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Development and testing of a prototype straw bale house

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This paper describes the research, development, construction and initial testing of an innovative low-carbon prototype house built using novel prefabricated straw bale panels. The use of straw as insulation provides an opportunity for value-added use of a widely available low-carbon co-product of farming. The research reported in the paper seeks to enhance the understanding and develop the modern mainstream acceptance and use of straw as a construction material in housing and other applications. The paper initially summarises development and construction of the panels and the house. Tests conducted on the panels and house reported in the paper include on-going durability assessment, fire resistance testing, acoustic transmittance testing, air permeability tests and thermal surveys.

1. Introduction

Straw bale construction emerged in Nebraska in the USA in the late 1800s from the need of European colonists to provide their own shelter. The oldest existing straw bale structure, the Burke house, is just over 100 years old, and is located in Alliance, Nebraska (King, 2006). Straw bale construction was chosen by the settlers, initially as a temporary solution, because no other viable construction materials were readily available. Interest in straw as a construction material decreased in the early twentieth century as industrially produced building materials became more readily available with development of transport (King, 2006). Interest in straw bale construction re-emerged in the early 1980s in the USA and has seen a further resurgence from the early 1990s. Straw bale construction arrived in the UK in the mid-1990s (Jones, 2009). The revival of straw as a construction material has developed as builders have recognised the advantages of straw in this capacity. Straw is a natural, renewable and biodegradable material that can be readily sourced locally in many areas and involves little further processing. It has low embodied carbon and therefore its use can help significantly to reduce the environmental impact of new building infrastructure.

The modern straw bale construction techniques used initially were inspired by the Nebraska buildings, with load-bearing walls and pins driven through bales used to enhance stability. Significant developments have been made and the technique has been embraced by self-builders around the world (King, 2006). Timber frame buildings with straw bale infill have become increasingly popular as the construction technique enables the straw walls to be built in an enclosed, dry environment.

Prefabricated straw bale building techniques take traditional materials and utilise them for modern methods of construction, taking the advantages of using straw into a controlled prefabricated process. This paper outlines the use of prefabricated straw bale construction methods to construct panels and a prototype house, built for research purposes. The panelised system focused on in this paper is ModCell (modular cellulose), first used in the University of the West of England's School of Architecture in 2002. The aim of this paper is to enhance the understanding of this technique for use in the UK. Initial results on the durability of the straw within the prototype house are reported, together with findings from investigations of the acoustic transmission performance, air permeability and thermal integrity. The sound insulation performance of individual test panels is also provided, together with their fire resistance.

2. Prefabricated straw bale construction

ModCell employs prefabrication as a method of construction using straw to provide panels for cladding and, more recently, load-bearing walls (see Figure 1). Straw bale benefits from the general advantages of prefabrication, including: improved quality; reduced construction time on site; minimisation of waste; and safer construction. However, very importantly prefabrication reduces the risk of weather delays and the straw becoming wet during construction and removes the fire risk from having loose straw on site. The disadvantages of this approach, however, are potentially increased costs and the requirement to transport and lift the large prefabricated units.

The panels have been designed and developed to enable the mainstream construction industry to use straw and other natural materials more easily. The highly insulated panels can replace materials with much higher embodied carbon, therefore reducing the embodied carbon in new buildings as well as reducing the energy requirements in use. The straw bales used in the panels are the common bale size of approximately 1 m long, 0·45 m deep and 0·35 m high. Straw bale construction provides diversification for farmers, enabling them to use straw as a valuable co-product. As demand for straw for use in construction escalates, baling techniques might be adapted to deliver straw bales in a range of sizes and specifications suited to various construction applications.

The prefabricated straw bale panel frames are constructed using engineered (glue-laminated or cross laminated) softwood timber. These open-sided frames are in-filled with straw bales (Figure 2) that are staked with timber poles. The straw bales are pre-compressed vertically within the frames using a fork-lift. Over seven courses the bales are typically compressed by 80–100 mm (depending on original size). Pre-compression of the straw is not significant for structural performance of the panels, but provides a stable substrate for the renders and prevents subsequent settlement and formation of gaps. The frames are braced with stainless steel bars. Once filled with straw the panels are spray rendered with three coats of formulated lime render, to a thickness of 30–35 mm. The render provides a water vapour permeable system, allowing moisture to transfer through and preventing humidity build-up that might otherwise cause deterioration of the straw. The panels used in the prototype house are 3·19 m wide by 2.66 m high and 0·49 m thick and were used in four different layouts: solid with no windows; two-bale with a window one-bale wide; one-bale with a window two-bales wide; and zero-bale with no straw, just a window, as shown as part of the prototype house in Figure 1. The panels weigh up to 1·8 t and are constructed in a temporary 'flying factory' (Figure 2) located close to the construction site, using local labour and straw where possible. The process also reduces the amount of waste created as the engineered timber comes pre-cut and most other materials come ready for use with little processing needed.

