Analysis and Comparison of the Hygrothermal Performance of a "Passive House"—Wall Systems in the Climate of Central Europe

Christoph Buxbaum, PhD **Albert Seiler** **Oskar Pankratz**

ABSTRACT

This paper represents the hygrothermal performance of new lightweight wall assemblies in "passive house technology" in the climate of Central Europe. Several different wall assemblies were developed, simulated, and analyzed with regard to hygrothermal performance and probable durability. The results of the simulations were compared with in-situ measurements, which were carried out at a test house built in South Austria. Due to the agreement of measurement and simulation results, future simulations for different climates in should be possible to analyze the potential transferability of the passive house technology.

INTRODUCTION

The efficient use of energy due to increasing energy prices and CO_2-emission excesses requires new forward-looking concepts. About 40% of the annual Austrian energy consumption is used in buildings. In the European Union, especially Germany and Austria, low-energy building concepts, such as "passive house technology," were developed to minimize the energy demand of buildings. Passive houses presume a high insulation performance of the building enclosure with U-factors lower than 0.15 $W/(m^2 \cdot K) \approx$ (0.026 $Btu/[h \cdot ft^2 \cdot °F]$), thermal bridge-free constructions and good airtightness, to achieve a very low annual space heating energy demand of 15 $kWh/m^2 \cdot yr$. The space heating of passive houses can be achieved by heating the supply air in the ventilation system because of the low heat load of 10 W/m^2. Comfortable internal space temperature is achieved in a largely "passive" way with the free heat gains of solar irradiation through windows, as well as the heat emissions of the occupants and household appliances.

The primary aim of this paper is to demonstrate the hygrothermal and durability performance of wooden lightweight wall constructions in passive house technology. Different construction types with varying envelope materials were designed, and they were analyzed and optimized with the help of hygrothermal simulations. In a second step, a test house in South Austria was built. Based on the in-situ measurements at the test house, further simulations with the current measured climatic data were carried out and compared. Due to the agreement of measurement and simulation results, future simulations for different climates should be possible to analyze the potential transferability of the developed passive house wall types.

DESIGNING WALLS IN "PASSIVE HOUSE" STANDARD—DESCRIPTION OF CASES

Carinthia University, together with partners from industry, insulation manufacturers, and timber-construction professionals, is conducting an research and development project on the hygrothermal performance of exterior walls in passive house technology. The main purpose of this research project is to characterize the long-term hygrothermal behavior of different wall systems exposed to various climates. During the design process, and together with the partners from industry, 12 different wall assemblies were selected. With the help of hygrothermal simulations, the assemblies were analyzed and optimized. This paper will present preliminary results for two of these constructions, which are described in Figure 1. The

__Christoph Buxbaum__ is an architect and lecturer for energy efficient and sustainable building design and __Albert Seiler__ is a research engineer in the Department of Architecture, Carinthia University of Applied Sciences, Spittal an der Drau, Austria. __Oskar Pankratz__ is an architect and consultant for building physics in Haidershofen, Austria.

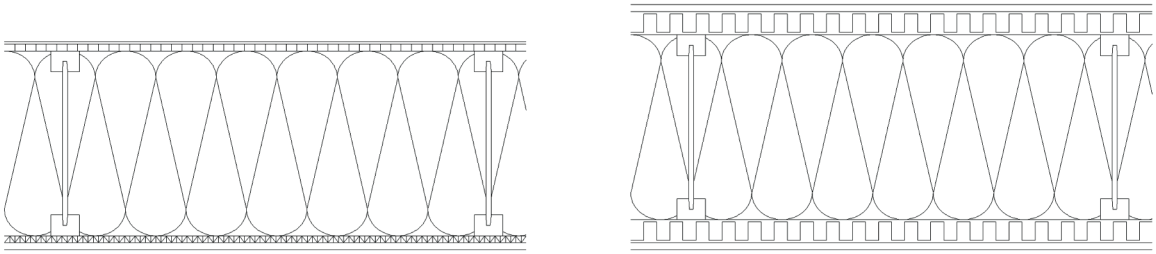

Figure 1 *Schematic draft of investigated wall assemblies, Cases 1 (left) and 2 (right).*

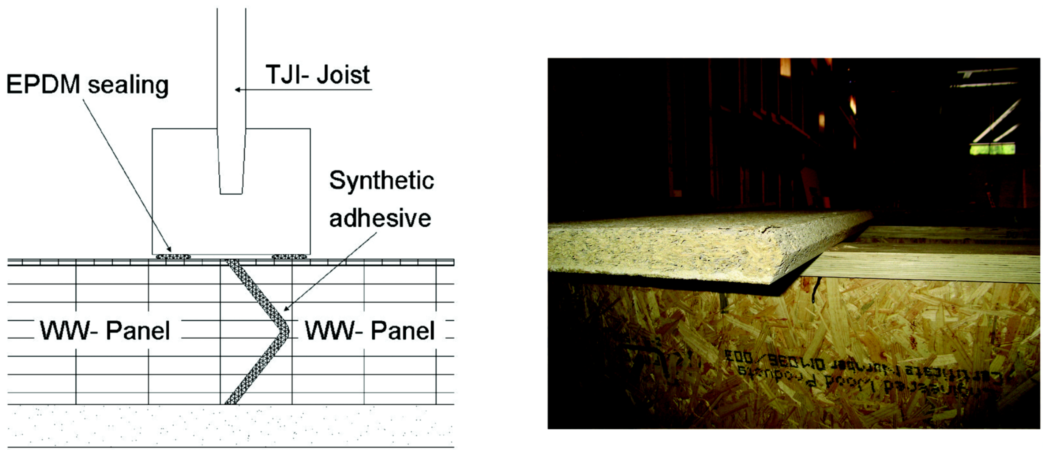

Figure 2 *Schematic draft of connection of wood-wool panel to joist (left) and a picture from the production process (right).*

hygric behavior and especially the water content and relative humidity in constructions were investigated to assess their drying potential.

