First monitoring results of three straw bale buildings in Belgium

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ABSTRACT

Straw bale use in buildings may be an interesting way to decrease our energy needs and our impact on environment. The present paper describes an experimental set up to monitor three straw bale buildings recently built in Belgium. For each building, results on temperature and relative humidity, inside and outside, are analyzed, as well as internal evolution of temperature and humidity distribution in the walls. The first building is an office building where two finishing are compared. Measurements also provide additional data on CO_2 levels and electric consumption. The two other buildings are dwellings where live one single family. In the first one, a wall in the bedroom and a retaining wall are analyzed. In the second one, a wall in the bedroom and a wall in the bathroom are analyzed. Their hygrothermal behavior is discussed based on simulation results obtained with WUFI Pro and WUFI Plus software. The criterion for the validation of wall behavior is based on water content distribution through the walls. The paper confirms the great potential of this type of building technology and helps to identify how to assess and validate their effective hygrothermal behavior.

Key words: *Straw bale, field measurements, whole building simulation, water content criterion*

INTRODUCTION

Straw bale building techniques are evolving since the XIXth century. Some techniques are still evolving and prefabrication of entire walls has started in Belgium since few years. The present paper presents results based on an experimental setup installed in three straw bale buildings in Belgium. For each of these cases, the straw bale walls were prefabricated in the same factory with the same building technique, except small variations. The wall is built with 46 cm or 36 cm of straw (structured with a timer framed structure), covered on the inside with an 4cm earth plaster and on the outside with a 1.6 cm bracing panel (open to vapor). This walls typology was presented in [Evrard et al., 2012].

The first building is a small office building (approx. 80m²) built in a large industrial hall in Franière. It is thus protected from rain and direct sun. The walls are built with 46 cm of straw. Preliminary simulation results were presented in [Evrard, 2013]. As the building is occupied since September 2013, almost 9 months of monitoring can be analyzed.

The second building is a family house (approx. 225 m²). The monitoring also started in September 2013, but because of undesired power supply failure, only less than 5 months of data can be analyzed. Two different walls are compared, both built with 46 cm of straw. One is facing west and inside environment is a bedroom; the other is a retaining wall in the entrance hall.

The third building is also a family house (approx. 120 m²) built in an urban context in Uccle. It has an attached house on one side. The monitoring started in November 2013 and around 7 months of measurements were thus analyzed. The walls are built with 36 cm of straw in this case. As in the other house, two different walls are compared. One is facing north and inside environment is a bathroom; the other is facing south and inside environment is a bedroom.

METHODOLOGY

The main objective of the monitoring setup presented in this paper is to enable the calibration of numerical simulations and to validate the performances of straw bale walls. It was thus necessary to gather complete climate data for each building (having a different location). For the three buildings, outside temperature and humidity was measured. Sun radiation was measured for the two family houses (west for the first one and south for the second one). Rain load was only measured for west wall in Tongrinne (second building). In addition, temperature and humidity of inside environment of the three buildings was measured, as well as temperature and humidity at different places through the wall. In this first building, complementary sensors were installed to measure CO_2 concentration, windows and doors openings, as well as a webcam to be able to assess occupation. Electrical consumption of monitored room is also measured.

All measures of temperature and humidity were made with the sensors Sensirion SHT75 (except surface temperature made with PT100). A special tube containing a chain of sensors was developed to monitor the temperature and humidity inside the wall, at specific positions. In the two first buildings, 5 sensors are respectively positioned at 2cm (under earth plaster), 11cm (first quarter in straw), 22cm (middle position in straw), 33cm (last quarter in straw) and 44cm (under bracing panel) from inside surface. In the last building, two chains of sensors were used, each with 4 sensors, respectively positioned at 2cm (under earth plaster), 11cm (first third in straw), 22cm (second third in straw) and 33cm (under bracing panel) and at 1cm, 12cm, 23cm and 34cm from inside surface. CO_2 concentration is measured with Gascard NG (3000ppm) sensor. All sensors are connected to a data logger Campbell CR1000 and sent by Internet on a dedicated sever. The data are processed with Microsoft Excel software to allow their use and comparison with numerical simulations. Simulations at wall level are achieved with WUFI Pro 5.2 software and WUFI Plus 2.1 software was used at the building level.