The prefabricated straw bale panels have been used as cladding on a number of non-domestic buildings; the design and construction of these have been developed significantly. Previous tests have shown the importance of external render to the strength and stiffness of load-bearing straw bale walls (Walker, 2004). In a previous 2-year research project, the prefabricated panels were tested and shown to provide sufficient shear-racking stiffness and resistance for modest (two- to three-storey) load-bearing applications (Lawrence *et al*., 2009). Development of the frame joint details and further investigations of shear-racking performance was continued by Gross *et al*. (2009).

3. Prototype house

The load-bearing panels have been utilised for a prefabricated straw bale housing concept, known as BaleHaus. The first house constructed using this system in its entirety has been built on the University of Bath campus and is known as the BaleHaus @ Bath. This prototype house is being monitored and evaluated as part of a Technology Strategy Board (TSB) funded research project being undertaken at the university. The

Figure 1. Prototype house

Figure 2. Panel construction process in 'flying factory'

objectives of the project are: to develop the understanding of the structural and environmental performance of a prefabricated straw bale house to provide data for use in various contexts, including design guidance; to optimise the system used, in terms of junction details, materials, finishes and fixings; and to monitor and review the durability of straw in buildings made of prefabricated straw bale panels.

The prototype house was constructed in the summer of 2009, with research monitoring starting at the end of September in the same year. The house was built using eight new panels built in a 'flying factory' 6 km away from the site and eight panels reused from a previous exhibition project, where they made up the ground floor. The house was designed, for monitoring purposes, with two bedrooms downstairs and an open-plan living/dining area and kitchen upstairs. The construction of the prototype house was built onto a conventional reinforced concrete slab foundation. A timber sole plate was attached to the slab which the ground floor panels sit on once craned into place, along with the four corner boxes filled with straw. The cross-laminated solid timber floor plate was then craned into position and another sole plate fixed to this for the first floor panels to sit on. Once the first floor panels were craned into place, as shown in Figure 3, the cross-laminated solid flat timber roof was installed, insulated with wood fibre insulation board and covered with a recycled waterproof membrane. Along the vertical edges between the wall panels, 20 mm of wood fibre insulation was inserted and the panels were fixed together using long screw connections, sealed with airtight tape and zipped together to provide structural integrity both internally and externally using plywood strips. Western red cedar cladding was then applied to the exterior of the house and construction was completed when the floors were insulated with wood fibre insulation and finished.

The house was built to fulfil some of the objectives of the research project through monitoring and testing its performance. An environmental simulation model of the house has been created and validated using data from simulated occupancy of the house over a 12 month period. Weather data have been collected using a station located close to the house. The heat generated from occupants, appliances and lighting is replicated using incandescent light bulbs placed on nine sets of timer switches throughout the house. Thermal performance of the straw insulation, the panels and the house has also been investigated. Initial results are presented in this paper on the durability of the straw, as well as the fire and sound performance of the panels, and results from an air permeability test on the prototype house and a thermal imaging survey.

A life-cycle analysis (LCA) was undertaken on the prefabricated straw bale prototype house as part of work conducted at Imperial College London. The LCA was used to ascertain the environmental impacts of the prototype house compared to a hypothetical brick and block house with the same layout as the BaleHaus, which was used as a benchmark (Seguret *et al.*, 2009). Cradle-to-dismantling and cradle-to-grave analyses were used and revealed, as expected, that the prototype house performs better than the conventional masonry house, especially in relation to its low global warming potential (Seguret, 2009).

Figure 3. Construction of prototype house

4. Straw moisture monitoring

Addressing concerns for the long-term durability of the straw is a significant factor in wider market acceptance of this form of construction. The moisture and temperature conditions of straw within the panels of the prototype house are therefore being monitored to improve understanding of material performance and, hopefully, provide reassurance of the longer-term integrity of building with straw.

