Straw bale construction in northern China – Analysis of existing practices and recommendations for future development

(Journal of Building Engineering)

Abstract

Straw bale buildings in China have been mainly limited to rural farm houses and self-builders. An expansion of straw-bale construction into main-stream medium-rise buildings has the potential to make a significant contribution to the reduction of both embodied and operational carbon in China as well as removing a major source of pollution. As a response, there has been the construction of straw bale buildings, however these buildings have several issues, resulting in the limited adoption of the technology.

This paper makes recommendations for future straw bale design in northern China based on an inspection of existing buildings. The issues identified with existing construction details were subjected to computational simulation analysis which identified shortcomings in existing practice and proposes revisions to design detail in order to accommodate the environmental conditions in northern China. The paper provides a unique insight into current straw bale practice in northern China and proposes a practical and environmentally sound solution to the pollution crisis in this region.

Key words: Wheat straw, Rice straw, Straw bale building, Construction quality, Thermal Bridging, Northern China, Environmental pollution, Carbon sequestration

1. Introduction

The Chinese government has set up a carbon reduction target of 40%-45% of each unit GDP by 2020 with reference to the 2005 level (1). As the building industry contributes 40%-50% of greenhouse gas emissions (GHG) globally (2), it is essential that this industry makes a substantial contribution to the reduction of GHG emissions.The design and construction of buildings in China are informed by five climate regions differentiated by the climatic characteristics of the regions (Figure1.). The climatic regions are described and the design of buildings is regulated by a national code for thermal designs of civil buildings(3). These regulations include a specification for the u-values of building envelopes ranging from 0.4 to 0.7 W/m^{2}K, depending on the number of stories in the building and the particular climate regions in which the construction site is located.

The health and welfare problems caused by air pollution within the severe cold regions and cold regions of China are exacerbated by the present approach to the disposal of agricultural waste which involves burning straw in the fields (4). This has been a strong motivation for the expansion of the use of straw within the building industry. The use of straw bales in the building industry would contribute to harmless disposal of straw and would provide an energy efficient alternative to the current building methods. Straw bale buildings use bales of straw to form building envelopes, and the straw used in the construction is commonly wheat, oats or rice straw (5).

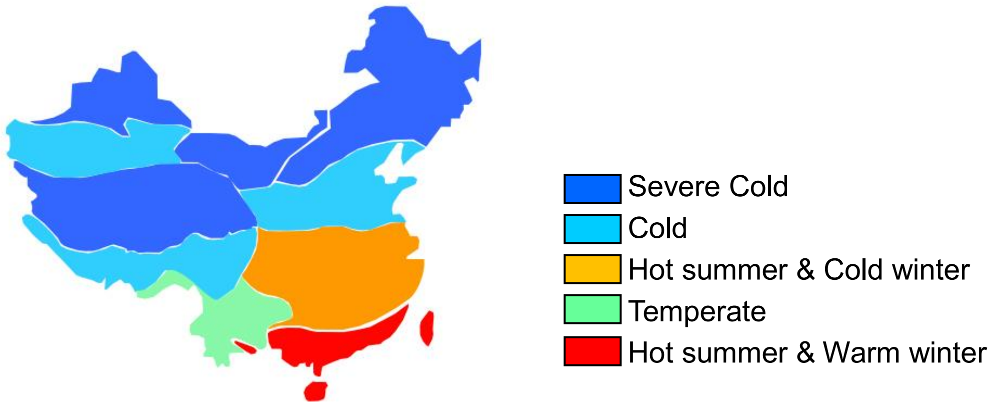

Figure 1. Climatic regionalization in the GB50178-93.(reproduced from (3))

The use of straw bale construction to replace building envelopes can deliver not only improved thermal insulation, but can also contribute to China's carbon reduction targets through lower emissions in the construction phase of a building. A typical 16kg wheat straw bale can sequester 32kg CO_2 through photosynthesis (6). Evidence for a reduction of operational energy through the improved thermal envelope delivered by straw bales can be taken from the Low Impact Living Affordable Community (LILAC) project in UK. A typical flat in the LILAC project has a heating energy use of 35.73 kWh/m^2/year (7) and this compares with average space-heating demand of existing housing stock of 140 kWh/m^2/year(8).

The first use of straw bales as a construction material was in Nebraska in the US, where they were used because of the unavailability of more traditional materials such as bricks and timber. This was enabled by the invention of mechanized baling machines in the late 19th century(5). The advent of the railways gave access to mass produce building materials and the system lost popularity by the 1920s. Modern straw bale construction was reintroduced in the western USA in 1980s(9) as part of the ecological building movement. There are two distinct structural solutions for straw bale construction: Load Bearing and Infill. Load bearing straw bale buildings use straw bales and a render layer to carry the vertical load of the building whereas the infill straw bale walling acts as an insulation layer within a separate structural system(10). The building types have historically mainly been constructed and occupied by self-builders in US and European countries (5, 6, 11). More recently, the construction system has been industrialized through the production of pre-fabricated structural elements in the UK(12) using straw bales within a structural timber panel and in Slovakia (13) where compressed straw is used as an insulating infill in timber framed elements. Both construction techniques use engineered timber to act as the structural element of a straw bale walling system which contains straw bales or straw stems inside a giant timber box(14). The methods combine straw and straw bales with a quality controlled prefabricated process(15).

Straw bale buildings in China were first constructed at the turn on the last century by the Adventist Development and Relief Agency (ADRA) - a central government and local government aimed at improving the build quality of farmhouses and reducing their construction cost for local farmers with low income. Although straw bale construction techniques have been used in China for 20 years, it is not a mainstream technology and represents a very small proportion of buildings in China. Straw bale buildings have been primarily used for housing and for community centres in rural areas (16). By the end of the project in 2006 the total number of straw bale buildings was in excess of 600 and many of these buildings are still occupied by local residents(17). Since completion of the ADRA project, few straw bale buildings have been constructed in China. The existing straw bale buildings are mainly in the form of a brick-concrete frame construction with straw bale infill although there is one steel structure straw building built for experimental purpose(18). Most Chinese research on straw bale construction is based on the ADRA project (16, 19, 20) with others discuss the application of straw bale construction in rural areas of the severe cold regions in China (21, 22).

Wang (16) reviewed the ADRA project and published an energy saving ratio for the energy consumption of straw bale houses in 2005-2006 in Jiamusi. Taking into account initial construction energy input, the total energy saving ratio is over 60% and coal consumption is reduced by 50%(16). Compared with typical farmhouse in northern China, operational heating energy of straw bale buildings can be reduced by 62% to 76.8% (20). In the research, coal use of simulated straw bale building was 2.6 tons less than a typical farmhouse with conventional constructions (20). Yang et al. (19) proposed the use of straw bale construction to replace existing cob (straw and mud mixture) houses in northeast China, concluding that in-fill construction is the most suitable type of straw bale construction for the regions. The conclusions are mostly based on interviews with local residents and reviews of other research. As a result, the research may only be relevant to straw bale construction for the ADRA project in Jiamusi rather than being generally applicable to straw bale construction in China. Developed from previous research on the ADRA project, Liu (22) discusses the applicability of straw bale construction in northern China, stating that straw bale construction has superior thermal properties and affordability when compared with more traditional construction systems in the regions(22). The construction cost of straw bale building was 300 ¥/m^2 comparing to 400 ¥/m^2 for the construction cost of a typical farmhouse in China in 2005 (20). Traditional wall construction of typical farm houses in the northern regions do not contain any thermal insulation materials(22). Compared to traditional brick walling construction systems used for farmhouses, straw bale wall construction is considerably cheaper and has a significantly better thermal performance. Following the ADRA project, the construction method and the connection design of a steel frame with a straw bale infill was investigated by Jilin Jianzhu University in 2010 (18). While this research demonstrated an improvement in straw bale building design, there has been no further application of these construction methods and designs, and it is not representative of the Chinese state of the art.

