Article:

Yin, X., Lawrence, M., Maskell, D. et al. (1 more author) (2018) Construction and monitoring of experimental straw bale building in northeast China. Construction and Building Materials, 183. pp. 46-57. ISSN 0950-0618

https://doi.org/10.1016/j.conbuildmat.2018.05.283

Construction and monitoring of experimental straw bale building in northeast China

Yin Xunzhi[1]*, Lawrence Mike[2], Maskell Daniel[3], Chang Wen-Shao[4],

[1,2,3] Department of Architecture and Civil Engineering, University of Bath, Bath, BA2 7AY, United Kingdom

[4] Sheffield School of Architecture, The University of Sheffield, Sheffield, S10 2TN, United Kingdom

** Corresponding Author*

ABSTRACT:

Straw bale buildings have the potential reduce the environmental impact of construction. Although the technique has been introduced into northern China more than a decade ago, the construction method and potential problems within straw bale walls have not been fully understood in existing research. Following an analysis of existing straw bale construction both in north China and worldwide, this paper proposes modifications to the straw bale construction details currently used in north China. The modifications involve in-fill raw material, toe-up design and lime render application. These modifications were incorporated into an experimental building constructed in north China, and after having been monitored for 12 months, the modified construction details were critically assessed. The data demonstrate that rice straw bale walls are resistant to agents of decay and offer reduced construction time and cost than standard wall construction in north China. The construction method has the potential to become a mature construction system in the Chinese market in the future offering significant benefits both in construction and operational cost and in environmental impact.

1. Introduction

Straw has been used for thousands years in building construction as reinforcement material of earthen constructions. During the 19th century straw was used in bales to form walls of buildings in Nebraska (1). The use of straw bale buildings ceased after the initial phase when it was replaced with more traditional materials such as brick, steel and concrete as these became more accessible due to the expansion of and improvement in transportation in the late 1800s (2). The energy crisis in 1970s led to an awareness of the environmental impact of human activity, and interest in low environmental impact materials increased. Straw bale buildings were initially introduced to northern China by the Adventist Development and Relief Agency (ADRA) in 1998 (3). More than 600 straw bale buildings had been finished in the project by 2006 (4). There are three significant advantages in using the straw bale construction:

- Straw bales act as a carbon sink building material and it has significantly lower embodied energy and embodied carbon than conventional materials (5).
- Straw bale walls can provide high-quality physical properties including sound insulation, seismic stability of structure and low fire risk (1).
- Because of the relatively high thermal insulation properties of straw bale walls, straw bale houses have low heating energy load and cooling energy load (6).

Provinces in north-east China produce very large volumes of agricultural products which include rice and wheat. The total rice production is around 203 million metric tons annually (7). Using straw in the construction industry could solve the straw disposal problem and decrease building heating load due to its high thermal resistance. Application of the properties of the construction system will help to deliver Chinese government's carbon reduction target of 40%-45% of the 2005 level of by 2020 proportionate to GDP (8).

The aim of the study is to develop a suitable straw bale construction system for the typical Chinese northern climate area and to verify suitability of the design in this climate area. This paper presents a design for a straw bale building which has been modified from existing practices worldwide. An experimental building was monitored over a period of one year for relative humidity and temperature within straw bale walls. The experimental building was visually inspected for defects and the monitored data was compared with an inspection of the condition of the straw bales at one year.

2. Background

2.1. Straw bale construction designs globally

There are two basic methods of constructing straw bale buildings (9): using straw bales as a primary structural element or as an in-fill with a frame construction (1, 2, 9, 10). Despite different approaches to building with straw, they share certain similarities.

The most fundamental element is the straw bales. The straw bales can be placed either flat or on edge in straw bale buildings(2). The laid flat construction is normally applied in load-bearing construction with no less than bale density of 130kg/m^3 (1). The laid on edge construction is always applied in non load-bearing constructions and curved walls (1). There is no strict bale density for non load-bearing straw bale buildings and the densities are normally greater than 70kg/m^3 in the industry (2, 9, 11). To stabilize bales within walls during construction phase, pinning systems are used in straw bale construction (1, 2, 9-11). There are two distinct approaches that have been designed for connecting straw bale walls and other building components (2, 9, 11). The top plate connects straw bales with the roof structure and the base plate connects the bale walls with the foundations (12). Plastering is applied to straw bales in a similar method to that used for conventional walls (1). For prefabricated straw bale panels, there is a separate frame for containing straw bales. Straw bale panels are connected to roof and foundation through different joint designs of the frame (13).

2.2. Predicting straw degradation within straw bale walls

To verify degradation potential of straw within sealed walls, research has been conducted into monitoring the hygrothermal environment inside the walls and the moisture content of straw bales within walls.

One of the early monitoring of hygrothermal environment within straw bale walls was supported by the Canada Mortgage and Housing Corporation (CMHC). The monitoring results involved relative humidity and temperature (RH/T) data of straw bale walls at different depths of wall sections (14). Studies have shown that the RH/T changes within straw bale walls synchronize with seasonal change in the local area of the monitored building (14). A purely experimental straw bale wall assembly, completed in Waterloo, Canada, was monitored immediately after construction and has been the object of subsequent research (15). The research used monitoring data to verify a WUFI simulation process (15). Moisture modeling is greatly affected by driving rain and the moisture modeling was not as precise as the thermal one (15), which also suggested that breathability of render materials is critical for straw bale status with respect to straw degradation (15). A similar result for the properties of render material was shown in research in UK. Use of low vapour permeable rendering material led to an increase in internal RH and would result in straw degradation behind the render (16). This research also showed that a rain screen can increase weather resistance of straw bale walls (16). However, the effect of rain screen has total different effect in another research in hot and humid summer area in Furyu in Japan (17), which demonstrated that a passively ventilated rain screen produced elevated RH in lower areas of straw bale walls (17).

The using of RH/T monitoring data can be analyzed in two methods to examine conditions within straw bale walls. By using the Tabata equation(18), the RH/T data can be converted to actual water vapour pressure data to know drying process of rendered straw bale wall:

$$\log_{10} e = 9.28603523 - 2.32237885\left(\frac{10^3}{T + 273.15}\right)$$

Where:

$T = \text{Temperature in degrees celsius}$

$e = \text{Saturation vapour pressure in T}$

$$\text{Relative Humidity} = \frac{e_{actual}}{e}$$

Where:

$e_{actual} = \text{Actual vapour pressure in T}$

$e = \text{Saturation vapour pressure in T}$

By making use of the sorption isotherm of straw, the moisture content data can also be converted to relative humidity data. Initial degradation of straw is triggered when moisture content becomes greater than 27% for extended periods of time (19). The critical RH level, taken from the sorption isotherm of wheat straw, to produce a moisture content of 27% is therefore around 85% RH (20).

3. Construction of the experimental building

3.1. Local climate of the design straw bale building

The experimental straw bale house was constructed in Changchun, in the Jilin province of northeast China. The area is subject to a typical temperate monsoon climate. Temperature peaks at around 30℃ in summer in the area and drops to below freezing after late October annually (21). The highest monthly air humidity level is 88% in January (Figure 1), where monthly humidity levels are from 63% to 72% in summer during which the highest temperature appears.

Buildings are required to have high thermal resistance for supporting human activities through cold winter months in the area and therefore straw bale buildings are widely considered to be a suitable building type for northern China (22). However, high air humidity levels in winter and summer time would slow moisture the movement from rendering of straw bale walls to atmosphere and therefore lead to an extended drying period for straw bale buildings. A combination of high temperature and high humidity levels in summer could also increase the potential for degradation of straw within the walls.

