Designing and Testing a Structural Insulated Panel (SIP) with the Help of Hygrothermal Model

Oskar Pankratz

Andreas Holm, Ph.D.
Associate Member ASHRAE

ABSTRACT

When building component manufacturers design new component parts, it is still common in Germany and Austria to use the "Glaser diagram" (dew-point method) to predict the hygrothermal behavior. One reason is that during the design process, experimental investigations are expensive and of limited transferability. An alternative is the use of validated models. The main advantage of modeling is that modeling can predict the long-term hygrothermal performance of the system under different climatic conditions, changes in the interior conditions, or the effect of different system components in a fast and cost-effective way (e.g., with or without vapor retarder). One problem is that after the computer design process, only few new building components are actually tested and monitored in practice. This paper will show the successful use of a simulation program during the early designing process of structural insulated panels and how the calculated results influenced the final design of the structural insulated panel (SIP) system. The designed construction was monitored intensively at the outdoor testing field in Holzkirchen/Germany. The comparison of measurement and simulation with WUFI demonstrates good agreement. Based on the experiments and calculations under various climatic—including indoor—conditions, this SIP's hygrothermal performance will be demonstrated.

INTRODUCTION

The task of this project was to develop a panel, with a 7 m (23 ft) to 10 m (33 ft) span, using a maximum 0.06 m^3 wood/m^2 panel (~0.2 ft^3/ft^2), to build roofs and walls for warehouses and industrial plants that is able to compete with conventional roof systems. Figure 1 shows the first sketches of the structural insulated panel (SIP) system. The idea for the innovative structure system was found in a very early stage of the design stage (Figure 2). The main idea of the SIP is that the I-beam is a static improvement of the system rafter, but it does not use the cover board to support the bearing system. We deleted the flange and butt-glued the chipboard at the cover boards (Figures 3 and 4). The cells are 300 cm long and 50 cm broad. The waved chipboard is 7 mm (~1/4 in.) thick. The structural material between the cover boards is only 3% of the whole volume. Compared with waved pasteboard, the structure material in the pasteboard is much more—it is about 11% of the volume. The overall height of this building component is much less, as all known wooden constructions referred to the relationship between load capacity and material expense.

THERMAL BEHAVIOR OF A 224 MM (8.82 IN.) THICK SIP

The second intuition was to fill the cavities with insulation. The 7 mm (~1/4 in.) thin waved chipboard creates a small thermal bridge and decreases the thermal resistance a little. The computed U-factor with a two-dimensional heat-transfer program is 0.207 W/(m^2·K), (0.0365 Btu/h·ft^2·°F). The 25 mm (1 in.) thick OSB edge-board and the waved chipboard are also taken into account. The calculation based on the Austrian Ö-Norm (ÖNORM EN ISO 6946, 1997) results in 0.198 W/(m^2·K), (0.0349 Btu/h·ft^2·°F). The difference is 0.009 W/(m^2·K), (0.0016 Btu/h·ft^2·°F), or 3.3%.

Oskar Pankratz is an architect in Haidershofen, Austria. **Andreas Holm** is a department head at Fraunhofer-Institut for Building Physics, Holzkirchen, Germany.

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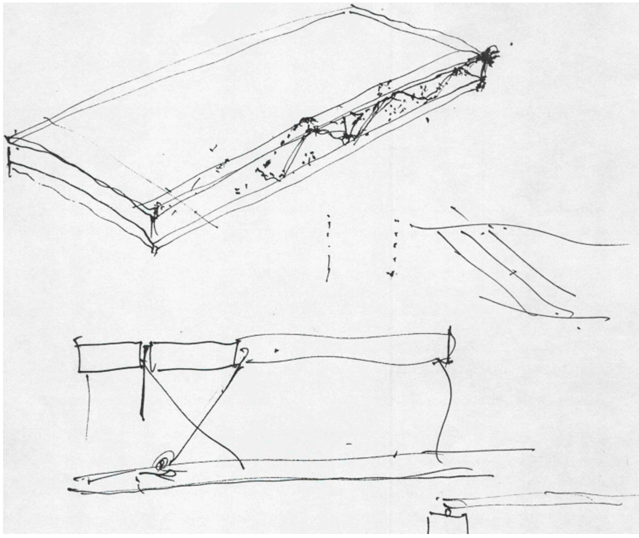

Figure 1 First sketch of the SIP system.

