STRAW CONSTRUCTION IN THE UK

Technical Guide First Edition 2022

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LIST OF FIGURES USED IN THIS DOCUMENT

STRAW CONSTRUCTION IN THE UK: TECHNICAL GUIDE

First edition 2022

Acknowledgements

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Who is this document relevant for?

- Architects, Consultants and Project Managers
- Construction Professionals
- Structural Engineers
- Building Control Officers and Approved Inspectors
- Contractors and Craftspeople
- Clients
- Planners, Strategic and Forward Planning Officers
- Conservation and Heritage Officers
- Affordable housing providers
- Self Build and Custom Build Sector
- Ecological and Healthy Building Sector
- Developers
- Farmers
- Facilities Managers
- Researchers and Students
- Finance Sector
- Insurance Sector

Purpose of the document

This document is intended to be a Guide to good practice in design and construction, and as a Guide to complying with UK Building Regulations and Technical Standards. It collates currently available data and performance factors in the design, construction and de-construction of buildings incorporating straw as insulation and as structure. It is expected that future editions will continue to add further data, expertise, experience and research.

SUMMARY OF TECHNICAL INFORMATION
to be found in this document

DESIGN VALUES FOR STRAW CONSTRUCTION

Structural test information for engineers [a]

Mean load at failure and 5th percentile of failure loads of straw bale with different types of render/plaster

	Render type	Mean load at failure, kN/m	5th percentile, kN/m
Strawbale wall tests*	All types	45.2	13.6
	lime:sand:cement	53.4	26.2
	no render	18.9	11.2
	(no test data for full walls with lime:sand render)		
Single strawbale tests	lime:sand:cement	53.4	26.2
	lime:sand	31.3	16.8

* Tested wall dimensions vary. Please see full report for complete details of each test (Appendix B)

Straw Density	**Straw Moisture Content**	
Minimum 80 kg/m3	25% dry mass basis	20% wet mass basis

Fire Safety Design Values [b]

Reaction to fire (BS EN 13501-1:2018)	Class B-s1, d0	*From tests of clay and lime plastered strawbale wall systems*
Resistance to fire (BS 476-7:1997)	120 to 135 minutes	
	135 minutes (Modcell) non loadbearing panel 120 minutes (Ecococon)	*From tests of prefabricated structural straw panels*

Thermal Conductivity Design Value [c]

0.065 W/mK (mean value). 0.08 W/mK (provisional 90/90 design value – see notes later in guide)

[a] Summary of analysis of results from the literature, as reported in Appendix B, *Loadbearing capacity of strawbale walls – a summary of results from peer-reviewed literature*

[b] Full details of fire test reports and certificates in Appendix F, *Safety of Strawbale Walls in the event of a Fire*

CLUSTER ECO CONSTRUCTION | SCHOOL OF NATURAL BUILDING | Hastings Borough Council | Benediktinerabtei Plankstetten | GEMEENTE TILBURG | strobouw nederland | Centre National de la construction paille Emile Feuillette

[c] Derived from analysis of published test data, as reported in Appendix C, *Thermal conductivity of strawbale – a review of published results meeting ISO 10456 requirements, analysed to provide robust straw lambda values*

> "The dearth of credible data and the lack of a knowledge base that flows from experience with working with sustainable construction materials acts as a barrier to designers and other building professionals, concerning the use of more unusual but sustainable materials and details. Further barriers include market trends and also designers wishing to stick to what they know best.
> Braithwaite, P. and Cowell, J. (2007)

This document aims to address this lack of knowledge, to provide information that can be shared with designers, clients, developers, construction professionals, funders and others. By compiling in one place a collection of the current (2022) credible data from research and experience, the aim is to increase confidence and remove the barriers to using straw and strawbale construction.

The document focuses on the design & construction of strawbale buildings to achieve indoor comfort, low energy consumption and a reduction in carbon dioxide and other greenhouse gas emissions throughout the lifecycle of the buildings.

CHAPTER 1 WHY BUILD WITH STRAW?

1.1 Climate change

According to the UK Green Building Council[1] the whole built environment sector contributes approximately 40% of the UK's total carbon footprint. Almost half of this is from energy used in buildings (operational carbon) and infrastructure (e.g. roads and railways). Approximately 10% is directly associated with the whole construction process, from extraction, manufacturing, transportation, construction and maintenance to disposal (embodied carbon).

It is essential to reduce both the operational and embodied carbon emissions of buildings.
Tools for the calculation of embodied carbon and Life Cycle Assessment (LCA) are emerging and rapidly maturing. These tools give designers, clients and developers the information needed to decide between construction options, comparing the combined operational and carbon impact across a building's lifespan. A useful briefing on this topic has been published by the London Energy Transformation Initiative LETI in their Embodied Carbon Primer[2].

Building with straw and other plant-based materials can significantly reduce both embodied and operational carbon compared to conventional construction. The embodied energy and LCA information for straw and strawbale construction is discussed later in this document.

1 https://www.ukgbc.org/climate-change-2/
2 https://www.leti.london/ecp

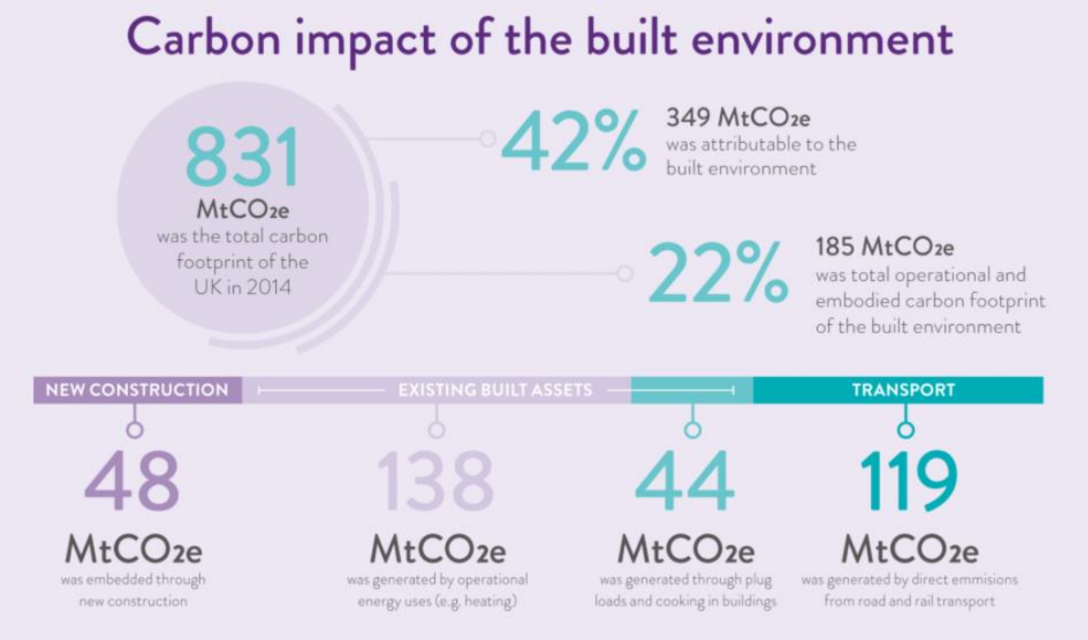

Fig.1 https://www.ukgbc.org/climate-change/ (Accessed Nov 2020)

1.1a Operational Carbon
Straw walls can create buildings that far exceed current UK building standards for thermal efficiency and can achieve Passivhaus standard. This means that operational CO_2 emissions from heating are vastly reduced.

1.1b Carbon sequestration
Straw is a co-product of grain production, an annually renewable crop. Like other plant-based materials, straw stores CO_2 as it grows. That CO_2 remains locked-up in the structure of straw buildings throughout their lifetime and can remain stored provided care is taken to avoid emissions at the end of the life of the building.

1.1c Embodied Carbon
The energy required to produce straw is minimal, as a result straw has very low embodied carbon (due only to carbon emissions derived from fuel consumption) even when carbon sequestration (storage) is not taken into account.

1.1d De-construction, re-use and end of life
At the end of the original purpose of a straw building, it is relatively easy to de-construct & to re-use the bales or modular panels, separate out timber and other materials such as brick and stone in plinth walls, tyres and gravel in rammed foundations, windows, doors, and roof materials, rather than sending them straight to landfill. Any straw that cannot be reused in new construction can be used as mulch, compost, or as a biomass fuel. As a last resort, the emissions associated with decomposition or combustion can be avoided by landfilling straw – there is growing evidence that biomaterials in well-managed landfill undergo minimal decomposition[3].

[3] https://tinyurl.com/sw5cxwr6

1.2. Health and Well Being

Strawbale construction can create healthier internal environments.

1.2a Indoor Air Quality.
By using good quality bio-based materials such as straw, clay and lime plaster, timber and wood fibre products, natural insulations and finishing paints, flooring and other materials, the internal air quality in strawbale buildings can contain zero or low volatile organic compounds (VOCs) and formaldehyde emissions compared with current mainstream building practices.

1.2b Breathability.
The fabric of a natural building manages moisture through its ability to absorb (natural fibres), adsorb (lime plaster) and desorb and because it has a vapour open structure. These natural systems are commonly called 'breathable'.

1.2c Hygiene.
Lime plasters are anti-bacterial and clay plasters absorb smells & toxins so both types of plaster are hygienic and effective particularly in bathrooms & kitchens. In addition, commercial and public buildings such as schools would benefit from natural plasters on their walls. Lime is also useful in flood areas as limed walls can be re-limewashed rather than replaced. Lime allows constructions to dry out once water has receded and gives protection from mould due to its alkalinity.

1.2d Hygroscopic.
Lime and clay plasters regulate internal humidity levels naturally through their ability to adsorb moisture, without causing condensation.

1.2e Storage of latent heat.
Cellulose (straw) stores heat effectively and regulates sharp changes in temperatures. When combined with natural plasters the wall system becomes a heat store. When used in lightweight construction walls and roofs, straw can provide protection from solar heat gains.

1.2f Thermal Insulation
Straw bale walls can meet Passivhaus standards and create a warm and cosy atmosphere.

1.2g Acoustic insulation
Straw has excellent acoustic properties and creates a peaceful environment that enhances well-being.

1.3. Traditional and Modern Methods of Construction

Straw and timber construction techniques have developed and matured significantly over the last 20 years to become suitable for mainstream use.

Straw bales have been used in private and social housing, commercial and office developments, community and leisure facilities, schools, public buildings, etc. Many completed strawbale buildings in the UK were commissioned by clients with a strong drive for ecological, natural and sustainable building solutions, such as the load-bearing straw meeting room at Ecology Building Society offices, and the sustainable learning and well-being centre at the Down To Earth Project.




Fig 2 Ecology Building Society, Silsden, West Yorkshire. Photos: Barbara Jones

Down To Earth Project, Little Bryn Gwyn, Llanrhidian, Swansea Photos: Down To Earth 2014

Straw has also been used as a retrofit solution in the Netherlands. See Roomley Sports Hall for an example of external insulation of an existing building in Udenhout, NL – in the synopsis of EU Straw Construction below.

Straw is now also used to make prefabricated panels, either via a factory press process or by using whole bales. These modular strawbale insulated products meet the Government and industry call for off-site and modern methods of construction. Modular systems such as Modcell Core+ System[4] and EcoCocon straw panels[5] together with the more traditional methods of building with straw have been shown to meet the stringent requirements of the Passivhaus Standard and to sequester carbon.

In 2020, the European Strawbale Building Association (ESBA) reported that 1,000 buildings are being built in straw every year in Europe. ESBA has a target to grow this number to 50,000 per year by 2030.

Fig 3 Knowle West Media Centre, Bristol 2008 Photo: Modcell

EcoCocon Passivhaus, Herefordshire 2017 Photo: George Mikurcik

1.4 Sustainability of straw

Straw is sustainable because:

- It is an agricultural co-product of grain crops and can be renewed (re-grown) on an annual basis.
- It sequesters biogenic photosynthetic carbon dioxide in its growth cycle
- It has low embodied energy and low emissions in processing from field to building.
- Due to excellent thermal properties it vastly reduces the need for heating, thus greatly reducing carbon in use.
- It is easy to disassemble for re-use & many of the constituent parts of straw buildings are biodegradable.

[4] https://www.modcell.com/technical/

[5] https://ecococon.eu/the-panel

- Panelised systems are available as a lower impact alternative to current mainstream SIPS (Structural Insulated Panel Systems) or ISPS (Insulated Structural panel systems).
- There is enough straw available annually in the Uk to build a substantial number of the new house builds required each year, without needing to grow more.
- Straw bale walls with plaster finishes have a low fire risk and have effective fire resistance to REI 120.

1.5 EU Context for Straw Construction: synopsis from the Interreg UP STRAW Programme

In 2016, the European Straw Bale Association (ESBA) was founded to enable straw bale builders and designers in European countries to share knowledge and experience, and to promote straw as a construction material.

Five countries from ESBA collaborated successfully to obtain €6.4m funding through the INTERREG North West Europe programme for UP STRAW: Urban and Public Buildings in Straw Project 2017-2020 - France, Belgium, the Netherlands, United Kingdom and Germany. The aim of UP STRAW was to effect a major positive change in the perception of straw construction.

As part of the programme, a straw construction context report was written & collated to provide a 'snap-shot' of policies and regulations (2020) in the five project countries. The purpose of the report was to identify the barriers, highlight achievements, and identify what was needed to remove barriers to straw construction, especially for urban and public buildings.

EU Context Report Synopsis

Pioneers in 19th century Nebraska in the United States of America began constructing temporary buildings with straw bales. They discovered that the buildings could not only endure the harsh winter weather but they could also provide decent insulation. The oldest known straw bale home still in existence is the Burke House in Bayard, Nebraska, which was built around 1896.

France has the oldest European straw bale house, Maison Feuillette in Montargis, near Paris built in 1920 with infill straw bales between a simple wooden frame. Strawbale building started to develop later in France following the creation of the national straw bale association Reseau Francais de la Construction Paille (RFCP) in 2006. Since then, the market has grown and there are over 6,000 completed buildings made of straw in France with approximately 500 new buildings being built per year, including one 7-storey straw bale property in Saint-Die-des-Vosges by Bet Gauchard.

Fig 4 France: Saint-Die-des-Vosges by Bet Gauchard

Belgium: Demonstration House Camp C by Mark Depreeuw

In **Belgium** the first straw house was designed and built in 1999 by the architect Mark Depreeuw. In 2009, the construction company Paille-Tech was established, focusing on building with prefabricated walls insulated with straw bales. In 2011 the aPROpaille research started in Wallonia to determine the characteristics and performance of "earth" and "straw" materials. In 2017, the UP STRAW project was granted Interreg funding with the Cluster Eco-construction as the Belgian partner. Since then, in 2017 the first straw school in Belgium has been built. The current market comprises about 20 straw built houses/year. The market is evolving to include schools & larger buildings but is not yet embedded in mainstream design practice and specification.

In the **Netherlands**, policy is generally enthusiastic about ecological solutions including building with straw. There is a National Straw Building Association – Strobouw Nederland SBN. In 2019 through the UP STRAW project, SBN was involved in significant research into the different uses of straw for mid-life thermal upgrade of existing urban buildings. One renovation technique was trialled on the existing Roomley Sports Hall in Udenhout, where timber panels insulated with blown-in straw were fixed externally to the existing building.

Fig 5 NL: Roomley Sports Hall, Udenhout

UK Tony Wrench and Jane Faith's strawbale roundhouse

In the **UK**, straw bale building started to grow in the 1990s after Barbara Jones, a UK builder, learnt the technique in the USA. She wrote the construction guide for building with straw in 2001, updated in 2002, 2009 and 2015. The first straw bale home to receive planning permission in the UK was built by Brian Stinchcombe in 1996 with Barbara's help as described in a YouTube video for BBC Countryfile: www.youtube.com/watch?v=RdXfhkvprVg&feature=emb_title

It was followed in 1997 by Tony Wrench and Jane Faith's low-impact turf-roofed strawbale roundhouse, as shown in a BBC news article In Pictures: Life in an eco-roundhouse: http://news.bbc.co.uk/1/shared/spl/hi/picture_gallery/06/in_pictures_life_in_an_eco_roundhouse/html/1.stm Also in 1997 the architects Sarah Wigglesworth and Jeremy Till received planing permission for their house in Islington, which includes straw walls.

'ModCell' developed by Architect Craig White in collaboration with Professor Pete Walker of the University of Bath, designed and built its first prefabricated straw-insulated panel in 2000.

The first two-storey load-bearing straw house was built in Pembrokeshire in 2003 by Barbara Jones and others and two pairs of loadbearing council houses were built by North Kesteven Council in 2009, designed by Jakub Wihan and Barbara Jones, meeting all legal and statutory requirements.

The Low Impact Living Affordable Community (LILAC) project in Leeds built two 3-storey apartment blocks in 2012 with Modcell panels. These houses met stringent scientific and industry standards, which ensured they qualified for regular mortgage and insurance.

In 2015, seven 3-bed homes in Bristol became the first residential houses built using the ModCell prefabricated system.

In 2014 the School of Natural Building was established and in 2016 the national organisation for strawbale building was formed, Strawbale Building UK (SBUK).

Public sector procurement issues for public straw bale buildings have been highlighted in the UP STRAW UK demonstration project. The main construction skills in straw bale building in the UK reside in small companies who may not have capacity for larger public projects. In this case SBUK, facilitated the creation of a consortium of four companies named CONSTRAWTIUM to build the visitor centre for Hastings Borough Council, built in

2020/1. Other public buildings have been built previously using informal collaboration by Amazon Nails and Straw Works. There are several hundred strawbale buildings in the UK with approximately 20 being built each year.