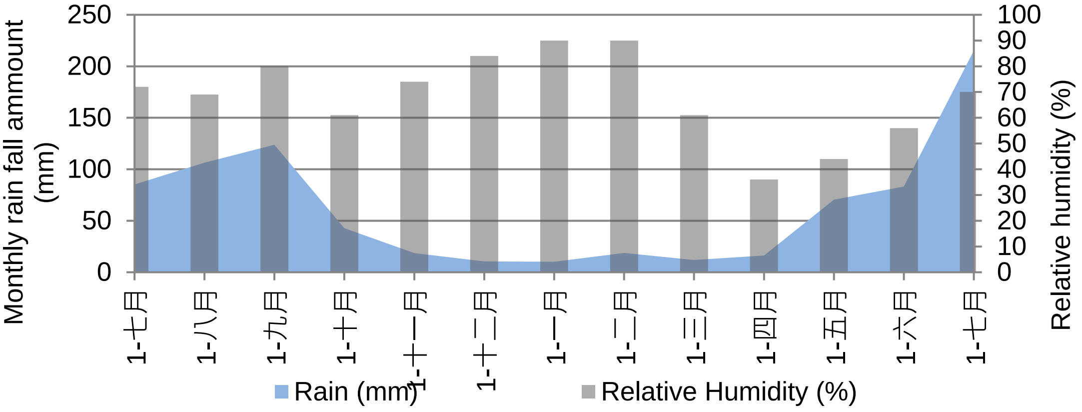

Figure 1. Average monthly Humidity and rain fall in Changchun from July 2016 to June 2017. (21)

3.2. Design of the experimental building

The design of the experimental building included the use of a specific straw type and new detailing designs. The raw material of the bales was rice straw. There are several advantages of using rice straw in the design of the experimental building. Firstly, rice straw is reported to be a better baling material than wheat straw by practitioners in California (1). Secondly, due to the rice straw is an agricultural waste in north China, rice straw should potentially be a much cheaper construction material for construction than currently used in-fill materials in north China. Thirdly, the air pollution problems in northern China demand environmental friendly disposal solutions for rice straw, rather than the current practice of burning in the fields (23). The rice straw was sourced from large bales produced by a New Holland Baler on the field and was re-baled in the factory.

The experimental building is a single story bungalow with pitched roof. The structure and foundation is made of cast concrete, being the construction technique with which the builders used in this project are familiar. Both laid-flat stacking and laid-on-edge stacking of straw bales are applied in the construction (Figure 2). A section of north facing wall with laid-flat straw bale is left unplastered on the interior surface of the wall and wood frames are used to create a truth window which only shows the straw bales. The truth window is designed on the mid height of the wall to visually examine straw degradations.

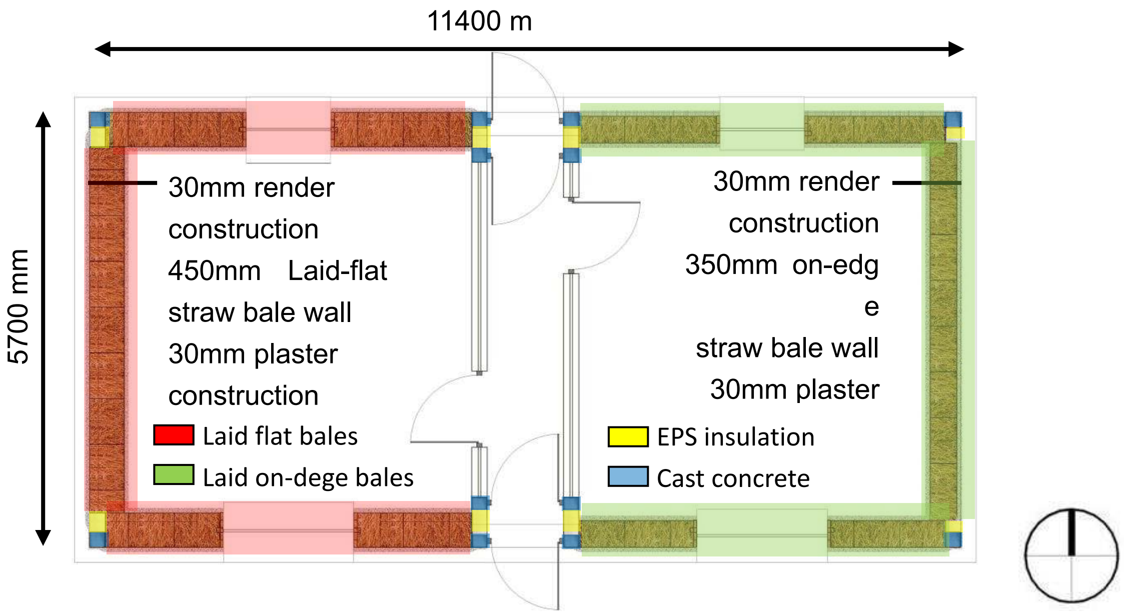

Figure 2. Floor plan and applied bale stacking.

3.3. Modification in the experimental building

Compared with current construction methods, there are three innovations of the straw bale house include introducing pinning system toe-up design of straw bale walls and render material selection in the area.

The experimental building introduces a pinning system in the construction. The pinning system uses pointed timber dowels to connect each bale. Connections between bales are referenced from Jones (9) and Myhrman & MacDonald (2). The pinning system introduces horizontal pins to fix the bale walls to columns. The horizontal pins are made of edged rebar and they are passed through preformed holes within the concrete columns. The horizontal rebar pins can increase buildability and stability of the bale walls during construction (Figure 3).

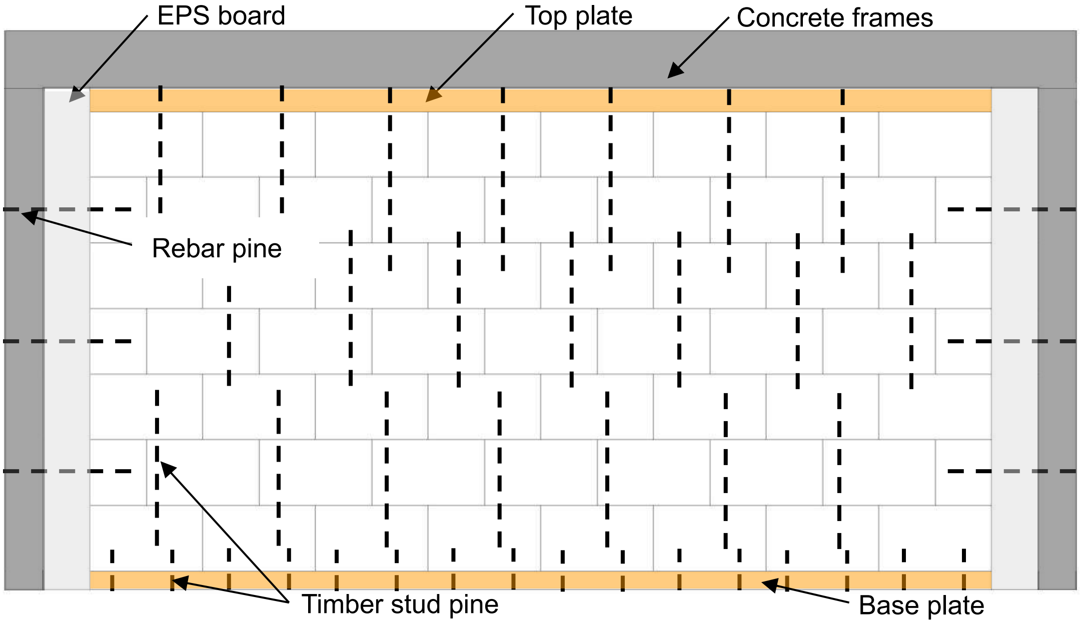

Figure 3. Pinning system of the experimental straw bale building.

The toe-up construction used is a variation of the typical timber base plate structure which is designed by Jones (24). The base plates in the construction contain 100mm x 50mm toe-up timber beam, timber noggin between the beams, timber stud pin and thermal insulation materials (Figure 4). The timber stud pins are used to replace hazel rod in the Jones's system (24) because of poor availability of hazel in north China. Because the industrial timber studs have round and smooth surface, each timber noggin contained two holes for pins to provide sufficient fixing to the bales.