FIRST MOISTURE DESIGN APPROACH

The goal of this task is to develop a moisture design that achieves “pretty good performance” in terms of the building physics. The solution must be practicable for construction companies, including the roof makers. Finishing the roof of an industrial plant may need more than two days of no rain. A heavy shower during building erection is possible. Commonly, the rate of drying is an important factor for building components. In our case, decisions about materials for the panel were partly considered. Upper and lower cover-plate are OSB; the waved sheet is chipboard. The investigation examined the roof skin, the insulation, and the vapor retarder. A series of previously conducted simulations of the roof construction showed marginal influences of different loose insulation or fiber insulation. The first examination dealt with the roof skin and the vapor retarder. Three possible scenarios were investigated with WUFI-Pro.

Description of the Simulated Cases

The following studies were carried out with the computer program WUFI-Pro, which allows the calculation of the transient heat and moisture transport in building elements and was developed at the Fraunhofer Institute for Building Physics in Holzkirchen. The following three roof assemblies (from exterior to interior) were used for the calculations:

Case 1:

- Roof skin (EPDM-rubber) with an s_d value of 50 m (permeance: 0.0656 perm)
- 12 mm (½ in.) OSB
- 200 mm mineral wool
- 12 mm (½ in.) OSB
- metal foil as vapor barrier with an s_d value of 10000 m (permeance: 3.3E-4 perm)

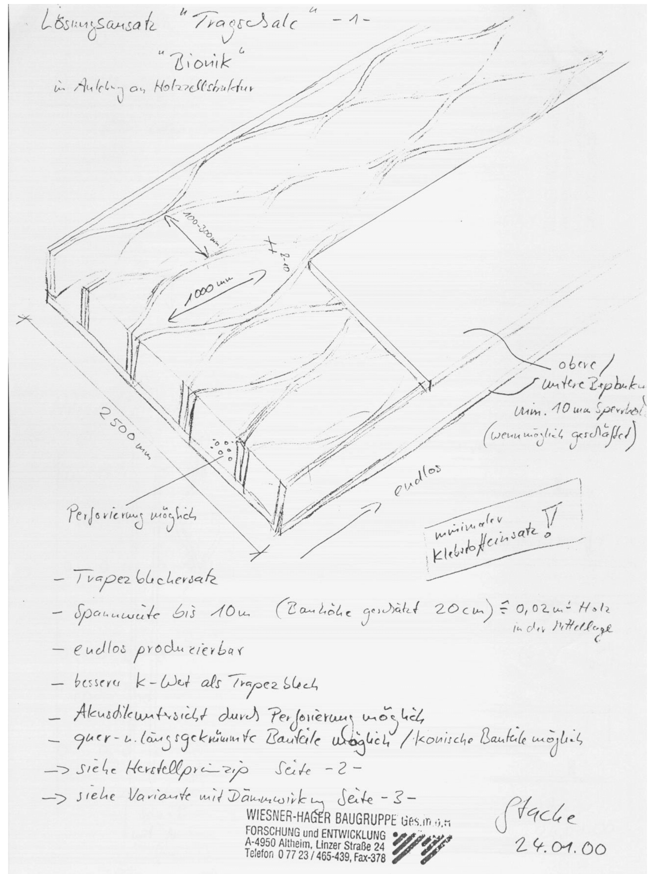

Figure 2 Sketch of the SIP system two days after the initial idea.

Case 2:

- Roof skin (PVC) with an s_d value of 20 m (permeance: 0.164 perm)
- 12 mm (½ in.) OSB
- 200 mm mineral wool
- 12 mm (½ in.) OSB
- vapor-retarder (poly) with a s_d value of 50 m (permeance: 0,0656 perm)

Case 3:

- Roof skin (PVC) with an s_d value of 20 m (permeance: 0.164 perm)
- 12 mm (½ in.) OSB
- 200 mm mineral wool
- 12 mm (½ in.) OSB
- adaptive vapor-retarder (permeance: 1.431 perm at 90% relative humidity—0.296092 perm at 26.5% relative humidity)