The aim of the paper is to provide an understanding of the state of existing straw bale construction in the ADRA project and to make recommendations for further straw bale construction in the northern China. The objectives of the research involved the evaluation of existing straw bale buildings of the ADRA project in Jiamusi, identifying and understanding potential problems associated with the design and construction method used by the ADRA project and developing recommendations for future straw bale construction informed by the analysis of the ADRA project. The following sections of this paper describe the straw bale construction technology applied in the ADRA project, giving examples of straw bale building in the ADRA project and discussing current straw bale building practices in northern China. The construction method used for the ADRA project is then compared with other straw bale construction techniques applied in other countries. The lessons learned from this analysis are then applied to propose an optimized approach for straw bale construction in northern China.

2. Reviews of straw bale constructions in China and globally

2.1. Design of Straw bale buildings worldwide

Despite the development of straw bale constructions, they all have similar components and constructions of the straw bale walls:

2.1.1. Toe-up knee wall

There is a generally accepted constructional approach used to connect straw bales with the foundations to mitigate against damp damage from rising damp (6, 23-25). The construction system is known as ‘toe-up’ and it elevates the straw bale walls off the surface of a slab (6, 23). Toe-up construction ensures that straw bale walls are kept away from ground water damage on slabs during construction and it provides protection against any potential leaks of water (23). There are three typical toe-up designs which are shown in Figure 2 (23). Toe-up construction should both have a vapour barrier layer to prevent damp damage from ground and allow moisture within the straw bale walls to drain away (23). The Toe-up system is widely used worldwide (23). A development of the typical toe-up is the baseplate construction which is designed by Jones (26). The baseplate incorporates the typical timber toe-up construction and hazel pins for fixing first layer of straw bale walls (Figure 3).

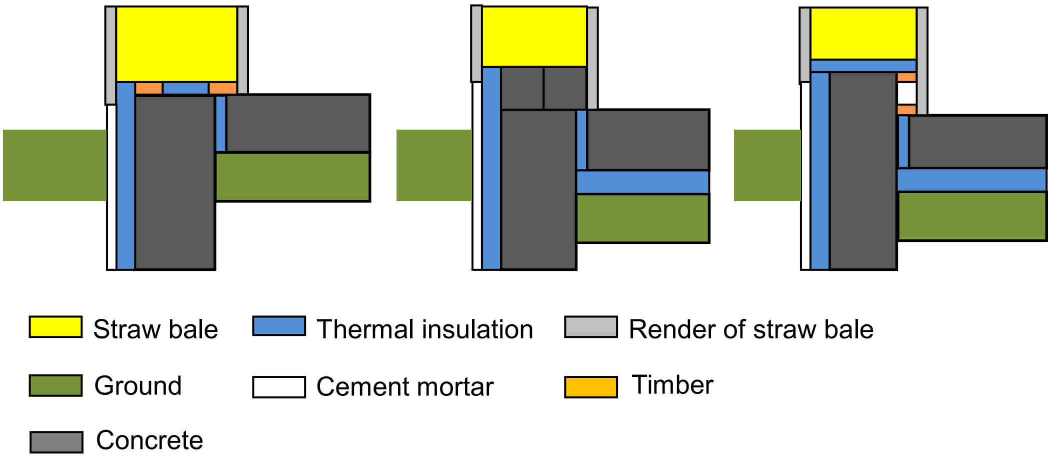

Figure 2. Typical toe-up (left), toe-up with blocks (middle) and toe-up with knee wall (right). (redrawn from (23))

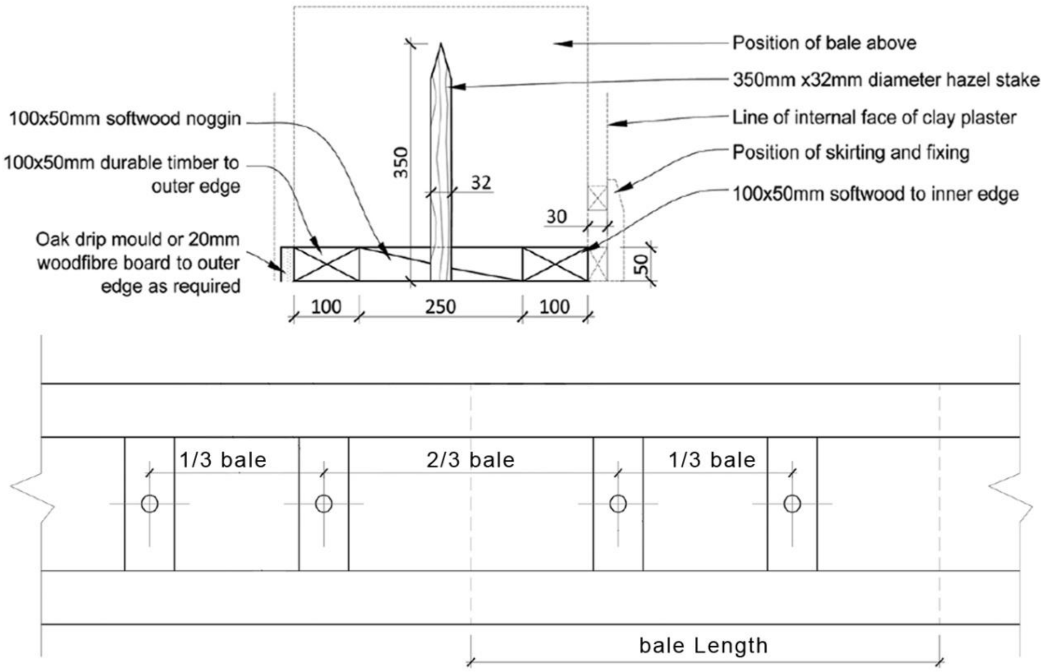

Figure 3. Baseplate design. (27)

2.1.2. Pinning system

In some international examples pins are incorporated to provide structural stability between bales (24). Although the effect of pins is not accounted for in the structural design of in-fill straw bale construction (23), the elements are still essential for the practicality of bale stacking of the walls (6). There are different forms of pins in current practice. Rebar staples and all-thread steel rod with pointed tips are used in load-bearing straw bale construction in the USA (Figure 4). The system is simplified by using natural shaped hazel studs by Jones (6). The irregular shapes of hazel studs provide similar effects as the all-thread steel rod. Because of the wide availability of the raw material, the modification is considered to be a cost efficient and environmentally friendly solution (6). To achieve better integrity of straw bale walls, bales are tied up at corners of first layer of the walls in the hazel pin system (6). However, due to the weakness of the ties, this tie-up construction cannot be accounted for in any structural calculation (6).