RESULTS

Building n°1: Small office building in Franière

Two different earth plasters on inside surface are compared. For each plaster, three chains of sensors were installed (high, medium and low height). Temperature and humidity evolution are similar for all of these cases, only small variation were observed. Temperature under inner plaster follows very closely the temperature of inside air, and temperature under the bracing panel follows approximately the temperature of outside air (in the hall). The difference is due to the thermal inertia of earth plaster (discussed in [Evrard, 2013]).

As shown in Figure 1 (left), outside temperature (in the hall) was almost never under 0°C. Inside temperature of monitored room falls sometimes under 12°C (6 times between end of November and beginning of February) and do not reach 20°C every working days even if the company installed three simple halogen lamp (400W) to heat the building (one in monitored room) end of November. The lamps are turned on in the morning (between 6am and 9am) and turn off at the end of the day (between 6pm and 8pm). As Figure 1 (right) shows, the occupancy is not regular and, sometimes, nobody is working in the office (i.e. end of December).

Figure 2 (left) presents the data collected in the straw bale for the wall with the plaster n°2, at an approximate height of 1m50 (medium height). It shows the evolution of relative humidity at the most humid point of the wall in winter, i.e. 1cm under the outer bracing panel, as well as the evolution of relative humidity at the driest point of the straw bale in winter, i.e. just under inner earth plaster. It appears that the relative humidity is always under 86% under the bracing panel. According to the sorption curve of straw bales measured in the laboratory, at this humidity, water content is around 16% of mass. Results obtained for plaster n°1 are relevant in this paper. Despite current regulation, no ventilation was installed. Figure 2 (right) shows the evolution of CO_2 concentration in monitored room.

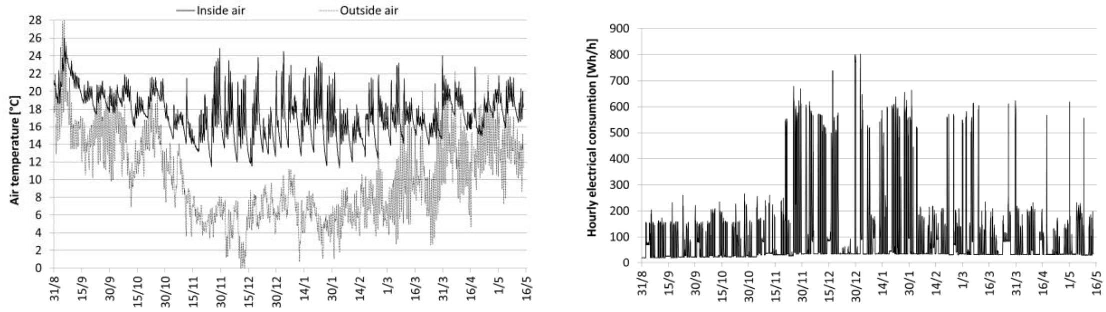

Figure 1 (left) inside and outside air temperature of monitored room in Franière (right) electric consumption of monitored room in Franière.

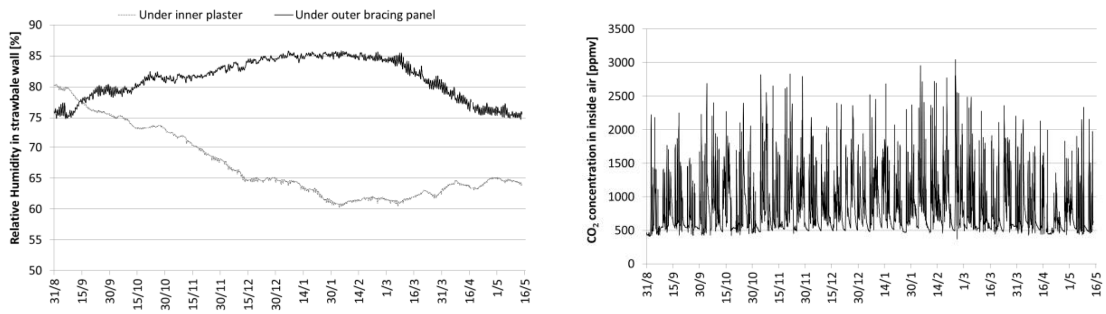

Figure 2 (left) relative humidity under inner plaster and under outer bracing panel of the wall with plaster n°2 in monitored room in Franière (right) CO_2 concentration of inside air in monitored room in Franière.