It is noted that the analysis was conducted while subjecting the envelope systems to good air tightness and insulation installation. The influence of uncontrolled air leakage (Grunewald 2006, Buxbaum 2006) and natural convection (Riesner 2004) is well known and will be investigated at selected wall assemblies within the following project years.

One main objective within the research was to develop construction systems with a reduced number of material layers to simplify the workmanship and therefore optimize the quality levels beginning from the production process up through the erection of the buildings. It was also very important to reduce the expected production costs due to an economical wall design to enhance the productivity and to increase the market share (Figure 1).

In this study, the two wall constructions case 1 and 2, displayed in Figure 1, were investigated. They are made up of a simple static structure, which is accomplished by using timber I-beams, which are faced with varying coverings. Case 1 is carried out with MDF- boards and exterior stucco at the outside, and OSB- boards covered with gypsum boards are arranged at the inside of the wall assembly. The OSB is acting as a horizontal stiffening of the wall system and at the same time as a vapor retarder. Furthermore, the OSB- board fulfils the function of an airtight surface. The assumed leaking slab joints are sealed with special airtight adhesive tapes, which are successfully used in Austria. An additional foil to reduce the vapor transmission and to prevent exfiltrating airflow is therefore not necessary.

The static structure of the second wall assembly case 2 is similar to case 1, but with varying coverings. On the inside, woodwool- panels with a one-sided compressed surface and a liquid vapor retarder coating (two-component epoxy resin) covered with stucco were used. The vapor diffusion through the inside panel is limited due to the use of the liquid retarder coating and the compressed surface of the woodwool- panel is providing airtightness. The slab edges are carried out V-shaped, and the connection between the panels (Figure 2) is bonded. Two EPDM sealings beside the joint avoid exfiltration across the slab connections. It is worth considering that additional foils acting as vapor retarders or air-proof layers are therefore not necessary. As the coating can be painted on during the fabrication process of the panels, this technique is more cost-efficient, too. Outside normal vapor, open wood-wool- panels covered with stucco were applied.

Case 1

- Water repellent exterior stucco system 5 mm ($^1/_4$)
- Medium-density fiberboard (MDF) 40 mm ($1^1/_2$)
- Mineral wool 400mm (16) between wooden I-joists

- Oriented strand boards (OSB) 15 mm ($^5/_8$) (the panel joints are airtight sealed with special adhesive tapes)
- Gypsum board 12.5 mm ($^1/_2$)

Case 2

- Water-repellent exterior stucco system 25 mm (1)
- Mineral-bound (magnesite) woodwool panel 50 mm (2)
- Mineral wool 400mm (16) between wooden I- joists;
- Surface-compressed, mineral-bound (magnesite) woodwool panel with liquid vapor-retarder coating 50 mm (2) (the panel joints are airtight bonded and sealed with caulking strips)
- Internal stucco 15 mm ($^5/_8$)

DESCRIPTION OF CALCULATION

The simulations were carried out using the software WUFI®. (Wärme und Feuchte instationär – Transient Heat and Moisture). This software was developed at the Fraunhofer Institute for Building Physics (Künzel 1994) in Holzkirchen, Germany and validated using data from outdoor and laboratory tests. The software calculates the transient heat and moisture transport in materials and building constructions that are exposed to natural exterior and interior climate conditions.

Default Program Settings

The heat transfer coefficient at the exterior surface is a variable that depends on wind and temperature at the interior 8 W/mK. For the external stucco or coating, a short-wave (solar) radiation absorptivity of 0,4 was chosen. Long-Wave Radiation Emissivity is 0,9. An initial temperature of 20 °C and a higher initial RH of 80% in the components was chosen to assess the drying potential.

PRELIMINARY SIMULATION—“CENTRAL EUROPE” CLIMATE

The main focus within the first project year was the analysis of the “base case” moisture situation in the wall assemblies. On the one hand, the constructions were chosen with north orientation due to the fact that the minimized solar radiation will reduce the inward drying effect of a higher initial moisture content within the wall construction. On the other hand, an orientation to the prevailing weather side was imposed to estimate the impact of driving rain, as in the case of in case of Holzkirchen’s southwest orientation.

Boundary and Initial Conditions

For the exterior boundary conditions, hourly weather data from 1991 Holzkirchen, Germany was used. The calculations were performed with the same year repeated five times, starting on January 1.

Holzkirchen is situated in southern Germany and known for its rather rough climate: low temperatures during the wintertime, high relative humidity and driving rain loads. (Figure 3). It can be assumed that constructions showing a good hygrothermal response in the Holzkirchen climate should also work in the Austrian climate. The year 1991 is considered to be a fairly typical moisture design year for this location.

The indoor air temperature and humidity for the preliminary simulations varies as a sine curve between 20 °C / 30% RH in the winter and 22 °C / 60% RH in the summer.

The initial conditions for the preliminary simulations were chosen generally for all layers with 80% RH and 20 °C. It was assumed that the relatively high humidity level would contribute toward the possible drying potential of the wall systems. (Karagiozis 1998)

Material Properties

The material properties (Table 1) employed in these simulations were taken from the WUFI® database and respectively determined through laboratory measurements.

SIMULATION RESULTS

This paper focuses on the “generally” hygric behavior of the chosen wall assemblies. It is commonly assumed that the control of moisture is recognized as a critical part in the design of building envelopes. Hence, the water content in different layers of the chosen constructions and results concerning RH in critical parts of the envelope was investigated to predict their drying potential and assess the possibility of mold and wood decay and fungi growth. The simulations were performed for a period of five years; please note that the graphs in this paper display only partial results for the whole period, but also only for the 5th year.