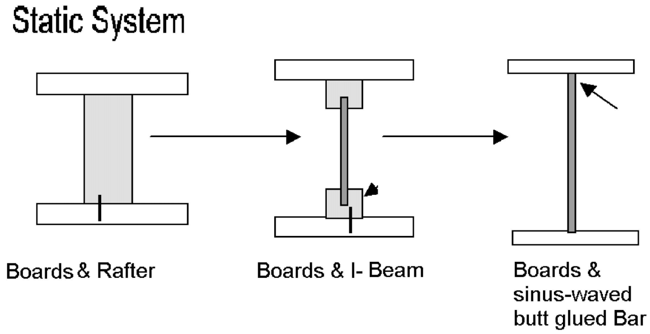

Figure 3 *Development of the bearing system.*

Figure 4 *View of the innovative support system. This photo was taken before the second board was glued.*

The hygrothermal material parameters required for each material were taken from the WUFI-Pro material database. Only the vapor diffusion resistance of the OSB was reduced according to measurements to µ 145 (permeability 1,083 in.). The heat transfer coefficient at the external surface is 19 $W/m^2 \cdot K$, and it is 8 $W/m^2 \cdot K$ on the inside. The shortwave absorption coefficient of the external roof skin is 0.4. Rainwater absorption effects were ignored. The inclination of the flat roof is 2° northwards. Hourly weather data measured in a typical year in Holzkirchen represent the climatic conditions. The room climate varies as a sine curve between 20°C and 35% relative humidity in the winter and 22°C and 65% relative humidity in the summer. These values correspond to normal usage as a residential building. The starting point is the beginning of January with an initial moisture content in both OSB boards of 41.75 kg/m^3 (2,61 LB/ft^3) (6.6 M-%). The hygrothermal behavior is simulated over a period of a four years.

Results

Figure 5 shows the evaluation of the water content in the two OSB boards and in the insulation during the simulation period for the three simulated cases. The black line represents the water content of the OSB under the roofskin, the red line represents the water in the mineral wool, and the grey line represents the OSB close inside, covered by the vapor barrier. It is good to see how the water in this panel swings between the outside and the inside board. For cases 1 and 2, the water content in the exterior OSB increases during winter to a maximum of about 80 kg/m^3. This accumulated moisture can dry out toward other OSB during the summer. The third case appears in the upper OSB 93.12 kg/m^3 (5.81 lb/ft^3) as a maximum water content. This is equal to 15 M.-%. This means that even in the third case there is no high risk of mold growing in the SIP.

THE OPTIMAL PANEL CONTEST

To find the optimal panel construction, we estimated the wetting influence of one week of heavy rain to an unprotected dry panel. The water content of dry SIP is 1 kg/m^2 (0.205 lb/ft^2) (6.6 M-%). Estimating the rain causes an additional 1.66 kg of water per m^2; the SIP starts with a water content of 2.66 kg/m^2 (17.6 M-%) (0.54 lb/ft^2). This assumption is the very worst case because results from Altheim, Austria, show that 1 m^2 of a dry 30-mm-thick unprotected OSB board was able to absorb 0.5 kg water during four days of heavy rain showers.

"In effect, the drying potential of a wall system should be considered as a critical design factor during decision making in the choice of a particular envelope design" (Karagiozis 1998). The design principle "drying potential" is valid for roofs too. Rain showers during erection time may occur and increase the water content of an SIP. The following simulations of the three cases should show their drying potential.

According to the WUFI simulations (Figure 6), the best performing roof assembly is case 3. The assumption is that the construction is mounted with initial moisture of 17.6 M-% in OSB, caused by heavy rain showers. In cases 1 and 2, the moisture acts as if in a prison. Forced by the surface temperatures the moisture swings between the roof membrane and the vapor retarders.

The results show how fast, compared with the others, the case with the adaptive retarder (third case) is able to dry out. In the first and second case mold growth in the assembly is predicted, in the third case mold growth may only occur for a short time. This results indicates that for the first and second cases a totally dry build-in is strictly recommended. For the third case, that means the same construction as case 1 and case 2, just with a smart vapour retarder; a modest buildup of moisture is permitted. In the Middle European climate the case with the adaptive retarder seems to be a good choice.