Building n°2: Family house in Tongrinne

The monitoring of this building started in September 2013, but because of undesired power supply failure, only less than 5 months of data can be analyzed. Two different walls are compared, both built with 46 cm of straw. One is facing west and inside environment is a bedroom; the other is a retaining wall in the entrance hall.

West wall is submitted to driving rain. A water-repellent render system (board, mineral under layer and finishing) was applied on outer surface. Figure 3 shows cumulative rain quantity and sun radiation for this wall, as well as relative humidity through the straw bale.

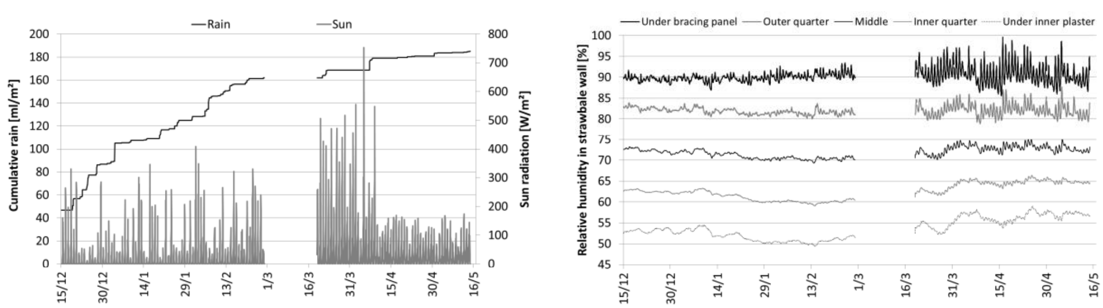

Figure 3 (left) cumulative rain quantity and sun radiation of vertical west wall surface in Tongrinne (right) relative humidity through the straw bale of west wall monitored in Tongrinne.

The other wall monitored in Building n°2 is a retaining wall. Inside environment is the entrance hall of the house. Outside environment is in the earth. A water barrier was installed again outer bracing panel, avoiding water to penetrate the wall, but preventing also vapor to transfer out of the wall on this side. Figure 4 (left) shows relative humidity through the straw bale in this wall (the sensor under the bracing panel do not send any information).

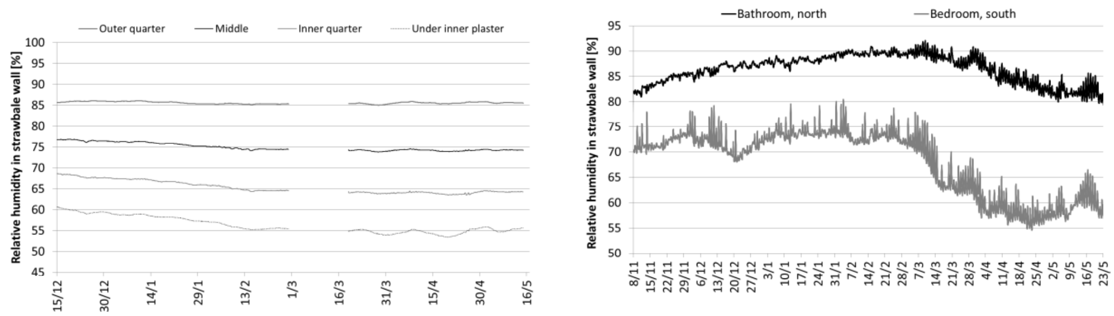

Figure 4 (left) relative humidity through the straw bale of retaining wall monitored in Tongrinne (right) relative humidity under bracing panel of north wall in the bathroom and south wall in the bedroom in Uccle.

Building n°3: Family house in Uccle

The monitoring of this family house started in November 2013 and around 7 months of measurements could thus be analyzed. As in previous house, two different walls are compared, both built with only 36 cm of straw in this case. The first wall is facing north and inside environment is a bathroom; the other is facing south and inside environment is a bedroom. Figure 4 (right) shows relative humidity under bracing panel (the most humid position in the walls) for both walls.