Case 1—Holzkirchen North Orientation

The total water content (TWC) in case 1 varies between about 2 kg/m in summer and about 2,9 kg/m in winter, which is shown in Figure 4. Except for these seasonal fluctuations, the total water content shows a constant trend without upward movement.

Ratios for the moisture content in the outside MDF and the interior OSB board during the simulation period are presented in Figure 5. It can be noticed, that in the 5th year the water content (WC) of all layers is also showing, apart from seasonal fluctuations, a constant trend. The WC varies for the MDF- boards between ~ 20 during summertime and ~ 35 kg/m during wintertime, for the OSB- boards between ~ 40 and ~ 70 kg/m. Although no continuous yearly moisture accumulation in the construction is predicted, it is especially important for the sake of wooden materials to investigate the existing risk conditions for wood decay and mold fungi growth. According to literature (Weiß et. al.), wood decay fungi growth is normally possible at a higher moisture content ≥ 20 M%. The temperature tolerance varies between +3 °C and +40 °C with an optimum depending on fungi species lying at about +18 °C to +20 °C, but usually in building constructions a critical limit of about ≥ 5 °C should be considered. The results displayed in Figure 5 indicate that the moisture content in the OSB-board is far away from the critical limit of 20 M%. The

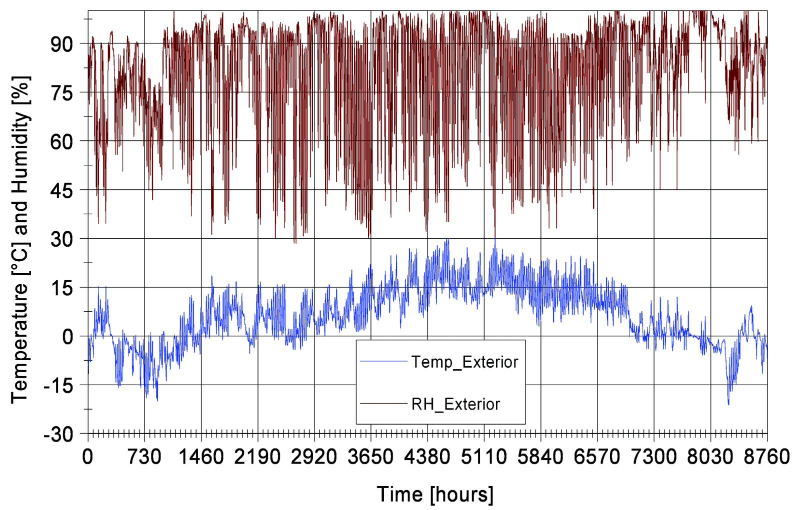

Figure 3 *Exterior RH and temperature in Holzkirchen, Germany.*

Table 1. Basic 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, –
Water-repellent final stucco coat	1380	0.36	850	0.87	8
Exterior stucco undercoat	1200	0.3	850	0.25	11
Mineral-bound wood-wool panel	320	0.40	2000	0.09	1.9
Compressed surface of mineral-bound wood-wool panel	750	0.15	2000	0.11	10
Medium-density fiberboard (MDF)	255	0.98	2000	0.051	5.0
Mineral wool	60	0.95	850	0.04	1.3
Oriented strand board (OSB)	555	0.6	1880	0.101	287
Liquid vapor retarder coating	1140	0.001	2300	2.3	50,000
Gypsum board	1153	0.52	1200	0.32	16
Internal stucco	850	0.65	850	0.20	8.3

MDF- board is exceeding 20 M% only during a few weeks in wintertime, when the temperatures are most of the time lower than 5 °C. This indicates that germination should be respectively limited.

Additionally, the relative humidity on the surface of the MDF- and OSB- boards was also calculated to assess the risk of mold growth. The simulations were begun with an initial moisture content of 80% RH. This higher moisture content at the start is useful to predict wall construction dryability. The simulation is predicting an RH in the outside MDF- board varying between ~ 60% in summer and ~ 85% during a few weeks in winter. In principle, mold growth is possible at RH of ≥ 80% and ≥ 5°C. Because of the low temperatures during this period of time, mold growth should be reduced and respectively limited. It is also clearly seen in Figure 6 that during summertime, when the MDF- board is drying, the vapor drives are inwards because of solar heating that causes the RH in the inside OSB- board to rise up to ~ 60% RH, which, from the perspective of mold growth, is negligible.

Provided that it was constructed with good workmanship, the developed wall construction case 1 is showing a relatively

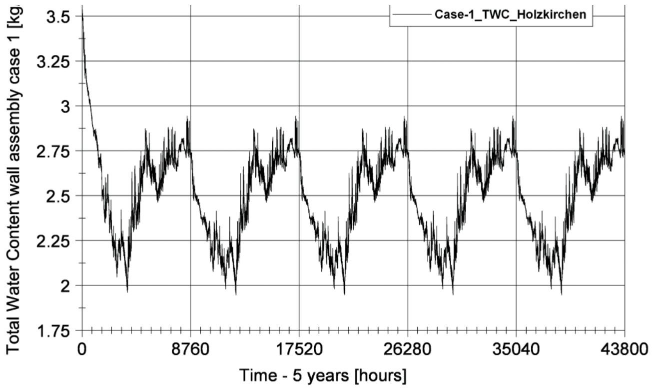

Figure 4 *Total water content (WC) wall assembly—Case 1: Holzkirchen, north orientation.*

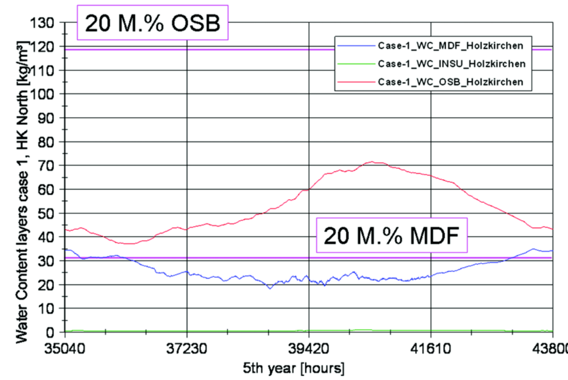

Figure 6 *WC of different layers and corresponding critical limit of 20 M%—Case 1: Holzkirchen, north orientation.*