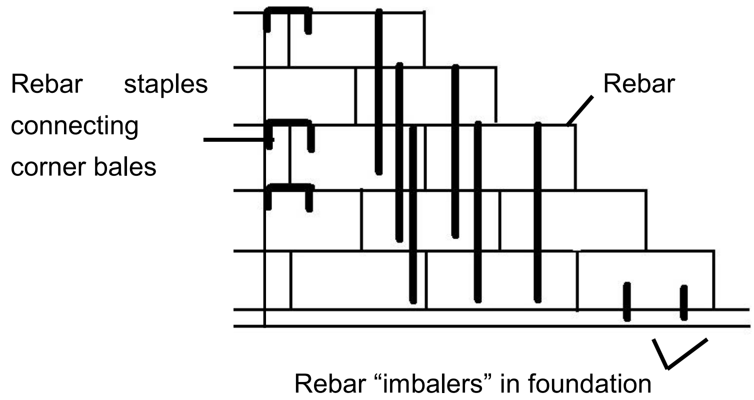

Figure 4. Pinning system for loading bearing straw bale walls with 3 tie bales laid flat (24).

2.1.3. Render types

There are four plaster materials which can be used in render layers of straw bale construction: cement, lime, clay and gypsum (24). The render layer should be breathable enough to allow trapped moisture to escape from the straw bales (5). Different plaster materials have different characteristics for straw bales walls (table 1). Considering render strength and drying potential within straw bale walls, cement, lime and clay can be applied as an exterior render finish in cold climates (28). Because of the different chemical reaction of cement and lime with water, lime plaster has significantly better breathability than cement render (6). The use of cement render should be cautious, as the presence of cement in the render will reduce its permeability and could lead to moisture becoming trapped within the bales (6).

Table 1. Render properties of different plaster materials (Reproduced from (24)).

Plaster / Property	Cement-based	Lime -based	Gypsum -based (Interior use)	Clay -based, Natural	Clay-based, Asphalt-stabilised
Workability of binder	Worst	Medium	Better	Best	Best
Rapid development of strength	Worst	Medium	Better	Best	Best
Breathability	Worst	Best	Better	Better	Better
Eventual hardness	Best	Medium	Better	Better	Better
No moist curing needed	Worst	Best	Best	Best	Best

2.2. The ADRA project in northern China

There are around 150 straw bale houses in Jiamusi Heilongjiang province which were a major part of the ADRA project. The project in Jiamusi is the largest single development of straw bale buildings in northern China. These buildings represent the first introduction of straw bale construction into China and they were designed and constructed with the support of the American architect Kelly Lerner (5). For training purposes, the ADRA organized and printed an unpublished training manual in advance of work commencing on construction. In the manual, standard construction details and construction methods are illustrated. The manual was later developed into a standard design guide book by Department of Construction of Heilongjiang Province (DCHP) in 2007 (29). Taking account of construction quality and the condition of the straw bales, the houses in Jiamusi are still in relatively good condition. A visual inspection in 2006 reported that there were no significant differences between these houses and conventional local farmhouses (16).

2.2.1. Bale selection

Wheat straw is recommended in the unpublished training manual due to ready availability of the raw material in the area. The straw should be completely dry or have a low moisture content and have no grain or root contained within the straw. The bales used in construction are two string bales and the reference dimensions of the bales are 900mmx460mmx360mm. Good quality bales should have moisture content no greater than 17%. Because the in-fill construction method is used in the project, the requirement of bale density is not specifically mentioned. According to the illustrations in the manual, the construction bales should be ‘solid’.

2.2.2. Designs of straw bale buildings

The designs of the straw bale buildings in the ADRA project has not been formalized in the unpublished training manual. As the following standard design guide book by the DCHP directly copy the initial designs of the straw bale buildings in the ADRA project without any adjustment (29), The designs of the straw bale building can reference from the design guide book. The straw bale houses are in-fill straw bale construction. The load-bearing structure is masonry-concrete (Figure 5). The bricks support the vertical load of the buildings and a poured concrete beam serves as ring beams and lintels over windows and doors.

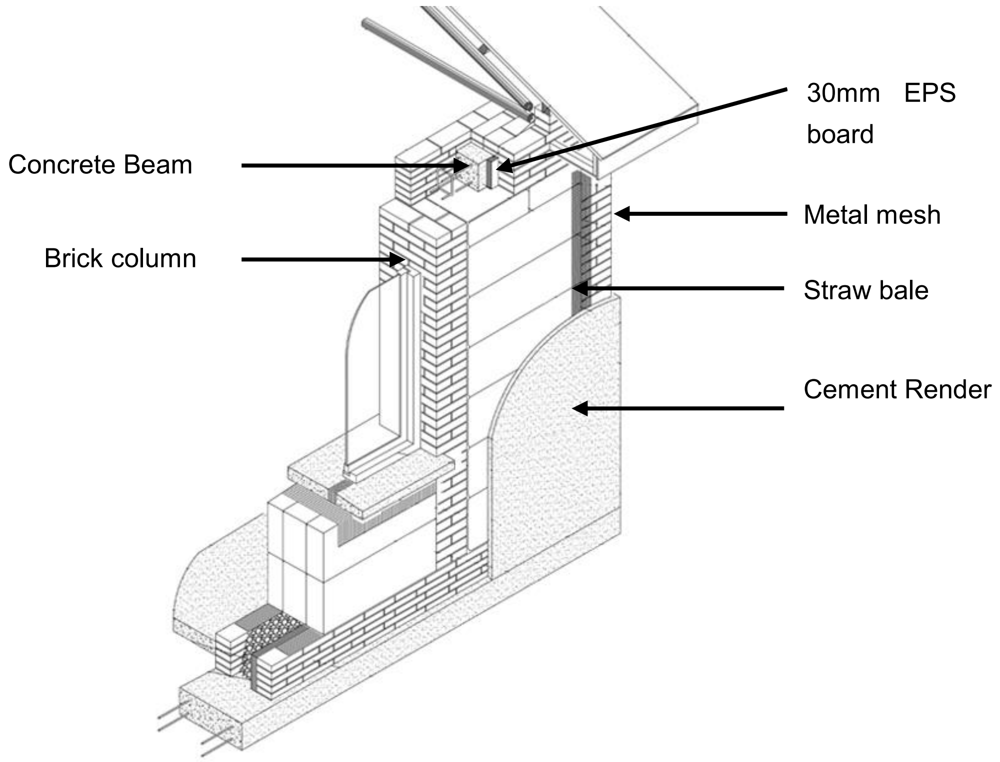

Figure 5. Construction detailing of ADRA straw bale buildings. (29)

The design of the structural frames may form serious thermal birding during cold winter months in Jiamusi. The design of the insulation layer of the structural elements are not consistent in the ADRA project and the following design guide book published by DCHP. The insulation layer only partially cover surface of concrete beam and therefore there is clear pathway of heat loss through the masonry bricks around the concrete frame (Figure 6). Due to the high thermal insulation property of straw bales, it is speculated that the high thermal conductivity of bricks and concrete used for the supporting pillars and lintels are not moderated by the use of sufficient insulation material. This design is likely to be the main cause of thermal loss inside the houses.