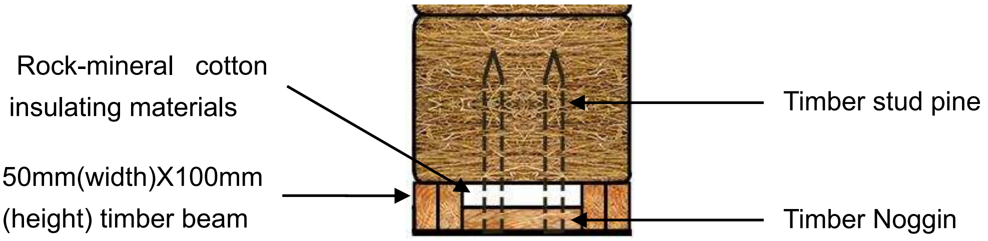

Figure 4. Toe-up base plat and timber rods

In contrast with existing Chinese straw bale design, the experimental building includes the first application of a lime render in north China. The lime based render is used in many projects in UK and US (1, 12). The construction references the construction detail and applying process of lime render in the Canada, the US and the UK. The render can provide breathability for straw bales within walls. A breathable render layer is essential for keeping straw in good condition and a cement render may not serve the purpose sufficiently (16). Because there is no current application and understanding of using lime based render in straw bale buildings in northeast China, the use of lime render might be problematic in dealing with thermal shock issues. However, because there is no thermal shock issues discussed in the Canadian research (15), the issue is not expected to be a cause for concern in this research project.

4. Monitoring of hygrothermal environment within straw bale walls

Long term monitoring of the experimental straw bale building began after the the construction was completed. Monitoring of the houses focussed on the hygrothermal environment within the straw bale walls. The monitoring equipment in the study consists of embedded hygrothermal sensors and data loggers (Figure 12). The sensors are the TRH-100 Temperature & RH Probe and they are manufactured by the Pace Scientific. The sensors have accuracy of ±0.3℃ from -25℃ to 85℃ and ±1%RH@50% (±3% 0%-95%RH). The data loggers are RHR300-W411 which are produced by the Dalian RHsens Technology Co., Ltd. Each logger connects to two sensors. The data logger records real time RH/T of sensors within straw bale walls each hour on the hour. The sensors were installed during the construction and they are linked with data logger after completion of lime plaster layer.

Total 20 sensor locations are designed to provide monitoring data inside every façade of the building. The placements of sensors was designed to monitor the most problematic areas for straw degradation seen in similar climatic regions in Japan(25) and Canada (15). The sensors are installed beneath the top bales, on the top of bottom bales and beneath the bale under the window sill on the south facing walls and north facing walls (Figure 5). Each location has two sensors in different depth in straw bale wall. The sensors were placed at a depth of 100mm below the external surface and internal surface of straw bale walls. The monitoring results were compared by examining the actual vapour pressure within walls and the duration of periods where humidity exceeded 85% RH.

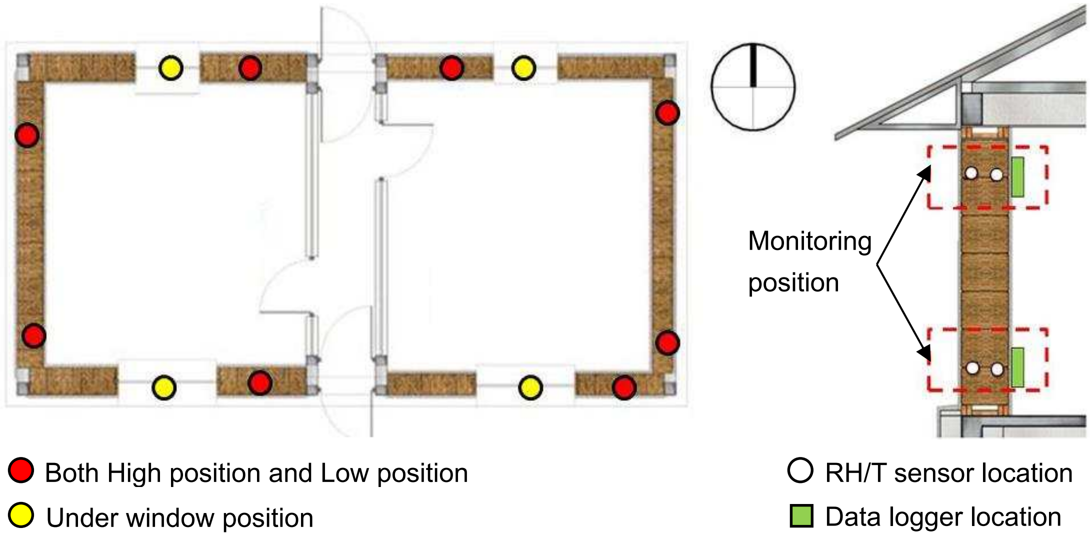

Figure 5. Floor plan (left) and walling section (right) with sensor location

The final stage of the monitoring research involved a visual check of the straw bale walls and the heating of the building to 25℃ for 12 hours half-way through the monitoring period (17th January to 18th January). The purpose of heating the building was to check for thermal bridging issues associated with the construction of straw bale walls.

5. Monitoring results

5.1. RH/T within straw bale wall

The data of all monitored locations are collected from 19th July 2016 to 19th June 2017. Three positions were faulty. There were no data recorded from the low position of the north face on-edge stacking wall, southern high position of west gable-end wall and northern high position of west gable-end wall.

The monitoring data showed high RH at the beginning of the monitoring period. The RH readings remained at 100% RH on all faces of the experimental building over the winter period, reducing in spring-time. Typical trends of the monitoring data can be taken from the high position of north facing wall with laid flat bales (Figure 6).

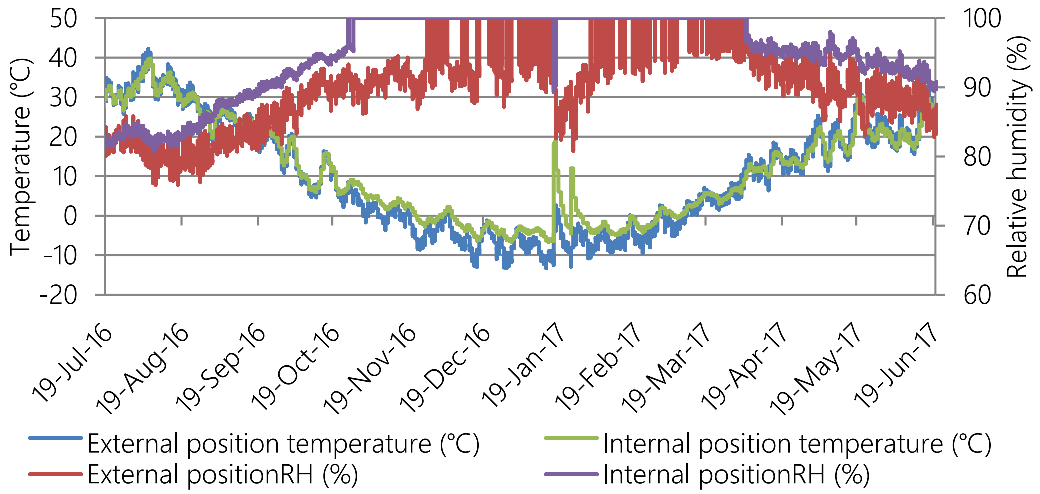

Figure 6. Monitoring data of the high position of north facing wall with laid flat bales

The monitored temperature of the position increased initially and peaked around two weeks after the monitoring began. The highest monitored temperature is 44.8 ℃ at the position under the window of the south face of the on-edge stacking wall. The monitored temperatures remained consistently below freezing point from around the beginning of November and the monitored temperature stayed below 0℃ until March of the following year. The lowest monitored temperature is -14.7 ℃ and it appeared under the window position of the north face of the on-edge stacking wall on 29th December 2016. The onsite visit had an impact on the monitored data from 16th

January 2017 to 18th January 2017, when the internal space was heated to examine the building for thermal bridges. The temperature of all the monitoring positions increased above 0℃ and the humidity levels of the positions decreased to around 80% between 16th January 2017 and 18th January 2017. These changes disappeared after 19th January 2017.