DISCUSSION

Building n°1: Small office building in Franière

Outside temperature and relative humidity from measurements, as well as heating input of electric power released in the room, where used as input in a WUFI Plus simulation (hygrothermal building zone analysis). All necessary material data were gathered during previous step of aPROpaille research. Main parameters are presented in [Evrard, 2013] (exterior wall type “S”). Occupation profile (one man working from 9am to 6pm on week days, with a break between 1pm and 2pm) did not take into account the lightings and the computer, as they are considered in the heating input of the room. Other inputs of the simulation represent real conditions of the unventilated office. A natural ventilation through door and window of 1vol/h between 9am and 10am and between 1pm and 2pm is considered together with a constant infiltration rate of 0.024 vol/h (equivalent to n_{50} = 0.6 vol/h, even if there was no blower door test). This case is thus similar to case S-2 of preliminary simulations presented in [Evrard, 2013].

As illustrated in Figure 5 (left), inside temperature resulting from simulation follows the same trend that measured values. Daily maximum temperature is quite close, but minimum temperature (i.e. after each week-end) is lower in reality. This difference can be due to the hypothesis on ventilation rate and occupation profile. The company should install an adapted heating system to reach comfortable temperature during working days.

Figure 5 (right) shows the evolution of relative humidity at the most humid point of the straw bale in winter, i.e. 1cm under the outer bracing panel, as well as the evolution of relative humidity at the driest point in the straw bale in winter, i.e. just under inner earth plaster. There is a sensible difference between measurements and simulation results in terms of relative humidity in the straw bale. Simulated relative humidity in the straw bale follows the same trend; however, the maximum value under the bracing panel and minimum value under inner plaster are respectively 5% higher and 5% lower in the simulation. This rather small difference is not further analyzed in this paper. As a matter of fact, the relative humidity is always under 90% under the bracing panel. At this humidity, water content of the straw bale is under 20% of mass. According to [Wihan, 2007], no decomposition will occur under a water content of 25% in mass and a degradation of 0,009% a day appears when water content of straw is between 25% and 39% of mass. This analysis depends on the sorption curve of the straw bale and on organic decomposition rate (the values may depend on the density of the straw bale, the type of plant…).

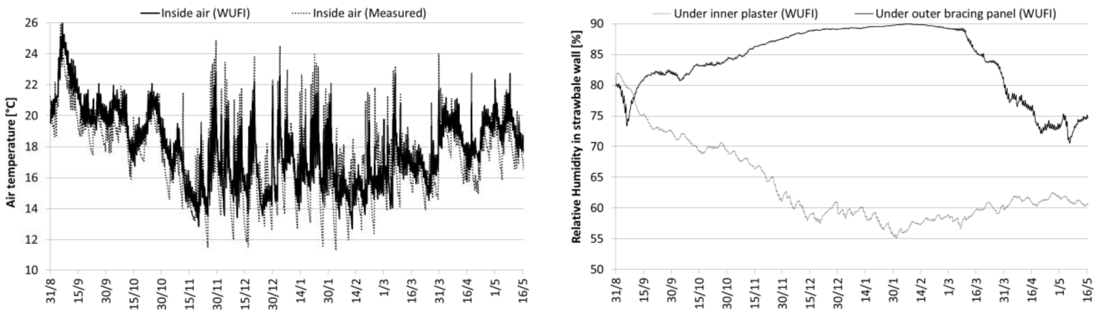

Figure 5 (left) inside air temperature in Franière, simulated with WUFI Plus software (right) relative humidity under inner plaster and under outer bracing panel in the straw bale with plaster n°2 in Franière, simulated with WUFI Plus software.

One last remark can be made on the evolution of CO_2 concentration in the simulation. As we defined a constant occupation every week-days (with a break at noon) and almost no ventilation, CO_2 concentration rises every week-days until around 3700ppmv (vs. maximum value measured is 3000ppmv). A ventilation system (around 30m³/pers) can be used to reduce CO_2 concentration under 1000ppmv (Belgian regulation NBN EN 1377-2007). A precise occupation profile could be assessed based on measured CO_2 concentration, but this goes beyond the scope of this paper because it would need, in addition, a complementary analysis of ventilation rate.

