

Condition monitoring and durability assessment of straw bale construction

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ABSTRACT: The use of straw bales in construction projects is still regarded by many as a novel technique with significant perceived risks. Barriers such as finance, certification and insurance all contribute to further restricting wider adoption. In all of the above cases long-term durability can be considered a prevalent concern. In particular construction industry concerns regarding long-term durability remain a notable barrier to mainstream adoption. Demonstrating the long-term durability credentials of straw bale construction can hence be considered one of the most significant ways of broadening the use straw bale construction within conventional construction markets. This paper presents a review of methodologies for condition monitoring, analysis, and interpretation of results for the short and longer-term assessment of straw bale buildings. The review is supported by research completed at the University of Bath and will help to inform and support future studies whilst also providing new insight into assessment criteria currently being developed.

1 INTRODUCTION

1.1 *Straw bale construction*

Contemporary use of straw bales in construction has increased significantly in recent years. Examples of straw bale buildings dating from the last twenty years can now be found in many countries around the world. These buildings are particularly numerous in the US, Canada and Europe (Fig. 1) though a notable number of buildings also exist across Japan, Australasia and China (Magwood et al. 2005, Holzhueter, K. & Itonga, K. 2010).



Figure 1. LILAC co-housing development in Leeds, UK

One of the oldest examples of straw bale building is commonly recognized as the Burke House in Nebraska, which was built in 1903 (King 2006). Now over a hundred years old, the

building is still in existence today and is often held up as an example of the longevity offered by straw bale construction. Nonetheless, the observed success of the straw bale dwellings of Nebraska can be attributed to the largely dry climate that they are exposed to.

It has been suggested that some of the Nebraska buildings may have been built with baled rushes and not cereal crops, which could also have an influence on their durability. Figure 2 shows a bale recently taken from one of these buildings that was built in 1913. This bale was made using twisted wire, was in good visual condition, and is understood to be largely made up from rushes taken from the site of the building though a significant proportion of grasses were also visible.



Figure 2. Bale recently removed from Nebraska dwelling built in 1913

As straw bale building has moved beyond the relatively dry climates of Nebraska the range of climatic exposure has also grown. The result has been that independent precedent, testing and monitoring has been necessary to understand and demonstrate the durability of straw bale buildings in a wider range of environmental conditions. The significant global straw bale building stock now in existence suggests that concerns surrounding durability in a well detailed building are in the main unsubstantiated. However, whilst this is true for the majority of cases the building stock is relatively young and is still being deployed in climates where long-term precedent does not exist.

The implication of this is that construction industry concerns regarding long-term durability still pose a significant barrier to mainstream adoption. Demonstrating the long-term durability credentials of straw bale construction can hence be considered one of the most significant ways of increasing adoption in mainstream construction markets. Monitoring hygrothermal conditions within walls provides an evidence base from which long-term durability can be assessed. However, the use of suitable methods of analysis and interpretation of monitoring results are critical in ensuring such studies are reliably assessed.

1.2 *Methods of construction*

There are three main forms of straw bale construction; load bearing, frame infill and prefabricated panel systems. These forms of construction can be more simply categorised as load bearing and non-loadbearing (Goodhew et al. 2010) where the primary vertical load bearing structure is provided by the straw bales in the former. In the latter, timber structural elements are typically used and the straw bale is used to infill either an in-situ or prefabricated structural frame. Traditionally straw bale buildings would make use of a large roof overhang to protect the exterior walls from direct wetting by rain. However, as shown in Figure 1 some contemporary straw bale buildings are moving away from this traditional form of construction. In part this can be attributed to improved quality control arising from prefabrication of building elements. Experience gained from field tests and monitoring programs have also aided in understanding the performance of straw bale walls that do not rely on roof overhangs (Wall et al. 2012).

To aid in maintaining acceptable moisture levels within straw bale walls best practice requires that walls are built as a vapour permeable form of construction. This is normally achieved through the use of lime and earth based plasters and renders or through the use of suitable cellulose board systems. The term vapour-permeable relates to the manner in which a wall's constituent materials allow water vapour to diffuse through it. In the UK the internal environment of a building will often be warmer than the outside air and can thus also contain a higher concentration of water vapour. This higher concentration of water vapour will result from the elevated temperatures but also from the use and occupation of the internal space.

Given these conditions, a vapour pressure differential is setup across external walls between the internal and the external air. The opposite can occur where high levels of air conditioning are used in a hot climate. In the former case, this differential in vapour pressure causes the warm interior air to pass through the wall towards the exterior face. If a barrier to the movement of water vapour is included in the cool face of the wall then moisture can become trapped and at low temperatures condense to form liquid water. To prevent this occurring in walls using cellulose materials, vapour permeable materials are used through the full thickness of the wall. This allows movement of water vapour to occur between the internal and external air, which facilitates drying of plasters and elevated straw moisture levels associated with extreme rainfall or accidental wetting.