The RH distributions through wall sections are different in north facing wall compared with the other three walls orientations. External sensors at the positions inside the north facing wall showed that the RH levels from the external sensor increased faster than internal positions and the RH levels were consistently higher than internal sensor locations. The RH distributions through wall section were the opposite inside the south facing walls, east gable-end wall and west gable-end wall.

There are two possible explanations for RH readings of 100%: Firstly, the sensors used lack sensitivity at very high RH levels, with the maximum reading jumping from 94% - 95%RH to 100%RH with no intermediate readings. As a result, the displayed 100% RH reading could actually be somewhere in the range of 94% RH to 100% RH. Secondly, the 100% RH reading could also be affected by the freezing of condensation. The monitoring data in Figure 11 showed fluctuating results for the RH level from 95% to 100% from late November to early December. The fluctuation of RH was occurring at the same time as the temperatures were fluctuating around freezing point. The results of the fluctuating temperature around freezing point may induce the freezing of condensation within the straw bale walls. If ice is formed on the surface of the RH sensor, the sensor is unable to measure the RH of the atmosphere. Because the mechanism of RH sensor is to measure electric resistance between two sensor nodes, measuring pure ice will give a faulty result of 100%RH to the sensor. As a result, the real RH situation is overestimated.

A study carried out in a similar climatic region to this research also identifies similar problems when using electronic RH sensors during the first year of monitoring (15).

Considering high atmospheric RH (80%-90%) and low atmospheric temperature (-10℃ to -20℃) in winter time in local area in this research, the use of electronic RH/T sensor may not function properly during winter time. Future research might benefit from the use of both calibrated wood stick probes (26) and electronic RH sensors to measure the RH levels within straw bale wall.

5.2. Actual water presence in monitoring positions

The monitored RH/T data is a guide to the hygrothermal environment within straw bale walls. However, it is difficult to predict either actual water content inside straw bale walls or vapor movement between straw bale walls and external environment. The vapour pressure of all monitored positions kept increasing to highest level two weeks after the beginning of the monitoring period. The highest vapour pressure levels were around 76-77 millibars and they appear in external sensor locations of low positions on south facing walls (Figure 7). Other than the low positions on south facing walls, the peak vapor pressures of the monitoring positions are all below 70 millibars. After initial increase of vapour pressure in all the monitoring positions, the vapour pressure levels decreased in the following months and rise again after January 2017.

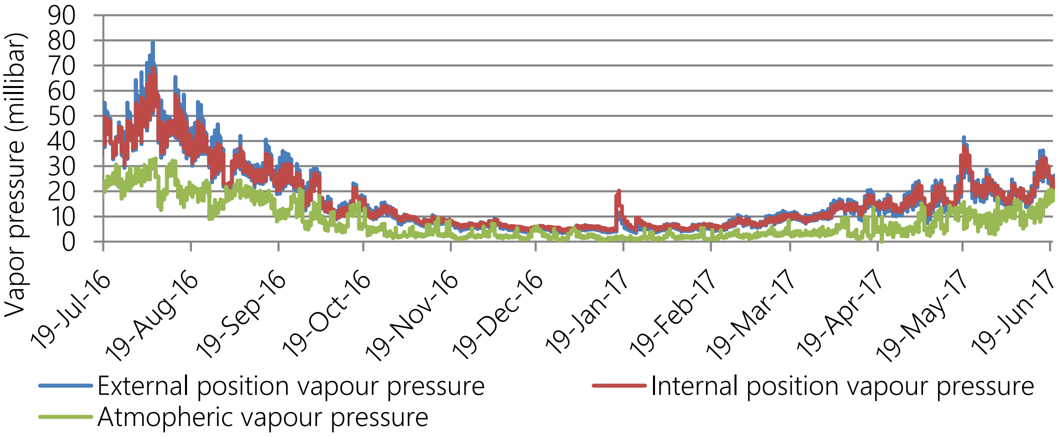

Figure 7. Vapour pressure of sensor locations (down) within low position of the south face of on-edge stacking straw bale wall.

The initial decreases of vapour pressure data present a drying trend of the straw bale walls. However, due to unreliable RH/T data from December to January, the actual vapour pressure data of all monitoring positions are not accurate during the period of time. A demonstration of the unreliable vapour pressure data is the significant increase of vapour pressure data during heating process during the on-site visit from 17th January 2017 to 19th January. At the end of the monitoring period, sensor locations within south wall have lowest vapour pressure data than the ones within other faces of wall.

6. Analysis of the monitoring data

6.1. Building orientation

The monitoring data at different positions show that the building orientation has a marked impact on the RH distribution within different faces of straw bale walls. The monitoring positions recorded lower RH levels in the south facing walls than the positions in other wall elevations. The lowest recorded RH level is 26% at the low position of the south face of laid-flat stacking straw bale wall on 4th May 2017 (Figure 9). The RH levels of the monitored location increase and fluctuate between 50% RH and 60% RH in June 2017. In comparison with the low position of north facing wall with the same infill stacking method of bales, the RH data fluctuate from 93% to 81% (Figure 8). The driving wind could speed up drying process of external render and results in lower RH levels of south facing walls than other facing walls.

The yearly data of wind direction and wind speed suggest that the wind is stronger and more rapid from south and south-west (27) than north and east of the building (Figure 9). Due to the wind comes from south face of the building; the lowest wind velocity would be outside north face of walls. As a result, the north face of walls may not have sufficient driving wind to dry the lime rendering. Comparing to the north facing walls and the east gable wall, the north facing walls have slower sufficient driving wind for drying the walls due to the dominating wind in the winter time is northerly (28). During that time, the temperature is lower than freezing point and vapour is likely to become ice during the time. The wind may not significantly take vapour from north face walls.

As a result, the highest RH levels are maintained in the north face walls rather than the east gable-end walls.

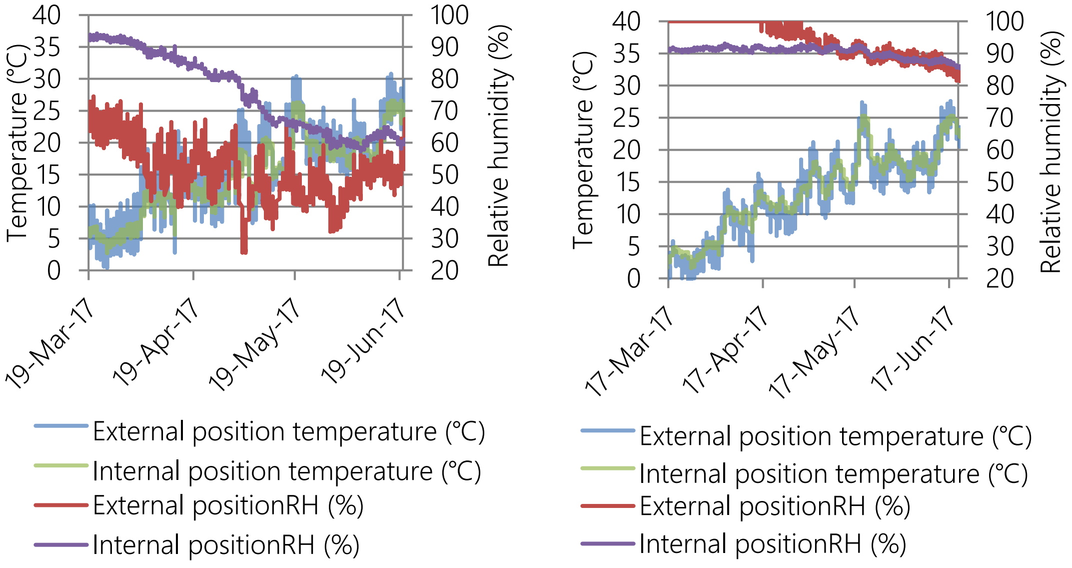

Figure 8. Monitoring data of the low position of the south facing wall with laid flat bales (left) and the low position of the north facing wall with laid flat bales (right).

