

DYNAMIC SIMULATION AND FULL-SCALE TESTING OF A PRE-FABRICATED STRAW-BALE HOUSE

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Abstract: Straw is an agricultural by-product and, after accounting for use in animal bedding, the mushroom sector, and Biomass power stations, there is an annual overall net straw surplus in Great Britain of approximately 5.5 million tonnes. The use of this non-food crop in construction is considered beneficial not least for the sequestration of carbon during production. The availability and inherent sustainability of this building material has led to a resurgence in its use over the last decade. As many countries strive towards low or zero carbon targets for building energy use, designers are exploring new methods of construction using natural materials such as straw, which, due to its insulating properties, has the potential to significantly reduce the energy required for space heating. However, there is a lack of scientific research into the thermal performance of straw-bale buildings, particularly in the UK. This paper presents the results of computer simulations and initial field-testing of the thermal performance of a BaleHaus constructed using ModCell pre-fabricated modular panels. A highly-instrumented two-storey BaleHaus has been built on the University of Bath (UK) campus. For this study, the internal environment was monitored by wireless Relative Humidity and Temperature (RHT) sensors at 12 locations whilst a weather station close to the building records the external environmental conditions. The results of co-heating and air-tightness tests are presented in addition to dynamic simulation modelling which predicts the annual energy use and CO₂ emissions.

Keywords: *Straw-bale, Co-heating, Simulation, Thermal transmittance.*

1. Introduction

Building with straw-bales appears to have originated in the Midwestern US but examples can be found across Europe and Australia. The oldest known straw-bale house still in existence, the Burke house in Nebraska, was constructed in 1903 (King *et al.*, 2006). Few viable construction materials existed in the vicinity and so straw-bales were used. Interest in straw as a construction material decreased as a result of the industrial revolution due, in part, to increased availability of modern, highly processed, building materials. In the UK, over the last 10 years straw and other natural fibre materials have become the focus of research and development aimed at producing modern innovative construction products with minimal environmental impact. Straw is a natural, renewable, and biodegradable material that can be sourced locally and requires relatively little processing for use in construction. A co-product of the agricultural industry, straw has low embodied carbon and high thermal resistance helping to substantially reduce the whole-life carbon impact of buildings constructed of this natural material.

Although straw-bale construction has over a century of use, the development of a wholly prefabricated load-bearing panelised building system is a new concept. Modern buildings and their component parts must satisfy performance standards for load-bearing capacity, fire resistance, thermal transmittance, acoustic performance etc. Accordingly, in order to advance the use of straw-bales in construction innovative methods must be employed to create a product suitable for use in 21st century dwellings and non-domestic buildings. The development of ModCell (a portmanteau of modular and cellulose) panels forms one part of ongoing research at the University of Bath investigating the performance of these straw-bale-filled structural timber units. The BaleHaus @ Bath (Figure 1) is the first house constructed using this system for the entire building envelope. The BaleHaus is a full-size, two-storey building built on campus at the University of Bath, constructed over the summer of 2009 as part of a collaborative research project funded by the Technology Strategy Board (TSB).



Figure 1: *The BaleHaus@Bath*

2. Materials and methods

In order to reduce the environmental impact of transportation and to protect the un-rendered straw-bales from rain, the ModCell panels are assembled in a temporary ‘Flying Factory’ close to the construction site (Figure 2). In the case of the BaleHaus @ Bath a suitable agricultural building was found approximately six kilometres from the Bath campus.



Figure 2: *ModCell panel construction in a Flying Factory*

Various combinations of straw-bale, door, and window panel are produced. A standard ModCell straw-bale panel is constructed from a 100 mm thick pre-cut engineered glue-laminated timber frame measuring approximately 3190 mm wide, 2660 mm high and 490 mm deep. The frame is filled with straw-bales which are pinned together every other row with wooden stakes. The straw is pre-compressed vertically to prevent future settling of the straw and the frame is reinforced with stainless steel threaded bars in the corners and vertically to provide rigidity. Conduit for electrical cables is fitted and the panels are then spray rendered with formulated lime in three layers before being delivered to site.

The organic nature of straw makes it liable to decay when subjected to certain combinations of temperature and humidity (Goodhew *et al.*, 2004) and, therefore, the conditions within the ModCell panels are monitored. A total of 66 wireless sensors recording relative humidity and temperature (RHT) are embedded within the panels with a further nine sensors monitoring conditions at the junctions of the panels. The results of within-panel monitoring will be presented in the near future. The focus of this paper is the energy performance of the building, which uses data gathered from 12 wireless RHT sensors located inside the house and referenced to the external conditions monitored on

the roof of a nearby building. The 12 wireless sensors record RHT at three heights (0.45 m, 1.6 m, and 2.1 m from the finished floor level) and at two locations per floor within the BaleHaus. The roof-top weather station is located on the Department of Architecture and Civil Engineering building very close to the site of the BaleHaus. The Weather station measures global and diffuse radiation on the horizontal plane, wind speed and direction, rainfall, relative humidity, temperature, and barometric pressure. A data logger records all measurements at 10-minute intervals.