Building n°2: Familly house in Tongrinne

Outside and inside temperature and humidity, as well as sun exposure and rain load on west wall were used to run WUFI Pro simulations (1D hygrothermal analysis). Missing data between the 28th of February and the 19th of March were filled with data measured between the 7th of February and the 26th of February for continuity of the climate file. Material data were gathered in previous step of the research (see [Evrard, 2013]).

For the water-repellent render system, density, thermal conductivity and vapor diffusion resistance factor of each layer were collected from producers. Other parameters (porosity, specific heat capacity, sorption curve…) correspond to a "Cement Plaster" in WUFI database, except liquid absorption coefficient (A-value). Finishing mattering is announced to be "water repellent" and A-value is set to 0.0017 kg/m²s$^{-1/2}$. The producer indicates that sd-value of this layer is higher than 0.5m. As layer must be minimum 1mm in WUFI Pro, the vapor diffusion resistance factor of this layer is set to μ=500 (500*0.001m=0.5m). A-value of the board and render are set to 0.0083 kg/m²s$^{-1/2}$ corresponding to the worst value in class II of standard NF EN 1062-1 (W2 announcer by producer).

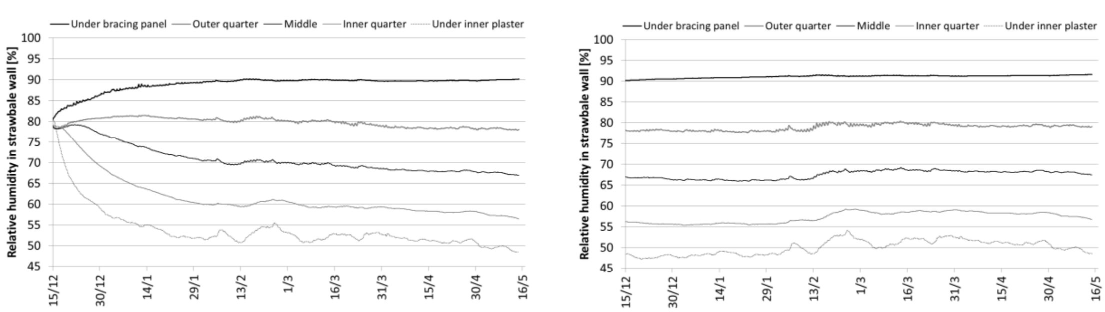

Figure 6 (left) relative humidity through the straw bale wall orientated to the west in Tongrinne (first period), simulated with WUFI Pro software (right) relative humidity through the straw bale wall orientated to the west in Tongrinne (second period), simulated with WUFI Pro software.

Figure 6 (left) shows the simulated relative humidity through the straw bale wall of the west wall in Tongrinne. Initial humidity of the straw bale was set to 80% (constant through component). The two first months are thus very different form measured value, but from the 15th February until 15th of May, the results are in very good agreement. The main difference is the higher daily amplitude of the variations of relative humidity (especially close to outside) in the measurements, but average values are similar.

Measured values are very often over 91.4% of relative humidity, corresponding to a water content over 25% in mass. Simulated values rise until 90% of relative humidity and seem to continue to rises as time passes. A second period (with the same climate file) was simulated starting with water content profile obtained at the end of the first period (which was rather rainy). Figure 6 (right) shows that an accumulation of humidity can be observed. The maximum water content during second period is over 25% of mass. An explanation of this problematic behavior is the rather high vapor permeability of finishing layer (sd = 0.5m or more). If this layer has a sd-value of 0.05m, the simulation shows no moisture accumulation and relative humidity under the bracing panel stays under 90%.

A this point, it has to be noticed, that equivalent simulations, using "test reference year" (TRY) in Uccle (50 km from Tongrinne) for outside climate and EN15026 standard for inside, do not reveal any problem in the wall. The relative humidity of the straw under the bracing panel gets close to 90% but decrease after the month of June. No accumulation is observed and no degradation should occur. It is thus too early to conclude that organic degradation will occur in the straw over time as a significant decrease of relative humidity at this specific place may be observed in following months (summer period).