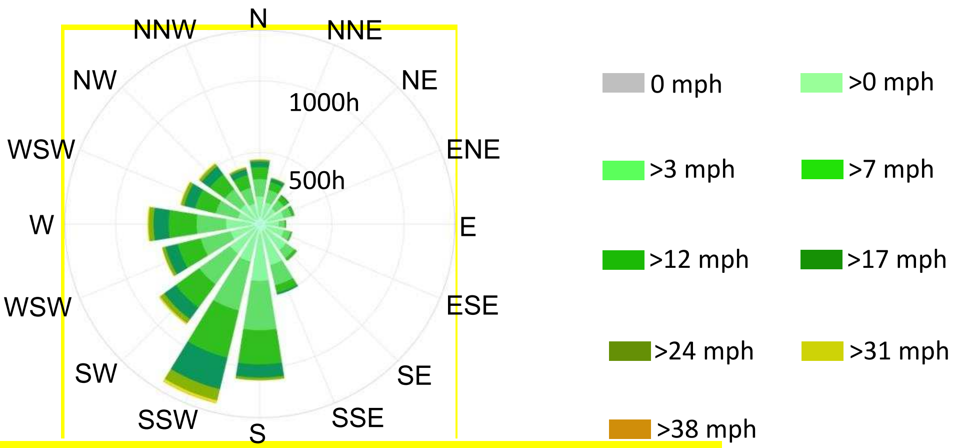

Figure 9. Annual wind intensity plot of Changchun. (27)

6.2. Effect of walling construction

The comparison of the monitoring data of low positions and under window positions of the same piece of wall can justify the RH distribution at similar height with different building constructions in the wall. To minimize the influence of solar radiation on the monitoring data, the analysis focuses on the north facing wall. In comparison with the monitoring data of the low position and the under window position of north facing wall with laid flat bales, the RH reading of the low position are more than 10% of RH lower than the under window position from 19th/September2016 during the monitoring research (Figure 10). Due to the temperature of the two monitoring positions, the monitoring data show less vapour pressure at the low position than the under window position and therefore the straw bales contain less moisture around the low position than the one around the under window position.

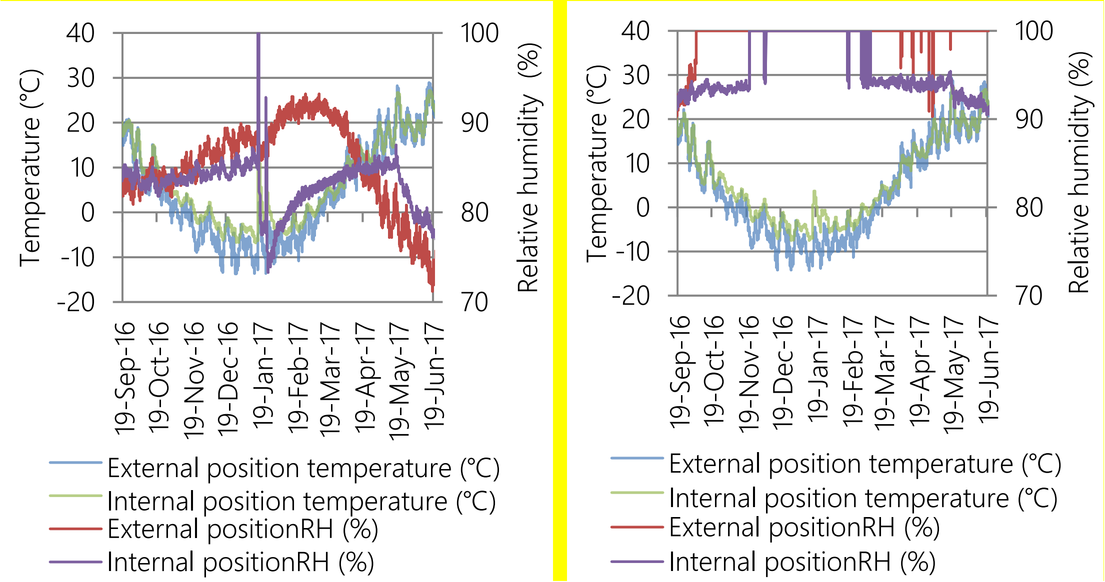

Figure 10. Monitoring RH/T data of low position (left) and under window position (right) of north facing wall with laid flat bales.

The different walling construction detailing of the two monitoring positions may be the reason of the different RH distribution during the monitoring period. The constructions of the under window areas of straw bale walls connect window sill and the insulation layers of the window sill and such constructions involve more detailing construction than the straight walls (Figure 11). The increased construction detailing of walls increase the potentials of issues of construction quality and leakage. The monitoring data in this research show notable higher moisture content of the bales at the location below window sills, care should be taken in improving quality control of the construction in further construction. Further research would focus on the methods and detailing designs for minimizing the issues of walling construction identified in this research.

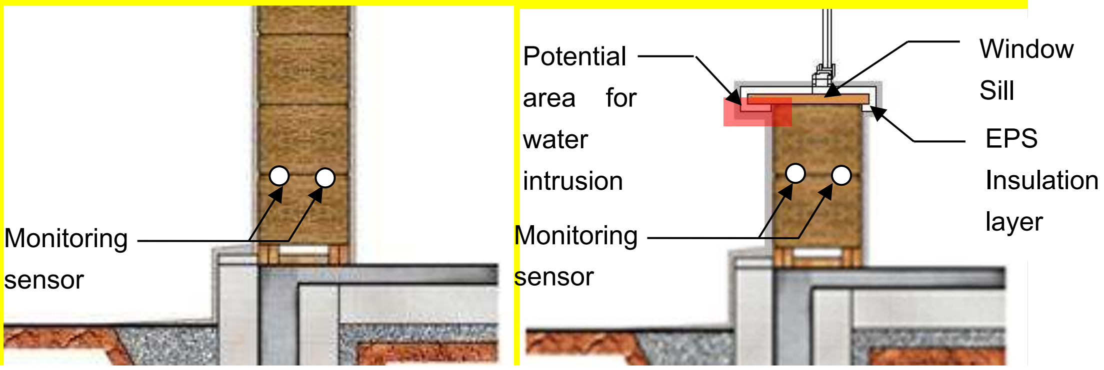

Figure 11. Walling construction of the straight walling (left) and the walling around window opening (right)

6.3. Drying trend of straw bale walls

The vapour pressure difference between the monitoring positions and the atmosphere can describe the moisture movement trends between the straw bale walls and the atmosphere. Higher vapour pressure data of the monitoring positions than the atmosphere indicate that the straw bale walls release moisture into atmosphere at the data collecting point and vice versa. Fully dried straw bale walls will establish moisture exchange between straw bales and external atmosphere and the fluctuation of the vapour pressure difference is an indication of fully dried straw bale wall. Constant higher vapour pressure data of the monitoring position than of the atmosphere are highlighted in blue to indicate unfinished drying process; the fluctuations of the moisture difference around 0 are the sign of fully dried walls and the periods of time are labelled in green (Figure 12 & Figure 13 & Figure 14). Considering unreliable monitoring data during winter months in the monitoring period, the monitoring data are analysed in two period of time in this research. The first period begins at the beginning of the monitoring research and ends at 1:00 am 19th November 2016. The second period is from 1:00am 19th February to the end of the monitoring research.