As heat loss are majorly through the structural frames of the straw bale buildings in the ADRA project, potential condensation issues would be serious in the straw bale buildings. Problems caused by interstitial condensation may lead to serious mould growth on the internal surface of walling construction in the ADRA project. Besides, due to a lack of experienced builders who are familiar with constructing straw bale buildings in China, the consequences may be even more serious in real situations. The worst case scenario is likely to relate to frost issues at internal corners.

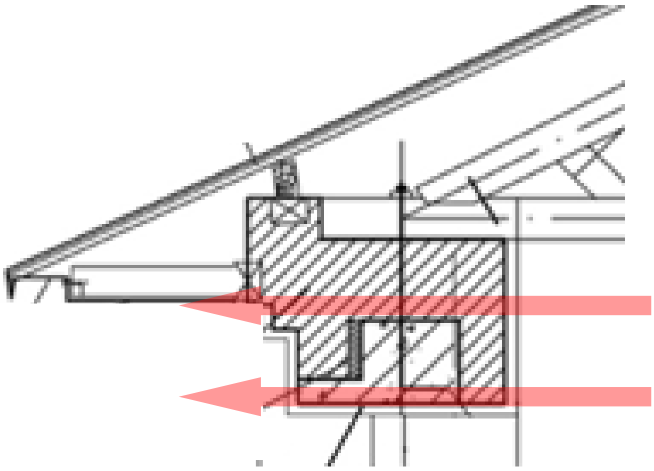

Figure 6. Thermal bridging issue and heat loss pathway (red arrow) in the ADRA project during winter months.

Detail designs and the connection of the straw bales with other building elements are shown in the standard design guide book (29). The major consideration of the foundation standards is to keep straw bales from water damage. In the training material, foundations are required to project more than 200 mm above ground level and must be higher than 300 mm in rainy climate areas. Because the straw bale buildings are constructed in cold climate regions, the foundations also should be laid lower than the frost line. The detail designs of foundation and opening designs are similar to typical farmhouse designs in the region (Figure 7). Damp proof courses are installed both beneath the windowsill and on the top of the foundation. A French drain formed by a trench filled with coal cinder acts to remove water away from the straw bale walls (29).

Designs of straw bale walls in the unpublished training manual and the standard design guide book include the bale stacking process and connections with other building elements. To increase structural strength and integrity of straw bale walls in earthquake areas, the manual also advises that cement mortar should be applied between each bale. This construction approach is problematic for a number of reasons. The thermal conductivity of a cement mortar is much higher than straw bales and the approach will reduce the benefits from thermal insulation characteristics of straw bale walls, by creating a cold bridge. Filing gaps in the wall with cement mortar is intended to improve fire resistance (24). The usefulness of these construction details is not certain. The earthquake construction method is not suggested in the technical drawing collection (29). However, there is no existing straw bale construction which applied this construction approach in the ADRA project in Jiamusi.

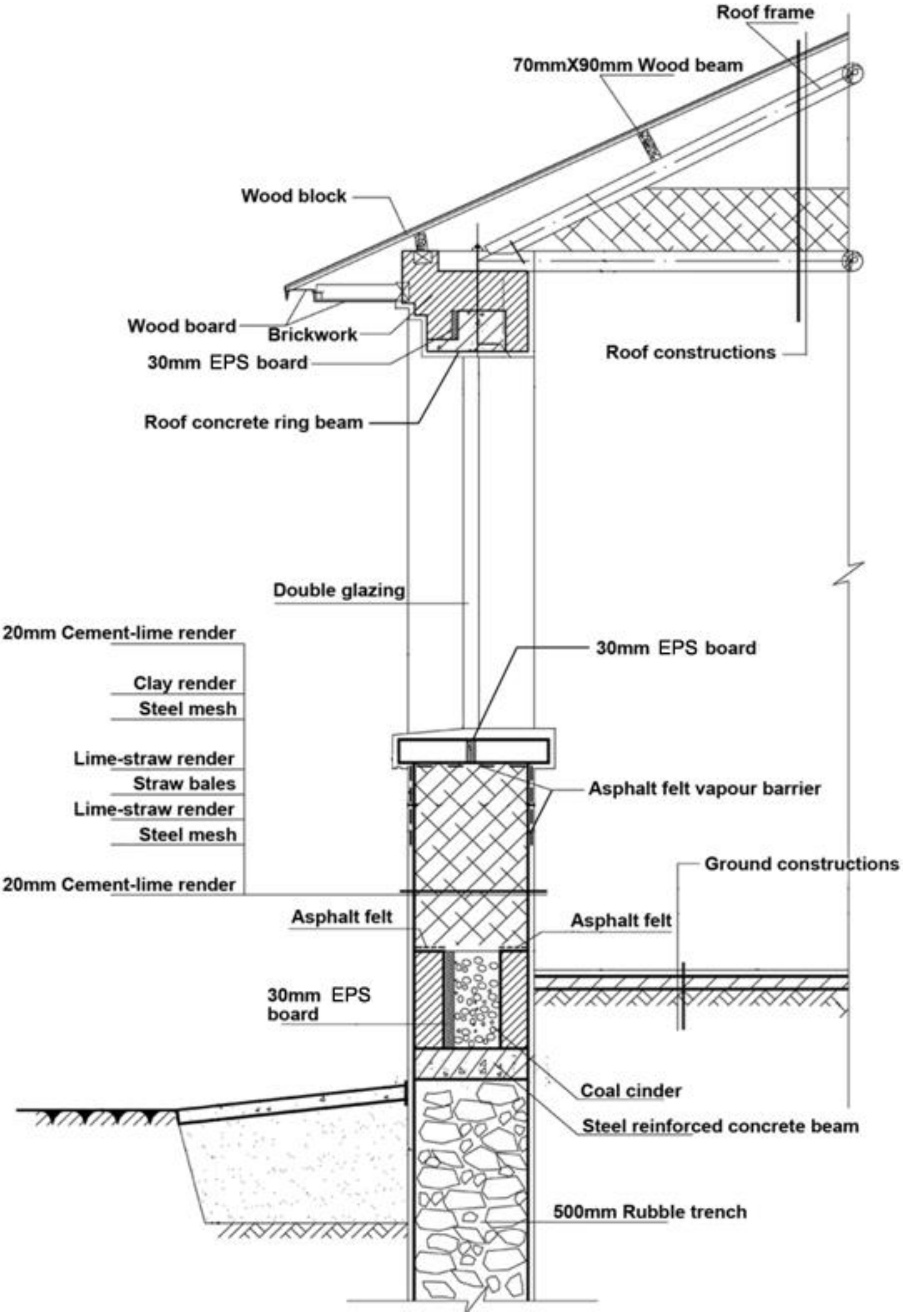

Figure 7. Reference wall section in the ADRA project. (Translated from (29))

2.2.3. Rendering construction

The unpublished training manual provides several options for the render and plaster mix for the straw bales houses in northern China (Table 2). The renders are lime-straw render, clay render, cement-lime render(29). The lime-straw render consists of hydrated lime, sand and chopped straw. The composition ratio of the three materials by volume is 1:2-2.5:0.5. In the manual, an alternative to sand is brick powder or coal ash. If replacing sand with brick powder or coal ash, the ratio will be 1:1:0.5. For the clay render, the render material can sourced on site and it is easy to work with straw bales. The clay render mix consists of clay and chopped straw. The ratio of these two materials by volume is 2:3. Adding one proportion of lime to the mix can increase the strength of the clay render. Cement-lime render is also proposed as an alternative in the construction. Good quality cement-lime render consists of one part of cement, one part of lime and 5-6 parts of sand.