3. Laboratory and full-scale testing

3.1 Thermal transmittance testing, U -value

A thermal transmittance (U -value) test was undertaken on a single panel at the British Board of Agrément's (BBA) Thermal Laboratory, Garston, UK. The facility uses a Guarded Hot Box test method in accordance with BS EN ISO 8990 (1996).

3.2 Air permeability testing, q_{50}

Current Building Regulations in England and Wales (ODPM, 2006) require the air-permeability of the building envelope to be less than $10 \text{ m}^3/\text{hr.m}^2 @ 50 \text{ Pa}$; often referred to as q_{50} . Air permeability tests were conducted in accordance with the ATTMA TS1 (2007) and BS EN 13829 (2001) test methodologies. The BaleHaus under test is presented in Figure 3.



Figure 3: Blower-door fitted to the BaleHaus

3.3 Co-heating test

A co-heating test determines the overall building heat loss coefficient through measurements of the heating power input (W) required to maintain a temperature difference (K) between the indoor and outdoor air. An electric resistance heater, rated at 3 kW, and two circulation fans were located on each floor of the BaleHaus. The heaters and fans were controlled by a thermostat. The interior space was heated to $25 \text{ }^\circ\text{C}$ and the external air temperature and solar radiation were monitored by the weather station. Electricity consumption for all fans and heaters was recorded by an energy meter with a pulse output connected to a data logger. All data were recorded at 10-minute intervals for the duration of the test. Data were recorded for approximately three days until unseasonably warm weather necessitated premature curtailment of the test. The contribution of 'free' heating energy from solar radiation was removed using regression analysis.

3.4 PassiveHaus Planning Package (PHPP) & Integrated Environmental Systems (IES) analysis

Dwellings constructed to PassivHaus standards have achieved space heating energy savings of more than 80% compared with existing building stock (Feist *et al.*, 2001) and the design philosophy has had

over 20 years' development. Accordingly, the German PassivHaus standard represents a proven standard enabling the development of ultra-low energy buildings. PHPP is a Microsoft Excel energy calculation tool specifically developed for certification of PassiveHaus dwellings. This design tool contains 16 core worksheets enabling calculation of building energy use plus a further 10 worksheets that permit calculation of non-standard items such as, for example, the contribution of energy from renewable sources. Integrated Environmental Systems (IES) is a suite of applications. The key modules used for analysis of the BaleHaus were ModelIT, an application for the input of 3D geometry used to describe the building, and ApacheSim, a dynamic simulation module driven by hourly weather data and used to simulate the thermal performance of the building envelope.

4. Results and inputs to models

Under laboratory tests at the BBA Thermal Laboratory a standard ModCell straw-bale panel with, nominally, 30 mm of lime render on inner and outer faces achieved a U-value of 0.19 W/(m²K). Internal and external surface resistances were calculated to be 0.132 (m²K)/W and 0.045 (m²K)/W, respectively. The thermal conductivity of the straw-bale, as with most building materials, varies with density such that a lowering of density of the product results in a lowering of its conductivity; subject to conduction remaining the dominant heat transfer mechanism. The bales used in the construction of the test house and the specimen subjected to laboratory testing were approximately 115kg/m³; the thermal conductivity of straw-bales across a range other densities has been tested as part of the BaleHaus project and these results will be presented in the near future. U-values for the remaining opaque elements of the BaleHaus @ Bath were calculated from conductivity data provided by their respective manufacturers and in accordance with BS EN ISO 6946 (1997); together with a typical window U-value and the measured wall U-value these are summarised in Table 1.

Table 1: *Summary of BaleHaus @ Bath U-values*

Element	BaleHaus U-value, W/(m ² K)	Regulatory limit ^a , (ODPM, 2006)
External wall	0.19	0.35
Ground floor	0.23	0.25
Roof	0.16	0.25
Typical window	1.3	2.2

^aUK Building Regulations in effect at the time of design & construction.

Using ATTMA TS1 (2007) Method B the BaleHaus @ Bath achieved an air permeability test result of 0.86 m³/hr m² @ 50Pa, based on an external envelope of 247 m² and enclosed volume of 262 m³, which represents an improvement of over 90% on current UK regulatory limits. The geometry, air permeability and fabric details of the BaleHaus were transferred to both PHPP and IES. In PHPP the q₅₀ test result was converted to suit the PassivHaus calculation method. The corresponding value for the PassivHaus test methodology, which is based on a reduced internal volume discounting internal partitions of 254 m³, is an air change rate at 50 Pa (n₅₀) of 0.84 ac/h. In both PHPP and IES, weather data for Manchester, UK, was chosen, in part, because this weather file is close to the UK population-weighted average but also because the on-site weather station is yet to record a full year of weather data; having only been operational since December 2009.