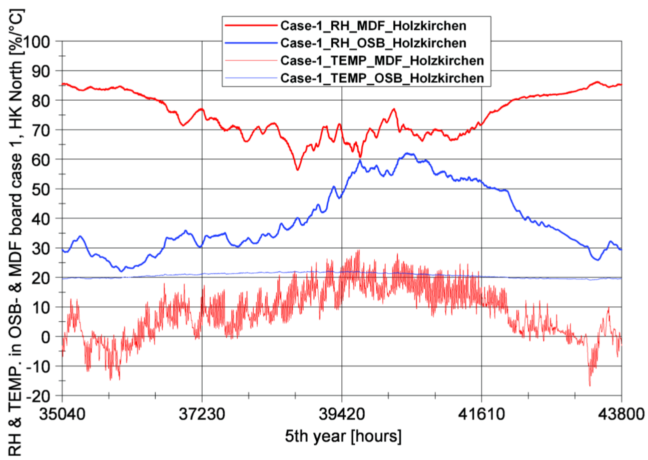

Figure 5 *RH and temperature in MDF and OSB boards—Case 1: Holzkirchen, north orientation.*

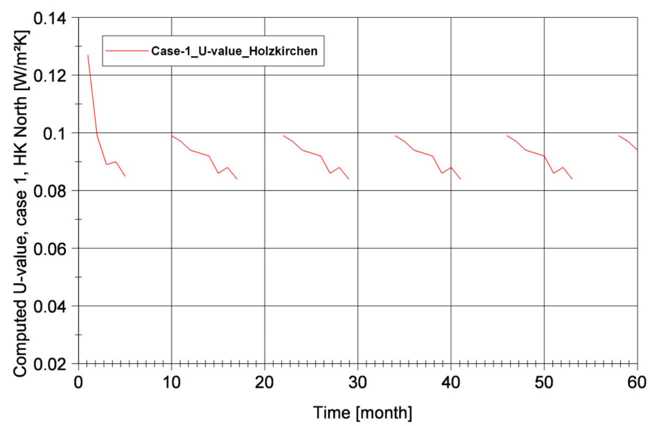

Figure 7 *Computed U-factors—Case 1: Holzkirchen, north orientation.*

good hygric behavior. Under these circumstances, moisture-related problems like mold and wood decay fungi growth at the MDF- and OSB- boards should be avoided.

As aforementioned, passive houses presume a high thermal performance envelope with U- values lower than 0,15 W/(mK) 0.026Btu/(h-ft-F). Climatic impacts may influence the thermal performance of building components; therefore, it is necessary to predict the real transmission heat losses at peak design conditions. Figure 7 gives the real U- values, calculated with WUFI®, depending on the actual hygrothermal conditions due to the given exterior and interior climatic exposure for case 1. The U- values were calculated from the transient WUFI results according to R = DT / (-Q) where DT = monthly mean value of temperature difference [K] between interior and exterior surface and Q = monthly mean value of heat flux [W/m] through the interior surface. Under these circumstances, the average U- value for case 1 is 0.093 W/mK 0.016Btu/(h-ft-F) when the influence of the wooden I- joists is ignored.

Case 1—Holzkirchen Southwest Orientation

In this study for both cases, a series of simulations was also performed with a wall exposure to the prevailing weather side, which in the case of Holzkirchen is the southwest orientation. Figure 8 indicates that the total water content (TWC) in case 1, arranged in the southwest direction, is varying in a wider range with ~ 1.75 kg/m up to ~ 3.25 kg/m, but also without rising moisture accumulation.

During most months within the course of the 5^{th} year the moisture content of the outside MDF- board (Figure 9) is lower than in the case with north orientation, except in the 4^{th} quarter of the year it is reaching the critical limit of 20 M% for a few weeks connected with also suitable temperatures varying between 0 and 15 °C (Figure 10). Because of the short period, it is assumed that decay fungi growth will not occur, but the risk of mold growth needs to be investigated. The moisture content of the OSB- board shows a similar gradient to the case with northern orientation but with a marginally higher

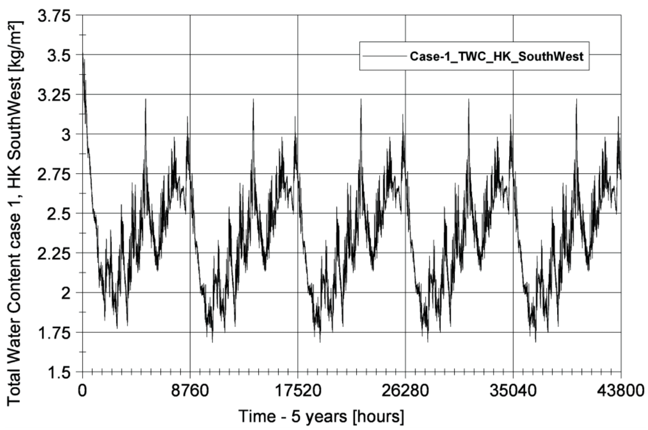

Figure 8 *Total WC wall assembly—Case 1: Holzkirchen, southwest orientation.*

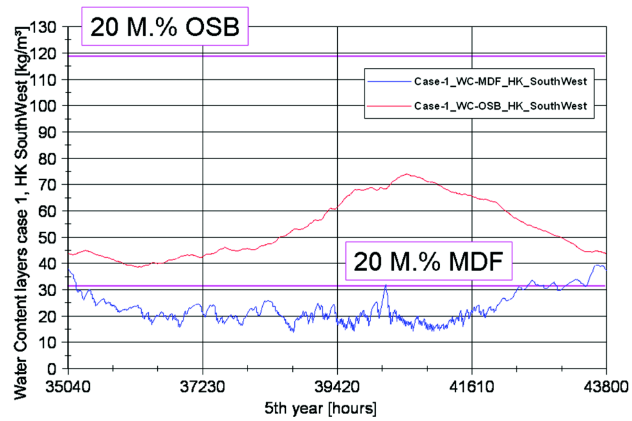

Figure 9 *WC of different layers and corresponding critical limit of 20 M%—Case 1: Holzkirchen, southwest orientation.*