Fig 6 Hastings Country Park Visitor Centre Photo Phil Christopher

Information about the development of strawbale building in other European countries can be found in Appendix A. It is worth noting that the UK began strawbale building earlier than other European countries and is now about 10 years behind France, who have several training centres nationally, a strong and growing national organisation, and are building over 500 straw buildings each year.

In **Germany**, the development of straw bale building is very much linked to the German Straw Bale Building Association (Fachverband Strohballenbau Deutschland FASBA), founded in 2002. A newly designed eco-village at Sieben Linden helped to develop the building technique, and through two research and development projects led by FASBA, straw bale building is now a recognised building technique in Germany. German building legislation is known to be severe and innovative building techniques have to be tested and proven thoroughly before they can be adopted on building sites. It is significant therefore that the German research results in the field of straw bale building have received national and international attention. There are approximately 20 straw buildings completed per year in Germany.

For the Context Report, the UP STRAW representatives from the partner countries France, Belgium, Germany, Netherlands and UK were each asked to comment on the following headings as they relate to their own country:

- Current support for straw in construction.
- Specific barriers that remain.

Current support for straw construction:

- The French straw bale association RFCP is encouraging clients - especially public clients - to require design and build teams to have training, knowledge and experience of straw construction.
- France, Belgium and Germany each have some specific supportive policies including official recognition and technical endorsement of straw construction within the building permit process.
- In some areas there is engagement of authorities and ministries in straw-built projects, including urban public buildings.
- France and Germany have achieved official ratification of high-quality technical 'professional rules' that are national technical guidance and best practice for straw construction.
    - French Professional Rules - rfcp.fr/librairie/regles-professionnelles-de-construction-en-paille-v3/ (New version and translation into English by Up Straw 2021)
    - German Professional Rules - https://fasba.de/wp-content/uploads/2019/10/FASBA-Strohbaurichtlinie-2019.pdf (Translation into English by Up Straw 2020)
- France has achieved a greater administration funding commitment for the development of straw construction, and a larger allocation of straw bales from annual yield for construction.

- Belgium is working with the administration to ratify an official thermal conductivity value (lambda) for standard vertical wall (to be defined) to assist in robust energy calculations.
- The UK has developed an example of positive public procurement practice where several small expert strawbale builders came together in an UP STRAW project to build a strawbale visitor centre in Hastings
- All of the countries involved have signed up to legally binding commitments on greenhouse gas emission reductions and are becoming more receptive to bio-based environmental solutions in the built environment, such as strawbale construction.

Specific barriers to the development of straw construction that remain:

- Lack of resources was reported for promotion of the benefits and capabilities of straw construction.
- All the countries in the programme reported poor perception of straw construction, and an absence of confidence, knowledge, experience and training amongst clients, developers, planners, designers, inspectors, constructors and building users/ managers.
- Belgium, Netherlands and UK noted the need to develop similar regulatory support and professional guidance as that in France and Germany.
- The UK noted that scope for farmers and the agricultural sector to be engaged in the supply chain has not yet been realised, particularly in the context of farming diversity and the potential for circularity in construction and farming.
- In the UK there is a lack of natural building content in the university course curricula, regional/local college skills training and in professional CPD training.

CHAPTER 2 GENERAL

2.1 What is straw?

Straw is the dry hollow stems or stalks of cereal plants (between the root and the grain spike), grown and harvested for edible grain such as wheat, barley and rye. It is composed of cellulose, hemicellulose, lignins and silica.

It is considered an agricultural co-product used for livestock bedding, roughage in animal fodder, mushroom growing, straw bale food gardening and construction. Since 2000 it has been used for straw-fired biomass power generation, such as at the 38MW Elean power station at Sutton in Cambridgeshire.

When grain is harvested, the stalks are golden to pale yellow in colour (increasingly cut whilst still green, depending on quality of growing season) and are cut close to the ground. The straw stalks left lying in the field to dry are baled afterwards.

The introduction of modern combine harvesters with follow-on balers enabled farmers/contractors to reap, thresh and winnow the grain and bale the straw in one mechanised operation, leaving just stubble on the land. The stubble can be ploughed-in or used as mulch to retain soil moisture and nutrients, or cover-planted to avoid leaving the soil bare for any length of time.

Before the Crop Residues (Burning) Regulations 1993 (England and Wales), stubble and loose straw were often left lying in the fields and then burned. The harmful effects of burning included loss of soil nutrients, carbon dioxide combustion emissions, pollution and air quality hazards from smoke, and the risk of fires spreading out of control. Since then, unbaled straw has increasingly been chopped by the harvester and ploughed back in.

The majority of straw is processed into bales, which are 'modules' tightly bound with twine, usually polypropylene, during mechanised harvest.

2.2 Varieties of straw and bale sizes

- Grass family – wheat and barley are the most common varieties.
- Other types used but less commonly available in the UK: rye, oats, rice.
- Recent research[6] has been conducted on miscanthus within bio-based materials programmes.
- Hemp bales have also been used on a small number of buildings.

Wheat straw is used for the majority of strawbale construction in the UK (it is the most plentiful), and there are many species and varieties. Optimised selection is an emerging area of research, such as why the hardiness of winter wheat makes it more durable in construction terms and how fertilisers affect the natural wax coating of the stalk.

Bales are produced in many sizes

[6] Progress in upscaling Miscanthus biomass production for the European bio-economy with seed-based hybrids (2017) Clifton-Brown J., BBSRC Core Strategic Programme in Resilient Crops: Miscanthus

Rectangular bales– jumbo or Heston

Cylindrical bales – 'Dougals'

Rectangular bales – small, Flat 8s or Field bales

Fig 7 Compressed straw in panels

Blown-in chopped straw

Rectangular 'field-bales' are the size most often used in UK construction, known as small bales or Flat 8s. These are primarily found in manual, non-prefabricated construction also known as Artisan strawbale building. The size and density of the bale and the tightness of the binding strings is determined by the type of baling machine and its settings.

Small bales in the UK have two strings and are usually measured in Imperial units. This is because most UK balers are quite old and were made pre-decimalisation, the newer American balers still use Imperial units. Usual dimensions are: 18" (460 mm) wide x 14" (357mm) high or 20" (510mm) wide x 15" (380mm) high and can vary in length from 31.5" – 47.25" (800 to 1200mm) although most bales are between 36" – 42" (915 – 1065mm). There are some variations even to these sizes as the UK has a large variety of ageing machines, plus many imported ones.

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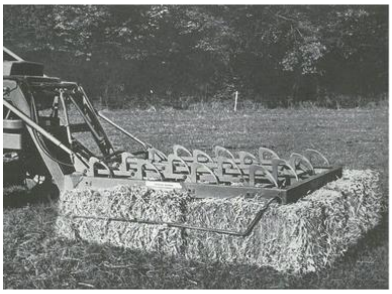

Fig 8 an example of a Flat 8 baler, picking up 8 small bales together

Other bales produced in the UK are:

- Heston 1200mm x 1200mm x 2500mm
- ¾ Heston 1200mm x 900mm x 2500mm
- Quadrant (or Quad) bales 1200mm x 700mm x 2500mm
- Mini Heston 800mm x 900mm x 2500mm
- Flat 8[7] most variations are between (460mm – 510mm) width x (357mm – 380mm) height x (800 – 1200mm) length.
- Circular bales 1.2m diameter x 1.2m high but can be up to 1.8m diameter.

All sizes vary depending on the type of baling machine used.

Fig 9 Types of bales M.R. Horn, Hay, Straw and Transport https://www.hay-straw.co.uk/

The width and height of bales from the same baler are constant because each machine has a fixed box size, but the operator can alter the length. There may be variation of up to 100mm between the longest and shortest bales in a single harvest, but on average all bales will be of similar length. The operator can also change the binder twine tension on most baling machines, affecting bale density. Many small farmers have old machines that are not able to keep the tension in the strings, causing fluctuations in bale density and length during harvest, but modern baling machines can create dense, uniform bales.

Variation in bale size has implications at build stage but Architects use standard dimensions of 450mm x 345mm x 1000mm in setting out construction drawings**.** This represents the most common dimensions of small strawbales *after trimming and compression*. It is part of the experience of the builder to know that this is

7

Flat 8 - this expression relates to a system that starts with a sled pulled behind the baler which gathers the bales as they eject from the baler and arranges them in a flat stack of 8 bales and leaves them on the field. A flat 8 grab on a loader is then used to stack the bales onto a trailer or to create a stack of flat 8's, which is then grabbed for transport by a three-point linkage mounted flat 8 squeeze or a flat 8 self-loading tipping trailer.

an average not a given and to act accordingly. If it is known at design stage that the baling machine to be used for the construction bales varies significantly from these sizes then other dimensions can be used, but this is often not the case. In this instance a professional strawbale builder will know how to adapt the construction to suit a different size of bale in the same way as bricklayers do with fired clay bricks, aligning perpends by selecting brick lengths.

A way to measure bale length is to take 10 bales at random, lay them tightly together end to end, measure their length and divide by 10 to find the average. Allow for each bale to lose 30mm in length as it is 'dressed' on site (physically manipulating the straw in the ends of the bales to make a flat surface, enabling the bales to fit together more tightly with no air gaps).

2.3 Orientation of the straw

The way the baler picks up the straw from the field into the machine box is thought to determine the major orientation of the straws in the bales. For bales laid flat, bottom-feeder balers make bales with mostly vertical straws whereas end-feeder or side-feeder balers make bales with mostly horizontal straws: all of these can be used for strawbale building.

Fig 10 Two string bale showing flakes
Photo: Wei Wu

When the strings are cut, the flakes separate
Photo Cynthia Hizer

There is some suggestion in research[8] that the orientation of the straws in straw bale walls has a bearing on the thermal conductivity of the bale. Vertical straws in bales used in walls - perpendicular to heat flow – were shown to provide better insulation performance. This research was carried out on hand-made bales of 100mm size where each straw had been placed vertically by hand, not on farm-supplied bales[9].
Other studies have found that straw orientation made little difference and one investigation[10] found that bales actually have random fibre orientation, and that the appearance of the bales to have straws in one orientation is misleading. Straw practitioners attest that when a bale is pulled apart it is clear that not all straws are either vertical or horizontal but are multi-directional. This is significant in determining an agreed thermal conductivity value that can be used confidently in design – see more detail about thermal conductivity in Chapter 3.

[8] Manufacture and characterisation of prototype straw bale insulation products
Shawn Platt, Daniel Maskett, Pete Walker, Aurelie Laborel-Preneron, Construction and Building Materials, Volume 262, 30 November 2020, 120035
[9] Fachverband Strohballenbau (FASBA). Thermal Performance: Strawbale Building Research Development 2003–2009. FASBA: Germany.
[10] Evaluation of the thermal performance of an innovative prefabricated natural plant fibre building system. Andrew Shea, Katharine Wall, Pete Walker, Building Service Engineering Research and Technology, Volume 34, November 2013

2.4 Construction Bale Standard

The Straw Works Bale Standard[11] has been developed over 20 years of practice and is the document many Building Inspectors have used as their reference on construction projects. Most built projects in the UK have relied on this Standard to find good quality bales sourced from local farmers. The Standard has also been verified and agreed with UP STRAW European partners in France, Germany, the Netherlands and Belgium.

In summary, bales should be dry with a moisture content below 20%, well compacted with tight strings, be of a uniform size and shape, and contain virtually no seed heads. Straws should be at least 150mm. There should be no sign of mould, or of vermin having nested during storage.

Bale standard

- Bales must be dry, with a moisture content below 20% and free from mould or black staining.
- Bales should be dense and compact. The baling machine should be set to maximum compression. For two-string bales, mass should be between 16kg and 25kg.
- Density should be at least 80 kg/m³. Greater density is recommended for loadbearing. Compression during construction will increase this by 3 - 6%, the equivalent of 1 – 2cm/bale settlement.
- Bales should be regular and uniform in shape. They should not have missing corners, nor be curved, nor be of different heights and widths.
- Bales should be more than twice as long as they are wide for loadbearing but can be shorter for infill. They are usually measured in imperial units rather than metric: about 41" (1.04m) long on average is optimum that reduces to 1m after dressing.
- Strings must be 'very tight' - as a practical guide the strings should be tight enough so that it is difficult to get fingers underneath. They should be about 100mm (4") in from the edges of the bale and not sliding off the corners.
- Variety of straw can be wheat, barley, rye, oats, rice etc. Rye would be a good choice as it contains a natural fungicide so is very resistant to rot, but currently (2022) is difficult to source. Winter wheat is a good choice as it is more durable than spring wheat, having had to survive harsh weather conditions.
- Straws should be long, preferably at least 150mm (6"). Avoid bales of straw chopped by the harvester.
- There should be no signs that vermin have set up home in the bales during storage.
- Stored bales should be raised off the ground on pallets or similar - by at least 150mm if outside - and weatherproofed but allowing for good ventilation especially at the top of the stack to prevent condensation wetting the bales.
- String will most likely be polypropylene but could be sisal or hemp baling twine for a lower environmental impact.

2.5 Sourcing and Availability of Straw in the UK

Although a small number of UK straw suppliers and farmers advertise construction bales for sale, there is little recognition of the undeveloped yield income potential for farmers from construction bales. If there was a shift to nature-based construction materials this would provide an additional income stream for farmers.

Currently there is no formal supply chain for construction bales in the UK and each project has to find its own supply. In one respect, this has the benefit that farmers are sought locally to a project location, but the consistency of the bale standard may not be so well-managed. Through the Up Straw project an Inventory of straw suppliers has been created, Suppliers can be sourced via an internet search for straw suppliers or agricultural suppliers. Suppliers are also sourced by asking straw builders.
Development of the supply chain is an area to be explored further with organisations such as the Agriculture and Horticulture Development Board, AHDB.

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11 https://strawworks.co.uk/resources/bale-standard/

2.6 Sourcing pre-fabricated panels

Prefabricated panels are available in the UK from two companies, sourced via their websites/UK representatives. Modcell[12] is a UK based company that uses whole bales for its panels, which are supplied pre-plastered. EcoCocon[13] is a Lithuanian based company currently importing (that will set up a UK factory when demand is sufficient) and makes panels in a factory-based system using compressed straw from round bales rather than whole small rectangular bales.

2.7 Is there enough straw in the UK?

Is there sufficient straw available in the UK for housebuilding? According to government statistics, the 2010:2020 average UK wheat yield (the amount actually removed from fields, i.e. average 73% of all wheat straw produced) was 5586 thousand tonnes.

A simple 3 bed semi-detached house requires 7.18 tonnes (350 bales) of straw:
if only 5% of the average annual wheat yield was allocated to construction, there would be 279 thousand tonnes available: sufficient straw for 38,923 homes per annum[14], which is just over 13% of the UK's annual target for house building in 2020. In 2019 over 173,000 new homes were built in the UK[15] - 22% of these could have been built with only 5% of the average annual straw yield

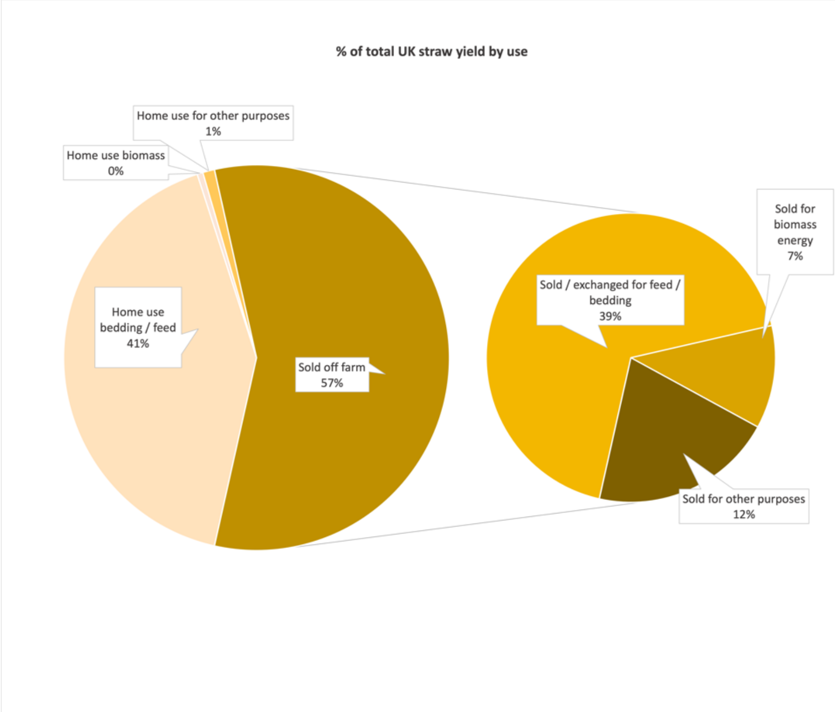
12 https://www.modcell.com/

13 https://ecococon.eu/

14 UK Gov. DEFRA, 2020, Statistical data set: Structure of the agricultural industry in England and the UK at June - United Kingdom Cereal Yields 1885 Onwards https://www.gov.uk/government/statistical-data-sets/structure-of-the-agricultural-industry-in-england-and-the-uk-at-june; and Area of crops grown for bioenergy in England and the UK: 2008-2019 https://www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2019

15 https://www.gov.uk/government/statistics/house-building-new-build-dwellings-england-april-to-june-2019

Fig 11 shows the currently-reported proportion of total UK straw removed from fields that goes to different



end uses (2010:2020 averages).

