

Figure 15 *In situ measurements at full-scale building.*

Figure 16 *Mounting of measurement sensors in the shaded roof area.*

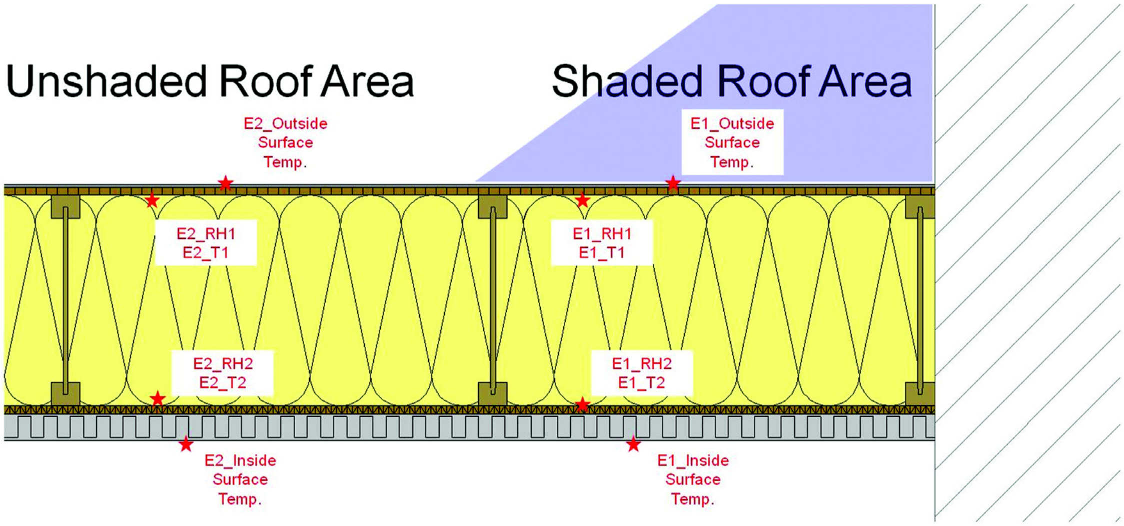

Figure 17 *Positioning of sensors in the unshaded and shaded roof areas.*

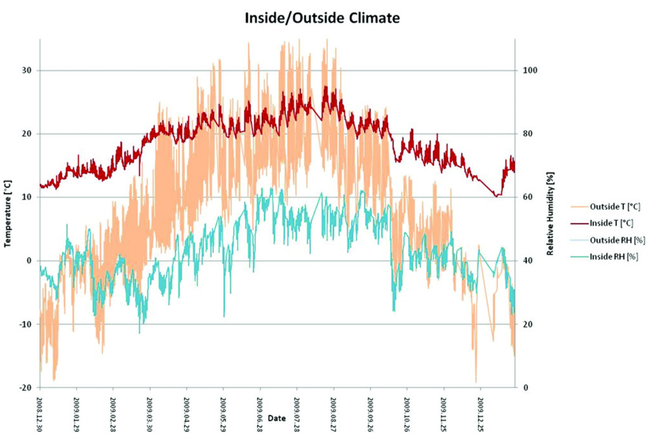

Figure 18 *Measured indoor and outdoor climate, relative humidity, and temperatures.*

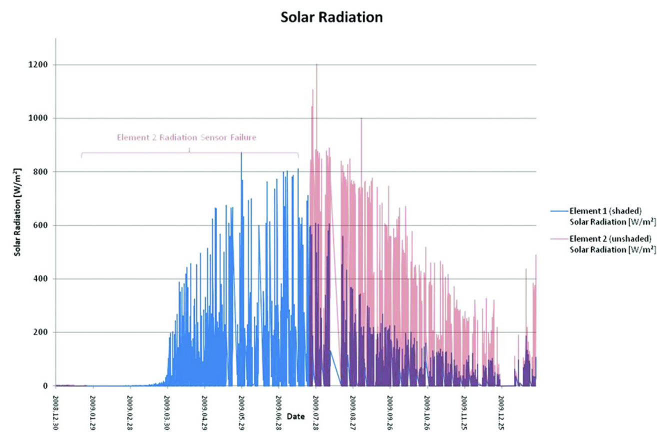

Figure 19 *Measured solar radiation on roof surfaces in unshaded and shaded areas.*

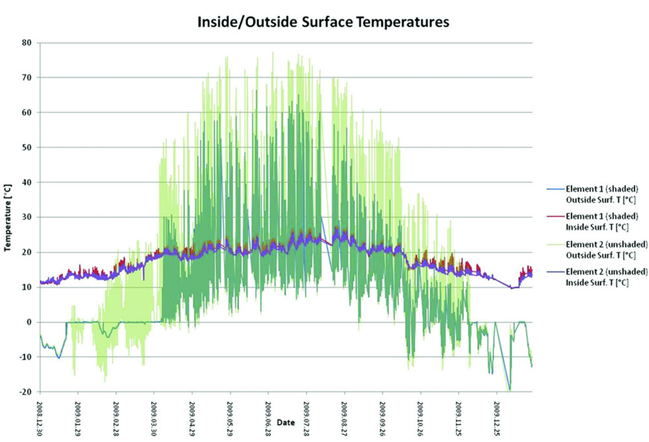

Figure 20 *Measured surface temperatures on inside and outside roof surfaces of unshaded and shaded assemblies.*