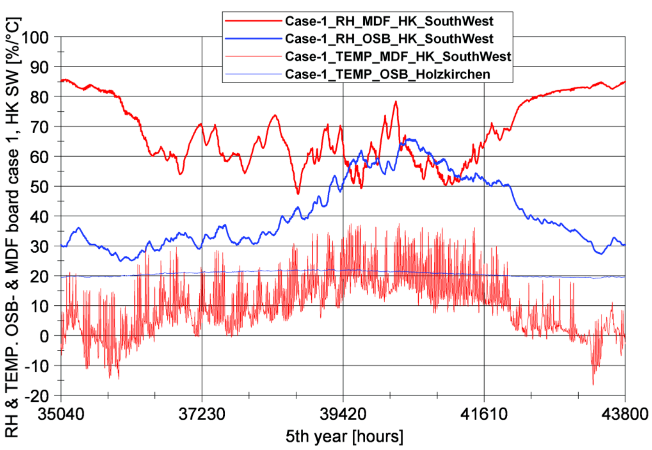

Figure 10 *RH and temperature in MDF and OSB—Case 1: Holzkirchen, southwest orientation.*

peak level up to ~ 75 kg/m. Wood decay fungi growth is therefore obviated.

The calculation of the relative humidity and temperatures on the inside surface of the MDF- board with 80 – 85% RH and > 5 °C indicates a potential risk of mold growth during the formerly discussed short period in the 4th quarter of the year. Figure 10 illustrates that the RH on the surface of the OSB-board is vacillating between ~ 25 and ~ 65% in the course of one year. Due to this low humidity level, mold germination should be avoided.

Summing up, it can be noticed that the rain penetration at the south-west orientation in Holzkirchen is influencing the moisture behavior of the selected case 1. During a short period of the year, higher moisture gradients at suitable temperatures exist, so moisture related problems, especially mold growth, cannot entirely be excluded for this location.

Case 2—Holzkirchen North Orientation

It was noted above that the wall assembly case 2 is made up of the same static structure but planked with woodwool-panels on both sides of its construction. The inside panel is a special form of the "typical" woodwool-panel with a liquid vapor retarder to reduce the vapor flow into the construction. The aim was to investigate if a higher initial moisture content due to causes like unfavorable material storage and wetting during erection work could dry out. Figure 11 illustrates that the total water content (TWC) of case 2 varies between ~ 4.7 and ~ 6,2 kg/m depending on the outdoor climatic conditions. The moisture situation remains stable and shows no increasing moisture accumulation over the course of the years.

The evaluation of the water content in the two woodwool-panels and the outer area of the I-beam is displayed in Figure 12. It can be noticed that the water content in the outside woodwool- panel is constant apart from seasonal fluctuations. It varies between ~ 50 kg/m in summer and ~ 65 kg/m in winter, but remaining under 20 M%. The gradient for the internal panel varies between ~ 22 kg/m and ~ 32 kg/m. Moisture related problems at both woodwool- panels should therefore not occur.

A potentially critical part of the construction is the outer area of the I- joist. The moisture content per weight in the outer corner of the I-joist is exceeding 20 M% over a long period beginning from fall through the end of winter. Hence, there are also temperatures over 5 °C given, which means it would be possible for mold decay fungi to grow in this part of the joist. The computed results concerning the relative humidity in this area confirm the higher potential risk of fungi growth (Figure 13). The RH is increasing beyond 80% almost the whole year. Even at the surface of the outside woodwool- panel, the RH is exceeding 80%. In practice, fungi growth on the facing of the woodwool- panel will not appear because the manufacturer's internal research has shown that due to the high alkalinity of the mineral bond woodwool (pH- values of ~ 11 to 12), fungi

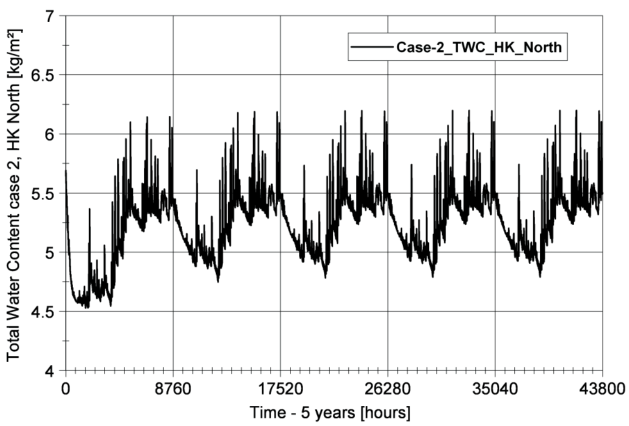

Figure 11 Total WC wall assembly—Case 2: Holzkirchen, north orientation.