Fig 11 % of total UK straw yield (straw removed from fields) by use

Fig 12 shows the amount of UK wheat straw (thousands of tonnes) and the percentages of straw by end use (2010:2020 averages) if just 5% of total yield is used for construction (5% straw for construction has been subtraced equally from from DEFRA figure for straw sold/exchanged for feed/bedding and straw sold for other purposes)

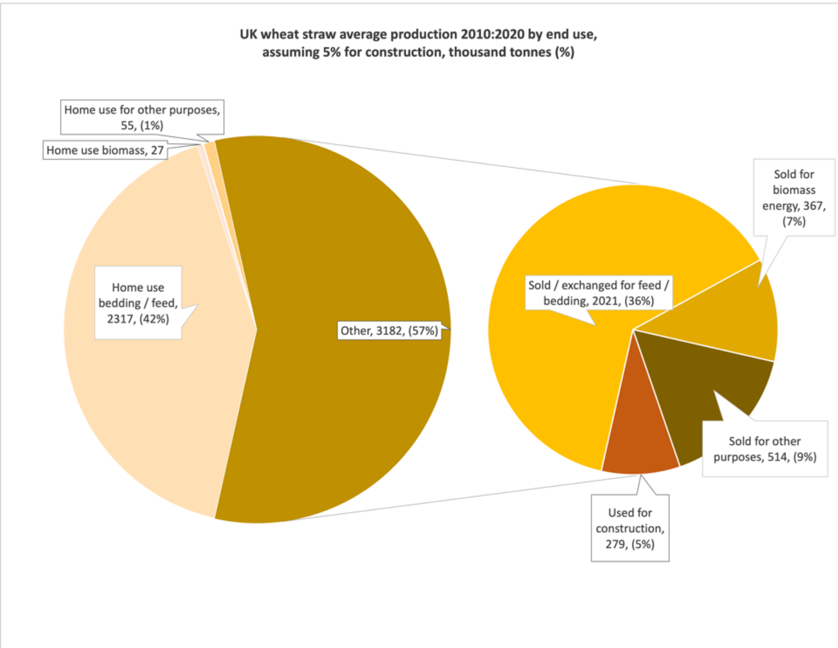


Fig 12. UK wheat straw 2010:2020 average production (thousand tonnes) and percentage by end use, assuming 5% for construction

2.8 Location, Storage and Transport

Location: Wheat is grown all over the UK but predominantly in central and eastern locations. Straw bales are often stored near the growing fields however variance in yield and availability due to climate change and altered agricultural practices has led to increased movements of straw in recent years, including export to other European countries. Much straw is harvested by large contractors who harvest for many farmers in one area, and they often also store and sell straw themselves and organise transportation as required. Some farmers sell surplus straw bales through merchants who have large storage capacity or via the internet and straw contractors regularly transport straw to agricultural outlets in areas that do not produce a lot of their own straw.

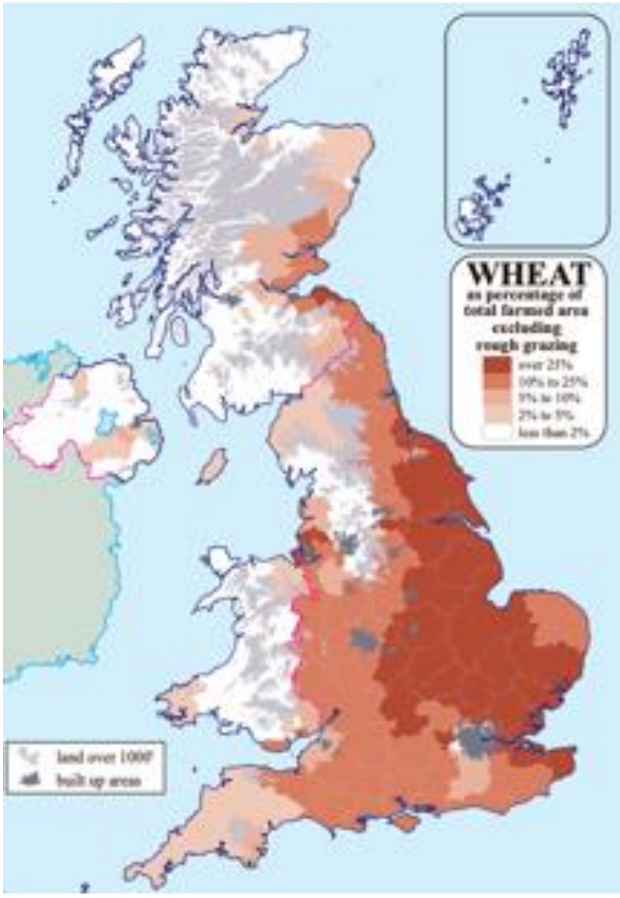


Fig 13 2012 Cereals map, Agriculture and Horticulture Development Board, AHDB

Storage outside: to avoid conditions that could lead to mould or decay care must be taken to avoid rain or snow ingress or the formation of condensation. Straw must be kept at least 150mm off the ground to avoid splashback – 2 or 3 levels of pallets are a common solution. Pallets are also placed on top of the bales to allow ventilation of the top surface. Very taut tarpaulins or rain proof, moisture vapour permeable sheeting should be strapped or weighted over the whole stack, allowing as much ventilation as possible.

Storage inside: bales should still be placed on pallets although one layer is sufficient. In barns they are often stacked with the first bales on edge as a sacrificial layer with subsequent layers laid flat. Barns are often open sided for ventilation. In this case edge bales may get wet, but natural ventilation will dry them as long as they are not subject to prolonged and persistent driving rain.
Storage inside a polytunnel can be a good option as this provides for adequate ventilation whilst keeping the bales dry, although again pallets should be laid on top of the stack with a vapor permeable covering to protect against condensation dripping from the roof.

A persistent drip through a roof or covering will result in all bales below the drip eventually becoming wet. However, this will remain very localised as water does not wick through the bale.


Fig 14 Location


Storage


Transport

Transport: Transporting bales long distances adds to project cost, and has a bearing on the 'carbon count' if bales cannot be supplied in the locality of the site. The worst case would be that bales would travel a long distance from the growing fields to be stored and then back again to a construction site because of lack of local supply information or project timing.

From the Highways England Carbon Tool V2.3[16], the carbon dioxide equivalent emission factor for a laden HGV is 0.11 kgCO2e/t.km.

Bales can be sourced direct from the field – this is the most cost-effective method of procurement as there is no added cost for storage. Carbon count is then limited to the harvesting machines and transport to a local site. The price of a bale normally includes storage and delivery, given as a single per bale cost. Bales purchased from an Agricultural merchant already have the transport cost to bring them to the merchant included. Some will add additional costs to bring them to site depending on the quantity and distance. Some merchants (e.g. Longhay Ltd) are brokers – the bales go straight from farm of origin to construction site (stored and delivered by the farmer or their contractors).

2.9 Pests

There is a perception about strawbale building that rodents will make their homes in the walls – however there is no greater risk of rodents in a straw house than in any other type of house. Rodents prefer warm cavities to dense straw walls and will be found in internal partitions, floors and ceilings sooner than in plastered straw walls. Straw is not a food source for rodents although they may nest in gaps between bales during storage.

In construction, a gap-free build is required for weather tightness, fire prevention, thermal, acoustic, air and wind tightness and structural performance - the dense bales are stretcher bonded or stacked in short walls and compressed, then rendered and plastered on each side to seal the building for airtightness. There should be no gaps in a strawbale wall. The hole size finger test suggests: one finger for a mouse and two fingers for a rat, corresponding to their skull and rib cage; if the holes in a straw wall are big enough for rodents, there are serious quality control issues.

Book Lice

Strawbale buildings can have incidence of insect infestation[17], as can all buildings. Infestation tends to be by Booklice:

Order:	Psocoptera (psocids or booklice)
Family:	Trogiidae
Genus/Species:	Lepinotus sp. (indet., probably Lepinotus patruelis)

[16] https://www.gov.uk/government/publications/carbon-tool

[17] https://www.strawbale.com/psocids/

Fig 15 Book lice

The genus Lepinotus includes 3 species recorded in Britain, all with similar biology. They only occur indoors (commercial and domestic buildings) They are not harmful to humans and shun the light keeping to gaps between skirting, cupboards and other construction joints.

Psocids do not naturally occur in straw, however, if moisture levels are high, Psocids can take up occupation. Very occasional incidents have been reported in strawbale buildings.

Psocids are generally confined to buildings, the most likely source would be amongst infested goods transported to the site or into the building from elsewhere, including anything transported on wooden pallets, packaged in wooden or cardboard crates/boxes, paperwork of any kind – foodstuffs and timber used in construction. Mould spores are the food source for Psocids and can bloom on the surface of all materials including straw as moisture increases during the building phase. Psocids can also bloom but die out as spores on the surface of the straw naturally die out as the building dries. The only way spores can re-occur is if the straw is exposed to the moisture in the wider environment.

Psocids are susceptible to various insecticides but control often proves difficult because the insects can hide in crevices and other inaccessible places, avoiding contact by many standard types of treatment, such as liquid sprays.

In the UK there have been very few (less than 5) reported cases of psocid infestation. These occurred at the end of the plastering process – when moisture levels are increased – and usually in the bathroom. Lots of small lice are unwelcome but harmless and can be hoovered up, although they may continue to appear until moisture levels drop as plasters cure. There are no known instances of them re-occurring.

2.10 Health and Safety on site

The mass of bales depends on size, moisture content and density. For small bales at the correct moisture content this can range from 16kg – 25kg, which puts them towards the medium to upper limit of what would generally be considered a safe load for repetitive lifting by one person; but the loads are concentrated to baling strings if lifted this way which can lead to friction burns.

Ideally manual handling is to be avoided to reduce the risk of injury, especially from repetitive and prolonged moving of loads. However on strawbale building sites it is common practice to move bales by hand. Practitioners are taught, therefore, to always lift bales between 2 people, and to carry from the bottom of the bale not by the strings to avoid distortion of the bale. Bales can also be moved by forklift on a pallet, this is more common on larger building sites.

Where manual handling is unavoidable, a manual handling risk assessment should be carried out and guidelines for safe practice provided to personnel on site.

Lifting by one person by the baling strings, if done for long periods could cause hand burn and muscular/ligament/nerve injury. On a practical level, this way of moving bales can also distort the regular shape of the bale required for construction, which may mean the bale has to be set aside. The practice of taking shifts in bale-moving and assembly to reduce the period of repetitive load-bearing work, and working in pairs, lifting the bale at each end from underneath, can help protect the personnel and the bales.

Loose straw is a slipping hazard, particularly on smooth surfaces or when wet. Much loose straw is generated during the building process as bales are dressed and notched. Loose straw is also a fire risk and for both these reasons sites should be kept clean and tidy and waste straw collected up regularly and taken off site at the end of the working day. Empty tonne sacks are ideal for this purpose. Composting on site would divert waste straw from landfill.

There should be no smoking or vaping on or within 5m of the site.
Hot works (plumbing, welding, soldering etc) should be closely monitored.
Electrical & plumbing installation should always be carried out by a competent person.
The formality of Hot Works permits may be necessary, early completion by services trade to ensure any lingering flames or sparks have a long time to mature whilst other trades are still present to spot them.
Hosepipes and fire extinguishers should be plumbed in ready to use, prominently displayed and available.

Dust is not a hazard when the build is well ventilated as it usually is outside but can be if in confined spaces. In enclosed spaces anyone working with straw or nearby may need to wear appropriate dust masks. It is rare for anyone to suffer from allergies to straw as it does not contain pollen (as hay does) but they do exist and suitable precautions may need to be taken.

Usual PPE will need to be worn when using power tools, and as appropriate for working at heights etc.

CHAPTER 3 MATERIAL PROPERTIES OF STRAW

3.1 Introduction

Knowledge about the physical characteristics of straw in construction is constantly being updated as more technical research is completed and more buildings are constructed. Data has been collected within the European database Zotero by the Up Straw partners, available for free download. The sections presented below represent data available in 2021.

Building Regulations/Standards
See Appendix L for a fuller discussion of how to comply when designing with straw and refer to the Approved Documents available online.[18] Compliance for all forms of construction can be demonstrated with calculations, drawings, and specifications by a Structural Engineer or other professionals (e.g. energy specialist) to evidence that the design meets the parameters for existing Design Codes or Standards. However, it is also important to note:

It is up to the Local Authority or private Building Control Inspectorate to prove you wrong, NOT for you to prove your design right.[19]

Compliance can also be agreed with the Building Inspector using technical design drawings and information using 'typical' details and evidence of previously built examples rather than via engineers and other professionals.

It is this second method that was used to gain approval for early built examples in the UK, and the suite of Standard Details produced by Straw Works have evolved from these.[20] Over-reliance on engineered solutions in a field where engineers do not sufficiently understand the subject can lead to restrictions in design if not solutions that lead to failure.

3.2 Structural Capacity

Structurally there are five types of strawbale construction:

1. Load bearing (Nebraska) - Straw bales carry the load.
2. Lightweight timber Frame – Straw bales carry the load.
3. Infill or framework construction – timber (or steel/concrete etc) carries the load.
4. Hybrid construction -straw/strawbales and timber carry the load.
5. Prefabricated systems – timber carries the load.

This section provides guidance on structural capacity for each type.

Within the Up Straw project in 2020, a review of published structural test results was carried out to determine usable design values for structural design of strawbale buildings[21]. These are the headline results:

[18] https://www.gov.uk/government/collections/approved-documents https://gov.wales/building-regulations-approved-documents https://www.gov.scot/policies/building-standards/monitoring-improving-building-regulations/ http://www.buildingcontrol-ni.com/regulations
[19] Correspondence with Surveyorlink.com
[20] Building with Straw Bales (2015) Barbara Jones p.198
[21] Loadbearing capacity of strawbale walls: A summary of test results, John Butler, 2020

	Mean load at failure and 5th percentile of failure loads of straw bale with different types of render/plaster		
	Render type	**Mean load at failure, kN/m**	**5th percentile, kN/m**
Strawbale wall tests*	All types	45.2	13.6
	lime:sand:cement	53.4	26.2
	no render	18.9	11.2
	(no test data for full walls with lime:sand render)		
Single strawbale tests	lime:sand:cement	53.4	26.2
	lime:sand	31.3	16.8

* Tested wall dimensions vary. Please see full report for complete details of each test.

Summary of analysis of results from the literature, as reported in John Butler / Up Straw report *Loadbearing capacity of strawbale walls – a summary of results from peer-reviewed literature*

Fig 16 Summary of structural test data
(Full details reported in Appendix B, *Loadbearing capacity of strawbale walls – a summary of results from peer-reviewed literature*)

1. Load bearing (Nebraska) - Straw bales carry the load.

In the Loadbearing or 'Nebraska'*[22] method the straw bales carry the load of the floors and roof above. Timber ringbeams/wall plates are used below the straw, at storey junctions and at eaves level; windows and doors are attached via timber fixing posts (structural boxes were used in the past). Construction developments now encourage the building of the roof or the first storey ringbeam first, which is then lowered onto the straw, for speed and to improve weather protection. Strawbales are laid flat on the timber base plate and built up in 'stretcher bond' like bricks; the assembly is pre-compressed at each storey level using either ratchet straps or hydraulic jacks depending on the design and construction method. Strawbale walls have a load-bearing capacity for use up to at least 3 storeys[23]. When both sides are plastered with lime, tests have shown that the resulting composite increases strength and stiffness.[24] It is common to plaster the interior with clay.
For load bearing, the average minimum density of the bales should be 100-110kg/m^3 [25] [26] with a maximum moisture content of 20%[27]. Compression during construction increases bale density by 3-6%. The oldest existing straw bale structure, the loadbearing Burke house in Alliance, Nebraska, USA is over 100 years old.[28] The Nebraska tradition of building began in the late 1800s.

Fig 17 An example of 2 storey loadbearing construction showing cement-free foundations (limestone laid with lime mortar) with a timber ringbeam at ground, first floor and eaves level. Photo by Barbara Jones of the Spiral House, County Mayo, Ireland 2001.

[22] https://www.baubiologie.at/download/strawbaleguide.pdf Page 8
[23] http://www.quietearth.org.uk/pictures.htm
[24] *Structural characteristics of load bearing straw bale walls* Huixiang Peng, Pete Walker, Daniel Maskell and Barbara Jones. Construction and Building Materials, Volume 287, 14 June 2021, 122911
[25] King, B. (1996) Buildings of earth and straw. Ecological Design Press.
[26] Jones, B (2015) Building with straw bales: a practical manual for self-builders and Architects
[27] https://strawworks.co.uk/resources/bale-standard/
[28] King, B. (2006) Design of straw bale buildings. The State of the Art, Green Building Press, San. Rafael

2. **Lightweight timber Frame – Straw bales carry the load**

In this version, the load is carried by the bales but a lightweight frame is used with bales between in a stack bond instead of a stretcher bond type of bale construction. The framing can be of many sorts but is often 75 x 50mm and set in the centre of each bale. With a light timber frame/ hybrid construction, lightweight timbers in the walls are propped and temporarily used to support the roof to provide early weather protection during construction, and the roof is later dropped into place. The final load-bearing element remains the compressed straw bales and therefore the same test data as load bearing strawbale construction above can be used to determine structural loading compliance.

3. **Infill or framework construction – timber (or steel/concrete etc) carries the load**

There are very many ways of using frameworks with straw as the insulation. The structure is usually a timber frame, but can be steel or concrete etc. Therefore, the structural capacity depends on the frame materials and design. Specialist information can be found from TRADA[29]. The maximum height of a building is determined by the structural design of the frame.

Framing posts can be located:

- notched in central to the straw bales
- between the straw bales
- at the same or different depth as the bale
- inside or outside the straw wall
- touching the straw or independent of it.

Straw infilled or wrapped around the frame must be compressed to achieve the desired stability and insulation value, which is usually done with either ratchet straps or hydraulic jacks.