A total of 66 wireless (combined relative humidity and temperature) sensors have been embedded within the panels. A further 12 sensors are located internally in the house. The sensors are also capable of indirectly measuring timber moisture content, through a wood block attached to the sensor by two screws, using electrical resistivity. Three sensors are placed at the centre of each panel (at the internal face, halfway through and at the external face) to investigate the moisture and temperature profiles through the walls. The sensors are placed between straw bales and are protected by the lime renders. There are 18 sensors placed along the base of the external surface of the panels, as this is considered the location at highest risk of prolonged wetting and straw decay. There are also nine sensors at the junctions between the panels.

Initial data from the timber moisture equivalent sensors are shown in Figure 4, covering the period from construction of the prototype house in September 2009 to July 2010. Although the moisture content of the embedded small (Douglas fir) timber block (measuring approximately 60 × 25 × 10 mm) will not respond to changes in environmental conditions as quickly as the lighter straw, it will show longer-term trends in moisture conditions. Initially the moisture contents of sensors on the faces are higher than the moisture contents of those embedded in the middle of the panel; this is attributed to moisture from the lime rendering. By October 2009 the moisture profile shows highest moisture levels at the external face and lowest on the internal face. During early summer months the moisture content has reduced significantly. Over the monitoring period, 435 mm of rainfall was recorded at the site, with only 46 mm falling after 1 May 2010. Over the monitoring period the average daily timber moisture contents did not exceed 22%. Prolonged moisture contents above 25% are considered a significant risk factor for straw durability (Summers, 2006). Further data from moisture monitoring will be reported at a later date.

5. Fire resistance of panel

Fire resistance of a prefabricated straw bale panel was tested in accordance with BS EN 1364-1: 1999 by Chiltern International Fire (2009). The panel tested measured 3·0 m high, 3·0 m wide and 490 mm thick. For testing it was placed in a frame and fixed to the front of the test furnace. The test panel was manufactured using normal procedures and specified materials and was transported to the test site after 10 weeks (Gross and Walker, 2009). Bales were weighed, moisture content tested and specimens of lime render taken and tested to ensure compliance with the specifications. The test procedure followed a heating curve set out in BS EN 1364-1: 1999. The furnace temperature increased to an average of 700°C after 12 min, 900°C after 42 min and up to 1000°C after 86 min (Chiltern International Fire, 2009). The air pressure inside the furnace was increased to 20 Pa above atmospheric pressure to replicate real fire conditions. Radiant heat from the outer surface of the panel, temperatures on the outer face of the panel and the temperature inside the furnace were recorded (Gross and Walker, 2009).

After approximately 90 min the lime render directly exposed to the furnace fell away from the panel to expose the straw. The straw alone was left for a further 45 min before the test was voluntarily stopped after 135 min. There are many criteria with which the panel can fail, including sustained flaming and increasing the average temperature of the unexposed surface temperature by 140°C (BS EN 1363-1:1999 (BSI, 1999)). None was met during the test. The temperature within the furnace