To simulate the retaining wall, only inside climate was used as an input for simulation. For outside climate (in the earth), a sinus variation of temperature around 15°C and with amplitude of 3°C (maximum on the 1st of August) and a constant humidity of 99% are chosen. No absorption of water is allowed in the wall and a 1mm layer with very low vapor permeability is considered (sd=1500m). As in previous simulation, initial humidity of the straw bale was set to 80% (constant through component). Figure 7 (left) shows that there is a difference of around 5% of relative humidity between simulated results and measurements at the end of the first period. Under the bracing panel, the relative humidity seems to decrease after the 15th of April (the sensor at this position does not send any information). At the opposite, relative humidity under inner plaster seems to increase after end of March. When repeating simulating a second period, starting with water content profile obtained at the end of the first period, a significant decrease in straw bale humidity can be observed, as shown in Figure 7 (right). The results are similar when using a usual inside climate ("normal moisture load") based on standard EN15026 with TRY reference climate in Uccle (50km from Tongrinne): the maximum relative humidity under the bracing panel during the third year is 83% (86% with "high moisture load"), with no accumulation. Before drawing any conclusion, positive results from simulations suggest to wait to have a longer measuring period to further discuss measured values.

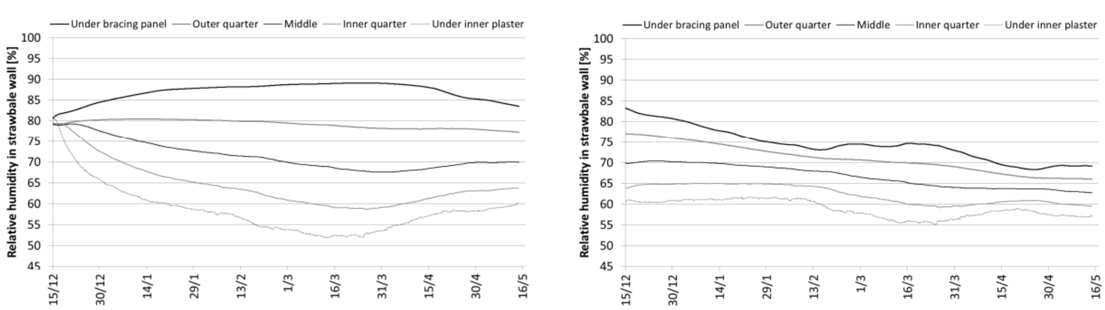

Figure 7 (left) relative humidity through the straw bale retaining wall in Tongrinne (first period), simulated with WUFI Pro software (right) relative humidity through the straw bale retaining wall in Tongrinne (second period), simulated with WUFI Pro software.

Building n°3: Familly house in Uccle

Outside and inside temperature and humidity (in both rooms), as well as sun exposure on south wall were used to run WUFI Pro simulations (1D hygrothermal analysis). Material data were gathered in previous step of the research (see [Evrard, 2013]). A render on outside surface (2cm) was applied on both walls on a wood-cement board (2.5cm) fixed on a wood structure (unventilated air layer of 3cm) directly on bracing panel. The total complementary sd-value of those three layers is supposed to be around 30cm. Rain absorption of outside surface is neglected in the simulations (no rain load was measured in Uccle and the render is supposed to be water-repellent). Inner finnishing is also neglected for both walls (thin lime plaster).

Figure 8 shows that there is a significant difference of relative humidity under the bracing panel between measurements and simulation results. In the bedroom, simulation results are 10% to 15% higher during the two first months and after four month. In the bathroom, results are similar at the beginning and at the end of the period, but diverge between the second and the seventh months (difference up to 15%). At this point, these simulation results cannot be used because they may not be relevant. This might be due to hypothesis on rain, or on material parameters (outside render and inner plaster). Further research is needed. However, it has to be noticed that measured values are fine in the bedroom (relative humidity of the straw under the bracing panel is always under 80%) and, for the bathroom, they exceed 91.4% of relative humidity under the bracing panel, only during few days.