Framing posts can be made of solid timber or can be DIY or manufactured I beams or vertical trusses

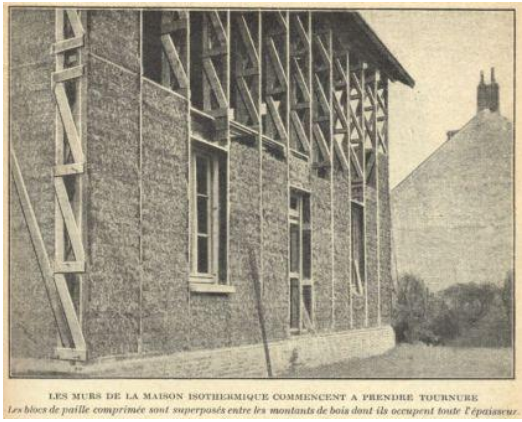


Fig 18 The historic Feuillette House in Montargis near Paris, built in 1920, uses simple truss frames between bales.

4. **Hybrid construction -straw/strawbales together with another structural material (usually timber) carry the load.**

Hybrids usually comprise a mix of the loadbearing method, with framework construction used for certain areas, such as large, glazed areas, where a structural frame is required. Careful design needs to be employed at the junction between the two methods to ensure even settlement.

29 https://www.trada.co.uk/

The rectangular section at the rear is loadbearing straw and the curved front section is timber and glass with straw infill. Foundations are rammed stone car tyres. This is also the first registered UK Living Building Challenge building.

Fig 19 Cuerden Valley Park Visitor Centre & Café. Photo by Barbara Jones

5.Prefabricated straw/timber Structure

In this method, timber panels or boxes are the structural element filled with straw or strawbales for insulation, usually made off-site although some methods are built on-site. They are usually made in panels bespoke to the project. This type of construction is appealing to large developers and self-builders alike for the speed of erection on site. Systems such as Agile[30], Modcell[31], Ecococon[32] and EcoFab[33] are available in the UK. The structural performance is part of the system's design and designers should refer to the manufacturer's structural information. Some panel designs can achieve 6 storeys high. Modcell and Ecococon panels achieve a density in the straw of 110kg/m3

Partially self-built it cost £1350/m2 to build

Fig 20 EcoCocon PassivHaus Photo by George Mikurcik

When demonstrating compliance the Structure Regulations/Standards in each case are concerned with the strength, stability, and resistance to deformation of buildings and their elements.

3.2.1 Foundations

Foundation design is an important aspect for Building regulations/Standards in terms of structural capacity.

In sustainable design, the foundations seek to avoid the use of concrete-based materials as a significant way to reduce embodied energy and carbon dioxide production. Building Regulations and Standards do carry a baseline assumption that concrete foundations are the routine design and construction method, however alternatives have been developed and approved as compliant for strawbale construction – these are not limited to straw buildings - in many completed projects in the UK.

30 https://agile.property/
31 https://www.modcell.com/
32 https://ecococon.eu/assets/downloads/brochure_ecococon.pdf
33 https://www.eco-fab.co.uk/ecofab-system.html

LOADING IN FOUNDATIONS

Foundation design for strawbale walls requires the straw to be raised above the ground by 300-450mm to protect from ground moisture. This can be done in several ways such as with a dwarf/stem or plinth wall, pillar type foundations e.g. rammed stone car tyres or gabions, or piles such as timber, steel screw or rammed stone. There is always timber beneath the straw, either a simple baseplate ladder on top of strip foundations, or a structural box beam on pillar/pile foundations. Physical DPCs are not always required depending on foundation type but when used they are at least 150mm above ground level.

On suitable ground conditions, gravel trench foundations can be built with a limecrete cap, which is a combination of natural hydraulic lime and lightweight aggregate or sand, instead of concrete.

Fig 21 Ready-mix limecrete foundation for a new conservatory Photo: the woodlouse.blogspot.com

Foundation design often draws on the excellent and enduring designs found in our Heritage housing stock, which often have shallow foundations and importantly do not contain cement. Cement was invented in 1824[34] and used in construction increasingly from about 1920, from which time we start to see an increase in structural cracking in buildings. History has proved cement-free foundations to be both durable and effective, facilitated in large part by the flexibility given to stone and brick by the use of lime (and clay) mortar.

Alternative foundations to concrete also seek to reduce the amount of excavation to reduce the disturbance of the natural ground to reduce environmental impact. **Designs using materials that are not susceptible to frost do not always need to be built at depths below the frost line.** Similarly, due to the flexible nature of both the straw and the cement-free foundations **a greater degree of ground movement can be accepted** by the Inspector, as flexible buildings can tolerate a lot more movement than rigid designs. It is helpful to look back at old engineering guidelines for these types of foundation, as modern engineering deals only with rigid structures, which behave very differently.

In appropriate ground conditions the foundation to dwarf walls can be achieved with shallow 300mm deep compacted gravel trenches lined with geotextile. Dwarf wall designs can be 450-550mm wide two-skin wall construction with stone or brick as the outer leaf laid with lime mortar, usually with an insulating (and loadbearing) core of foamglass chunks and an inner skin of foamglass block.

Pillar or rammed stone car tyre foundations can also be used, with suspended timber floors. Experience has shown that the optimum fill material is 10mm draining gravel or pea shingle and this type of foundation has been load tested successfully to 1000kN/m^2 [35]. Examples of the above two details can be seen below in Standard Details drawings as developed by Straw Works.

[34] https://en.wikipedia.org/wiki/Joseph_Aspdin
[35] See Appendix M of Technical Guide

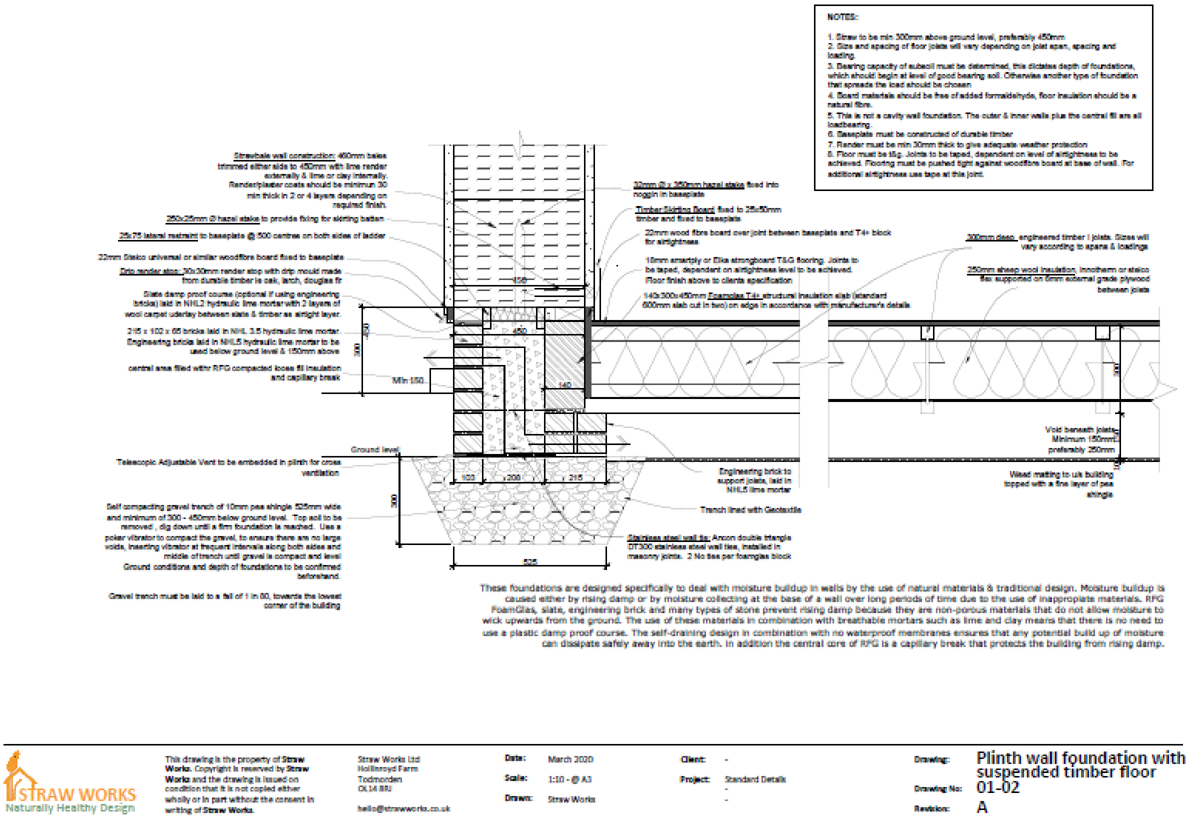


Fig 22 Cement free foundation with foamglas block and chunks

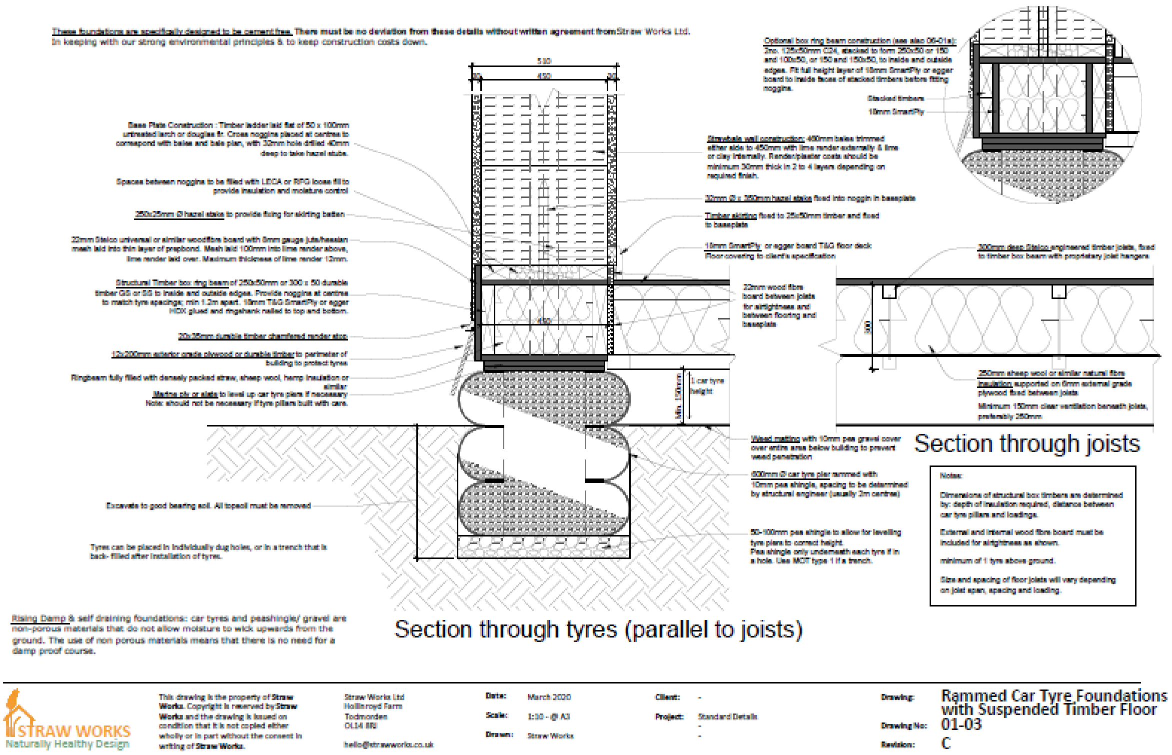


Fig 23 Rammed stone car tyre foundations

Other cement-free options are rafts made from foamglass chunks, steel screw or helical piles, rammed stone piles, timber posts and piles, pad stones, brick pillars laid with lime etc.

Inspectors will need to see evidence that the depth of good bearing soil or rock has been investigated and the existence of moisture or frost ground heave, susceptible clay soil or the presence of compressible peat, or other soil-type conditions has been acknowledged. Photographic evidence and written analysis of the results of trial pits dug on site at the corners or adjacent to the points where foundations will be built must be provided.

Fig 24 Box beam on rammed tyre foundations, Suffolk straw bale cottage Photo Strawbuild

3.3 Fire Safety

Fire Test results provide evidence that firmly dispel old perceptions of the fire risk of compressed straw bales. The density of straw in strawbale construction methods provides a near airless environment so that fire ratings can be compliant with Building regulations/Standards. In addition, their compactness, lack of air gaps, conductivity, specific heat capacity, density and thickness also prevent the spread of heat and therefore combustion beyond the wall. Also, the application of clay and lime plasters seal the bales, further increasing fire resistance. From this evidence, designers can specify straw walls with confidence that end-users are within and beyond the correct safety margins.

There are variations in the requirements for England and Wales, Scotland and Northern Ireland and the simplified summary for each region and for differing heights of buildings is available in the report in APPENDIX F 'Safety of Strawbale walls in the event of fire' by John Butler,2020[36].

The headline results of this report are:
Reaction to Fire: Clay and lime plastered strawbale wall systems have achieved ratings of **B-s1,d0**
Resistance to Fire: Clay and lime plastered strawbale walls (all incorporating timber elements in differing ways) have achieved formal test results of **120 – 135 minutes** without failure (equivalent to **REI 120 to 135**)

Further information is also contained in Appendix L Building Regulations & Standards

[36] For detailed evidence, refer to Appendix F 'Safety of Strawbale walls in the event of fire', John Butler, 2020.

3.3.1 Building Regulations and Standards require buildings to meet 2 main criteria:

a) **Reaction to fire** (concerned with the contribution of a building element to the spread of flame, the production of smoke, and the generation of flaming droplets).

Reaction to fire testing methods are designed to simulate the growth phases of a fire. The purpose is to evaluate how products and materials contribute to the early stages of a fire.

b) **Resistance to fire** (how well the wall resists the penetration of fire or transfer of excessive heat from one side to the other, and in the case of loadbearing walls: the resistance to collapse).

Resistance to fire is marked in time (minutes) to classify the ability of a whole structure or an individual compartment (external wall, beams, doors, and fire barriers, etc.) to resist a standard fire for a determined amount of time to its: stability, integrity, and isolation capability.

3.3.2 Fire Safety Design Values

Note: These are likely to be strengthened in 2021/22 post Grenfell Tower Enquiry.

a) Resistance to fire for external walls:

- For straw bale buildings – either dwellings or non-residential - with a storey height up to 10m, the Building Regulations require the reaction to fire performance of external surface of walls to be Class B-s3, d2 or better to BS EN 13501-1:2018
- For plastered strawbale walls systems, tests have shown:
  Reaction to fire under BS EN 13501-1:2018[37]**:** clay and lime plastered strawbale wall systems have achieved the higher standard of Class B-s1, d0

Fire resistance is measured in minutes.

For ground or upper storeys with a height up to 18m in any of the building purpose groups listed in the documents, the minimum fire resistance required ranges from 30 -120 minutes.

b) For plastered strawbale walls systems, tests have shown:

- Resistance to fire to BS 476-7:1997[38]: clay and lime plastered strawbale walls (all incorporating timber elements indifferent ways) have achieved formal test results of 120 to 135 minutes without failure (equivalent to REI 120 to 135)[39].
- Fire safety tests have been carried out on two pre-fabricated panelised straw construction systems available in the UK: Modcell achieved certified fire resistance of 135 minutes[40] and Ecococon[41] achieved certified fire resistance for 120 minutes.

In comparison, BRE carried out fire resistance tests on PUR- or EPS-thermally insulated SIPS panels with 18mm OSB board facings and concluded the average result was 60 minutes fire resistance.[42]

[37] BS EN 13501-1:2018 https://shop.bsigroup.com/ProductDetail?pid=000000000030348263

[38] BS EN 476-7:1997 https://shop.bsigroup.com/ProductDetail?pid=000000000030296639

[39] For detailed evidence, refer to Appendix F 'Safety of Strawbale walls in the event of fire', John Butler, 2020.

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

[41] https://ecococon.eu/assets/legal/04-reaction-to-fire---fire-resistance-(en).pdf

[42] BRE, 2010 IP21/10: Fire performance of structurally insulated panel systems.

c) Resistance to fire for compartment walls
For any building without a sprinkler system, above ground compartment walls and floors up to 18m must have fire resistance of 60 minutes.

For plastered strawbale walls systems, tests have shown:

- Resistance to fire to BS 476-7:1997[43]: clay and lime plastered strawbale walls (all incorporating timber elements indifferent ways) have achieved formal test results of 120 to 135 minutes without failure (equivalent to REI 120 to 135)*.

This video called "MancFireTest'[44] demonstrates that straw bales are difficult to set on fire and the need to pay attention to joints between bales that may introduce too much air.

On a building site it would be expected that there would be fire precautions in place such as:

- a readily available plumbed in ready to use hosepipe, and a fire extinguisher.
- site to be kept tidy at all times.
- loose straw to be cleared off site regularly and at least at the end of each day.
- Hot work permit principles in place for service pipe installers (and any other insitu welding or soldering)

All sites should conform to the Construction Design and Management (CDM) regulations[45] and some may require special precautions. It should be noted that sites with timber frames are more of a fire risk than sites using loadbearing straw because timber will more readily combust. Guidelines have been issued by TRADA for timber frame buildings.[46]

3.4 Moisture Content and Mould

Construction research, details, calculations, and the specification for construction are the usual routes to demonstrate compliance of Resistance to Moisture for Building Control Officers and Inspectors. See Appendix L for more information on compliance, and also the end of this section.

There has been limited research on mould growth in straw buildings. Mould requires specific conditions of moisture and temperature to thrive. Strawbale buildings are comprised of breathable materials which have specific properties that in themselves regulate relative humidity and therefore mould growth. These are described in Chapter 1.2b but include straw, clay and lime plasters. In addition, lime plaster is alkaline and therefore reduces the risk of mould growth. Mould can occur within stored bales before construction and those affected should not be used in a straw bale building.