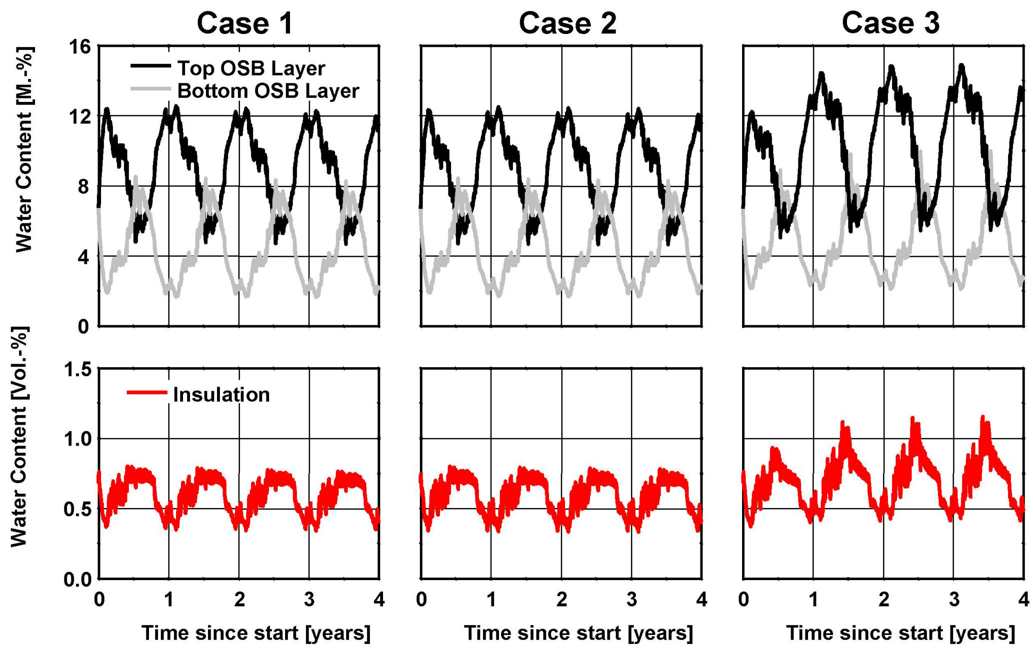

Figure 5 *Water content in the different layers for all three cases.*

THE FINAL DESIGN STAGE: FIELD TESTS CARRIED OUT IN HOLZKIRCHEN

"The proof of the pudding is in the eating." So far only WUFI calculations have been carried out, but an important issue is the validation of these results by real life experiments carried out under well-defined boundary conditions. Therefore, the following experiments were carried out on the IBP test site in Holzkirchen. In September 2001, five roof SIPs, 2.5 m (8.2 ft) by 6.5 m (21.3 ft), were mounted on a existing building (Figure 7). Three different types of insulation materials were tested: mineral wool, cellulose grains, and sawdust. In the center of the three different insulated SIPs, we installed sensors to measure temperature and hygric behavior at different levels. Additional sensors are in the mineral-wool SIP in the base area and in the northern overhang and the northwest edge at the overhang. Monitoring was done from October 2001 till November 2002 (see Figures 8 to 10). The room below the panels was tempered at about 20°C (68°F). In April 2002 and October 2002, we took samples of OSB and insulations for gravimetric tests. During the monitoring time, the climate inside and outside was recorded continuously.

Results

Moisture pins were installed to measure the moisture content on a weekly base (see Figure 11). They were placed in the center of the panels. The data were recorded over a period of 14 months. Table 1 gives an overview of the resulting water content in the different layers observed at two different days during the observation period.

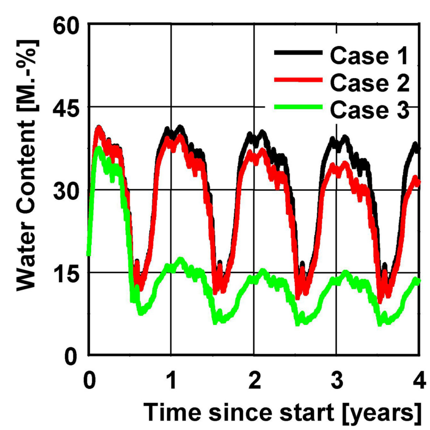

Figure 6 *Hygrothermal performance of the three different cases assuming that water content in the upper OSB layer increased to 111 kg/m*^{3} *(6.93 lb/ft*^{3}*) (17.6 M-%) due to a week of heavy rain.*

To achieve credible predictions, the measurement and simulation with WUFI were compared. Figures 12 and 13 show the comparison of the measured temperature at the roof skin on the SIPS system insulated with sawdust and the relative humidity under the top OSB board. The lowest temperature in the winter was –20°C (–4°F). The highest temperature in the summer was about 70°C (158°F). It can be seen that the computed roof skin surface temperature correlated very well with the measured ones, but the measured and computed rela-

Figure 7 *Photographs from the experimental studies of the SIP carried out at the IBP in Holzkirchen.*