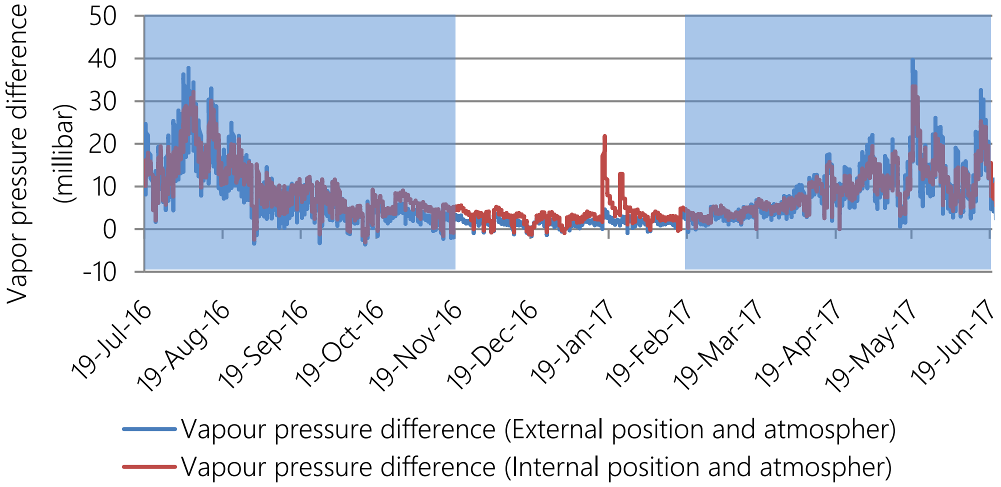

Figure 12. Vapour pressure difference of the northern high position of the west gable wall

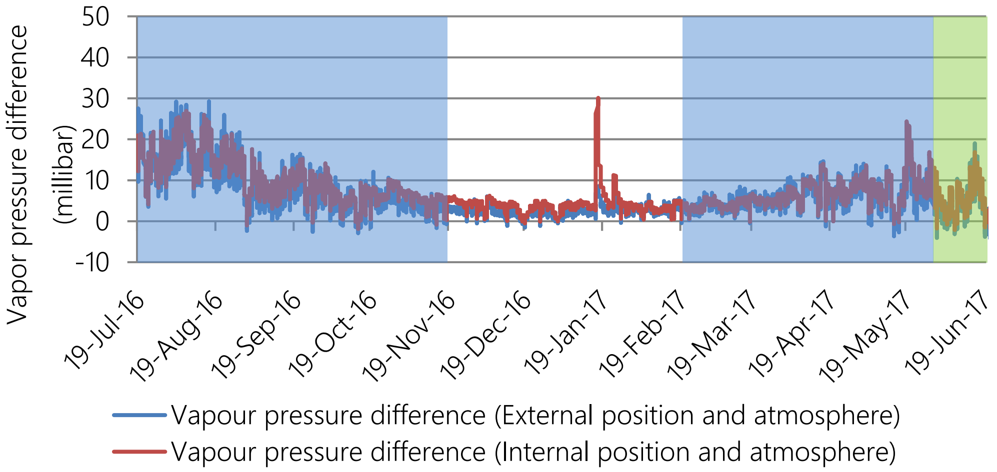

Figure 13. Vapour pressure of sensor locations of the low position of the south facing wall with laid on-edge bales

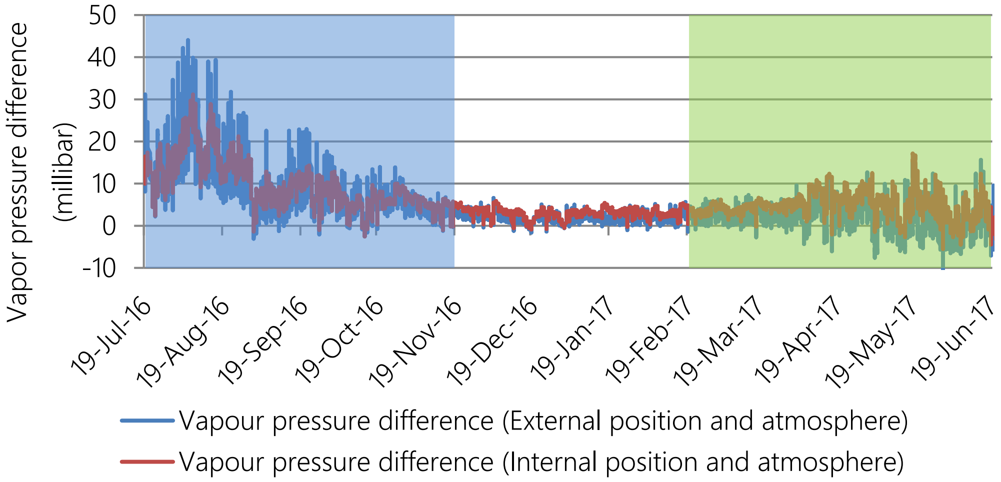

Figure 14. Vapour pressure of sensor locations of the low position of the south facing wall with laid flat bales

The long drying process of the straw bale walls maps the continuously high RH data of the monitored positions. Vapour travels from straw bale walls to outer environment in the walls other than the south facing walls during the whole monitoring period. The drying trend of south facing walls is an effect of the higher southward annual wind intensity on the construction site. There are two period of dry months which are October and April annually in the local area. The higher southward wind intensity helps to drive moisture from the south facing straw bale walls during the dry months.

The comparison of the vapour pressure difference data of the laid-flat bale walls and the laid on-edge bale walls show that the method of bale stacking has notable impact on the drying process of the straw bale buildings in northern China. The south facing wall with laid-flat bales were complete dried after the first drying months and established moisture exchange with atmosphere after half year of the monitoring process. The south facing wall with laid on-edge bales experienced longer drying process than the laid-flat walls and it fully dried after April 2017.

Compared with on-edge stacking bale wall, the laid-flat bale wall have greater vapour pressure gradient between the exterior sensor location and the atmosphere than the one located in the same sensor location in the laid on-edge bales (Figure 18 & Figure 19) during the first period of the analysis. Due to the drying process of the walling constructions is not finished during the period of time; the higher gradient indicates that the laid-flat bales adsorb more moisture from rendering construction than the laid on-edge bales. A hypothetical theory for explaining the situation is that the moisture adsorption and desorption process of straw bales is mainly through the cross section of straw. Therefore the straw bales with laid-flat stacking method adsorb more moisture than the laid-on edge bales during the drying process of rendering construction. For the same reason the laid-flat bales have quicker response to low air humidity levels in dry months and result in faster drying process of the laid-flat bales within the south facing walls. The hypothesis of adsorption and desorption process of straw need to be analysed in further research.

The vapour pressure difference data during the heating process suggest potential condensation within straw bale walls. During the heating process of the internal space, the monitoring RH/T changed significantly because of a much warmer internal space. The actual vapour pressure data of each monitored position are also increased significantly during the heating process. Since the straw bale walls are sealed by plaster layers, the increasing vapour pressure within straw bale walls is mostly from moisture inside straw bale walls. As a result, the monitoring RH data suggest the internal air is fully equilibrium with vapour, it is highly possible that the vapor became condensation and ice when temperature dropped down to 0℃ at the end of October. The condensation would become ice when temperature drops below 0 ℃ and therefore the condensation would initiate degradation during winter time. However, the frozen ice will become liquid water when temperature rises again above the freezing point after March 2017. With presence of liquid water, straw degradation is likely to occur. The degradation conditions of straw need to be justified through visual inspect of the straw behind the rendering layer.