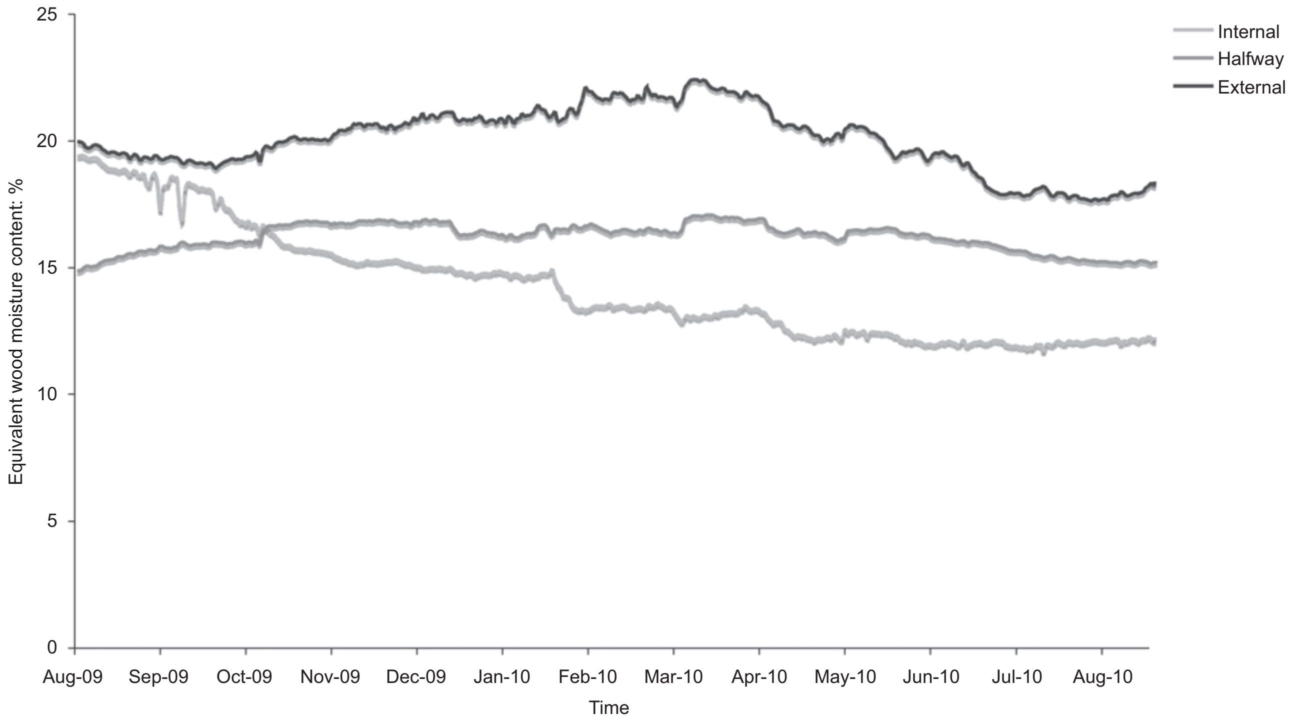

Figure 4. Wood moisture equivalent through straw in prefabricated panels

reached an average of 1065°C at 135 min (Chiltern International Fire, 2009). The temperatures monitored on the outer surface of the panel started at 12–14°C and raised to 36–60°C (Chiltern International Fire, 2009). The panel was removed from the furnace after the test was stopped (Figure 5), hosed down and inspected. The straw exposed to the furnace had charred black in a similar manner to the timber, although at a faster rate. On the side still covered in render, once some of this was removed, yellow straw was still visible.

The current UK Building Regulations 2010 Part B *Fire Safety, Volume 1 – Dwelling houses* (DCLG, 2010a) state that 30 min is the minimum period of fire resistance for an external wall in a residential dwelling, where the height of the top floor is not more than 5 m above the ground. The prefabricated straw bale panel met this requirement, exceeding it by more than four times the required performance.

6. Sound insulation performance

An acoustic transmittance test was undertaken on a prefabricated straw bale panel in accordance with BS EN ISO 140-3:1995 (BSI, 1995). The panel was constructed in situ and left for 7 days for the render to cure before testing was undertaken (Gross, and Walker, 2009). The panel was 3·6 m wide by 2·7 m high, with three whole bales and just under half a bale used for each of the six layers. The prefabricated straw bale panels usually consist of complete layers which are compressed to enable this. It was not possible to compress the bales in the test panel; their uncompacted density is around 110 kg/m^3 compared to a compacted density of around 120 kg/m^3. The lack of straw compaction has arguably reduced acoustic performance, although external much denser rendered finishes were unaffected.

The test was carried out in a horizontal transmission suite which consisted of two acoustically isolated rooms, the source room and the receiving room at the BRE. The division between the two rooms contained an aperture into which the panel was constructed. The gaps between the timber frame of the panel and the edge of the aperture were filled with acoustic insulation and sealed with acoustic sealant. During the test there were microphones in each room and noise at different frequencies was made in the source room and its volume measured in both the source and receiving rooms. These measurements were then used to calculate the sound level drop across the panel. A sound level drop, R_w (weighted reduction) value, of 48 dB was recorded (BRE, 2008).