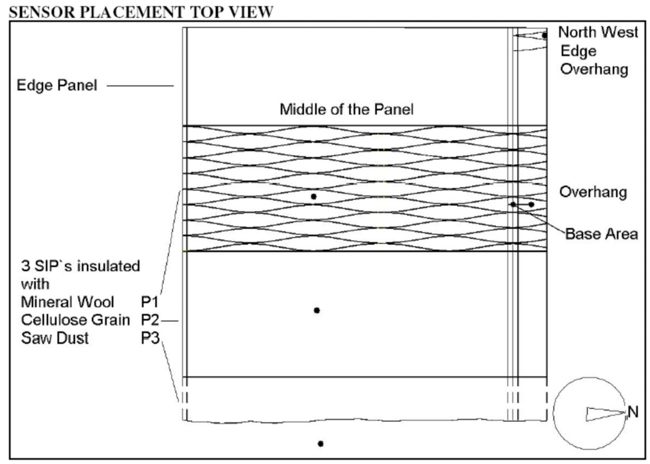

Figure 8 *Top view of the sample roof, showing the position of the sensors.*

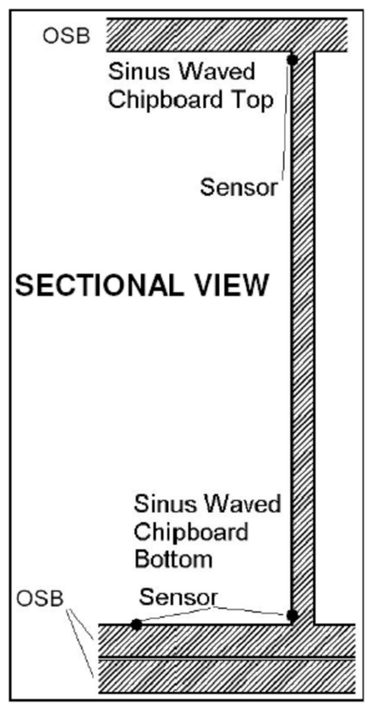

Figure 9 *Sensor placement in sectional view.*

Table 1. Gravimetric Measurement at the Start and During the Test Time in the Panel Centers

Gravimetric Measurement in the Center of Three Different Insulated Panels						
			1. Sample April 4, 2002	Mean Value	2. Sample October 10, 2002	Mean Value
	Material	Moisture Content at the Start [M.-%]	Moisture Content [M.-%]	Moisture Content [M.-%]	Moisture Content [M.-%]	Moisture Content [M.-%]
Sawdust	OSB top	7.0	8.4	7.65	5.5	6.80
	OSB bottom		6.9		8.1	
	Sawdust top	12.4	12.2	11.37	10.0	10.47
	Sawdust center		11.2		10.9	
	Sawdust bottom		10.7		10.5	
Mineral Wool	OSB top	7.0	7.2	6.80	4.9	6.00
	OSB down		6.4		7.1	
	Mineral wool top	0.5	0.7	0.70	0.7	0.77
	Mineral wool center		0.7		1.0	
	Mineral wool down		0.7		0.6	
Cellulose Grain	OSB top	7.0	6.2	5.85	4.1	5.10
	OSB down		5.5		6.1	
	Cellulose grain top	4	6.1	5.80	5.1	5.13
	Cellulose grain center		5.7		5.1	
	Cellulose grain bottom		5.6		5.7	

tive humidity shows different values at low temperatures. We suppose the accuracy of the sensor is considerably affected by the low temperatures, a known problem for measuring such conditions. The gravimetric measured values, translated to relative humidity, indicate that the computed data are credible. The low temperatures during times with relative humidity of about 90% prevent mold growth. The measurement of the sensor above the lower OSB shows better conformance to the simulation.