2 MOISTURE LEVELS IN STRAW BALES

2.1 *Avoiding the risk of degradation*

Drivers for increased moisture content in vapour permeable walls made with hygroscopic materials are summarised below. Focus is given to hygroscopic vapour permeable wall types though these drivers are common to all wall types and materials:

- Direct wetting from precipitation;
- Water vapour diffusion due to pressure differential across the wall;
- Rising moisture absorbed from the ground;
- Accidental exposure (e.g. flooding or a burst pipe).

Where excess moisture is present, factors that influence the long-term durability of wall materials often relate to microbial activity associated with fungal growth. Degradation of this form will occur under specific environmental conditions influenced by the following factors (King 2006, Summers 2003):

- Availability of nutrients;
- Availability of oxygen;
- Temperature;
- Availability of moisture;
- Time periods of exposure.

Of the above factors, controlling moisture levels is considered the most important aspect of ensuring the success of straw bale construction. Robust detailing of a building will prevent the direct ingress of water from occurring. The straw bales that make up the walls are commonly protected from direct wetting through the use of a vapour permeable lime based exterior render (Fig 1). This render is permeable to water vapour but absorption of moisture from precipitation sources is limited to the extent that the straw behind is not adversely affected.

Straw is a hygroscopic material, which means that it will adsorb water vapour from the air and absorb liquid water when exposed to a suitable source. Adsorption is the process by which water vapour molecules are held on the surface of a material through polar attraction. Materials that store water vapour in this way are termed hydrophilic. In the field of wood science, the point at which a material can store no more water vapour through adsorption is termed the fibre saturation point. At this point liquid water will begin to form within the pores of the material and this liquid moisture will be stored through capillary suction (Berry 2005). King (2006) notes that this behaviour is also applicable to straw though the moisture content for the fibre saturation point of straw is not given. It is at the fibre saturation point that decay of timber becomes a concern.

The moisture content of straw materials is typically expressed as a percentage of the dry mass of the material. Occasionally it is expressed on a wet basis and in this case the moisture content is given as a percentage of a material's wet mass prior to drying. For the purposes of this paper dry basis moisture content values will be used throughout unless noted otherwise. The dry mass of a sample is obtained through oven drying specimens at 105°C until stable mass readings are observed over a 24 hour period.

2.2 *Assessing risk*

Specifying limits for the acceptable moisture content of straw bales in construction is not straightforward. This is because the degradation of straw is influenced by many factors; perhaps most importantly the duration that the high moisture content is maintained but also what may be considered an acceptable or indeed unacceptable level of degradation. Lawrence (2009a) provides a concise review of recommended moisture content limits published in literature. It is recommended that straw bales not exceeding 14-15% moisture content are used for construction in the first instance but that moisture contents maintained at or above 25% will lead to degradation of the straw. However, whilst literature provides these guidelines the duration of exposure and subsequent severity of degradation are not developed further.

It is proposed in this paper that there may be two broad cases to consider when assessing the durability of straw bales in construction. The first is the risk associated with the germination and growth of mould arising from elevated relative humidity levels. The second is the risk of serious decay resulting from the ingress of water or sustained levels of high humidity associated with the use of the building or the climate that it is built in. This decay would be recognised as causing detrimental damage to the building structure through significant breakdown of the straw.

An example of this is observed in the field of timber construction where blue stain fungi or surface mould can grow causing staining and discoloration of the timber when high relative humidity or moisture content allows. However, whilst the discoloration caused by the blue stain fungi affects the value of the timber it does not cause loss of mechanical strength (Ingold & Hudson 1993, TRADA 2004). Of greater concern in timber is the presence of wet or dry rot. These fungi occur when timber is maintained at moisture contents above 20% for a sustained period. They cause decay of the cellulose and lignin that forms the structure of the timber and are thus detrimental to its integrity. Dry-rot is particularly difficult to deal with as it is malignant due to its ability to translocate moisture from one location to another.

3 CONDITION MONITORING TECHNIQUES

3.1 *Measurement of straw moisture content*

There are several ways to monitor the moisture content of straw bales used in buildings:

- Electrical resistance measurements of timber blocks buried within the wall;
- Indirectly using measured %RH and temperature and determining equivalent straw moisture content;
- Direct measurement of the straw electrical resistance with a purpose built probe;
- Gravimetric determination of moisture content through removal and oven drying.