In the UK the highest levels of moisture accumulation within the building fabric occur during the coldest months, and mould growth is likely to be inhibited if exposed to low temperatures. Mould growth in strawbale buildings can be prevented during building operation, if the appropriate materials – which provide rainwater protection and allow drying - are used in conjunction with straw bales, and as long as straw bales are kept dry from harvest to construction.

During construction, competent appropriate weather protections must be in place.
The upper limits for good construction practice as regards moisture content in straw can be quantified in these two ways below:

Moisture content no higher than 25% on DRY mass basis
Moisture content no higher than 20% on WET mass basis

[43] BS EN 476-7:1997 https://shop.bsigroup.com/ProductDetail?pid=000000000030296639
[44] https://www.youtube.com/watch?v=9QfqUHxaZXE&t=3s
[45] https://www.hse.gov.uk/construction/cdm/2015/index.htm
[46] https://www.trada.co.uk/publications/archive/fire-safety-on-timber-frame-construction-sites-version-3/

Mould can develop on straw when it is stored prior to construction. Most wet or mould-affected bales are clearly obvious (black mould/silvering on fibre surfaces) and should be rejected at source. Damp bales, or bales that have been damp but dried out are not necessarily mouldy and will dry if well ventilated. See 2.8 for storage guidance. If still in storage they should be kept off the ground and under cover on pallets to allow air movement underneath, around and above. Initially, observation and smell should be used to detect if strawbales are damp and/or mouldy. Damp (or previous damp) is obvious in the form of discoloured patches, dark spots, or a whole side of the bale being silvered or discoloured compared to the rest of the bale. These signs do not necessarily mean that the bale is mouldy, but that it has been wetted and dried during storage – this is common for bales at the outside edge of well-ventilated barns and is not usually a problem. Straw gets wet quickly in rain, but also dries quickly afterwards. It does not wick water much, so the limit of rain ingress to the side of a bale wall is determined largely by how much the force of the wind can drive it into the bale. In dense, well compressed straw this is no more than 100mm maximum.
Physical wetness inside the bale, green shoots, white fuzz or filaments, mushrooms, and/or a musty, mouldy smell like a damp cellar or undergrowth *are* signs of mould. Also, bales that are very wet are noticeably much heavier than others.

Fig 25 Mould in a straw bale Photo: Scottish Farm Advisory Service

Moisture ingress needs to be managed from harvest and drying in the field to baling, from bale storage to transport, from site storage to building and during construction. In practice, almost all excessive moisture in strawbales enters the straw during the construction process via inadequate weatherproofing methods or by catastrophic accident such as storm damage.

Fig 26 Example of rain and weather protection on site for bale storage and construction. This arrangement also provides protection for the lime during application and carbonation[47]

If there is water ingress it is relatively easy to allow wet bales to dry out by providing adequate ventilation in a dry environment. In the worst cases where this cannot be done, bales/straw can be replaced relatively easily as the timber elements provide structural integrity and/or act as lintels. there is evidence that even with water ingress through cracks over a number of years, the alkali and anti-fungal/antiseptic properties of lime plaster will keep the straw healthy and in good condition. See Appendix N

47 Harries, K., Sharma, B. Nonconventional and vernacular construction materials 2nd Edition, 2019 Woodhead Publishing

CLUSTER ECO CONSTRUCTION · SCHOOL OF NATURAL BUILDING · Hastings Borough Council · Benediktinerabtei Plankstetten · GEMEENTE TILBURG · strobouw nederland · Centre National de la construction paille

Once built, strawbale buildings are not static in their moisture content and have diurnal and seasonal cycles[6]. Straw is an organic material with hygroscopic properties, which means it has the capacity to absorb and store moisture vapour from its surroundings into the fibres in a dry form known as Bound water until equilibrium is reached. In environments with high relative humidity, this may influence the desired thermal performance[48] [49] and lead to the possible biological degradation of the material, affecting the building's durability. In research over a 3 year monitoring period of BaleHaus@Bath[50] (lime rendered inside and out) moisture content was seen to rise and fall daily and seasonally - as low as 8% in summer and as high as +22% on the outer face of walls exposed to driving rain in winter.

The dynamic nature of the hygrothermal performance of straw bale walls rendered internally and externally requires hygrothermic modelling (e.g.WUFI[51]) to take account of the variable conductivity due to moisture content and to assess the likelihood of excess moisture content.

Design to prevent moisture ingress during the lifetime of the building is straightforward and includes a good hat, a good pair of boots and a good overcoat - as developed for cob (earth) buildings. These are:

- a good roof overhang to the walls, usually 450mm. This can be reduced in some circumstances depending on wall finishes and location relative to coasts and wind driven rain index.
- raising the straw above ground level by a minimum of 300mm and preferably 450mm to protect against splashback using a non-permeable plinth or pillars,.
- providing adequate weatherproofing to the walls, usually either at least 30mm of lime plaster or ventilated timber cladding.

Encasing the bales in vapour-closed membranes or materials can cause moisture problems as they do not allow the straw to breathe and release excess moisture. Such materials include modern skin forming vinyl paints, gypsum plasterboards, gypsum plaster or cement render.

There are specific digital tools for direct measuring of bale moisture content (MC) with long (600mm) probes, such as the Protimeter Balemaster[52]. Conventional surface moisture / damp meters will not work nor give a representative or useful result.[53]

Fig 27 Photos: Protimeter Balemaster

[48] Lawrence, M.; Heath, A.; Walker, P. Determining moisture levels in straw bale construction. Constr. Build. Mater. 2009, 23, 2763–2768.

[49] Mesa, Arenghi Hygrothermal behaviour of straw bale walls: experimental tests and numerical analyses, 2019, Sustainable Buildings Journal Volume 4 Article 3.

[50] http://dl.lib.mrt.ac.lk/bitstream/handle/123/9222/16.pdf?sequence=1&isAllowed=y

[51] https://wufi.de/en/

[52] https://protimeter.com/balemaster.html

[53] https://lowcarbonbuildings.wordpress.com/2019/01/10/assessing-damage-in-strawbale-walls/

These probe meters can be useful during both the sourcing and construction stages but are invasive once the walls have been plastered. They are used by farmers to monitor the quality of their straw but rarely by practitioners unless there is reason to suspect a problem. Professional strawbale builders should not need to use them.

Another way to monitor moisture is to embed monitors within the walls during construction, and this was done at an infill strawbale Passivhaus in Norfolk. In an interview for Issue 19 Passive House Plus magazine in 2017[54], Architect and Client Fran Bradshaw said:

> "we are using the AECB monitoring tool Omnisense[55]. We installed 10 temperature and moisture sensors in the walls as we built them, with one measuring internally and one externally too.

This building has been monitored since 2015 using the AECB approved moisture monitors (see Appendix XX) and data collected by Dr.Valentina Marincioni of University College London (UCL). The evidence shows that the conditions for mould growth have not occurred apart from a very small number of instances even when the house was unoccupied. This supports empirical evidence that the variation in relative humidity both inside and out is not likely to cause mould problems in straw buildings.

Fig 28 Omnisense remote monitor

Fig 29 Straw bale house in Norfolk 2017 Photos: Hannah Devereux

3.4.2 Design considerations to meet Approval

Strawbale design has benefited from Heritage designs for building with earth (cob in the UK) using the maxim 'a good hat and a good pair of boots' meaning a large overhang - typically 450mm - and raised foundations – usually 450mm. To this has been added 'a good overcoat' meaning 30mm of lime plaster or lime with a timber cladding.

RESISTANCE TO MOISTURE FROM THE GROUND

The foundation and ground floor/wall junction details usually provide higher-performing self-draining conditions than for other buildings, protection from rain splashback and a capillary break to prevent any upward movement of water from the soil.

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54 https://passivehouseplus.ie/magazine/new-build/norfolk-straw-bale-cottage-aims-for-passive

55 https://www.aecb.net/tag/omnisense-remote-monitoring-system/

Protection from upward movement of water can be achieved in the modern way with impermeable DPMs under the ground floor and natural slate or plastic DPCs installed at minimum 150mm above finished ground level.
Increasingly sustainable buildings are using more traditional capillary breaks instead of plastic and fossil fuel based DPCs and DPMs. These usually comprise a 75- 250mm layer of foamglass chunks that acts as hardcore, capillary break and insulation all in one material. Additionally, rammed stone car tyre pillar foundations provide cost effective flood resilient foundations: the tyres themselves act as DPC, and the height of the pillars can be specified such that any rise in ground water during flooding passes safely underneath the building. Specifying materials that do not wick water from the ground is also a way of avoiding using manufactured DPCs. eg slate, granite, some types of sandstone, foamglass blocks/chunks etc.and coupling these with materials that naturally deal with moisture effectively such as lime mortar provides a robust foundation.

RESISTANCE TO MOISTURE FROM PRECIPITATION

The weather exposure of the site should be given heightened attention for straw buildings, including consideration of worsening seasonal wind speeds due to climate change causing horizontal rain, sleet, and snow conditions. These conditions may affect the orientation of the building and whether the external finish facing the exposed side may be different from protected elevations.

In general, provide designs with large eaves and other overhangs that give protection to lime render on external strawbale walls. Lime render performs as an impervious coating but needs protection from heavy water exposure. Compliance can be achieved with meticulous attention to the technical detailing and construction of eaves, balconies, and projected floors. Additionally, timber cladding can be used for exposed surfaces. For maximum weather protection lime render should be 30mm thick.

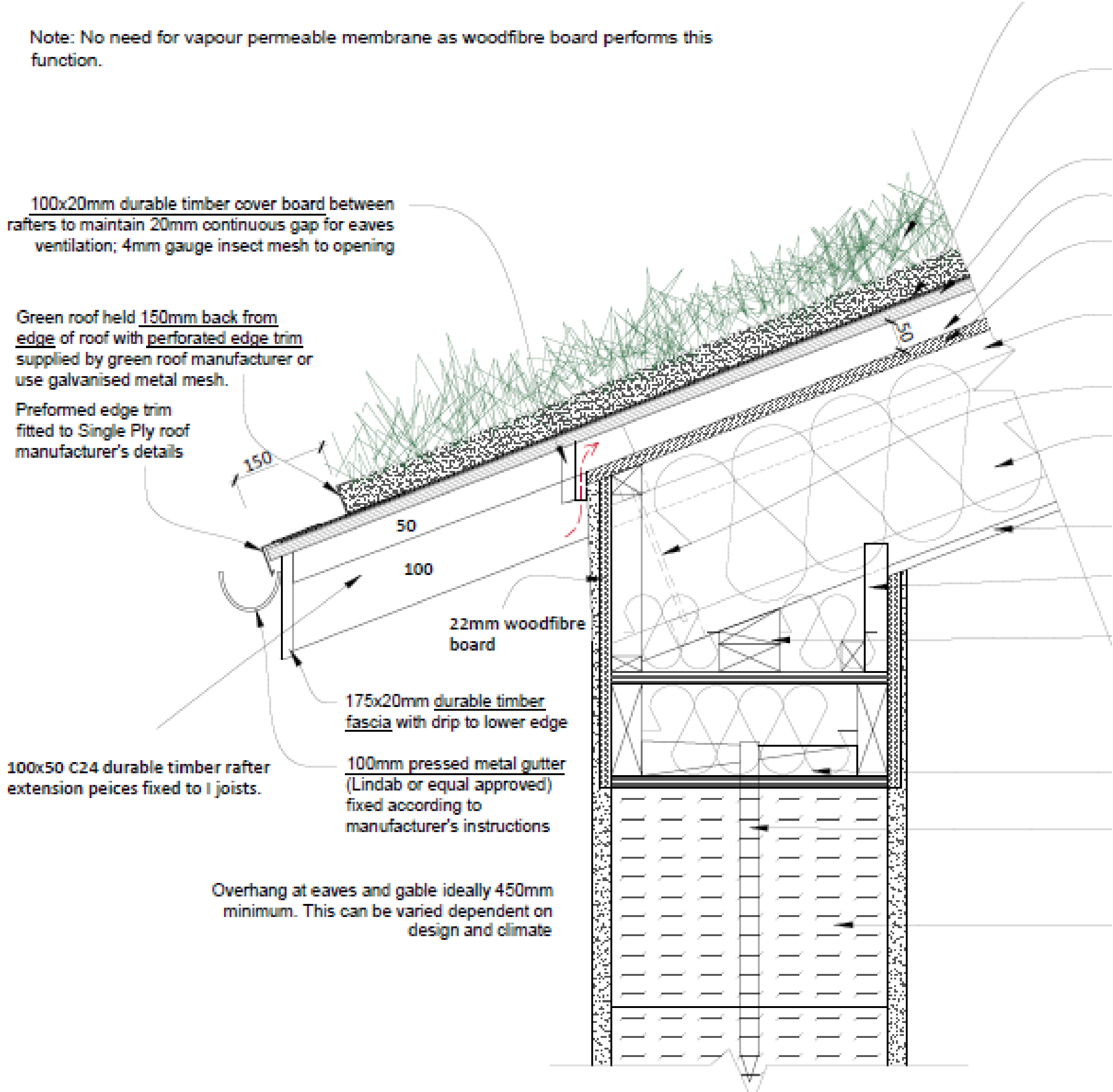


Fig 30 Straw Works technical detail showing wide eaves protecting lime-rendered walls below[56]

Where external cladding is used, these should be designed as ventilated rainscreen solutions, with a lime render key coat to the straw walls behind. If timber weatherboarding or other timber rainscreen is used where sawn or textured boards face the rain splashes, consider that water can track up to 450 mm above the external paving by capillary action. Consideration should be given where wet weatherboarding may carry moisture towards the straw bales behind.

Special care is needed at gullies and at external taps to keep water well away from straw bale walls.
At lower roofs abutting external walls, ensure any risk of rainwater gutter overflows are anticipated and detailed accordingly.

Some pre-fabricated panel systems specify a vapour open membrane on the outside of the panel with 60mm of woodfibre board and either a lime plaster or timber cladding[57] in order to achieve Passivhaus standards and keep the structure weathertight during construction.

[56] https://strawworks.co.uk/resources/technical-details/
[57] https://ecococon.eu/the-panel

RESISTANCE TO INTERSTITIAL AND SURFACE CONDENSATION

In the design of straw buildings, the use of straw, timber, lime render and clay plaster lend themselves to a successful vapour-open construction strategy that must be followed through with all other materials – other insulations, boards, floor finishes, paints, etc.
If a vapour-open approach has been followed through correctly in the construction strategy and materials choices, the building physics intrinsic to this method lead to conditions that tend not to support interstitial or surface condensation.

Compliance can be demonstrated with condensation risk analysis and interstitial condensation calculations to BS 5250: 2002 Code of Practice for Control of Condensation in Buildings or BS EN ISO 13788, such as the Glaser method DIN4108-3 or dewpoint method for assessing the risk of interstitial condensation due to water vapour diffusion.
Alternatively, software can be used such as BuildDesk U or more sophisticated hygro-thermal moisture movement software like WUFI[58] or Delphin.

3.5 Acoustic properties

The quality of acoustic performance of plastered strawbale walls has been perceived as being subjectively 'very good' by users. For designer's the primary concern with straw and straw bale constructions is having evidence of the acoustic performance of proposed constructions that will avoid the need for pre-completion testing.

Requirements for protection against sound or noise separation differ in the different countries of the UK, see Appendix L. To prove performance attainment, Building Regulations and Standards state the requirement for pre-completion sound testing, which can be costly and time consuming.
As an alternative, designers and developers can use the 'Robust Details' in the technical design of separating floor and separating wall components and their junctions to demonstrate compliance.
For now, there are no Robust Details for straw construction.

Building Control Inspectors can also accept empirical and research test evidence.

Some acoustic research and tests have been carried out regarding airborne sound:

In Appendix K, there is the sound insulation report for the party walls at North Kesteven semi-detached social housing designed and built by amazonails in 2009 and below is the party wall build-up that was accepted by Building Control.

Fig 31 Semi-detached loadbearing straw affordable council houses, North Kesteven Photo Rae Parkinson

[58] https://ecococon.eu/professionals/downloads

Party wall thickness 540mm
350mm straw bales
30mm lime plaster to each room face
On one side of party wall - independent 100mm x 50mm timber stud frame infilled with 100mm mineral wool quilt and 2 layers 12.5mm acoustic plasterboard and skim

Measurements were carried out through the party wall between the units from 2 locations – one from the Kitchen/ Living Room and one from a bedroom.

The weighted and corrected result for both locations is an airborne sound reduction of 58dB. Compared to a requirement of 45dB (56 in Scotland)

	Table 1: Airborne Sound Insulation Results - 29/07/2010						DnTw+Ctr				
Test	ANC Test	Source	Vol (m3)	Receiver	Vol (m3)	Element	Criterion	DnTw	Ctr	DnTw +Ctr	Pass/ Fail
A1	1342640203	16 LivRm/Kit	108	15 LivRm/Kit	108	Wall	≥45	65	-7	58	pass
A2	1342640204	16 BedRm	23	15 BedRm	23	Wall	≥45	64	-6	58	pass

Fig 32 Airborne sound insulation results for North Kesteven Council Houses

Research to determine the airborne sound insulation of a peripheral non-load bearing wall made of straw bales was conducted by Jiří Teslík, Radek Fabian And Barbora Hrubá in 2017 in the certified acoustic laboratory at the Faculty of Mechanical Engineering at Brno University of Technology.
https://core.ac.uk/download/pdf/161955087.pdf

The table of results below shows the increasing airborne sound insulation performance attained by incremental measures:

Measured variant	Density of material (kg/m^3)	Basic weight of material (kg/m^2)	Weighted Sound Reduction Index R_w (dB)	Improvement to the sound insulation ΔR_w
Straw wall th . 350 mm	90	31.5	28	-
Clay plaster (wet) th. 25 mm Straw wall th. 350 mm	2000 90	50 31.5	35	8
Clay plaster (dry) th. 25 mm Straw wall th. 350 mm	1650 90	43 31.5	42	14
Clay plaster (dry) th. 25 mm Straw wall th. 350 mm Air gap th. 40 mm Wolf PhoneStar Tri boards th. 15 mm	1650 90 - 1350	43 31.5 - 14	57	29
Clay plaster (dry) th. 25 mm Straw wall th. 350 mm Clay plaster (dry) th. 25 mm	1650 90 1650	43 31.5 43	54	26
Clay plaster (dry) th. 25 mm Straw wall th. 350 mm Air gap th. 40 mm Ecopanel th. 58 mm	1650 90 - 379	43 31.5 - 22	57	29

Fig 33 Airborne sound insulation results for a peripheral non-load bearing wall


Straw wall


Clay plaster, straw wall


Clay plaster, straw wall with panels

Fig 34 Airborne sound insulation test demo walls

3.6 Thermal Performance

When considering thermal performance, it is common to focus on the energy efficiency of a given thickness of material (thermal conductivity, K value or lambda value). However, thermal performance is not just about reducing heat loss[59]. Controlling the rate and pattern of heat loss as well as heat gain during weather cycles and in response to the seasons are equally important. The thickness and density of strawbales are advantageous as they give buildings greater thermal mass, which in turn tempers conductivity heat loss and solar heat gain and improves indoor thermal comfort.