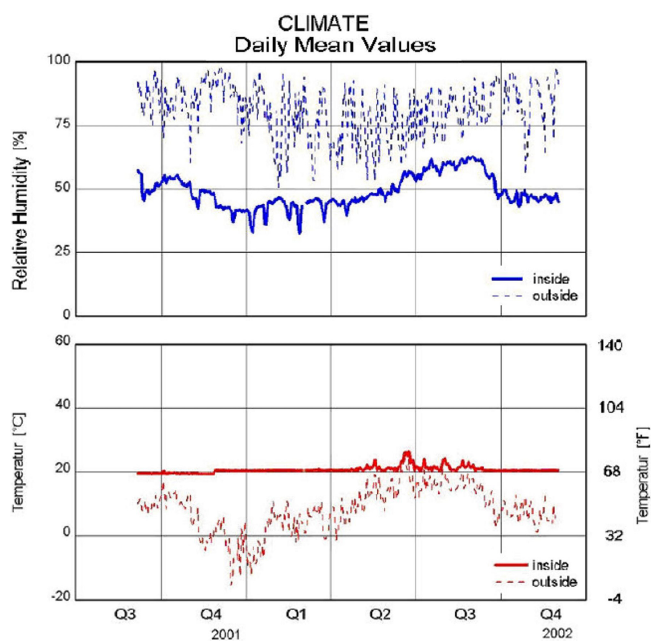

Figure 10 *Monitored indoor and outdoor climate during the testing period.*

OTHER LOCATIONS AND INDOOR CLIMATES

The benefit of the test series is the secured behavior expectation of the SIP under different circumstances. Moreover, it is possible to make design changes to the panel and still produce credible predictions.

The same SIP as built in the outdoor testing field at Holzkirchen/Germany performs in Anchorage with mineral wool well and with sawdust poorly (see Figure 14). In this simulation, the water content of both panels at the start is 1.872 kg/m² (0.38lb/ft²) or 52 kg/m³ (3.25 lb/ft³) (8.3 M-%) OSB; this is 0.360 kg/m² (0.073 lb/ft²) more water in the panel than the dry SIP. The weather file for Anchorage is the colder one. The influence of the insulation material is remarkable. In the Holzkirchen climate, it is marginal.

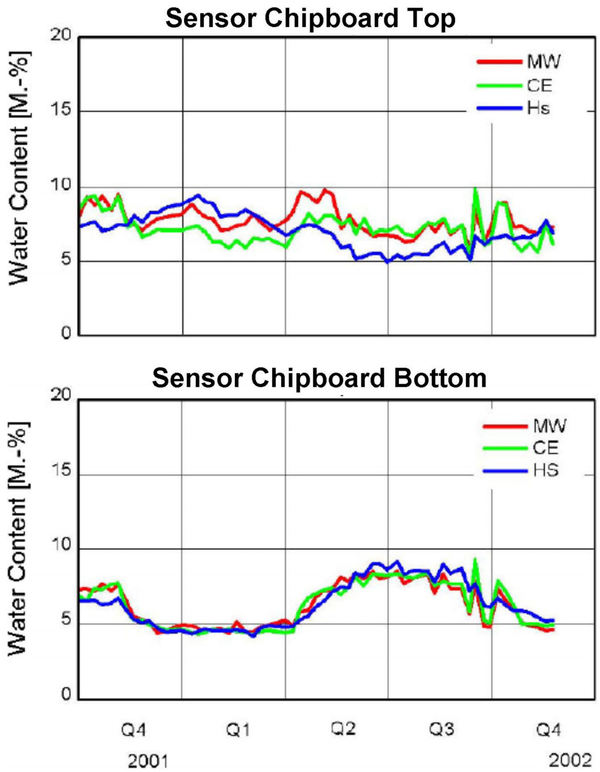

Figure 11 *Weekly measured moisture content in the center of the panels. The data were recorded over a period of 14 months. The red line represents SIP systems insulated with mineral wool, the green line represents cellulose grain, and the blue line represents sawdust.*