3.2 *Electric resistance of timber blocks*

Electrical resistance measurements of wood block and disc sensors buried within straw walls have been used in several studies (Goodhew, S. et al. 2004, Carfrae, J. et al. 2011, Wall, K. et al. 2012). The studies reported by Goodhew et al. (2004) and Carfrae et al. (2011) highlight the importance of calibrating the moisture content of the wood used to that of the straw being monitored. Goodhew et al. (2004) reported that the wooden discs used in their study allowed the measurement of straw moisture content to within $\pm 2\%$ (e.g. a range of 23-27% for a 25% straw moisture content). Carfrae et al. (2011) show that use of the timber species *ramin* improves this accuracy further to within 1.5%. However, the isotherms presented by Carfrae et al. (2011) also

show that pine has a moisture content 6% lower than that of wheat straw at a relative humidity of approximately 93% and temperature of 23°C. This highlights the importance of calibrating wood sensors used with straw bale. To not do this risks significantly underestimating the moisture content of a straw bale wall and potentially not identifying elevated moisture levels prior to the onset of serious decay.

3.3 *Monitoring of hygrothermal conditions*

Relative humidity and temperature sensors are widely available and can be relatively inexpensive. However, these sensors will typically also need to be wired into a data logger which can be a limitation when installing them within a wall. It is possible to get wireless sensors which allow continuous, remote logging but these are significantly more expensive. Relative humidity and temperature data can be used to calculate an equivalent straw moisture content and in general this has shown to be reliable up to a relative humidity approaching 90% (Lawrence, M. et al. 2009a,b). However, beyond this point isotherms become asymptotic and thus an unreliable estimate of straw moisture content. A more appropriate method of using hygrothermal monitoring data may be to use it in its raw state and not to convert it to the moisture content equivalent. For example this could allow high relative humidity levels experienced in cold weather, where degradation risk is reduced to be more reliably assessed.

3.4 *Direct electric resistance measurements*

Manual moisture content readings can be taken using a stainless steel ‘balemaster’ probe produced by GE Ltd. This device is specifically calibrated for use with straw bales and is reported to be reliable to within +/- 0.5% for bales of average density (Carfrae et al. 2011).

3.5 *Gravimetric measurement*

The gravimetric measurement of straw moisture content through oven drying at 105°C and weighing of a specimen taken from a building is very accurate. However, it is also largely impractical and would only typically be done if there were good reason for opening up a straw bale wall.

4 MOULD GROWTH

4.1 *Using hygrothermal data for assessment*

In order to assess the risk of mould growth in a straw bale wall it is necessary to have knowledge of both the prevailing temperature and relative humidity conditions. This allows an understanding of the likelihood and severity of mould growth to be determined. For instance conditions of 90% RH and 5°C would not be of significant concern whilst the same relative humidity at 20°C would suggest a high risk of mould spore germination and growth.

A significant amount of research has been completed at the Fraunhofer Institute of Building Physics to characterise the mould resistance of many different building materials (Hofbauer 2005, Hofbauer, et al. 2008, Sedlbauer et al. 2011). A specialist test setup was developed to allow specimens to be subjected to a range of climatic conditions through varying temperature and relative air humidity. The findings of these tests were subsequently presented using a graphical ‘isopleth’ system. This isopleth system provides a traffic-light guide to climatic conditions that can support mould growth. A green area indicates no risk of mould growth and yellow indicates ‘attention’ as mould growth is possible. The red zone is to be avoided as mould growth is likely to occur when the material is held under these conditions.

The experimental test setup was initially used for investigating mould growth on the surface of mineral based materials used as internal and external wall finishes (Hofbauer 2005). The specimens measured 5 x 5 x 2.5 cm and were sterilised prior to testing using gamma radiation. Known fungi were subsequently used to inoculate an area of the specimen. Visual measurements of mould growth were conducted for 100 days after inoculation of the specimens. After this point germination of the inoculated spores was not expected (Sedlbauer et al. 2011).

Visual monitoring of mould growth on the specimens was recorded by taking photographs, which allows comparison to be drawn over time. The results of the study allowed climatic conditions to be determined that will support mould growth over the 100 day period of exposure. However, although the isopleth traffic light provides a visual guide to exposure under steady state conditions for 100 days, it is noted by Hofbauer et al. (2008) that initial measurements under dynamic conditions indicate that resistance against mould can be influenced and controlled by climatic changes.

4.2 Case study

An example of the isopleth assessment method is shown below in Figure 3 for monthly average relative humidity and temperature data. The data were recorded from 2009 to 2012 from an unheated exposure facility in the south west of England. The location of the sensors was at the base of the middle panel shown in Figure 4. This panel had 30-40mm thick lime based render applied to the interior and exterior face of the straw bales and faces due south-west, which is the prevailing wind direction.