Greater density usually means poorer k value but better decrement value. Specific Heat capacity is the property which relates to thermal mass when considered with k value and density.

Compliance with Regulations/Standards for energy efficiency in each country is based on calculations of the amount of carbon dioxide emissions caused by the heating and operating (fixed building services), of the building as well as the energy efficiency of the building. These calculations are required at design stage, and again on completion of construction to prove that the building was constructed in accordance with or better than the list of specifications. The calculations following completions are used to produce the EPC Energy Performance Certificate.

Currently, approved calculation methodologies include:

SAP 2012 Standard Assessment Procedure for domestic buildings
SBEM Simplified Building Energy Model for buildings other than dwellings

The essential component of the calculations for straw construction is the U-value of the straw wall or roof component. Increasingly, it is becoming understood that insulation can and should also contribute other benefits to the building such as a reduction in embodied carbon, ability to store thermal heat and delay heat loss/gain, breathability to improve indoor air quality, resistance to fire and especially not to produce toxic gases in a fire. These aspects are expected to become part of Building Regulations and Standards in the near future[60].

The regulations also cover limiting the effects of thermal bridging, lack of airtightness, heat gains in summer, and heat losses and gains from circulation pipes, commission of fixed buildings services, and providing information for users to understand the energy efficient operation of the building.

Thermal conductivity

Thermal conductivity is one aspect of a material's thermal performance. Several factors influence this, in straw and strawbale insulation, including straw orientation, build quality and density.

59 https://asbp.org.uk/briefing-paper/the-multiple-roles-of-insulation
60 https://asbp.org.uk/all-resources?tx_category=briefing-paper

Thermal Conductivity Design Value

Designers need a confirmed design thermal conductivity for calculations during the design process. In 2020, all available research and test results were comprehensively analysed[61] in order to provide a UK headline thermal conductivity for straw bale. The measure of heat transfer through materials, thermal conductivity, is denoted by the Greek letter λ (lambda) or k.

Thermal conductivity for straw bale,

Mean λ value: 0.065 W/mK

λ 90/90 value: 0.08 W/mK (use with caution – see below)*

There is uncertainty over whether the λ 90/90 calculation should be applied as it has in this analysis, to a range of published results from different sources and slightly differing test procedures. The 90/90 test is intended to be used on a single set of results from samples tested under the same conditions. Further tests of UK strawbale samples are planned, to establish a formal λ 90/90 value.

Until further testing has been conducted, it may be more appropriate to use the mean λ value of 0.065 W/mK.

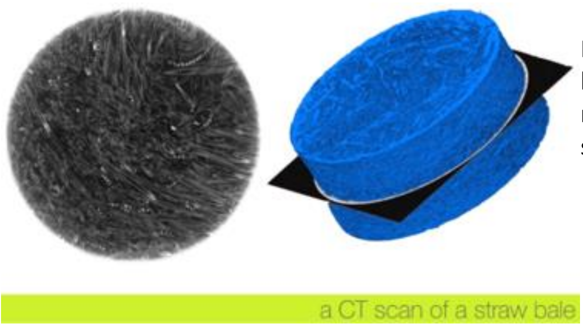
*This is the material conductivity and not the U-value for a straw bale wall, which should be calculated in the normal way to BR 443 (2019) Conventions for U-value Calculations.

This figure is based on straw in random orientation and orientation parallel to heat-flow, contained in bales. Loose-fill chopped straw may behave differently and have a different lambda value.

3.6.1 Straw orientation

Visually it can seem as though straw is either vertical or horizontal in bales because bales have what is termed a cut side and a folded side. Tests and practical experience have shown that this is not actually the case, and straw in a bale is more haphazard.

Baling machines pick up straw in different ways according to manufacturing type. Most UK baling machines bring the straw into the box from the back and this produces bales that appear to have horizontally aligned straws when the bale is laid flat, as seen by the cut and folded sides of the bale. Massey Ferguson produce a machine that brings the straw into the bale from underneath and these appear to have the straws vertically aligned as the top and bottom of the bale have cut sides. However, practitioners verify that although bales can seem to show a particular orientation of the straw in a bale, when opened up it is clear that many straws are not aligned in the same way. Also, some bales are made from short chopped straw and in these bales orientation is even more haphazard.



Research by Peter Walker at Bath University for Modcell has shown that bales, using short stem varieties, have random orientation. A bale was put through an MRI scanner to demonstrate this.

Fig 35 ModCell (2015) 'A CT scan of a strawbale'. *7ª Conferencia Española Passivhaus*, Barcelona, November

In the analysis, Butler, looked at the significance of straw orientation on thermal conductivity and found:

[61] John Butler, 2020: Thermal conductivity of strawbale – a review of published results meeting ISO 10456 requirements, analysed to provide robust straw lambda values.

"Uncertainty over the degree to which bale orientation effects thermal conductivity, with only a small sample of results indicating a difference. More research is needed in this area especially given the anecdotal and academic evidence that actual orientation in all bales is somewhat random."

Therefore the lambda value stated above is the most reliable figure to use with strawbales.

For Passivhaus designs using straw as insulation, the International Passivhaus Association, iPHA produces a Passivhaus Fact Sheet[62] . The fact sheets states that a lower thermal conductivity of 0.052 W/(mK) based on German research can be used for bales with vertical straws (perpendicular to heat flow).

3.6.2 Build quality and density

Thermal efficiency is affected by build quality. Leaving gaps at joins between bales, and between bales and timber in framed systems, or applying insufficient compression (not creating enough density) will reduce thermal integrity and efficiency.

The hollow sturdy stalks of straw form still air voids that are insulating. The density of straw and straw bales in construction influences the air gaps between the stalks and between the bales themselves and therefore the thermal conductivity efficiency. A minimum density of 100kg/m^3 has been stated[63] as required for structural use and this can also be applied as an appropriate density for thermal insulation efficiency.
Research by Shea et al in 2013[64] showed that chopped straw density can be lowered to 100 kg/m3 and achieve the same thermal conductivity values as bales at 115-125 kg/m3. This is due to an optimised balance of air to straw and reduced conductivity through reduced straw length (to c. 20mm), and this gives highly randomised heat flow. In practice, straw of this length could only potentially be used for panel construction or for blown in types of straw insulation. Bales made with this length of straw would not hold together.

3.6.3 Decrement factor/thermal buffering

The term 'decrement delay' refers to the time it takes for heat to pass through an element of a building (such as an external wall or roof). Typically this is taken to be the delay in hours between the peak temperature of the outer surface of the element on a summer day and the resulting peak temperature of the internal surface. This concept reflects increasing awareness that the thermal behaviour of buildings is dynamic, rather than static, and that thermal mass, as well as thermal insulation, has a significant impact on the energy efficiency of a building. For example, two buildings with identical U-values may perform very differently depending on their decrement delay, with a longer delay likely to reduce peak loads on building services systems. Materials with a low lambda value, high specific heat capacity and high density will tend to have a high decrement delay. To reduce summer overheating, a low decrement factor is required, and a decrement delay of 6 to 12 hours. Low fabric thermal mass leaves buildings vulnerable to uncomfortably high internal temperatures in summer. Using straw as the insulant adds significant thermal mass that protects against this.

Thermal mass (heat capacity) is the ability of a material to absorb and store heat energy and is measured in J/°C or J/K. A lot of heat energy is required to change the temperature of high-density materials like concrete, bricks and tiles. From BuildDesk U information high thermal mass would be c.500kJ/(m^{2}K) for a solid masonry construction, and low thermal mass would be c. 55 kJ/(m^{2}K) for a lightweight timber frame[65]. Thermal mass of

[62] https://passipedia.org/_media/picopen/17_fact_sheet_straw_as_insulation.pdf
[63] Walker, P., 2004, Compression load testing straw bale walls
[64] Evaluation_of_the_thermal_performance_of_an_innovative_prefabricated_natural_plant_fibre_building_system, Shea et al, 2013
[65] http://www.builddesk.co.uk/software/builddesk-u/thermal-mass/#:~:text=The%20Thermal%20Mass%20Parameter%20(TMP,total%20floor%20area%20(TFA).

straw (at density of 110 kg/m³) is 206 kJ/(m²K).[66] This can be increased further by the use of clay and lime plasters.

Materials that store heat (have thermal mass) not only buffer the building from high external temperatures, but also contribute to the indoor comfort of a building. For example, if a building suddenly loses all its warm air in winter, as a result of opening doors and windows, the stored heat from the thermal mass is transmitted to the indoor climate once the reason for loss of heat is removed.

Thermal inertia for over-heating and heat loss
Buildings with a large amount of thermal mass will display a reduced and delayed reaction to a sudden rise in external ambient temperature. This transient behaviour is referred to as the thermal inertia of a building. Thermal inertia is the degree of slowness with which the temperature of a building approaches that of its surroundings. This is important in protecting internal environments from over-heating during high, summer external temperatures.
Research shows that straw bales walls have a 'high thermal inertia potential'[67] but offers no numerical results that would be useful to Clients and designers.
Further research, into thermal inertia is required on completed site-built and pre-fabricated straw and strawbale buildings to establish robust design values.

3.7 Air Permeability/airtightness

Airtightness as a concept has been discussed as a desirable goal for buildings in order to increase energy efficiency since the 1970s. It means the reduction or even elimination of air leakage from a building that is not managed or deliberate. Deliberate air movement or ventilation in a building is achieved by opening windows/doors, using a passive or a mechanical ventilation system.

Air leakage can be measured by Air Permeability or Air Changes per Hour.

Air Permeability (AP): The volume of air passing through each square metre of the fabric of the building per hour measured in m^3hr/m^2. This is calculated from the total volume of air in the building, the area of the external envelope – including walls, floors, ceilings, and the results from a blower door test that shows how often $1m^3$ of air leaks through $1m^2$ of wall.

Air Changes per Hour (ACH): The number of times that the air within a defined space is changed in one hour, measured by the volume of air removed from the space in cubic metres/hour (airflow) divided by the volume of the space measured. It is often written as ACH_{50} and is measured with a blower door test.

Both AP and ACH are usually measured at a pressure differential of 50 Pascals (50 N/m2) between the inside and the outside of a building to enable comparison of results.

Airtightness is a measure of build quality, as good detailing and implementation results in lower air leakage. Lime and clay plasters have successfully been used to provide airtight layers as well as or in conjunction with tapes and membranes.

Designs cannot be targeted for any specific air permeability value other than zero. There is no suite of details that are guaranteed to attain $ACH<3^h$ or $ACH<5^h$ or any other number.
Air leakage is dependent on the early development of a simple air barrier strategy which can be tapes, membranes or good quality detailing and plastering, the use of buildable airtightness detailing and services interfaces, and the meticulous quality of construction.

66 G. Minke and B. Krick Straw Bale Construction Manual, 2020. ISBN 978-3-0356-1854-9
67 Arumi-Noe, K.Hamilton, 2013 Thermal inertia of straw bale walls

A comprehensive document to guide designers through the process is called 'Delivering Airtight Buildings: A 12 Step Program' by Paul Jennings, Aldas[68]

Straw Works also publishes standard details on its website that have achieved 2.6 ACH with no tapes or membranes.

The Passivhaus standard uses ACH as a measure of airtightness and requires less than 0.6 ACH_{50}.

Only a small number of straw bale buildings have as yet been tested for airtightness via ACH, but straw walls must be plastered both sides to avoid air leakage. Unpublished experience by tester Paul Jennings[69] reports that un-plastered straw bale walls are 'too leaky for use in buildings'. This correlates with air tightness lab tests on plastered bales[70] , which showed that un-plastered bales at 50Pa have mean airflow results of 21.5 l/s.

Further lab tests in the same research showed that in plastered straw bale walls, ACH <3[h] is readily achievable. The research also characterised the relative impact of the size of cracks in the lime plaster coatings.

Airtightness membranes are not required on straw walls because either internal clay or lime plaster and/or external lime render can be used effectively as the air barriers, provided care is taken at the junctions of plaster with other materials and door/window openings and at plinth and eaves. In the sequence of construction, strips of membrane can be installed at junctions and later have a taped junction with the plaster if ACH values at or close to Passivhaus standards are required.

Alternatively, these junctions can be detailed using woodfibre board and good plastering. Some purpose made tapes have meshes to embed into in situ finishes which are particularly useful at window or door abutments with plaster or render adjacent.


Fig 36 2 part tape used to seal between a wall/ window/ membrane and a plaster air barrier

The Haven Cottage Passivhaus in Suffolk built in 2015 is a two-storey load bearing strawbale house that achieved 0.26 ACH^{-1} @50Pa in a preliminary air leakage test and 0.42 ACH^{-1} @50Pa at final test. This design used the external lime render as the airtight layer, with two-part tape used around windows, doors eaves and between the straw and foundation.

Fig 37 Haven Cottage Photo Barbara Jones

The two storey loadbearing straw Council Houses designed by Amazonails and built in 2009 for North Kesteven Council achieved 2.6 ACH^{-1} @50Pa. using amazonails standard details (now Straw Works) which do not contain tapes or membranes of any kind, and it was lime plastered both internally and externally.

68 https://carbonlite.net/wp-content/uploads/2017/04/Aldas-12-Steps-to-Airtightness-revised-June-2019.pdf

69 https://goodhomes.org.uk/standard-member/aldas, doorfanman@hotmail.com

70 Brojan,L., Weil, B., Clouston, P., 2015 Airtightness of straw bale construction, Journal of Green Buildings Volume 10 Number 1

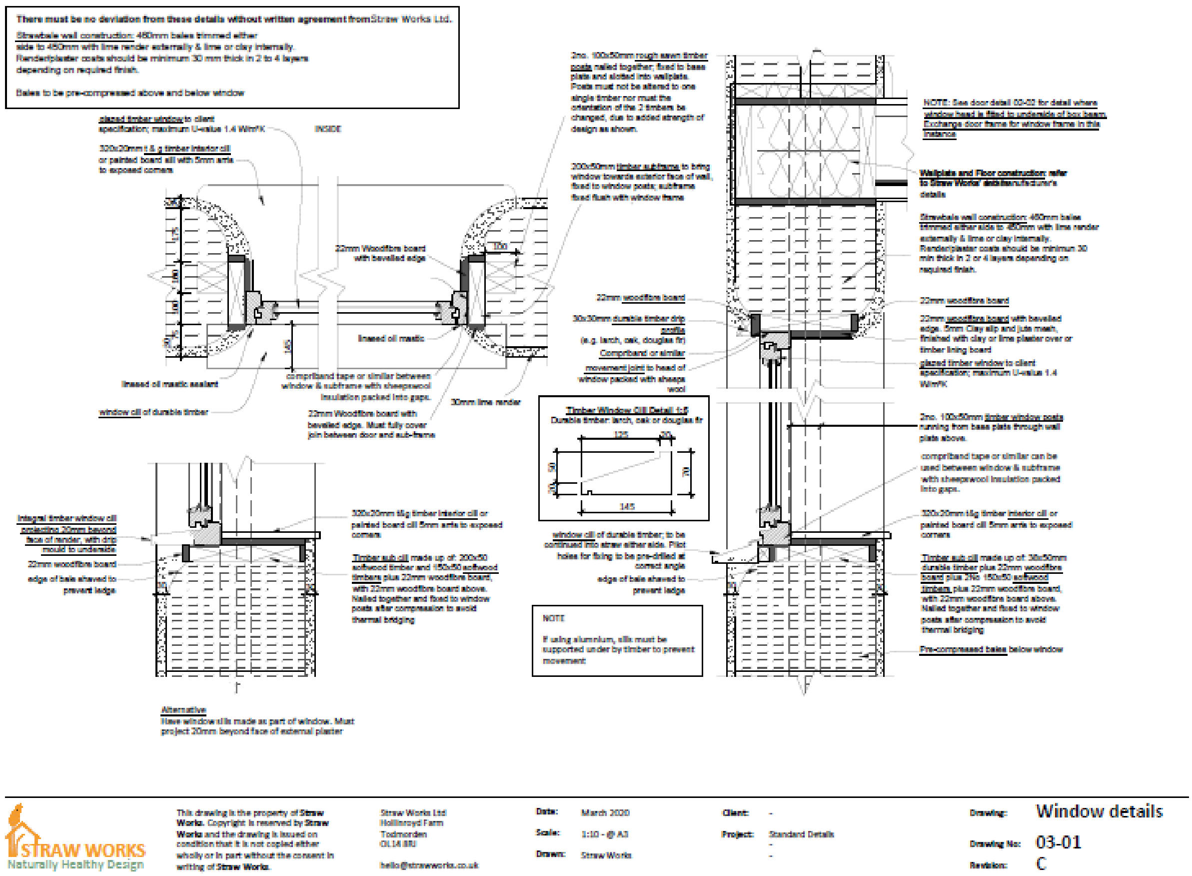


Fig 38. Straw Works Standard Detail as used at North Kesteven Council houses, updated to show woodfibre board to add greater thermal efficiency after research investigating Psi and fRsi values. See Appendix D

3.8 Embodied & Lifestyle Carbon

Please see Appendix L for Building Regulations and Standards for the Conservation of Fuel and Power

Plants absorb CO_2 from the atmosphere as they grow, storing it in their structure as biogenic carbon. Straw and other plant-based materials continue to store this carbon while they remain part of the fabric of a building. At the end of life of that building the carbon can either remain stored or be released (wholly or in part) depending on what happens to the materials after deconstruction or demolition. EN 15804[71] (the European standard governing life-cycle assessment (LCA) and Environmental Product Declarations (EPDs)) allows inclusion of biogenic carbon in EPD calculations, but unless that carbon remains stored for more than 100 years it must be classed as emitted at the end-of-life stage. The latest version of the standard (EN15804+A2) requires the reporting of biogenic carbon separately from fossil fuel carbon emissions, and emissions resulting from land use change.