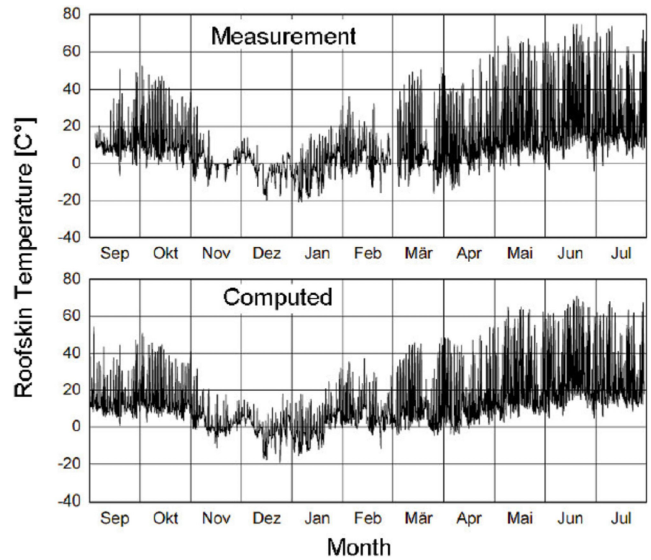

Figure 12 *Recorded and computed roof skin temperature on the sawdust SIP.*

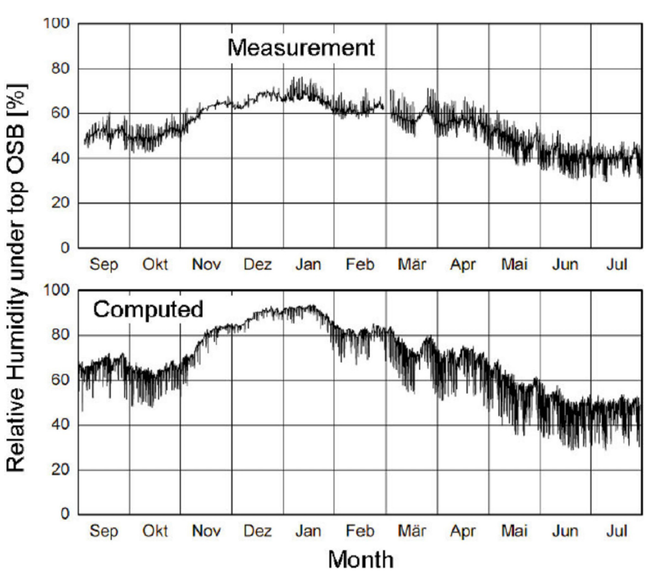

Figure 13 *Recorded and computed relative humidity under the top OSB in the sawdust SIP.*

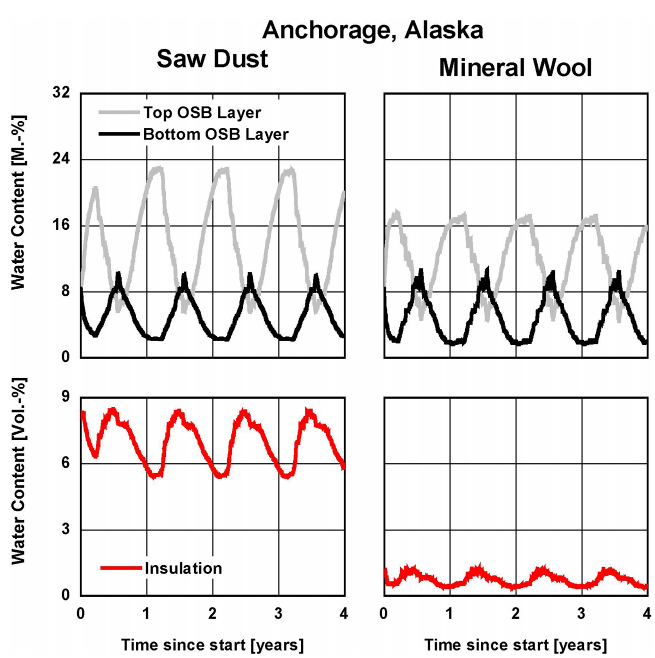

Figure 14 *Comparison of two insulation materials in the climate of Anchorage, Alaska. The SIP with mineral wool show no risk of growing mold.*

DISCUSSION AND CONCLUSIONS

This paper shows how new types of construction can be designed with the aid of a hygrothermal model. The reason to use a moisture simulation tool instead of the common dew point method was the need for accurate predictions of behavior under different circumstances. The early design process with WUFI helped to come up with a hygrothermal safe construction. Before the new construction type was applied successfully in practice, the final proof was done with the help of well-documented field tests. The direct comparison of measurements with the simulations shows a good agreement of the roof skin temperatures (Figure 12). The relative humidity under the upper OSB demonstrated poor agreement of the low temperatures. Gravimetric measurements show agreement with the computed values. In other words, in our particular case, the computing was more credible than the electronic measurement. To predict the moisture course in the center of SIPs, the one-dimensional WUFI software can be used. The one-dimensional restriction does not compute the two-dimensional view of moisture distribution at the edges and overhang. Measurements in these areas show different but harmless water content in the OSB and insulation. Parametric analysis employing other exterior environmental conditions using the same SIPs was found to give a similar distribution of water content in the SIP, analogous to the recorded results in Holzkirchen. Further examinations are needed to examine the effect of SIP interfaces, the effects of the overhang, and the base.

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