The first run of the PHPP and IES models was used to determine the heat loss coefficient of the test building for comparison with measurements from the co-heating test. Preliminary results from the co-heating tests are limited, for reasons outlined earlier, and additional, longer duration, tests are planned. The average whole-building heat loss coefficient for the duration of the test period was 50 W/K. The heat loss coefficient determined by PHPP and IES was 80 W/K and 78 W/K, respectively. The average for all dwellings currently in the UK housing stock is approximately 247 W/K (Utley and

Shorrock, 2008). Figure 4 presents the calculated and simulated results of PHPP and IES with the measured data from the co-heating test.

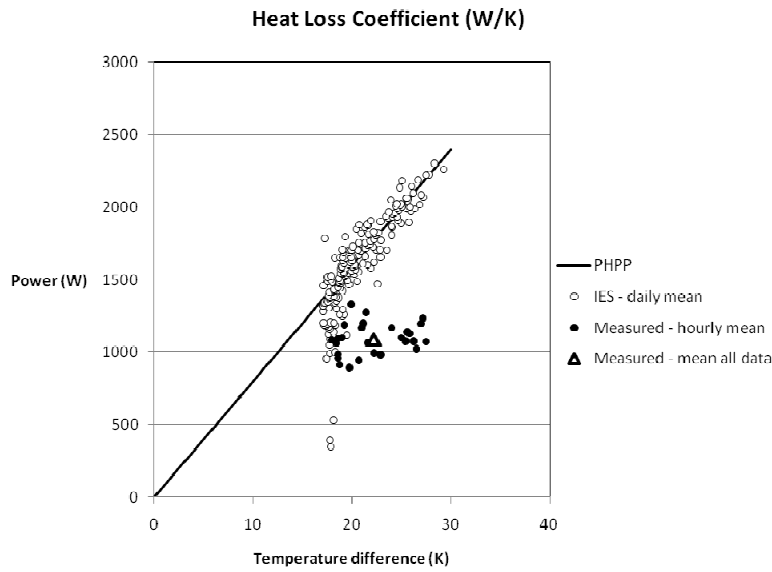
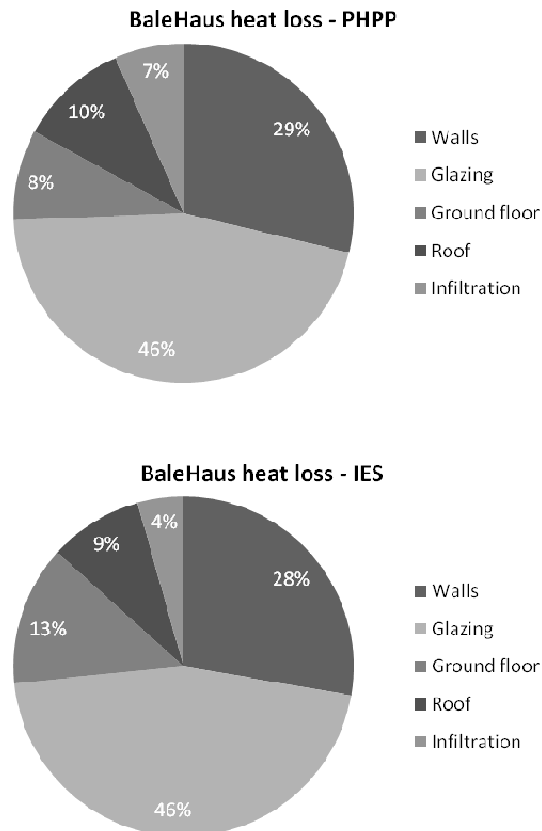


Figure 4: *BaleHaus Heat loss coefficient*

Figures 5a and 5b present the breakdown of heat losses as determined by PHPP and IES



Figures 5a and 5b: *Breakdown of BaleHaus heat loss.*

Presently the BaleHaus @ Bath has no mechanical services installed. In order to estimate the annual energy use of a 'real' BaleHaus the following heating, ventilation, and domestic hot water (DHW) services were added to the PHPP evaluation of the BaleHaus:

1. Gas condensing boiler – seasonal efficiency 88.2% (gross).
2. Mechanical ventilation system with heat recovery – heat recovery efficiency 78%.
3. Solar hot water system – 2.5 m² vacuum tube collector, facing south and tilted 45°.