If straw is re-used at the end of a building's life then its biogenic carbon remains stored. If it is composted or incinerated then the carbon is released. If placed in landfill it is likely that some carbon will be released by decomposition, with the majority remaining stored. Straw-specific research is needed, but for timber it has

71 BS EN 15804:2012+A1:2013 Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products
https://shop.bsigroup.com/ProductDetail/?pid=000000000030279721

been estimated that 20% of the carbon in timber decomposes in landfill, with the rest remaining stored.[72] Conversely, where there is decomposition in landfill it is often anaerobic, resulting in production of methane which is a more potent greenhouse gas than carbon dioxide.

Various carbon calculation and life cycle assessment (LCA) tools are being developed to assist low-carbon building design. In the UK guidance from RICS (which details an approach to following EN15978) is standard methodology for calculating whole-life carbon of buildings[73]. It relies on data from EPDs and a series of built-in assumptions derived from available data and research. The guidance is currently being updated to reflect the latest research. As with EN15804 and EPDs, storage of biogenic carbon can be included only in the case of whole life assessments, where the release of stored carbon is calculated.

NIBE have produced LCAs for Up Straw of straw in five European countries including the UK. The resulting data was then implemented into EPDs for each country.

The EPD for 'Straw as Insulation Material UK'[74] has been externally verified and is now published. For the first time this gives an accurate assessment of the environmental impact of straw production in the UK. It gives the impacts for a cubic metre of strawbale at 100kg/m^3 density. As straw is used in constructions in varied ways, this data allows the impact of straw to be included in building LCA regardless of construction method.

The LCA was informed by data compiled from UK Government/DEFRA statistics on grain and straw yields; nutrient removal (as part of straw); quantities of fertiliser and pesticide use by type per hectare and per kilo of grain; and fuel use per hectare. Straw and grain prices were collated figures from the AHDB[75]. The division of emissions between grain and straw is allocated according to the economic value of each. End of life figures assume 95% incineration of straw, and 5% landfill.

LCA and EPD data is divided into different life cycle stages. Life cycle stages A1-A3 relate to production and manufacture. Stage B relates to use, including maintenance and replacement (usually over a 60-year reference lifespan for buildings). Stage C relates to end of life and disposal.

The EPD gives an extensive series of Environmental Impact Indicators. The figures below concentrate on carbon, reflecting the urgent need to reduce the carbon impact of construction.

Across the whole lifecycle, the A-C carbon emissions of 1 cubic metre of UK straw are 14.12 kgCO_2e/m^3. A1-A3 carbon emissions are 12.97 kgCO_2e. A cubic metre of straw stores 129.25 kgCO_2e. The whole life carbon impact from land use and land use change is 0.02 kg kgCO_2e/m^3.

To achieve the same level of thermal performance, different amounts of different materials are needed due to their differing thermal conductivities. So to compare to other materials it is helpful to look at complete wall constructions, or at the emissions per square metre of insulation with the same U value, accounting for the differing thicknesses needed.

72
https://www.researchgate.net/publication/260122306_An_Application_of_the_CENTC350_standards_to_an_Energy_and_Carbon_LCA_of_timber_used_in_construction_and_the_effect_of_end-of-life_scenarios

73 RICS, *Whole life carbon assessment for the built environment 1st edition, November, 2017*, https://www.rics.org/uk/upholding-professional-standards/sector-standards/building-surveying/whole-life-carbon-assessment-for-the-built-environment/

74 Straw As Insulation Material UK, https://www.environdec.com/library/epd3854

75 https://ahdb.org.uk/dairy/hay-and-straw-prices and https://projectblue.blob.core.windows.net/media/Default/MI%20Reports/D&A%20Arable/Daily%20and%20Weekly%20Price%20Reports/UK%20Delivered%20Cereals%20%20Oilseed%20Prices.xlsx

Fig 39 Shows the whole life (life cycle stages A-C, spilt into manufacture emissions (A) and use/end of life emissions (B-C)) emissions resulting from four walls of similar structure, insulated with straw, cellulose fibre (from recycled newspaper), mineral wool quilt, and sheep wool insulation. The insulation is placed between timber I Beams, with wood fibre board and lime render externally, and plasterboard with gypsum plaster internally (this is used to provide a fair comparison between the insulation materials, not as a recommendation of building technique). The U value of all four walls is 0.15 W/m^{2}K. The walls are assessed using a standard reference lifespan of 60 years. The reference life span allows fair comparison between structures, as it cannot be known exactly how long a building will last. Effectively, the longer the life of a building, the lower its relative environmental impact (assuming an energy efficient construction). There are examples of strawbale buildings in France and USA that are already over 100 years old. As the charts below show, even over a 60-year lifespan straw-insulated walls result in lower carbon emissions than alternatives.

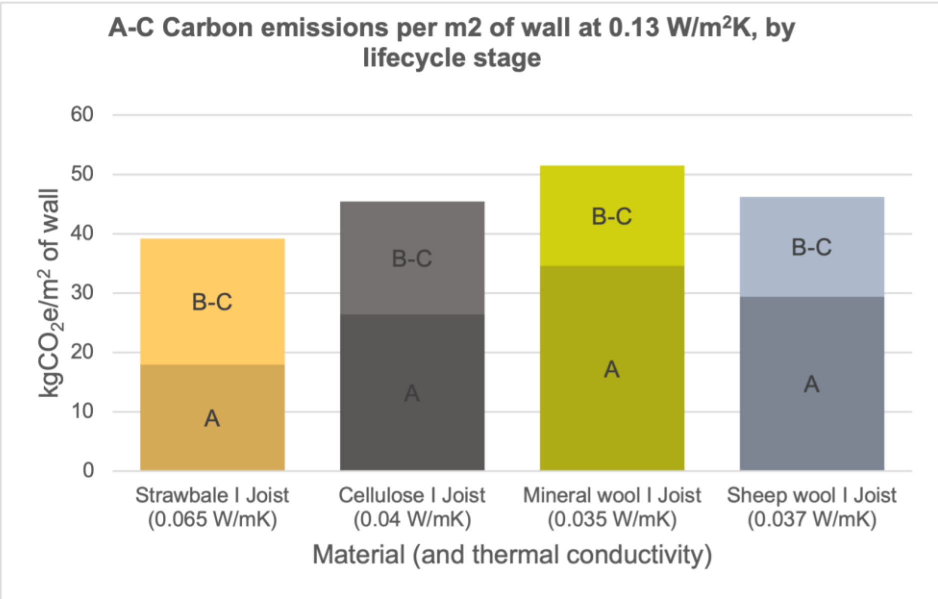


Fig 39 Whole life (stages A-C) emissions of four walls with identical U value and similar structure, over a reference 60-year lifespan (calculations used AECB PHribbon tool).

The straw wall results in the lowest carbon emissions of the four.

When designing a building it is crucial that design choices are based on whole life carbon comparisons that include end of life and the different quantities of materials involved, as above.

It can also be helpful to look at the amount of carbon stored in construction (though this cannot substitute for choosing materials with the lowest possible whole life carbon). Though stored carbon will likely be released at the end of a building's life, it remains usefully stored for as long as the building remains. This highlights the need to design for a long building life, including allowing for adaptation of use to enable that.

Fig 40 Compares the amount of carbon stored in the same four walls as above.

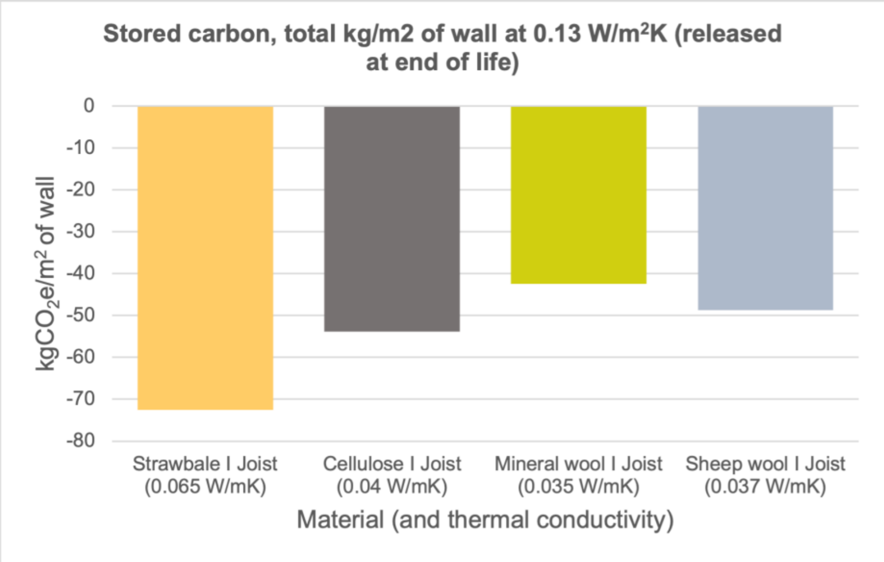


Fig 40 Carbon stored in four walls with identical U value and similar structure (note: carbon is stored in the timber and wood-fibre elements as well as straw, cellulose, and sheep wool) (calculations used AECB PHribbon tool).

Fig 41 Compares the whole life (A-C) emissions of straw and other insulation materials at thickness to achieve a U value of 0.14 W/m^{2}K (looking insulation material without other elements). Fig42 Shows the amount of carbon stored in the same.

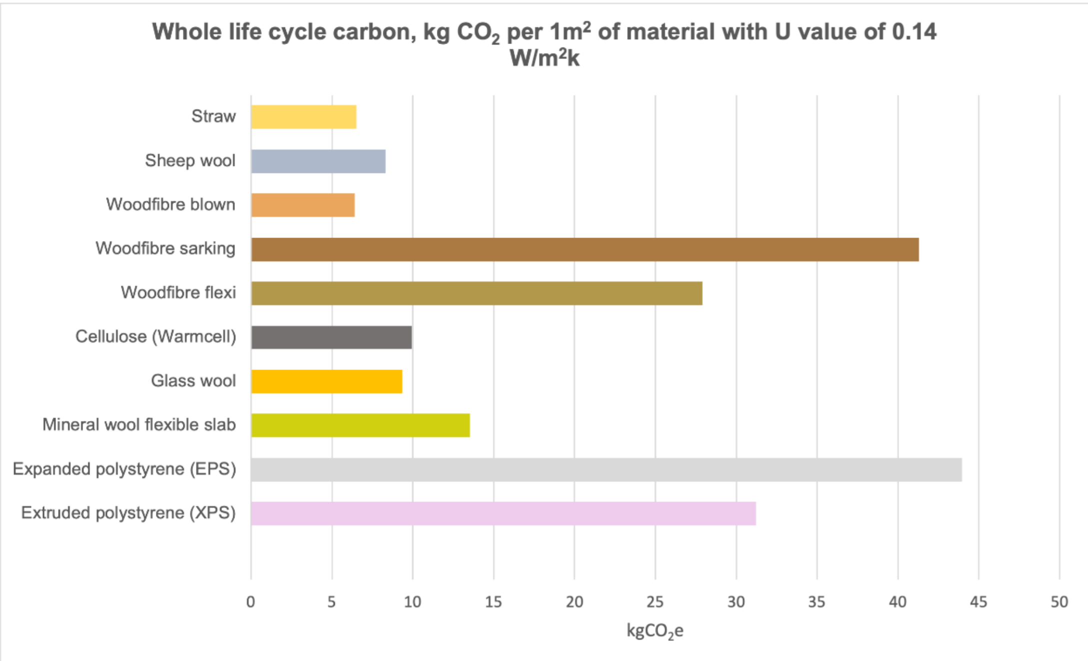


Fig 41. kgCO_2e whole life emissions per 1m^2 of material with U value of 0.14 W/m^{2}K

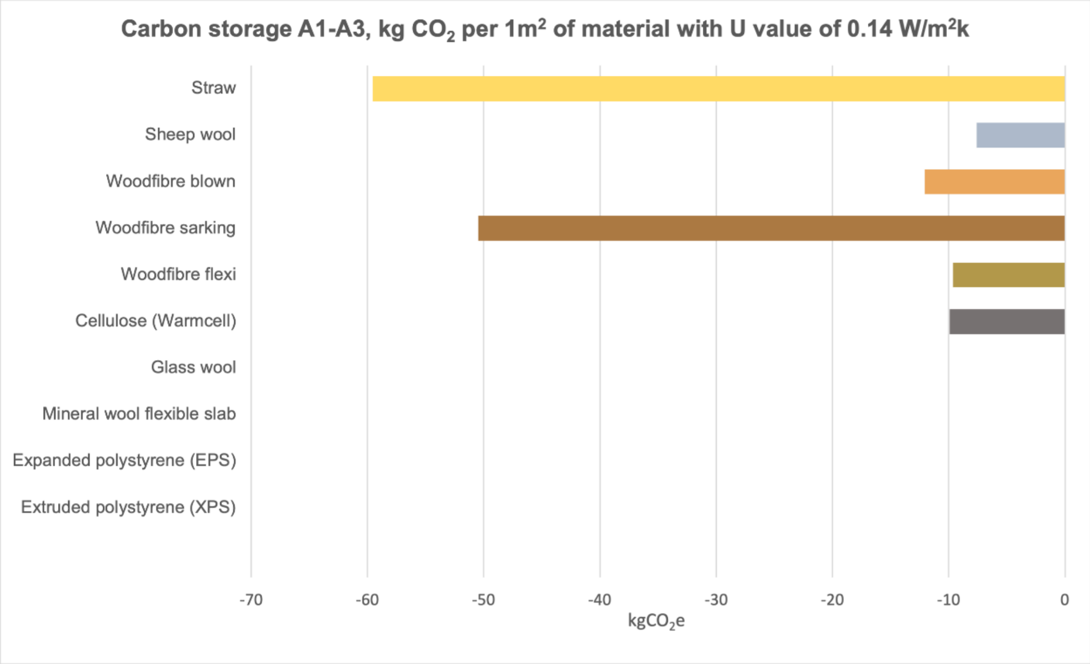


Fig 42 $kgCO_2e$ stored carbon per 1m² of insulation material with U value of 0.14 W/m²K

3.8.1 Useful Tools, Resources & Materials

Green Building Encyclopedia are developing a Green Building Calculator to allow designers access to U value calculations, decrement delay, bill of materials, cost planning, embodied energy, embodied carbon and LCA calculations all in one calculator[76].

The Alliance for Sustainable Building Products has a membership of product makers and partner supporters with a purpose to provide well-informed and expert briefings, CPD, tutorials, case studies and featured sustainable products. They also hold information on EPDs for natural products[77]

Cradle to Cradle is a curated certification for safer more sustainable products made for the circular economy[78]. Ecococon straw panels have Cradle to Cradle certification

AECB's PHRibbon tool (https://www.phribbon.co.uk/) (which plugs into Passivhaus Planning Package) and standalone embodied carbon calculator (et/product/aecb-embodied-carbon-calculator/) enable calculations of whole life embodied carbon (and operational carbon with PHRibbon), with comparison to RIBA and LETI carbon benchmarks.

Use of low embodied energy and carbon co-materials to reduce overall carbon footprint and enhance Indoor Air Quality

Approximately 16% of the material volume in a strawbale building is the straw itself, but it is possible to ensure that almost all the other 84% is made of natural, recycled and low embodied energy materials as well.
An important aspect of straw buildings is that many of the other co-materials used are also low in embodied energy and have a low or zero carbon footprint. Atkinson conducted research as part of her PhD thesis in 2008 that highlighted this see the table below.