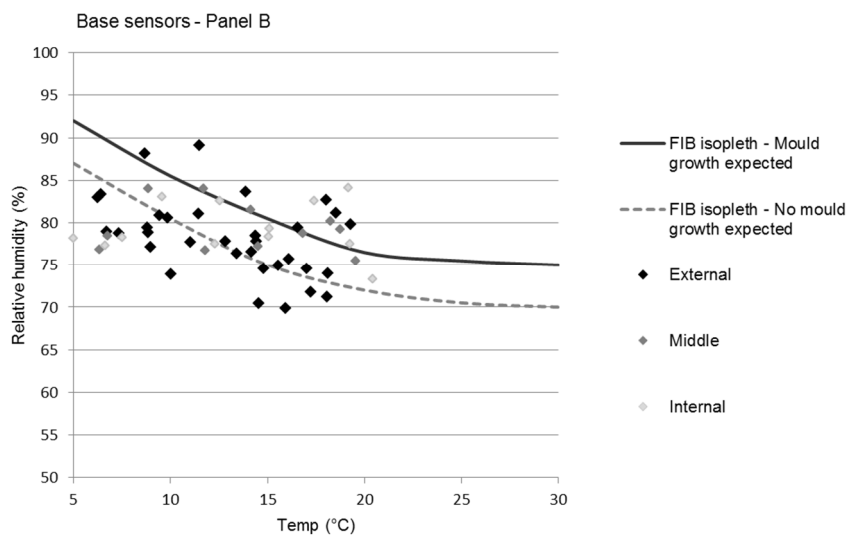


Figure 3. Monthly average data plotted with isopleth boundaries



Figure 4. Exposure test facility in south-west England

It is apparent that a significant number of the data points fall above the red threshold for mould growth. It would therefore be expected that a certain level of visual degradation would have occurred within the base of this panel. In order to investigate this further a visual inspection of the straw was made by removing a 150mm diameter core of render at the base of the external face of the panel. This core is shown in Figure 5. It was apparent from inspection of the straw that serious degradation of the straw had not occurred within the base of the panel and the fixity of the straw to the render remained. Some discolouration of the straw was however

apparent which would be associated with previous mould growth. At the time of inspection (November 2012) the gravimetric moisture content of the straw immediately behind the render was 28.4% on a dry basis. Based upon the literature this relatively high moisture content would also suggest that deterioration of the straw would be likely. Nonetheless active signs of decay were not evident beyond a slight dampness to the straw immediately behind the render.



Figure 5. External render core removed from exposure test facility

4.3 Long term performance

The findings from the straw bale exposure facility raise the question of how the risk of straw degradation can be reliably assessed without being overly conservative. There is a need for the means to assess hygrothermal monitoring data for both transient mould risk and serious degradation or decay. The results shown in Figure 3 suggest that mould growth will have occurred at certain periods within the panel in question and this is supported by discoloration of the straw. However, long-term decay was not apparent upon removal of the render. The high moisture content recorded at the time of render removal also suggests that mould growth should have been present at the time of inspection though this was not observed. This suggests that in the long-term mould growth may be arrested within a wall due to the restriction of a viable nutrient supply following previous colonisation by fungi. This hypothesis is supported by on-going research at the University of Bath but is beyond the scope of this paper.

Whilst the hypothesis that straw may be able to withstand relatively high transient moisture contents without suffering serious decay is encouraging it raises some interesting questions. Firstly if the conditions for mould growth are met within a new wall made with fresh straw it is possible that a certain level of mould growth could occur. If this is the case this is likely to raise any health concerns, perceived or otherwise? Secondly, if elevated transient moisture levels are not of concern in terms of serious decay of the straw how long can they be maintained before serious decay does occur? It is feasible that like timber the risk of colonization by serious decay fungi such as dry rot is only an issue when unfavourable conditions are maintained in the long term.

5 CONCLUSIONS

Current study at the University of Bath is focused on understanding the resilience of straw to transient exposure to high relative humidity conditions. An isopleth as set out by Sedlbauer et al. (2011) is compared with monitoring results from an exposure test facility. The isopleth was derived for fresh wheat straw. The work suggests that mould growth as defined by the Fraunhofer Institute isopleth may not be a long-term concern in terms of decay of straw bale walls. However, there may be associated concerns surrounding health if a significant growth of mould occurs. It is considered that an extension of the isopleth is necessary to include less conservative boundaries that address the time of exposure and the risk of serious decay above that of mould growth. This would allow monitoring results to be interpreted more reliably and avoid over conservative assessment.

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