Construction and Building Materials 183 (2018) 46–57

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Construction and monitoring of experimental straw bale building in northeast China

Xunzhi Yin *, Mike Lawrence, Daniel Maskell, Wen-Shao Chang

Department of Architecture and Civil Engineering, University of Bath, Bath BA2 7AY, United Kingdom

HIGHLIGHTS

- Designs of straw bale construction in context with climatic conditions in northeast China.
- Effectiveness of the designs are justified through the construction of a experimental building and the following monitoring research.
- Care should be taken in preventing condensation within straw bales during the periods which temperature fluctuates around freezing point.

ARTICLE INFO

Article history:
Received 8 December 2017
Received in revised form 30 April 2018
Accepted 30 May 2018

Keywords:
Straw bale construction
Modifications
Rice straw
Straw bale Wall
Hygrothermal environment
Monitoring data
Straw durability

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

* Corresponding author.
E-mail address: xy433@bath.ac.uk (X. Yin).

https://doi.org/10.1016/j.conbuildmat.2018.05.283
0950-0618/

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 130 kg/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 70 kg/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 = Temperature in degrees celsius
e = Saturation vapour pressure in T

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

where:
e_{actual} = Actual vapour pressure in T
e = 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 °C 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 (Fig. 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.

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