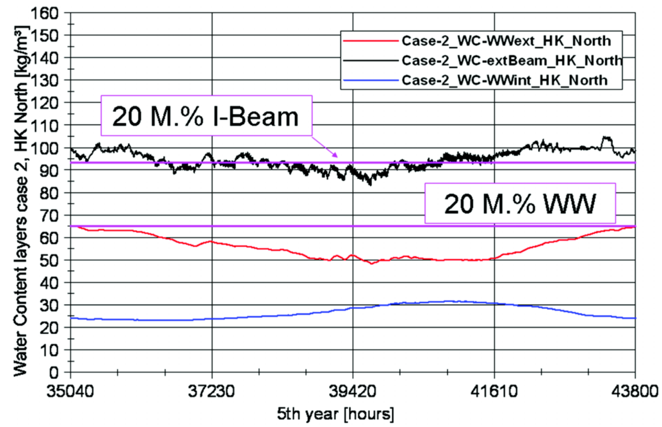

Figure 12 WC of wood-wool panels, outer I-beam area, and corresponding crticial limit of 20 M%—Case 2: Holzkirchen, north orientation.

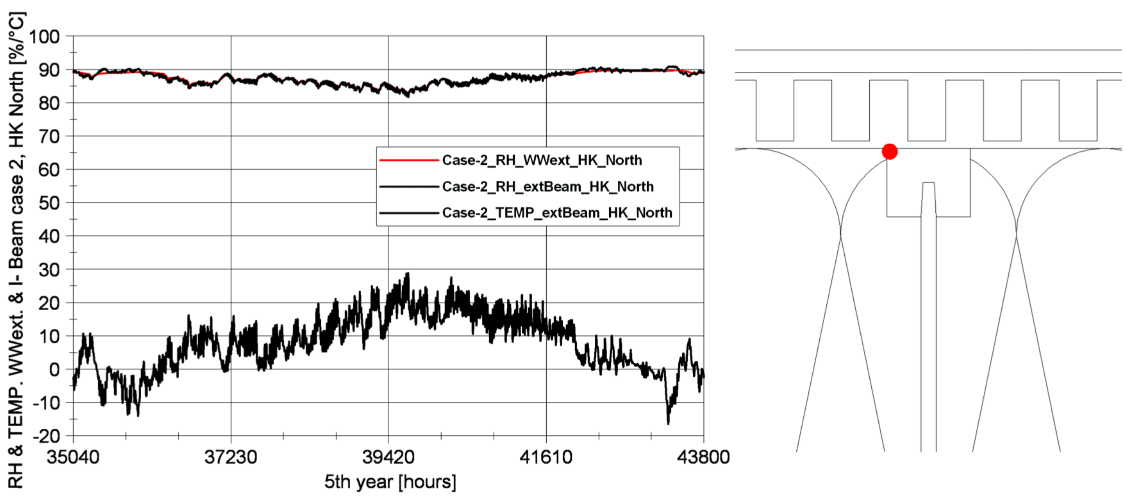

Figure 13 RH and temperatures on the inner side of the exterior wood-wool panel and in the outer corner of the I-joist—Case 2, Holzkirchen, north orientation.

growth even at higher humidity and temperature levels didn`t occur.

Considering the thermal behavior displayed in Figure 14, one can observe that case 2 also show a good thermal performance with a computed average U- value of ~ 0.097 W/mK 0.017Btu/(h-ft-F). The influence of the wooden I- joists was also ignored.

Case 2—Holzkirchen Southwest Orientation

Case 2 also shows simulations with an exposure to the prevailing weather side in the southwest that were performed to investigate the influence of wetting due to driving rain. Under these circumstances, the total water content (TWC) shows a critical tendency to a constant upward moisture accumulation during the course of the years.

Figure 16 further illustrates that the water content of the exterior woodwool- panel exceeds 20 M% during most of the months in the 5th year. The gradient in the assumed critical exterior area of the I- beam shows a similar trend and is increasing up to ~ 26 M% in the 5th year; hence, sooner or later wood decay is suspected to form. It can be seen that the different sorption isotherm of the woodwool- panel, compared with the MDF- panel in case 1, tends toward a higher moisture accumulation in the exterior layer of the wall assembly. Accordingly, during summer, solar heating generates high vapor pressures in this area and causes inward vapor flow. This leads to increased moisture conditions at the interface to the interior woodwool- panel. The water content in the I- joist in that area reaches 20 M% during a short period in summer.