Table 2. Alternative render mixes (29)

Type of render	Composition material	Composition ratio
Lime-straw render	Hydrated lime, Sand, chopped Straw	1:2-2.5:0.5
Clay render	Hydrated, Brick powder (coal ash), chopped Straw	1:1:0.5
	Hydrated lime, Clay, chopped Straw	1:2:3 Or
Cement-lime render	Clay, chopped Straw	2:3
	Cement, Hydrated lime, Sand	1:1:5-6

Render application is described in the training manual. There are three layers of external render in the standard construction (Table 3). The first layer is 10mm thick and it is applied to the straw bales. This layer will provide basic support for the second layer and creates a flat wall surface. Following the initial render layer, a second layer of render is applied. The layer will be 7.5mm-10mm thick and forms an integrated render layer over the straw bale walls. The top surface render layer is 5mm thick and it is designed to fill small cracks and for aesthetic purposes. The first two layers must be mixed either with hemp fibre, glass fibre or chopped straw. There is also a non-fibre construction illustrated in the training manual. On the first layer of the render metal mesh can be applied and fibres can be avoided in this construction (29). Metal mesh should be applied at the interface between straw bales and first render layer in both render construction systems.

Table 3. External render layer of standard straw bale constructions. (29)

Render layer	**Thickness (mm)**	**Type of render**
Inside	10	Lime-straw render or Clay render
Middle	7.5-10	Lime-straw render or Cement-lime render
Outside	5	Lime-straw render or Cement-lime render

2.2.4. Modifications involved in the standard design collection

Comparing to the initial unpublished training manual in the ADRA project, there are two major modification involved in the following standard design collection published by the DCHP to adapt to real situations in the local area.

Firstly, the design guide book involve more detailed requirement of straw bales in regarding to real situation in the area. As rapid growth of rice farming in the Heilongjiang province, other than recommended application of wheat straw in the training manual, both wheat straw and rice straw are recommended in the standard (29). Considering various types of balers in the Heilongjiang province, the dimensions of bales are in a range of 700mm-900mm (length) x 450mm-500mm (width) x 340mm-360mm (height) rather than specified dimensions in the previous manual (29). The detailed requirements in the design guide book also involve requirement of specified bale densities in constructions. The bale lowest densities of dry basis straw bales should be over 80kg/m^3 in straw bale buildings (29). In the second, During the construction process of straw bale buildings in

Jiamusi and following standard design published by DCHP, the rendering construction apply 2 rendering layers with cement-lime render outside and clay render inside (29). Due to lack of skilled plasterer on lime render, the lime render was never applied both in construction and in the design guide book (29).

2.3. Comparison of Chinese straw bale design with global straw bale design

There are three major differences in straw bale wall construction between those used in China and those more generally used worldwide which are the design of toe up knee wall, application of pinning system and the rendering construction. Each difference is discussed below.

Firstly, the toe-up design is different in China. A unique toe-up which is innovated from the knee wall toe-up is used in the ADRA project. The knee wall is formed by brick and a trench of gravel. The foundation design of the ADRA project may not fully serve the purpose because of the direct connection of the masonry work to the ground (Figure 8). As the damp issues are long term processes, any water damage may not be initially evident (6, 24). Bale conditions within the walls will be a concern after long term exposure to moisture.

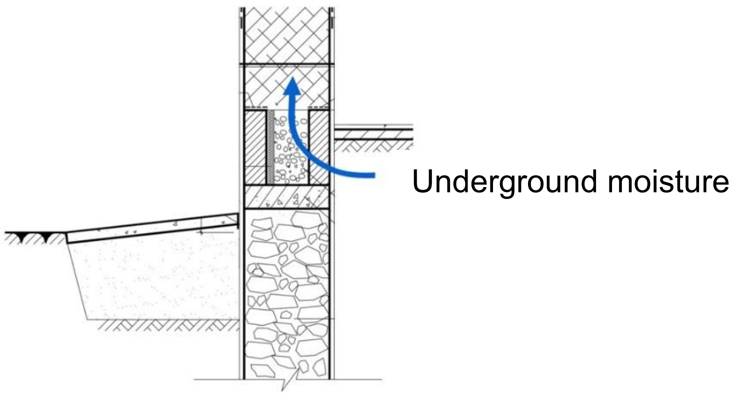

Figure 8. Potential ground damp damage routine (blue arrow) of foundation design of ADRA project

In the second, both the ADRA project and the following standards published by DCHP do not involve pinning systems within straw bale walls. Metal mesh is used to fix bales to the structural frames in the ADRA project (29). Both internal surface and external surface of straw bale walls are fixed to brick column by the mesh. The internal and external mesh is connected by steel wires through bales (29). Compared to the pin system, mesh connection is weaker in preventing movement between bales. The steel frame straw bale building project uses a similar method to stabilize the bales. Rather than being applied between bales and column, metal mesh is used around the junction of bales and frames. The existing Chinese method of stabilizing bales may not provide sufficient support for limiting movement of bales and could not be applied in construction of long straw bale walls.

A third difference of the existing straw bale construction and the straw bale building worldwide is the multiple layer rendering construction with various rendering materials. The idea of using the rendering construction is to form a flexible intermediate layer between the straw and other render materials and therefore increase stability of the rendering construction (29). Only the ADRA project and the following standard design published by DCHP have applied these multiple render layers. However, the method is not mentioned in any other research or construction practices and the effectiveness of the rendering construction is highly doubtful. Renders elsewhere in the world generally use a single render material rather than combination of different materials.

3. Research method

Informed by the literature, the current status of straw bale buildings in Jiamusi may therefore have potential issues relating both to thermal bridging and to straw degradation. To clarify the hypothesis, both a site visit and computational simulation were conducted.

A site visit was conducted to observe and record the condition of the buildings of the ADRA project in Jiamusi in January 2015. The on-site visit concentrated on two particular straw bale farmhouses. The first house had been occupied by a local farmer since the completion of the building and the other uninhabited building had been abandoned 4 months before the on-site visit.

To verify the hypothesis of thermal bridging issues, the ADRA design is simulated using THERM. The simulated areas are the joint construction of gable ends and straw bales, the joint construction of south and north walls and a section through the gable ends (Figure 9). There are three sections of walls in the simulation process. There is no specific drawing of joint constructions of walls in the published design collection. The joint constructions can be deduced from the drawing of construction detailing (Figure 2) and the design of the wall section (Figure 3). The wall section is referenced from the layout of the design of farmhouses in the published design collection (Figure 10).