Additionally, internal useful heat gains were specified at 0.25 W/m², in line with typical PassivHaus values. The space heating demand, a function of conduction and infiltration losses but offset by useful solar and internal gains, is presented for both PHPP and IES analyses in Figure 6.

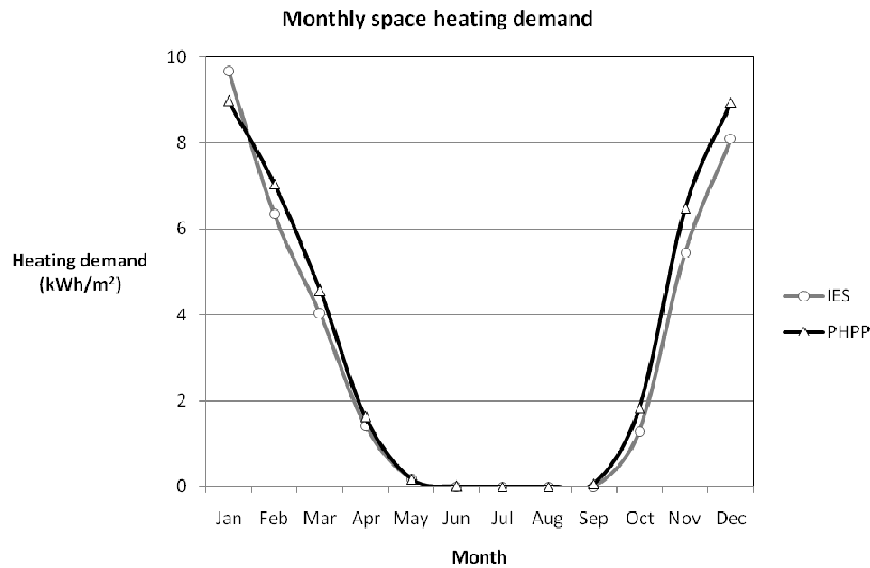


Figure 6: Space heating energy demand.

5. Discussion

Annual Space heating demand for the BaleHaus was calculated as 39.7 kWh/m² and 36.5 kWh/m² by PHPP and IES, respectively. The pressurisation test n_{50} air change rate was 0.84 ac/h and total primary energy demand, calculated in PHPP, using SAP 2009 (BRE, 2010) primary energy factors, was 108 kWh/(m² a), which includes a 14 kWh/(m² a) saving due to the contribution to DHW heating from the solar hot water system. It is evident from the breakdown of heat losses (Figures 5a and 5b) that a considerable amount of the space heating demand is due to heat loss through the glazing. The typical U-value for the glazing was 1.3 W/(m²K), whilst better than UK building regulations it is significantly higher than the recommended maximum of 0.8 W/(m²K) suggested for PassivHaus dwellings – this modification alone would result in an annual space heating demand reduction of almost 10 kWh/m² to 30 kWh/m². The PassivHaus standard presents strictly defined criteria that include three key elements, which are determined using the PHPP workbook:

1. The energy required for space heating must not exceed 15 kWh/(m² a).
2. A maximum air change rate pressurisation test result of 0.6 /hr @ 50 Pa.
3. A primary energy demand of not more than 120 kWh/(m² a).

For the BaleHaus, any further significant reduction in space heating demand, i.e. towards the PassivHaus standard, would require changes not only to the thermal performance of the glazing but also the area and orientation of glazing in combination with the provision of shading devices to ensure a suitable balance between useful, winter-time, solar gain and overheating in summer.

In the UK, primary energy use per unit floor area was an average of approximately 365 kWh/(m².a) in 1990 and 382 kWh/(m².a) in 2005 (TSB, 2009). Accordingly, 108 kWh/(m².a) represents a 70% reduction on the 1990 average for the UK stock. In carbon emissions terms this level of primary energy use equates to approximately 22 kgCO₂/(m².a); comparable to the CO₂ emissions level required by the Association for Environment Conscious Building's Silver Standard, and equalling a 70% reduction on the current UK stock average (AECB, 2007).

6. Conclusions

The results of full-scale field and laboratory tests in addition to dynamic and steady-state modelling results have been presented for the first ModCell straw-bale panel-constructed 'BaleHaus' located at the University of Bath, UK. These results indicate a high level of thermal performance is achieved from the use of straw-bales as part of an innovative pre-fabricated load-bearing panelised unit. Great Britain has a surplus of straw exceeding 5 million tonnes per annum (Copeland and Turley, 2008); sufficient resource for over a million BaleHaus dwellings. The use of local, natural, materials to construct dwellings capable of meeting the performance standards required by building codes and achieve a 70% reduction in primary energy use and CO₂ emissions represents a promising opportunity for designers to make a significant contribution to meeting national and international CO₂ emissions targets and other legislation aimed at improving building energy performance.

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