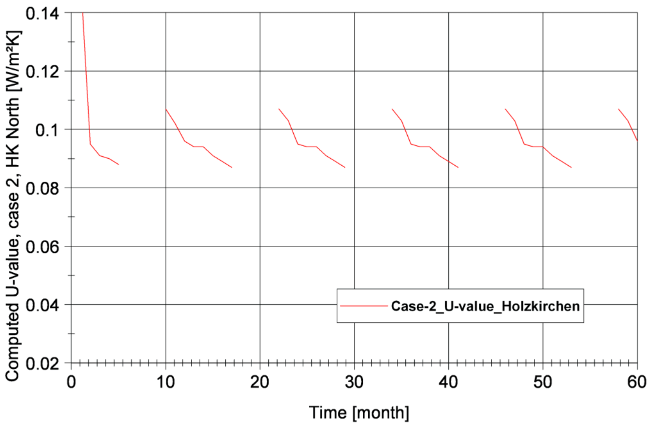

Figure 14 *Computed U-factors—Case 2: Holzkirchen, north orientation.*

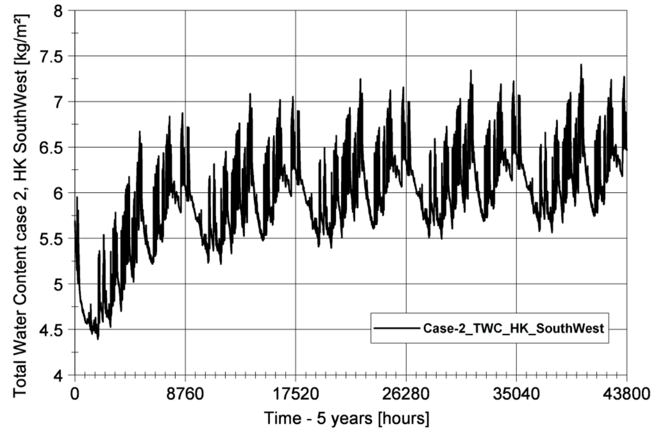

Figure 15 *Total WC wall assembly—Case 2: Holzkirchen southwest orientation.*

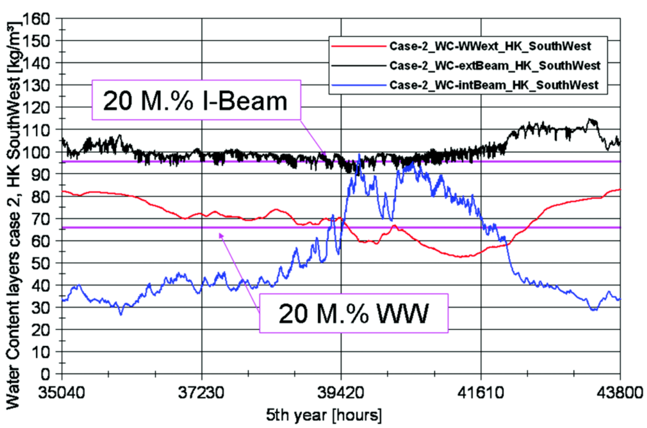

Figure 16 *WC of exterior wood-wool panel, outer I-beam area, and corresponding critical limit of 20 M%—Case 2: Holzkirchen, southwest orientation.*

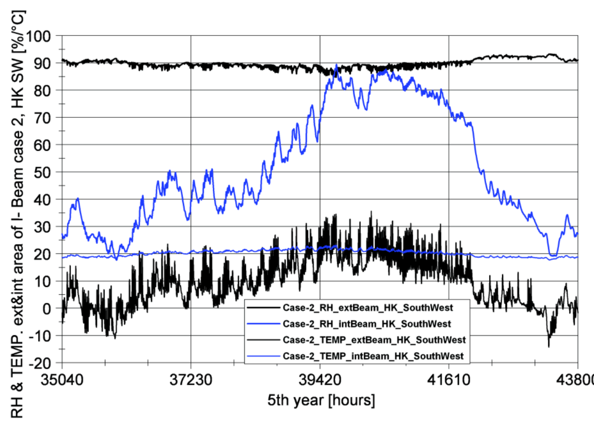

Figure 17 *RH and temperatures in the outer and inner areas of I-joist—Case 2: Holzkirchen, southwest orientation.*

This effect is better understood on the basis of Figure 17, where the relative humidity for this area is shown. The RH in the corner of the I- beam varies between ~ 20 and ~ 90%. Hence, 80% RH during summer is exceeded, making mold growth possible even at the inside of the wall construction.

In conclusion, it should be pointed out that the moisture performance of case 2 highly depends on the dimension of wetting due to driving rain. The weather conditions in Holzkirchen, which were used in the simulations, represent the "worst case" for the Central European region. It should be noted that woodwool- panels for exterior cladding of conventionally Austrian framehouses have been successfully tried and tested during the last decades. This consideration should be supported with another simulation, where, instead of Holzkirchen, the more moderate Austrian climate from Vienna was applied. To investigate the wetting influence due to driving rain, the orientation for the prevailing weather side to the west was chosen.

Figure 18 illustrates that the total water content (TWC) now, beginning from the start, is decreasing and varies between ~ 4.2 and ~ 5,5 kg/m in the 5th year. Due to the reduced driving rain penetration, the moisture accumulation even at the prevailing weather side at this location is stabilized. The water content of the exterior woodwool- panel, displayed in Figure 19, is showing a constant gradient and even in the outer area of the I- beam, the moisture content per weight is not exceeding 20 M%. So summing up, we can assume, that the application of woodwool- panels for exterior wall cladding highly depends on the impact of rain penetrations. High driving rain loads, like in Holzkirchen, could be critical and lead to moisture related deficiencies.For moderate climates, such as in Austria, the use of these panels at the exterior surface of lightweight wall constructions shouldn`t be problematic, provided that good workmanship was done.

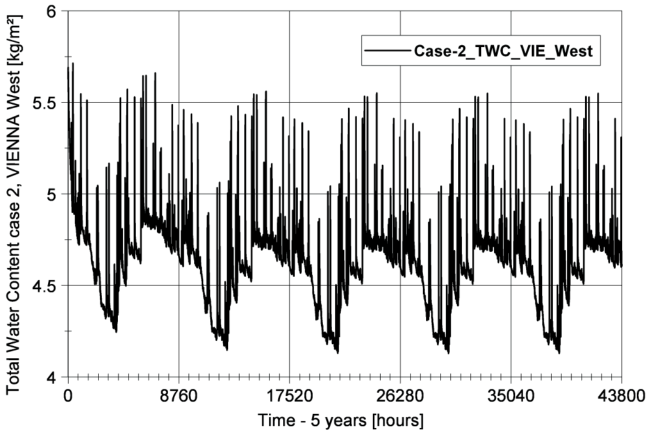

Figure 18 Total WC wall assembly—Case 2: Vienna, west orientation.

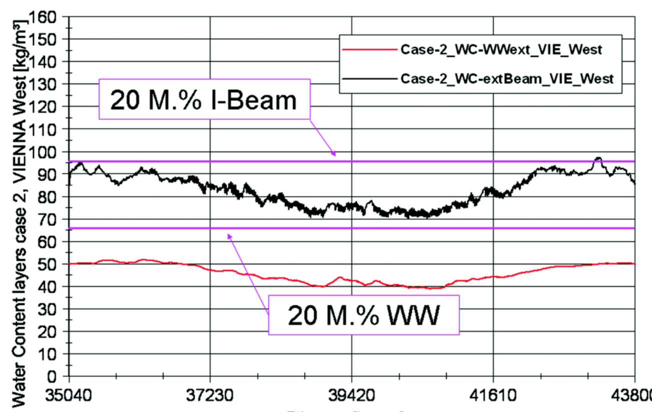

Figure 19 WC of exterior wood-wool panel and the outer area of the I-beam and corresponding critical limit of 20 M%—Case 2: Vienna, west orientation.