A second sound insulation test was undertaken on the prototype house, shown in Figure 6, on 14 May 2010 in accordance with ISO 140-5:1998 (BS EN ISO 140-5:1998, (BSI, 1998)). The aim of this test was to investigate the sound insulation performance of the prototype house and to verify the results from the previous test. The test was carried out by emitting 100 dB of 'white noise' to the exterior of the house and its volume was measured on the exterior face of the building and in an isolated room inside the house. The isolated room was created in an attempt to exclude all sound leakage through the window and partitions. The window was sealed using two layers of sound insulation board, which were held in place by a frame around the window but were arranged in such a way that vibrations could not flow from the timber frame to the internal space. Background noise within the isolated room was also measured when the 'white noise' was not being emitted. The measurements were used to calculate a sound level drop, R_w value, of 44 dB (Mach Acoustics, 2010).

Figure 5. Panel being removed from furnace after fire test (Chiltern International Fire, 2009)

Figure 6. Sound insulation performance test being conducted on prototype house

The current UK Building Regulations 2010 Part E *Resistance to the passage of sound* (DCLG, 2010b) provide a minimum figure for R_w of 40 dB for the 'laboratory values for new internal walls and floors within dwelling-houses' for airborne sound insulation (ODPM, 2000, p. 13). The tests undertaken on the panel and on a wall of the prototype house both exceeded this figure, with the result for the panel being slightly better at 48 dB compared with 44 dB from the test carried out on the house. This difference in measured performance may be due to variations in test procedure or panels (straw density) and building details.

7. Air permeability

Modern buildings are expected to meet requirements to minimise air leakage and therefore reduce unwanted heat loss. An initial air permeability test was undertaken on the prototype house on 29th September 2009 in accordance with ATTMA TS1 and BS EN 13829:2001 (BSI, 2001). The test was conducted to identify any air leakage paths within the prototype house in preparation for the final test, which is standard practice. The house was sealed where necessary, around pipe inlets and where the automatic window openers were due to be installed, to allow the fabric to be tested. The fan unit used to undertake the test was located in the front door opening. The building was heated up to 20°C to enable cold air streams entering the building to be clearly identified using smoke detection. Initially the house was subject to a negative pressure of 50 Pa. The pressure differential was then reversed to cause air to be forced out of the building through the fabric. The house was filled with smoke to identify points of air leakage.

Measurements of the flow pressure and building differential pressure were recorded at a minimum of ten different fan speeds. These data were used with the volume of the building to calculate the air permeability, which represents the air flow associated with a pressure of 50 Pa normalised for the area of the building envelope and can be widely compared with other buildings. The prototype house achieved 1·36 m^3/h per m^2 at 50 Pa in the initial test (Building Analysis and Testing Ltd, 2009) and the various details were identified as possible areas for improvement from the smoke tests and thermal images. These included areas around inlet pipes, around the windows and junctions between panels. These areas were investigated and sealed where necessary before the second and final test was undertaken.

The second test was undertaken on 15 December 2009 to the same standard to determine that the building met the current UK Building Regulations standard of 10 m^3/h per m^2 at 50 Pa and to provide an air permeability figure to be used in calculations for further research. An air permeability at 50 Pa of 0·86 m^3/h per m^2 was measured, which is within the current UK Building Regulations 2010 Part L2 (DCLG, 2010c) and was noted as 'exceptionally low' (Building Analysis and Testing Ltd, 2009, p.6) in the test report.

8. Thermal survey

A thermographic building performance survey of the prototype house was undertaken on 16 February 2010, to assess the thermal performance of the building and identify areas of conductive heat loss, thermal bridging and building defects. The house was heated to 20°C to gain a sufficient temperature difference between internal and external conditions to enable clear external images to be captured. During imaging of the interior of the building it was placed under negative pressure using a fan to draw air flow through any gaps, which could then be identified in the image. The images taken were adjusted to highlight any anomalous areas and therefore show heat loss to be more extreme than reality.

A thermal image of the external east façade, shown in Figure 7, shows no sign of heat loss, thermal bridging or building defects of the building envelope. It does, however, highlight some heat loss around the door, which was thought might be due to ineffective seals. Externally there were two images which showed small amounts of heat loss through the fabric of the BaleHaus; these were from the left-hand side of the window on the north façade, which was also seen internally as air infiltration. The cladding at the top right-hand corner of the west façade was the second incidence which showed a small amount of heat loss, again seen internally as air infiltration.