The simulation uses an external air temperature of -30℃ which is representative of winter air temperatures in Jiamusi. The internal temperature is set at 16℃ which is typical of indoor air temperatures in farmhouses in the rural areas of northern China (16). Thermal conductivity of each building material in the simulation process is listed in Table 4. The use of mortar between straw bales is only referenced in the unpublished manual, and there is no evidence that existing straw bale buildings have applied such a construction method in northern China. This paper does not therefore consider such a construction method.

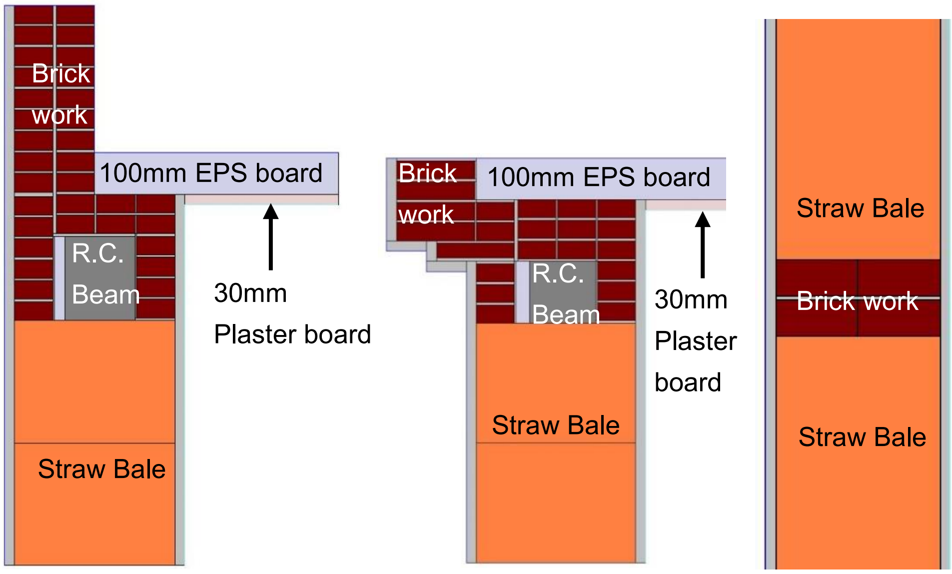

Figure 9. The joint construction of sidewall (left), Joint construction of south and north wall (middle) and section of sidewall in the THERM simulation

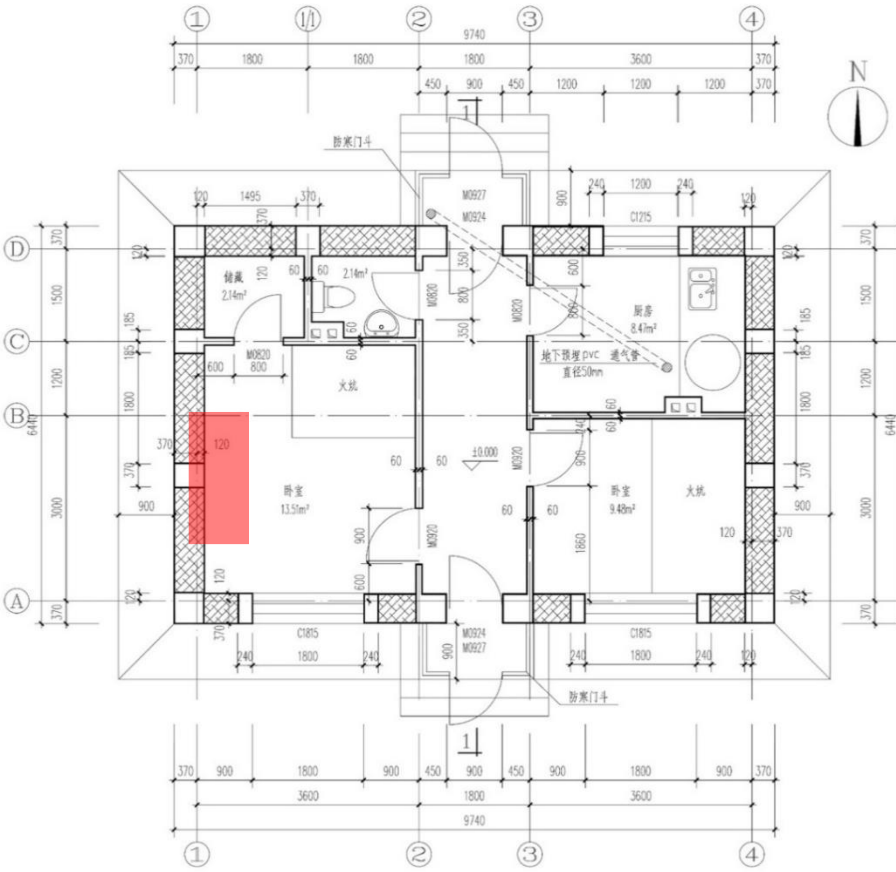

Figure 10. Layout of design of farmhouse in the ADRA project in Jiamusi and simulated section of gable end (in red). (Redrawn from (29))

Table 4. Thermal conductivity value used in THERM simulation.

Building Material	Thermal conductivity (W/mK)	Reference
Straw bale	0.07	(30)
EPS board	0.038	From THERM database
Ceiling board	0.061	
Cement mortar	0.93	(31)
Reinforced concrete	1.28	
Masonry brick	0.81	

Simulations are made for both the designed construction and the likely construction used in the buildings. A gap between the EPS board and the brick frame is included in the simulation process to take account of poor quality installation. This simulated installation error consists of a 2mm vertical linear gap between EPS board and the brick work in the joint construction of gable end and joint construction of south and north wall. The gap is in the range of allowable error in the Chinese standard (32).

4. Evaluation of the ADRA project

4.1. On-site visit of the ADRA project

During the site visit of the straw bale building in the ADRA project in Jiamusi. Two problems were identified in the inhabited building which are condensation issues and the cracking issues.

4.1.1. Condensation and frost issues

Firstly, condensation was found on the internal corner in the inhabited straw bale houses. The surface temperature on the internal corner is lower than the freezing point and the liquid condensation developed into frost during the visit (Figure 11). According to the owner of the farmhouse, the condensation is serious on the internal surface of sidewalls. The owner also reported that the frost appears from late December to early January when the lowest air temperature appears annually. However the problem was never happened on the internal surface of either the south wall or the north wall.

Figure 11. Condensation at the junction of the north wall and the west wall inner corner of one of the straw bale house in Jiamusi.

4.1.2. Cracking issues on rendering construction

A second problem is linear cracking on external surface of gable ends. The cracks were observed both on the inhabited house and the uninhabited house. It is important to appreciate the detailing of gable ends to understand the cracking issues on the walls. Making use of the photograph which was taken in 2006, the construction beneath the external plaster can be appreciated (Figure 12). The construction of gable end is similar to the construction of non-opening area of south walls and north walls (Figure 2).