7. Degradation Potential of straw bale

7.1. Analysing the Monitoring data

The monitoring data are compared with the potential degradation level of RH (85%). As microorganisms cannot survive without presence of liquid water, the degradation potential is not examined when monitoring temperature is lower than freezing point in winter months (19). The RH levels are measured as being constantly higher than 85% within all straw bale walls during the monitoring period and therefore the period of potential degradation is determined by the periods when temperature remains consistently above 0℃. The yellow rectangle in Figure 15 shows the period of time for supporting straw degradation during the monitoring research. The straw within walls also experienced high temperature and high humidity situations (over 30℃ and over 85% RH) in which straw would experience serious degradation. The period of time is around 1.5 months and it is shown in red rectangle in Figure 15. Such long period of hot humid environment within straw bale walls has been few reported in other research papers. This period of time may have potential to lead to serious degradation of straw bales within walls initially after the completion of the experimental straw bale building.

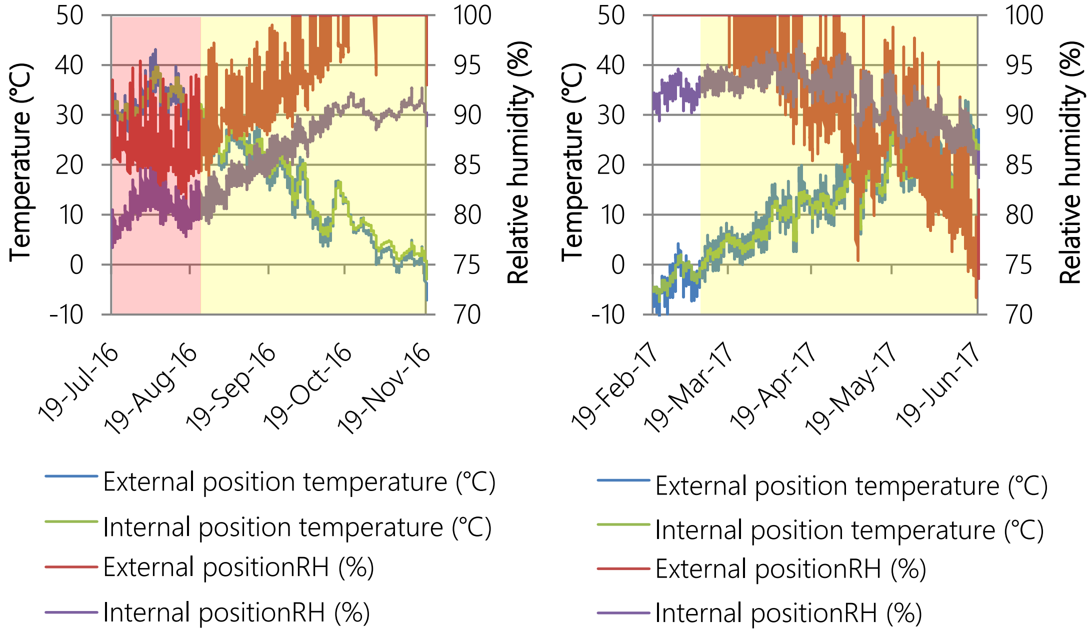

Figure 15. RH/T data before winter months (left) and after winter months (right)

The high degradation potentials of the straw bale walls in this research are the effect of high initial relative humidity and temperature and long drying process of rendering construction. The experimental building was finished in mid-July when is the rainy season in the local area. The high air humidity in the rainy season brings moisture into the straw bales both during the stacking process and after completion of the building. As the rendering constructions also introduce moisture into the straw bales in the walls, the high initial RH levels are established in the experimental building in this research. Because of slow drying process of the rendering construction, the high RH levels within straw bale walls were trapped in the straw bales during the monitoring period.

The monitoring results of the experimental building show that the local climate has significant impact on degradation potential of straw bale wall for the on-site construction. Further construction process of straw bale buildings can benefit from brining the construction schedule forward to March and April in northern China. The dry months will accelerate drying process of the rendering construction and bring low levels of air humidity into straw bale walls.

7.2. On-site visit

Based on the monitoring results, the straw bale walls of the experimental building have high risk of degradation. A visual examination of the experimental building was conducted to verify the potential. The examination involved two separate site visits to the experimental building. The first site visit involved heating the building to 25℃ and taking infrared images to examine potential thermal bridging of the straw bale walls. The second site visit focused on a visual check of the straw condition inside the walls.

During both on-site visits to the experimental straw bale building, the rendering construction straw bale walls were found to be in good condition. Comparing with the condition after construction, there is no notable change to the walls. The lime render withstood low winter temperature of the area and there is no noticeable cracking after the initial drying process of the outer layer of the lime render. A comparison of the lime render in this research and the cement render in the ADRA project demonstrates that the lime render would be a more suitable rendering material (Figure 16).

Figure 16. The lime render in this research during the first site visit

The infrared image of the straw bale buildings also suggests that there is no significant thermal bridging through the straw bale walls (Figure 17). The surface temperature of the gable end wall with infill straw bale has lower surface temperature than the PVC insulated columns. If the straw had undergone serious degradation before the onsite visit, the thermal image would present thermal bridging caused by hollows within the walls. The thermal bridging free straw bale wall suggests that the straw within the walls remained in good condition and there is no significant degradation within the walls.

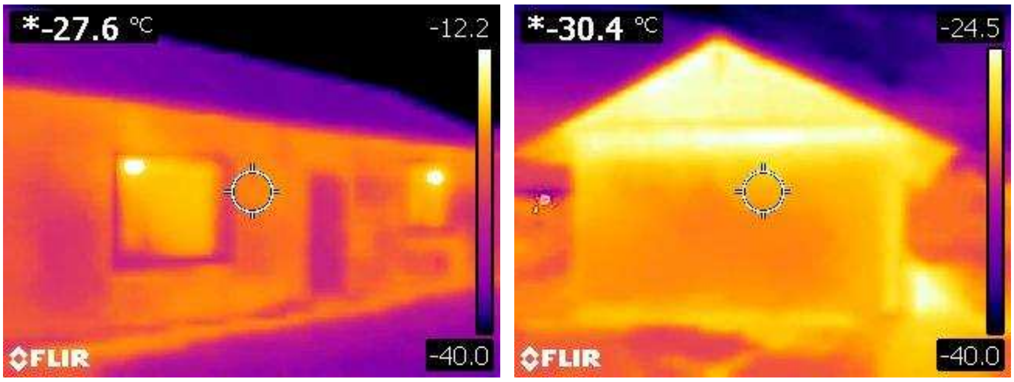

Figure 17. Thermal image of south wall (left) and west gable end wall (right).

The straw within walls was also examined through the ‘truth’ window on internal surface of the north facing wall with laid flat straw bales. The truth window was located a central point on the internal surface wall. Despite high degradation potential which was expected from the monitoring data, the straw can be seen to be in good condition. The colour of straw stayed unchanged during the site visit and there was no notable sign of straw degradation of the straw behind the truth window. The straw condition behind truth window suggests that straw had not experienced serious degradation in the way that the monitoring data would imply.

To examine the straw condition behind rendering layer, several positions of rendering layer were removed to expose the straw inside the bale walls (Figure 18). There was found to be limited degradation of straw at the interface between straw bales and external rendering. Decolourization appears 1-2 cm deep into the straw. Straw remain golden colour inside the walls. The site visit confirms that the straw is in good condition in the straw bale walls. The degradation only appears on the interface between straw bales and the rendering layer. The degradation may be associated with the long drying process of the straw bale walls and the resultant condensation at the interface between straw bale and rendering.

Figure 18. Opening of external render (left) and straw adjacent rendering layer (right)

Despite the high degradation risk of the straw in the experimental building, the twice on-site visit of the experimental building show that the straw experienced limit levels of degradation during the one year monitoring research. There are three possible explanations for the results in this research:

- Firstly, there is a subtle difference between the moisture content of straw bales within walls and the moisture content of the surrounding environment of the straw bales. Due to lag of adsorption process of straw from surrounding environment, the critical relative humidity levels may be underestimated estimated in this research.