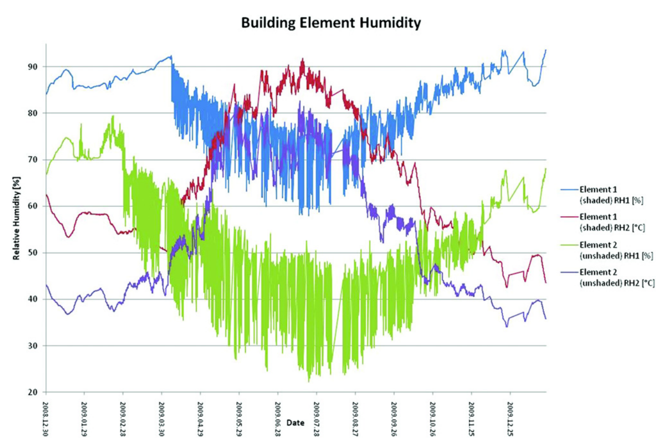

Figure 21 *Measured relative humidity on the external and internal OSB-cellulose interface at unshaded and shaded roof assemblies.*

addition, the relative humidity at the interface between the cellulose and the internal OSB decking increases up to ~82% RH in summer 2009 and up to ~45% RH in winter 2009, also without increased risk of moisture-related problems. The relative humidity was also monitored in the shaded roof section. In that case, the relative humidity at the interface of the external OSB decking to the cellulose varies between ~58% RH in summer and a maximum of ~94% RH in winter 2009/2010. The higher moisture content of the roof construction also influences the relative humidity gradient at the interface of the internal OSB to the cellulose.

The relative humidity value levels between ~45% RH in winter and up to ~92% RH during a few days in summer 2009. Although the critical limit for mold germination, 80% RH, was exceeded, no mold or wood decay fungi growth was detected until Summer 2010, during the inspections. So it is assumed that the fungicidal additives in the cellulose reduce the possibility of fungi germination on wooden surfaces until there is proper contact between cellulose and timber.

Further, temperatures at both surfaces were measured (Figure 22). The temperatures at the interface of the external OSB decking and cellulose vary in a wide range for the shaded and unshaded roof constructions. On the OSB-cellulose interface of the unshaded roof, the temperatures are more than 20°C higher than in the variant with shading, which is a result of the different affecting solar radiation. It is also clear that from February to March 2009, the temperatures in the case of the shaded roof remaining at ~3°C due to snow covering and increase to ~30°C to 40°C in the unshaded case due to a lack of snow covering and therefore improved solar radiation gains.

Although the period of measurement is quite short, it is expected that the developed roof construction without vapor retarder foils will show a good hygric performance in the Austrian climate if the roof is not shaded, but it is recommended to take additional shading effects (e.g., shading due to attics, other buildings, etc.) into account when designing such roof structures.

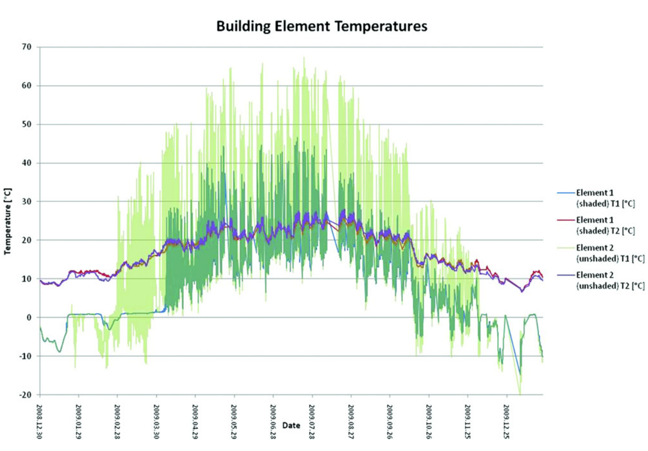

Figure 22 *Measured temperatures on the external and internal OSB-cellulose interfaces at unshaded and shaded roof assemblies.*

DISCUSSION AND CONCLUSIONS

This paper presents initial theoretical results concerning the hygrothermal behavior of nonventilated, highly insulated timber-frame flat roofs in the climate of Austria. The investigations indicate that the interactions of different external roof surface temperatures due to varying solar radiation and the use of vapor retarders such as OSB deckings and other foils strongly influence moisture migration and accumulation and therefore the durability performance of low-sloped roof constructions. Darker membranes increase the temperatures in the exterior part of the roof assemblies and therefore optimize the solar-driven diffusion to the interior. Combined with humidity-adaptive vapor retarders at the inside, the drying process can be improved rapidly.

Shaded timber-based roof structures are, as a matter of principle, more vulnerable. The best achievable drying rate for shaded roof structures is only found to be realizable if humidity-adaptive vapor retarders are incorporated in the system, which, from the practical point of view, is not possible for larger roof structures in most cases.

The results also indicate that the initial moisture conditions in timber-based construction systems should be considered during the construction process. Unforeseen wetting processes lead to higher moisture loads and strongly affect the durability performance of these roof constructions. Regarding the risk of mold growth, it has to be mentioned that the results of the currently ongoing fundamental laboratory investigations should verify the actual interplay between fungicidal additives and mold germination on wooden surfaces.

The first in situ measurements concerning roof structures executed with only inside OSB deckings (no foils) indicate that these constructions are more or less unproblematic regarding moisture-related damages if they are not shaded by attics, higher buildings, etc. If shading occurs, the hygrothermal performance reacts differently with high moisture gradients within the construction. Summing up, it is mentioned that roof shading has to be considered as a critical influence on the dryablity of unventilated low-sloped roofs, and modern computer-based simulation models should always be used to analyze the hygrothermal performance within the early design process.

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