Figure 12. Detailing beneath external rendering of gable end in the ADRA straw bale building project in Jiamusi. (33)

The cracks were observed both on the surface of brick frame of gable ends and between the structural frames and infill straw bale walls (Figure 13). As the owner of the straw bale house indicated, the cracks were formed during the first winter after the completion of the construction in 2006. The metal mesh between brick frame and straw bales failed to resist crack generation. Because of the serious cracking issues, the owner of the uninhabited straw bale farmhouse decided to move out 4 months before the on-site visit by author. Because cracking issues have a close relationship with straw degradation (23), the straw in gable ends is expected to be in a poor condition. Straw degradation was identified by drilling an opening on the gable end of the uninhabited house (Figure 14). Decolourization of straw behind rendering construction as well as the rusty metal mesh were identified in the opening. Due to low temperature (-19 ℃) during the onsite visit, moisture in the straw bales freeze the straw bales firmly. As a result, there is no sample was taken from the drilled opening.

Figure 13. Cracks (highlighted in red) on surface of brick frames (left) and between straw bales and frames (right).

Figure 14. Straw degradation in the gable end of a non-resided straw bale house in ADRA project.

4.2. Thermal bridging and consequential defects

The simulation results show serious thermal bridging issues in the ADRA project in Jiamusi. The majority of the heat loss is associated with the non-straw bale elements (Figure 15). There is a clear linear boundary at the straw bale and brick-concrete interface in the thermal transmittance figure. Heat transfer through straw bales is close to 0 W/m^2 whereas it is 26-36 W/m^2 for the brick work for the joint design and 26-53 W/m^2 for gable ends. The concrete beam conducts the most heat through internal space to outside. The high conductivity of the concrete ring beam forms clear thermal bridging in the joint design of south and north wall design. The heat transmittance figure shows that heat is exchanged more rapidly through non-straw bale elements and the more frequent temperature cycling may lead to thermal shock issues during external temperature swings around the freezing point which will lead to cracking on the surface, as has been observed from figure 13.

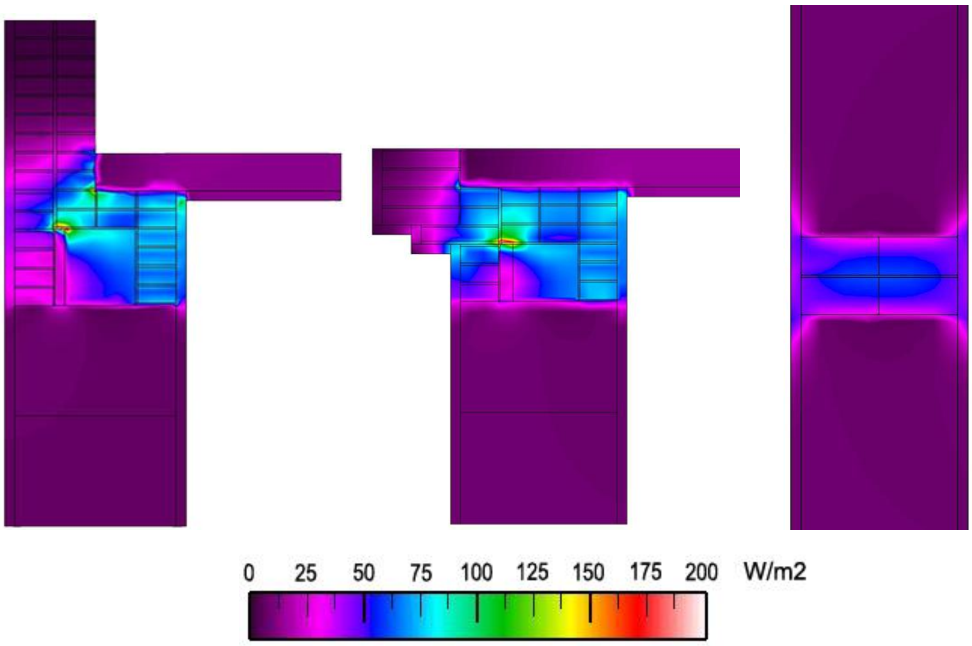

Figure 15. Thermal transmittance of the joint construction of sidewall (left), Joint construction of south and north wall (middle) and section of sidewall in the THERM simulation

The heat transmittance data indicate potential for rapid temperature changes at the external surface. The external surface temperature differences in the simulated situation can be used to estimate the potential for differential thermal expansion of the external surface. According to simulation, greatest surface temperature difference occurs on the gable end section and the joint construction of the gable end. The surface temperature of cement mortar is approximately -30℃ on straw bales whereas the temperature can reach -23 ℃ on surface of masonry bricks (Figure 16). The simulation results explain the linear cracks on gable ends. The large surface temperature difference can lead to differential temperature expansion issues within external surface render. Because cement render is weak in tension, the cracks are likely to occur and can have serious consequences, including the ingress of water into the underlying straw bales.

The frost issues on internal surface which is observed can be explained by the gap between the insulation material and the brick work on the gable end walls. The gap between the insulation material and the brick work can result in the surface temperature on internal corner being lower than freezing point (Figure 17). As a result, failed installations of insulation construction as per the design specification have great influence on the internal surface temperature on the gable end walls.

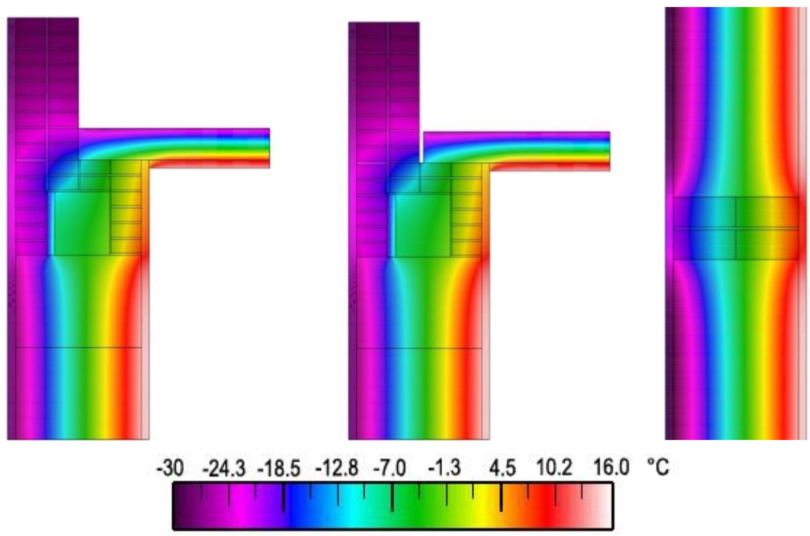

Figure 16. Temperature distribution of design joint construction of gable end (left), realistic joint construction of gable end (middle) and gable end section (right).

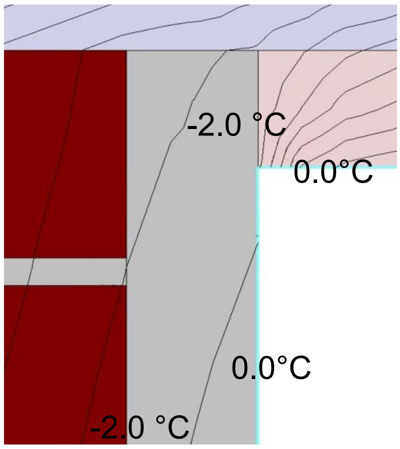

Figure 17. Thermal simulation result of the realistic joint construction within allowable range of error (right)

The situation for the south and north walls is different. Regardless of clear thermal bridging identified in the image of thermal transmittance, there is no significant surface temperature variation on the south north walls in the simulation. The surface temperature was similar in both design joint construction and realistic joint construction (Figure 18). The situation can be explained by the decorative overhang brick construction at the eaves. The additional thickness of brick provides extra thermal insulation to the non-straw bale elements and decreases the variation of the surface temperature. The external surface temperature distribution only initiates differential expansion causing cracking to appear on the gable ends.