- In the second, existing prediction for straw degradation are based on the research on wheat straw rather than rice straw applied in this research. The rice straw is considered a more durable type of straw than the rice straw empirically (1). As a result, the rice straw would be able to withstand the environment for supporting degradation of wheat straw.

- Thirdly, the adsorption isothermal model for predicting the moisture content assumes a steady diurnal variation, whereas in reality diurnal variations are irregular and can vary quite rapidly. Existing adsorption isothermal model is based on saturated adsorption of straw which is not based on rapid random diurnal variations of relative humidity and therefore the critical RH for straw degradation is unlikely to be achieved as rapidly as the model would predict due to the natural lag in adsorption kinetics. For this reason moisture content levels predicted are likely to be overestimated in reality when it comes to the analysis of the degradation potentials of straw in the experimental building.

To verify the degradation potential of straw bale buildings in northern China, further research would focus on prediction of degradation situation for rice straw and modified adsorption isothermal model of straw based on real life situations.

8. Conclusion

This paper presents construction of a novel straw bale building in northern China and analysis of its performance following monitoring for a year. The construction is validated by monitoring RH/T levels within straw bale walls and visual checking of straw status at the end of the monitoring period. The construction involves three modifications which are based on the ADRA project in the same region. The monitoring research achieved understanding of the hygrothermal environment within straw bales in the straw bale building in local area.

They key conclusions that can be drawn from this study are:

- Detailing designs used in this research have been shown to be appropriate for the straw bale buildings in the local climatic area. This design presented none of the problems identified in the ADRA buildings. The straw bale walls remained good condition throughout the period of the study.

- The electronic RH/T sensors were shown to be problematic in monitoring conditions at the low temperatures experienced in this study. The mechanisms employed by the sensors do not appear to be appropriate for the provision of accurate monitoring data in conditions below 0°C and with high humidity levels. The use of wood stick sensors might provide more reliable data in such conditions.

- Straw is resilient at low temperatures but care needs to be taken in periods where temperature fluctuates around freezing point. There is a high potential for condensation within the straw bale walls during their first year of use whilst they are still drying out.

- There is a low degradation potential for rice straw bale construction in the climate of northern China. The straw was found to be in good condition within the walls in spite of the high temperature and high humidity environment prevalent in the local area.

- Existing predicting methods for straw degradation may overestimate the degradation potential of straw bale buildings in northern China. The straw bale buildings constructed by rice straw bales are more durable than the existing estimation of straw degradation.

The main reason for bringing this method of construction to NE China is to reduce the use of conventional building materials by using straw, which is an agricultural bi-product. This is particularly effective in the region given its harsh climate and this can help deliver the Chinese government’s energy reduction target since this technique can save up to 60% of the heating energy requirement compared to conventional construction used in the area.

Acknowledgement

The authors firstly would like to acknowledge the support of the China State Construction Engineering Corporation Eighth Division Dalian Company Funding for the construction in this paper. The authors also gratefully acknowledge the financial support provided by the Engineering and Physical Sciences Research Council – United Kingdom. The support from University of Bath colleagues and Jilin Jianzhu University is also acknowledged.

References:

1. King B. Design of straw bale buildings : the state of the art. 2nd ed. ed. Aschheim M, editor. San Rafael, Calif.: San Rafael, Calif. : Green Building; 2006.
2. Myhrman MA. Build it with bales : a step-by-step guide to straw-bale construction. Version 2. ed. MacDonald SO, editor. Tucson : Totnes: Tucson : Out On Bale
Totnes : Green Books distributor; 1998.
3. (ADRA) ADaRA. What is a Straw Bales Building? http://www.adrachina.org/site/program_details.php?ID=262006 [
4. GB50178-93. Standard of climatic regionalization for architecture. GB50178-93: Ministry of Housing and Rural Urban Development; 1994.
5. Menet J-L, Gruescu I-C. A comparative life cycle assessment of exterior walls constructed using natural insulation materials. Environmental Engineering and Sustainable Development Entrepreneurship. 2012;1(4):14 p.
6. Bigland-Pritchard M. An assessment of the viability of strawbale wall construction in buildings in maritime temperate climates: University of Sheffield; 2005.
7. Andrew AS, Jiang JY. Peoples Republic of China Grain and Feed Annual 2014 [Available from: https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Grain%20and%20Feed%20Annual_Beijing_China%20-%20Peoples%20Republic%20of_4-2-2014.pdf.
8. Gong YC. China will notably cut CO2 emissions by 2020 2013 [Available from: http://china.org.cn/environment/warsaw_climate_talks/2013-11/21/content_30663021.htm.
9. Jones B. Building with straw bales: a practical guide for the UK and Ireland: Green Books & Resurgence Books; 2009.
10. Bergeron M, Lacinski P. Serious Straw Bale, A home construction guide for all climates. Chelsea Green Publishing Company, Vermont; 2000.
11. Magwood C. Straw bale details : a manual for designers and builders. Walker C, editor. Gabriola Island, B.C.: Gabriola Island, B.C. : New Society; 2003.

12. Jones B. Technical Details 2013 [Available from: http://www.strawworks.co.uk/wp-content/uploads/2014/08/standard-details-140531-05-41-first-floor-floorplate-baseplate.pdf.

13. Modcell. Technical 2016 [Available from: http://www.modcell.com/technical/.

14. Jolly R. Strawbale moisture monitoring report. 2000.

15. Bronsema NR. Moisture movement and mould management in straw bale walls for a cold climate. 2010.

16. Lawrence M, Heath A, Walker P, editors. The impact of external finishes on the weather resistance of straw bale walls. 11th International Conference on Non-conventional Materials and Technologies, NOCMAT 2009; 2009: University of Bath.

17. Holzhueter K, Itonaga K. The Influence of Passive Ventilation on the Interstitial Hygrothermal Environment of a Straw Bale Wall. Journal of Asian Architecture and Building Engineering. 2014;13(1):223-9.

18. Tabata S. A simple but accurate formula for the saturation vapor pressure over liquid water. Journal of Applied Meteorology. 1973;12(8):1410-1.

19. Summers MD, Blunk SL, Jenkins BM. How straw decomposes: Implications for straw bale construction. Ecological Building Network. 2003.

20. Lawrence M, Heath A, Walker P. Determining moisture levels in straw bale construction. Construction and Building Materials. 2009;23(8):2763-8.

21. Online WW. Changchun, Jilin Monthly Climate Average, China 2017 [Available from: https://zh.worldweatheronline.com/changchun-weather-averages/jilin/cn.aspx.

22. Zhang F. Study of Straw Bale Building. Architecture Technology. 2006;37(8):624-6 (in Chinese).

23. Li L, Wang Y, Zhang Q, Li J, Yang X, Jin J. Wheat straw burning and its associated impacts on Beijing air quality. Science in China Series D: Earth Sciences. 2008;51(3):403-14.

24. GB50189-2015. Design standard for energy efficiency of public buildings. Ministry of Housing and Urban-Rural Development: Ministry of Housing and Urban-Rural Development; 2016.

25. Holzhueter K, Itonaga K. The Hygrothermal Environment and Potential for Mold Growth within a Straw Bale Wall. Journal of Asian Architecture and Building Engineering. 2010;9(2):495-9.

26. Carfrae J, De Wilde P, Littlewood J, Goodhew S, Walker P. Development of a cost effective probe for the long term monitoring of straw bale buildings. Building and Environment. 2011;46(1):156-64.

27. Meteoblue. Climate Changchun 2017 [Available from: https://www.meteoblue.com/en/weather/forecast/modelclimate/changchun_china_2038180.

28. Guoyu R, Jun G, Mingzhi X, Ziying C, Li Z, Xukai Z, et al. Climate changes of China's mainland over the past half century. Acta Meteorologica Sinica. 2005;63(6):942-56.