Figure 20 Test house in south Austria.

IN-SITU MEASUREMENTS AND SIMULATION COMPARISON

In June 2006, a test-house was built at Lake Weissensee in South Austria to investigate the hygrothermal performance of the selected wall systems exposed to the natural weather conditions. All wall components were equipped with special measurement equipment. The measurements started on the 1st of July, 2006 and will probably continue until the end of year 2009. Based on these measurements, further simulation comparisons with the actual weather data are carried out. These weather data are recorded with a separate weather station located at the test-house. The indoor conditions in the test-house are controlled at a constant about ~ 22 °C and ~ 45% RH through the use of a mechanical ventilation system with an automatic air humidifier. These ventilation systems are usually used in passive houses and are provided with a heat-exchanger to reduce the heat losses through ventilation. The indoor conditions are also monitored continuously. The wall assemblies are oriented both at the north- and westward side of the test-house, but it is clear that the analyzed wall assemblies case 1 and 2 are only arranged at the northward façade.

Description of the Test House

Results and Discussion—Comparison In-Situ Measurements and Simulation Case 1

In this paper, a preliminary comparison between measured and computed results for the period July 2006 to May 2007 for the wall system case 1 is shown. On the surfaces of the MDF- and OSB- boards to the mineral-wool layer, capacitive humidity sensors were installed to measure the hourly values for relative humidity and temperature. Figure 22 gives an overview of the measured values at these surfaces compared with the corresponding computed values. Note that the correlation between measured and computed RH is currently not absolutely accurate; hence, the simulations were initially performed with still imperfect climatic data. Never-

__Figure 21__ Prefabricated wall assemblies and built-in measurement equipment.

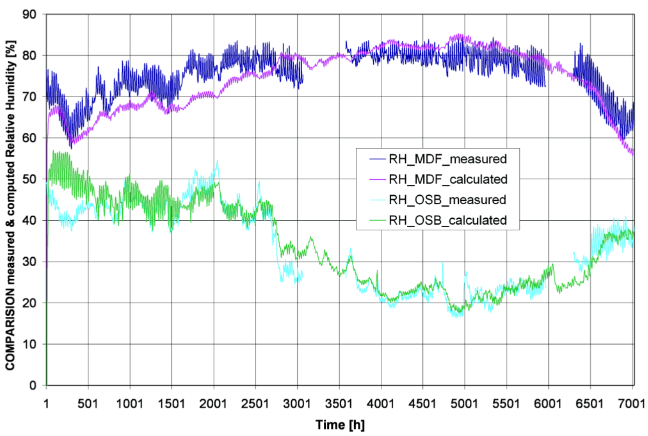

***Figure 22** Comparison of measured and computed relative humidity of the surfaces of OSB and MDF boards—Case 1: Measured climate, south Austria.*

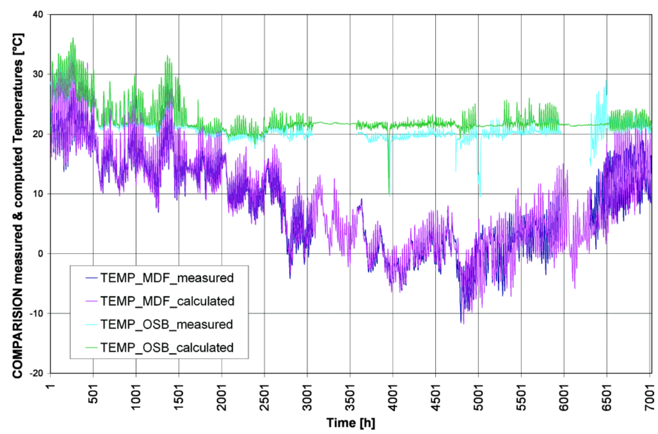

***Figure 23** Comparison of measured and computed temperatures on the surfaces of OSB and MDF boards—Case 1: Measured climate, south Austria.*

theless, the values for both show a similar gradient. The measured relative humidity on the outside MDF- board varies between ~ 60% at the beginning up to a maximum of ~ 85% during the wintertime, which is similar to the results of the presimulation for the Holzkirchen climate. The RH at the inside OSB- board is raising from ~ 40% at the beginning to ~ 55% in fall and decreasing during the wintertime to ~ 20%.

The temperatures at both surfaces were measured (Figure 23). The temperature at the MDF- board varies between ~ 28 °C in summer and ~ -12 °C during wintertime similar to the computed results. It is well to see that the measured temperatures on the inside OSB- board are much higher than the calculated ones, which is caused by the missing outdoor shading of the building at the start of the research project. Although the period of measurements is quite short, it is suspected that case 1 shows a good hygric performance in the Austrian climate.

DISCUSSION AND CONCLUSIONS

This paper shows that new types of lightweight wall constructions should be designed with the help of hygrothermal models. The used dew-point- method (Glaser Diagramm) usually used in Austria is not accurate enough to predict the influence of different solar irradiation influences, especially wetting processes due to driving rain.

The developed wall system case 1 shows good hygric behavior, and even in the rough Holzkirchen climate, moisture-related problems should be avoided. The results of the investigations concerning case 2 offered that the application of woodwool- panels on the exterior side of timber walls highly depends on the driving rain penetration. An execution of such wall assemblies at locations with high driving rain loads could probably result in an unacceptable moisture accumulation not only in the woodwool- board but also in the outer areas of the wooden structural system. Further simulations for more moderate climates, like that of Austria, indicated that under these circumstances harmless moisture accumulations in the critical construction parts would occur. Summing up, we can observe that both investigated wall systems have the potential for successful use in passive house technology, but possible affecting influences due to boundary conditions (e.g., exterior climate, etc.) should be considered.

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