Internally the panels showed uniform temperatures across their surfaces with some air infiltration around the edges; this is shown in Figure 8, an image of the first floor, right-hand panel on the south façade. The image also shows no sign of cold air bridging between the bales within the panel. Internally there were a number of incidences where air infiltration was identified as being present on more than one occasion, including: around the ply surround of the panels; at junctions between panels; through the window and door frame support; around the timber frames; and at both ends of the support beam.

The 'building envelope is performing very well thermally' (InfraRed Vision, 2010, p.5). Externally the majority of panels showed no sign of thermal anomalies and there was also no sign of thermal bridging through the timber frames, floor or roof. Heat loss was identified from the door frame and was thought to be due to ineffective seals, and there was slight heat loss seen externally on two panels. Internally there was no sign of cold air bridging between the bales within the panels and an even temperature across the surfaces of panels was noted. The majority of incidences of air infiltration internally were from

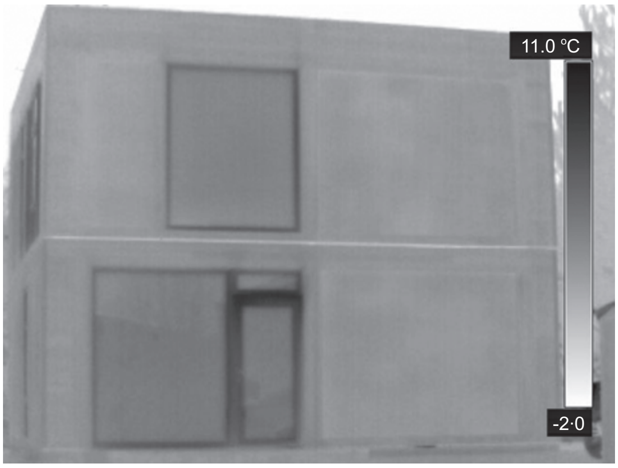

Figure 7.External thermal image of east façade (InfraRed Vision, 2010, p. 8)

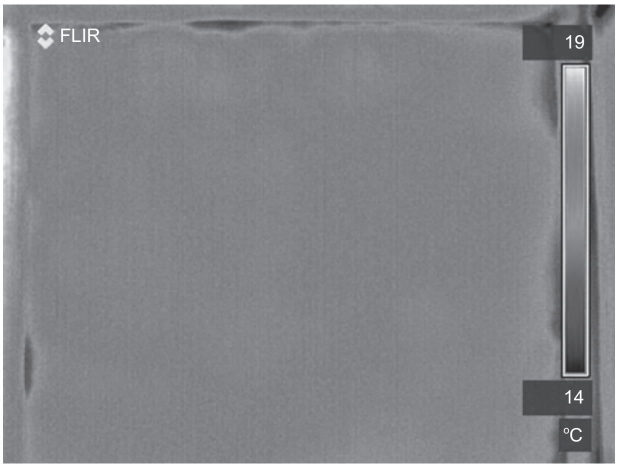

Figure 8. Internal thermal image of first floor, right-hand panel on the south façade (InfraRed Vision, 2010, p. 34)

the ply surround of the panel and the corner of the panel surrounding the window.

9. Conclusion and future research

The research presented has provided results in relation to the prefabricated straw bale panels and the prototype house that can be used to prove performance in certain areas or highlight aspects that need to be developed further. The images from the thermal building survey showed detailing within the prototype house that may need to be refined, including the internal ply strips around the panels, junctions between panels, internal corners of the timber frames and the junction with the support beams. The permeability and sound insulation performance of the prototype house could further be improved if these details were to be addressed. This could then enable future pre-fabricated straw bale houses, with all services installed (which could adversely affect the permeability), to meet the stringent Passivhaus standard of 0·6 air changes per hour at 50 Pa (Passive House Institute, 2010). The initial durability data provided show that the panels are performing as expected in terms of condition. This and the other aspects of the research project, outlined earlier in this paper, are to be published in the coming months and will focus on: the thermal properties of straw and prefabricated straw bale panels; the structural performance of render, panels and the prototype house; and durability of straw in the prototype house, an exposure test site and a larger commercial building.

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REFERENCES

BRE (Building Research Establishment) (2008) *Laboratory Airborne Sound Insulation of Prefabricated Straw Bale Panel System with Lime Render*. BRE, Garston, UK, 249137.