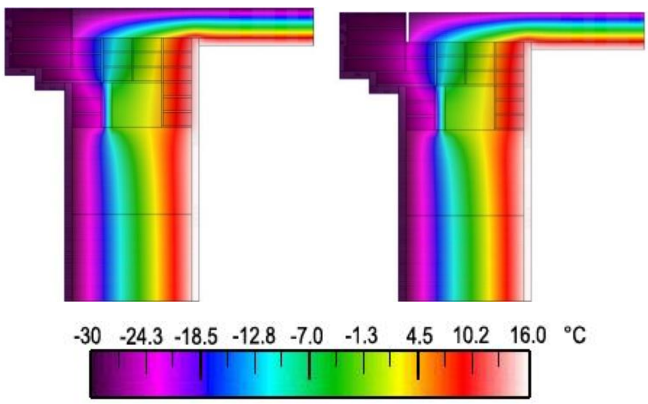

Figure 18. Temperature distribution of design joint construction of south and north

wall (left), realistic joint construction of south and north wall (right)

4.3. Summary of the results and recommendations for future straw bale construction in northern China

The design of the ADRA project is inadequate with respect to thermal insulation material on the structural elements. This design results in thermal bridging issues on joints between straw bales and structural frames. Because of the additional layers of brick work on external surface of south (north) walls, the thermal bridging produces a lower temperature difference between structural elements and insulation on both the external surface and internal surface. On the gable ends, the thermal bridging issue produces a large temperature difference between structural elements and insulation on the surface of the walls. This issue is the likely cause of external surface linear cracking issues around the area between straw bales and structural frames. Taking into account potential human error factors in construction, the thermal bridging can result in frost issues on the internal surface when low temperature occur in winter seasons.

The existing straw bale constructions have proven to be problematic in responding to local climate conditions in northern China, therefore several recommendations can be made:

1. Design to minimize thermal bridging issues is crucial for straw bale construction in northern China. Without sufficient thermal insulation to the non-straw bale construction components, the external render can have cracking issues which will result in straw degradation. To correct the issues identified in this research, modifications of the existing straw bale buildings are needed. With installation of consistent layer of insulation material to replace the brick work, the identified thermal bridging issues can be effectively fixed in the straw bale buildings in the ADRA project (Figure 19).

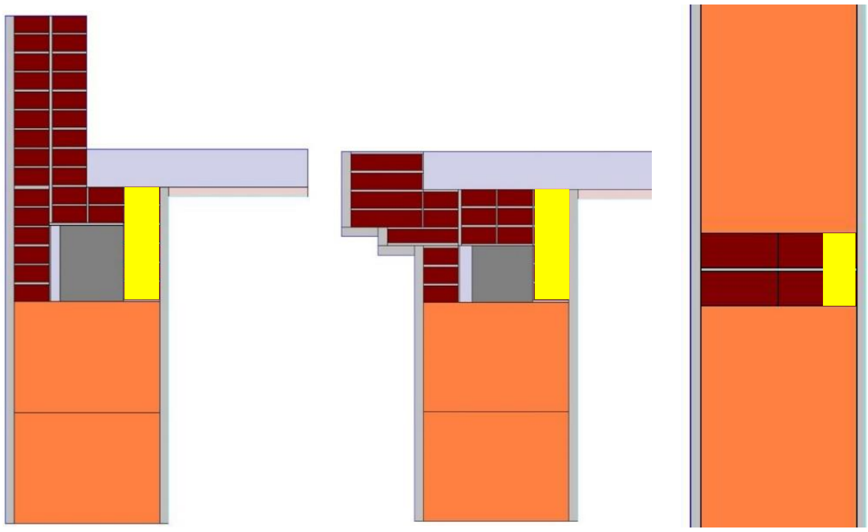

Figure 19. Proposed installation of thermal insulation material (yellow rectangle) in the straw bale buildings in the ADRA project.

2. Foundation design should prevent a clear pathway between straw and underground ground moisture to prevent rising damp issues. As the brick knee walls in the ADRA project provide are moisture permeable, installation of a waterproof layer around the brick knee walls should be required for further construction straw bale buildings which reference the construction detailing from the design guide book of the DCHP (Figure 20).

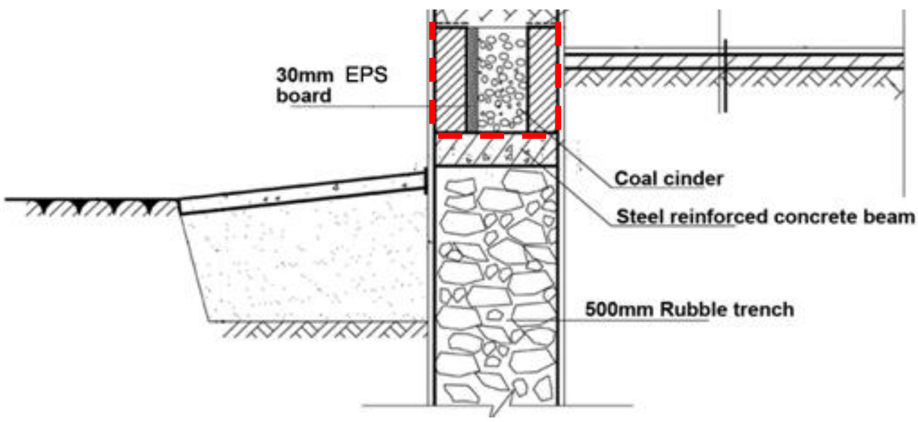

Figure 20. Proposed modification of the installation of water proof layer in the standard design guide book published by the DCHP.

3. The pinning system is crucial for stability of straw bale walls during the construction phase. Introducing a pinning system can improve the buildability of straw bale walls.

4. With regard to the breathability requirement of straw bales, lime render is a better choice than cement render. However, the capability of lime render to resist thermal shock remains uncertain and needs to be researched further.

5. Conclusion

The existing design of the straw bale buildings in China fail to minimize thermal bridging through the straw bale walls. Based on the on-site inspection of the straw bale buildings in Jiamusi and following computational simulation, the thermal bridging issues are shown to have a close connection with the cracking issues on the external surface of render layer. Compared with straw bale practices globally, the design may also be inferior in preventing rising damp and in the choice of render material. However, the design of straw bale buildings can be modified by simple changes to the designs of existing straw bale buildings. As the positive aspects of straw bale design included in the ADRA project and the following standard design guide book by the DCHP, straw bale buildings would be applicable in northern China.

Further research should focus on improving the straw bale construction systems and detailing to minimize the issues identified. The impact of this paper is to identify the failure of previous straw bale buildings in resisting low temperature in northern China, whilst also establishing the potential for a re-designed construction system to make a large impact on the reduction of carbon emissions in the region.

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