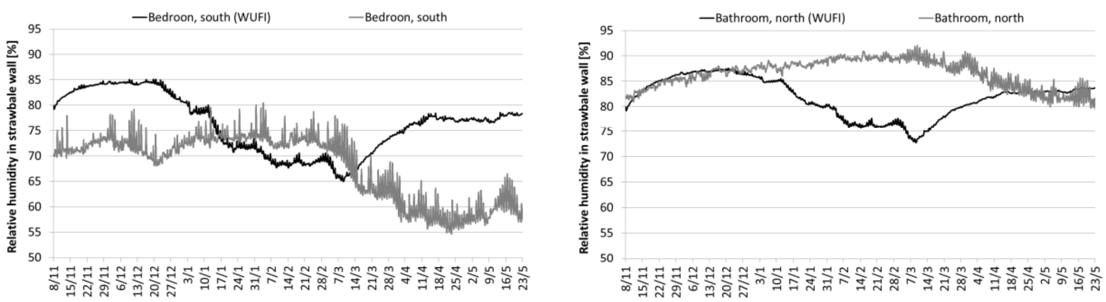

Figure 8 (left) relative humidity under bracing panel of south wall in the bedroom in Uccle, simulated with WUFI Plus software (right) relative humidity under bracing panel of north wall in the bathroom in Uccle, simulated with WUFI Plus software.

CONCLUSION

The paper presents the first analysis of the data collected in three straw bale buildings in Belgium: one office and two family houses. All data are collected on a dedicated server and are analyzed after a processing with Microsoft Excel software. Based on [Wihan, 2007] and [Evrard et al., 2012], validation of wall behavior focusses on the humidity in the straw bale. Relative humidity of straw should not exceed 91.4% (corresponding to a water content of 25% of mass). The most humid place in the walls (if no undesired source of humidity exists), is located few centimeters under the outer bracing panel. Results at this place are discussed based on simulation results, either with WUFI Pro (using indoor and outdoor climate from field measurements) or with WUFI Plus software (when data on occupation and heating load are also available).

The office building in Franière (Building n°1) was built in an industrial hall and is not submitted to rain or sun. Therefore, the analysis of occupation and heat load was simplified. All data were analyzed with WUFI Plus software. The behavior of all walls was validated (no decomposition will occur). A relatively good agreement between measured relative humidity and simulation results were observed (i.e. less than 5%). Inside temperature from simulation follows the same trend as measured values, but do not decrease as fast at night and during the week-end. Additional research on occupation profile and ventilation rate should help to calibrated more precisely the simulations (e.g. in terms of CO2 concentration of inside environment).

In Tongrinne (Building n°2), west wall seems to have a problematic behavior as the relative humidity in the straw under the bracing panel is often higher than 91.4%. In addition, simulation results indicate that the wall may have a moisture accumulation problem. However, other simulations using test reference year (TRY) in Belgium did not confirm this result, and a new analysis of monitored data should take place after summer period. This uncertainty may come from unknown material parameters of outer render added on prefabricated straw bale walls.

The second wall in Tonginne is a retaining wall. Unfortunately, one sensor (under bracing panel) does not send any data. The simulation is rather positive as it shows that on a longer period, the humidity of the wall should decrease under critical value. A special attention will be given to this wall in the future as it is normally avoid designing retaining wall with straw bales.

In Building n°3 (in Uccle), simulation results did not fit measurements. Again, this could be due to unknown material parameters of outer render added on prefabricated straw bale walls. In addition, west wall is submitted to driving rain, but no rain measurement was implemented in this case. Further analysis of this building is needed to validate hygrothermal behavior of the walls. Nevertheless, measured values are not considered to be critical (only few days over 91.4%) in this case.

If many data can still be not explored, the monitoring implemented in three straw bale buildings can already confirms that it is possible to design and validate straw bale walls based on a single quantified criteria: moisture content of straw few centimeters under the bracing panel. More research is needed to understand the link between critical moisture content and other parameters (density of the straw bale, type of plant, forming process of the bale…).

In the meantime, straw bale walls can be trusted to design high efficiency house and to offer comfortable and sustainable living places.

ACKNOWLEDGMENTS

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