BSI (1995) BS EN ISO 140-3:1995: Acoustics – Measurement of sound insulation in buildings and of building elements – Part 3: Laboratory measurement of airborne sound insulation of building elements. BSI, London, UK.

BSI (1998) BS EN ISO 140-5:1998: Acoustics – Measurement of sound insulation in buildings and of building elements – Part 5: Field measurements of airborne sound insulation of façade elements and façades. BSI, London, UK.

BSI (1999) BS EN 1363-1:1999: Fire resistance tests – Part 1: General requirements. BSI, London, UK.

BSI (2001) BS EN 13829: 2001: Thermal performance of buildings – Determination of air permeability of buildings – Fan pressurization method. BSI, London, UK.

Building Analysis and Testing Ltd (2009) *Envelope Integrity Test: BaleHaus, University of Bath Campus*. Building Analysis and Testing Ltd, Bristol, UK, B1248-ALTRDF-P-151209.

Chiltern International Fire (2009) *A Fire Resistance Test Performed on a Non-Load Bearing Wall System*. Chiltern International Fire, High Wycombe, UK, Chilt/RF09001.

DCLG (Department for Communities and Local Government) (2010a) Fire safety approved document B, volume 1 – dwellinghouses (2006 edition incorporating 2010 amendments). DCLG, London, UK, National Building Specification (NBS).

DCLG (2010b) Approved documents E: resistance to the passage of sound (2003 edition) (incorporating 2004 and 2010 amendments). DCLG, London, UK.

DCLG (2010c) Approved documents L2A: conservation of fuel and power in new buildings other than dwellings (2010 edition incorporating further 2010 amendments). DCLG, London, UK.

Gross C and Walker P (2009) *BaleHaus: A Modern Innovative Low Carbon Housing System Using Prefabricated Straw Bale Panels*. University of Bath, UK, internal report on structural, acoustic, thermal and fire testing on behalf of ModCell Ltd.

Gross C, Fovergue J, Homer P *et al*. (2009) *Lateral stability of prefabricated straw bale housing. In Sustainability in Energy and Buildings: Proceedings of the International Conference in Sustainability in Energy and Buildings (SEB'09)* (Howlett RJ, Jain LC and Lee SH (eds)). Springer, Berlin/Heidelberg, Germany, pp. 147–154.

InfraRed Vision (2010) *Thermographic Building Performance Survey Report: University of Bath – BaleHaus.* InfraRed Vision, Abergavenny, UK.

Jones B (2009) *Building with Straw Bales: A Practical Guide for the UK and Ireland.* 2nd edn. Green Books, Totnes, UK.

King B (2006) *Design of Straw Bale Buildings: The State of the Art*. Green Building Press, San Rafael, California, USA.

Lawrence M, Drinkwater L, Heath A and Walker P (2009) Racking shear resistance of prefabricated straw-bale panels. *Proceeding of the Institution of Civil Engineers – Construction Materials* **162(3)**: 133–138.

Mach Acoustics (2010) *BaleHaus ModCell Project: Sound Insulation Case Study*. Mach Acoustics, Bristol, UK, 100707.

ODPM (Office of the Deputy Prime Minister) (2006) *Resistance to the Passage of Sound, Approved Document E*. National Building Specification (NBS), London, UK, 2003 edition incorporating 2004 amendments.

Passive House Institute (2010) *What is a Passive House?* Passive House Institute, Darmstadt, Germany. See http://www.passiv.de/07_eng/PHI/Flyer_quality_assurance.pdf (accessed 11/05/2010).

Seguret A (2009) *Life Cycle Assessment of BaleHaus at Bath*. MSc thesis, Imperial College London, UK.

Seguret A, Murphy RJ, Clift R and Chesseman CR (2009) Life cycle analysis (LCA) of BaleHaus at Bath. In *Proceedings of the 11th International Conference on Non-conventional Materials and Technologies (NOCMAT)* (Walker P, Ghavami K, Paine K *et al*. (eds)), 6–9 September 2009. University of Bath, Bath, UK.

Summers MD (2006) Moisture and decomposition in straw: implications for straw bale construction. In *Design of Straw Bale Building* (King B (ed.)). Green Building Press, San Rafael, California, USA, pp. 162–172.

Walker P (2004) *Compression Load Testing Straw Bale Walls*. University of Bath, UK, internal report.