[76] https://GreenBuildingCalculator.uk
[77] https://asbp.org.uk/
[78] https://www.c2ccertified.org/get-certified/product-certification

energy rating	materials	% volume of all materials
extremely high	(plastic straps, lead flashing, hinges, locks, handles, nails and screws, galvanized down pipe)	0.14%
very high	(double glazing)	0.09%
high	(OSB, external plywood, tywek membrane)	2.19%
medium	(baler twine, floorboards, wooden gutters, cork underlay, celenit fibreboard, door/window frames, lime plaster, hessian)	7.34%
low	(local timber)	5.28%
very low	**(strawbales, sheep wool insulation, hazel, clay plaster, cedar shingles)**	**84.95%**

Fig 43 Embodied energy of typical materials found in a strawbale house. Atkinson 2008

Natural/ recycled/low impact materials commonly specified for straw and strawbale projects include:

- Timber: floors, frame, ring beams, roof, roof covering (shingles & shakes), windows and doors, internal partitions and fittings, cladding, hazel pins
- Stone products: sand, gravel, shingle, stone, slate - used for foundations and plinth/stem walls, with mortars, plasters and solid floors, for roof covering.
- Brick and tile: outer skin of plinth/stem walls, foundations, inspection chambers, roof covering
- Recycled glass sand: to replace sand in solid floors and plaster.
- Recycled Cellular glass (Foamglas) as a block: foundation insulation - usually inner skin of stem wall.
- Recycled foamed/cellular glass (rfg) as chunks: insulation, hardcore, capillary break - often underneath limecrete slab, as raft under whole building and as loadbearing central core of stem walls
- Natural insulations: straw, sheepswool, hemp, cotton denim, cork, recycled newspaper, LECA (light expanded clay aggregate), woodfibre (board and blown) etc.
- Lime: mortars, renders and plasters, floors, paints
- Clay: mortars, plasters, floors, paints
- Hemp: as insulation for floors and roofs, as fibre in plasters, with lime for walls (hempcrete)
- Woodfibre board: insulated sarking board (to replace breather membranes), for thermal break around windows/doors, timber etc as external layer for straw panels before cladding or lime render.
- Glass: windows and doors
- Linseed oil: with burnt sand as mastic and as oil for weatherproofer/sealer for timber and clay floors/plaster
- Timber board materials: only those free from added formaldehyde
- Other breathable board materials
- Ceramic underground drainage pipes: to replace plastic
- Recycled car tyres: for foundation pillars
- Retrofit - straw external insulation panels

Small amounts of other materials that are not natural are also used such as:

- Membrane products – these are kept to a minimum and designed out where possible: breather membrane, Gas/DPC/ DPM, (clay and fabric based), intelligent moisture permeable air/wind tightness products
- Plastic avoidance as much as possible - only plastic essentials: baling twine, polyester tie-down straps, airtightness products, rainwater goods (metal alternatives), service pipes and ducts, EPDM for living roofs
- Poured products: concrete and concrete screeds with eco-improvements – low carbon blended GGBS, recycled aggregates
- Metal - flashings, roof covering, fixings and fastenings, rainwater goods, ironmongery, rainscreen cladding

An example of the low impact co-materials in load bearing strawbale buildings is hazel pins used in the building of bales in load bearing walls.
"Hazel rods normally 25mm – 40mm diameter and pointed at one end. The rods should be as straight as possible and are driven down through the straw bales to pin and hold them together during construction. The hazel can be used to secure the roofplate to the straw bale walls …. The length of hazel varies depending on construction detail."[79]

Fig 44 Pictures1 and 2: Cutting hazel from coppice for bale *coppiceapprentice.org.uk*

Picture 3: Hazel 'stub' stake in the base plate ready *coppice-products.co.uk*

3.9 Deconstruction, reclaim & reuse.

Straw construction has many advantages including being easy to design for disassembly, which ensures that materials and components do not become future waste and that they maintain their environmental and economic value.
Straw buildings are easy to extend and adapt to changed circumstances, and at end of life much can be re-used or re-cycled. Clay and lime plaster can be removed from the face of straw bales by mechanical means e.g. claw hammer end.

Straw Panels can be disassembled and re-used. EcoCocon panels have both an EPD and a Cradle to Cradle[80] certificate that take into account end of life - independent proof they are part of the circular economy. Lime plaster with no additives or paint can be crushed as aggregate for more lime plaster or limecrete and can also be used for tracks and pathways. Similarly clay plaster can be mixed again with water and re-used.

Further information and guidance on designing for deconstruction can be found in this paper by Alliance for Sustainable Building Products (ASBP):
https://asbp.org.uk/resource-report/designing-for-the-deconstruction-process (Accessed Sept 2020)

The table below shows the potential consideration for the principal materials in strawbale construction:

79 https://coppice-products.co.uk/

80 https://ecococon.eu/professionals/downloads; https://www.c2ccertified.org/get-certified/product-certification

Material	Technique for disassembly (in order of preference)	Potential value (in order of preference)
Untreated timber frame	Disassembly Demolition	Re-use Fuel for energy generation Landfill
Fixings, nails, screws	Remove, unscrew, set aside	Re-use Recycle material Landfill
Clay plaster without additives or paint	Chisel off	Re-use after re-mixing with water Direct deposit on the ground, possibly mixed with straw
Lime render or clay plaster with additives or paint	Chisel off	Landfill
Straw	Removal of whole bales Broken up bales	Re-use Agricultural use (soil improvement or bedding for animals) Horticultural mulch Fuel for energy generation

Fig 45 Extract from French Professional Rules, RFCP 2020

3.10 Indoor Air Quality & Covid Resilience

If strawbale building fabric qualities are going to perform at a sustainable optimum to maintain the inherent high standard of indoor air quality (IAQ) for health and well-being, materials that off-gas toxins, volatile organic compounds (VOCs), formaldehyde, particulates and other pollutants cannot be used. In these areas, health and wellbeing standards are being developed where strict sampling, research and testing protocols for performance verification are required as part of certification.
The most harmful ingredients and materials are already on several 'red lists' of proscribed materials and chemicals by global and UK organisations[81]

COVID-19 RESILIENCE

In 2021, designers are asking questions about how their work could reduce infection transmission and support infection control.

> "Poor indoor air quality is being brought into focus as it can amplify the effects of airborne viruses. Adequate ventilation – passive or mechanical, air filtration, humidity regulation and temperature control are key strategies that can be combined to improve indoor air quality and protect occupants. Clients and designers need to embed provision for user-control of these factors. The specification of

[81] https://resources.wellcertified.com/tools/performance-verification-guidebook/
Living Building Challenge: https://living-future.org/declare/declare-about/red-list/
Greenspec: https://www.greenspec.co.uk/building-design/red-list-of-banned-toxic-construction-materials/
Perkins and Will Precautionary List: https://transparency.perkinswill.com/lists/precautionary-list
SVHC Substances of Very High Concern under REACH regulations
SIN Substitute It Now List promoted by NGOs to REACH
SUBSPORT Substitution Portal under REACH Regulations

non-toxic, breathable and moisture-regulating materials and surface coatings such as lime and un-fired clay are a low-energy strategy to improve indoor air quality and long-term respiratory health"[82]

It's important to consider the effectiveness of anti-viral and anti-bacterial coatings and finishes. Some products have a very high environmental impact, such as high titanium oxide TiO_2 paint[83]

Anti-bacterial metal finishes such as copper and copper alloys (brasses, cupronickel, copper-nickel-zinc etc) stainless steel, silver can be specified instead of chemical coatings and finishes.[84]

Further research and guidance is required and will become available for all buildings, including straw and straw bale buildings.

3.11 Positive Provision for Nature

Bats

Bats should be encouraged to occupy roofs in preference to walls and provision for bat occupation in walls should ensure the integrity of the roof/wall thermal and acoustic performances are maintained. For initial guidance, refer to the BCT RSPB RIBA book 'Designing for Biodiversity' 2013[85]. It does not show straw bale construction; hemp-lime construction drawings are the closest to straw bale constructions in their simplicity though dimensions would need adjusting. Roof design should avoid using breather membranes as bats can get tangled in the fibres and die[86]. As an alternative, woodfibre sarking board can be used.

Birds

Nesting boxes can be built in or attached to buildings for swifts and other birds (different types of box for different birds). Large eaves/overhangs facilitate swallows nesting.

Biophilia

There is growing awareness of the need for design to link people more closely to nature. Many of the new environmental standards mentioned above require biophilic design. This can be achieved through use of natural lighting, increased daylight, natural ventilation, views of nature from windows, indoor plants, vegetable beds close by, indoor and outdoor water features, gardens and ivy that grows on outside walls, natural materials, natural colours, natural images.

82 Sloan Brittain, O.,Wood, H.,Kumar,P. Prioritising indoor air quality in building design can mitigate future airborne viral outbreaks, 2020

83 https://www.ecomerchant.co.uk/news/paint-human-health-and-the-environment/

84 Rosenberg,M., Ilic, K., Juganson,K., Ivask, A., Ahonen, M., Vrcek, I., Kahru, A. Potential ecotoxilogical effects of antimicrobial surface coatings: a literature survey backed up by analysis of market reports, 2019. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6375256/

85 https://www.bats.org.uk/resources/guidance-for-professionals/designing-for-biodiversity-a-technical-guide-for-new-and-existing-buildings

86 http://centaur.reading.ac.uk/33044/

Chapter 4 PLASTER, RENDER AND RAINSCREEN CLADDING

4.1 Introduction

Straw is a breathable and vapour permeable material and requires materials with the same properties to be used with it. Since clay and lime are also breathable and vapour permeable both can be used to coat straw walls. They are also air humidity regulators and help to keep indoor air quality healthy as long as they are not coated with impermeable materials, such as 'unbreathable' skin-forming paints – see more below.

- Clay (or earth) and lime are both suitable as an internal plaster.
- Lime is suitable as an external render.
- Clay plaster can be used outside if it is protected from direct rain e.g.by a veranda, or if it is stabilised, usually with lime, then limewashed.

They both maintain a degree of flexibility, allowing movement if walls flex, and clay can be re-worked over time. They can be locally repaired almost invisibly and at building end-of-life they can be separated from the straw for re-use - lime recycled as aggregate for lime plaster or used on roadways etc. or clay can harmlessly go back to the earth.

Modern (Portland) cement external renders and gypsum internal plasters are not suitable for strawbale construction as they are much less vapour open, do not regulate moisture and they are classed as rigid materials.

4.2 Lime render & plaster

For the purposes of this chapter we use the term plaster to describe both a render and a plaster, as a render is an external plaster and the same mixes are often used internally and externally.

Lime plasters contain lime as a binder with sand and/or recycled aggregates (e.g. glass, cork) and may also contain fibre (chopped hemp, straw, polyester fibres) depending on the purpose of the plaster.
Lime plasters are either made from pure lime (also called lime putty, fat lime, air lime) or from Hydraulic lime, categorised as, in increasing strength: NHL2, NHL3.5 NHL 5 (NHL is Natural Hydraulic Lime).

Within the pure limes, what is known as Hot Lime is made directly from quicklime rather than from lime putty. Within the hydraulic limes, they can be made from naturally occurring hydraulic limestone, in which case they are NHL manufactured products, or artificially from pure limes by adding a pozzolan (burnt clay).
All limes carbonate[87] after application and this needs to be managed carefully. In addition, hydraulic limes have a chemical 'set' which increases with the strength of the hydraulicity. It is generally accepted that only the weakest (NHL2) hydraulic limes should be used on strawbale buildings although opinions differ. The stronger hydraulic limes have reduced flexibility and breathability, but not so much as to resemble the properties of cement.

Manufactured products can be supplied in wet form ready-mixed as key coat, body coat and finish coat and also as lime putty, that requires the addition of other materials. Wet hot lime mixes are also available. Wet products are usually made from pure lime because the 'set' of the hydraulic limes means they have to be used quickly. Products can also be supplied in dry form including in silos on site (usually NHL2). Dry products are always hydraulic except for quicklime, some require the addition of other materials on site, others are pre-mixed with sand/aggregate and/or fibre and only require the addition of water.

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[87] Carbonation is the process whereby hydrated calcium oxide – lime putty or hydraulic limes - transforms to calcium carbonate in the presence of carbon dioxide in solution (usually from the surrounding air)

Traditionally fibre in lime plaster was cow hair, and hair is still available as an additive, usually Yak (from China) or goat (possibly from outside the UK). Other fibre options are chopped hemp (mixture of shiv and fibre, can be sourced from the UK although often from France) and polyester – although environmentally the use of this plastic additive is not recommended.

In general, the choice of lime type would be the same throughout for example all coats would use either lime putty, or hot lime, or NHL2, but this may not always be the case. For instance, sometimes a finish coat of NHL 2 or 3 may be specified if the lime has to be applied late in the year (after mid-September), or when there is the chance that appropriate protection will not be applied, or the build is in a zone with severe weather. Some practitioners are of the opinion that the added effect of the hydraulic set gives greater short term protection, whilst others are of the opinion that the pure limes are always superior and in adverse conditions a hot lime should/could be used.

In all cases, external lime plaster should be 30mm in total thickness to give the appropriate protection. External lime plasters will NOT give weather protection until they have carbonated, and plasters should be protected until this has happened. Carbonation cannot occur when temperatures fall below 5°C and as a rough guide, plaster requires a minimum of 3 months to carbonate sufficiently to provide appropriate winter protection. In cold winter months carbonation may take much longer than 3 months during which time the plaster is also susceptible to frost.

Harling[88] may be used as added protection in areas where adverse weather is common, especially in Scotland.

Possible specifications

These are not exhaustive but are examples of appropriate specifications. Measurements are by volume not by weight.

Lime putty plaster

Key coat: lime putty alone OR lime putty : sand 1:2

applied by hand or spray and rubbed well into the straw. Both of these options can be supplied as ready-mixed wet products and the latter can be mixed on site from raw materials

Dubbing coat**:** key coat: short chopped straw (100mm or less) 1: 1

or until all the straw is covered with key coat and adheres together. This is always mixed on site.

Body coat: Lime putty: sand : chopped hemp 1: 3: 1

This can be supplied as a ready-mixed wet product or mixed on site from raw materials.

Finish coat (if required): Lime putty: sand 1:3

This can be supplied as a ready-mixed wet product or mixed on site from raw materials

OR NHL3 : sand 1:3

This is usually supplied as a dry bagged product mixed with water on site.

Hydraulic lime plaster

Key Coat: NHL 2: sand 1:2

Body coat: NHL 2 : sand: fibre 1:3:1

Finish coat (if required): NHL2 or 3 : sand 1:3

All the above are supplied dry. Some product manufacturers ready-mix the lime and sand together before supplying, but it is usual to add the fibre at the time of mixing.

Hot lime plaster

Key coat: quicklime: sand 1:2

Body coat: quicklime: sand: fibre 1:3:1

Finish coat: quicklime: sand 1:3

All the above can be supplied wet as ready-mix or made on site from raw materials.

88 Harling, also called rough cast, is the application by throwing on of small stones into the wet body coat plaster to provide a much larger finished surface area that allows for faster evaporation after rain.

Since quicklime bulks up with the addition of water, the hot lime mixes are twice as lime rich as the other types of plaster, but if made on site are more cost effective.

Some practitioners do not use a key coat as such but add small amounts of extra water and/or lime to the body coat and apply directly to the straw.
The body (second) coat can be applied up to 25-30 mm thick or in two coats of 10-15mm. Lime plaster on straw is able to carbonate from the back as well as the surface due to the air trapped in the straw itself, therefore a thicker coat than usual can be applied.
The finish (top) coat is usually applied 3-5mm thick. This can include colours and decorative additives. Finish coats are not always required as a good quality body coat can be rubbed up to give the required finish.

Application[89] can be done by hand, with tools - usually wood and plastic floats rather than steel, or by spray. The straw should not be damped down before application but a light misting should be applied to each plaster surface before applying the next lime coat. Finishes can be smooth (floated), textured (using sponge floats) or harled (thrown on small stones into the wet plaster).

There are many types of lime plaster available in the UK including manufactured products and raw materials from which plasters can be made. There are different opinions amongst practitioners and manufacturers about the exact mix and type of lime to use and so it is recommended to take advice from a practitioner with experience of using lime plaster on straw, and to follow advice from the Building Limes Forum[90] see appendices for more information.

Mesh and fibre reinforcement
Mesh and fibre are used as reinforcement and to prevent cracking. Usually, mesh is not specified in a body coat as the fibre suffices but is usually specified at 300mm width around windows and doors with at least 100mm overlap between joins, laid into the wet body coat. 8mm mesh should be used and ideally be of jute, although fibreglass may be specified by manufacturers for use with their products. Practitioners may use extra fibre at these more vulnerable places instead of mesh. Short chopped fibre - 12-25mm - is more effective than longer fibres.

When plastering over different materials placed close together for example straw next to woodfibre board, mesh should be used to cover all joints by a minimum of 100mm either side into the wet plaster.
When plastering onto backgrounds that are not straw walls for example woodfibre board or other smooth boards with less suction/grip a lime product made specifically for use on such boards should be used with a mesh into the wet plaster followed by a finish coat so the overall build up is no more than 10mm.

After care of lime plasters is essential. The key coat may take 24 -48 hours to carbonate ready for the body coat. Body coat plasters should take a few days to become green hard (the point at which a thumbnail cannot be impressed into the plaster). During these first days any cracks that develop in the body coat should be rubbed in and the atmosphere around the lime must be kept humid. Lime needs to absorb carbon dioxide from the air in order to carbonate, but can only take it in if it is in solution, hence the need to keep a humid atmosphere around the fresh lime at all times. This is usually done by hanging hessian on the scaffolding or from the eaves and keeping this damp, but can also be done by regular misting of the air around the plaster. The plaster must be protected from frost, direct sun, rain and excessive wind for a minimum of 3 weeks after the final coat is applied, possibly longer depending on weather conditions.
Lime plaster should not be applied externally if temperatures are 5°C or below and should not be applied if there is risk of frost for the subsequent 3 months. Generally, this means no application between mid-September and the end of April. If it is applied outside of these times, extra protection will be needed, and for longer periods of time.

[89] See Ch 15 of Building with Straw Bales by Barbara Jones for application techniques
[90] www.buildinglimesforum.org.uk

Potential Problems
Excessive cracking in body or finish coat – usually due to excess water being added at plastering stage. This is a common problem when practitioners used to working with cement/gypsum transfer to using lime without enough knowledge/skill. It is common to add water to cement/gypsum plasters to improve workability. In limes, water has a different function, it is the medium whereby carbon dioxide is transported into the plaster and it evaporates during carbonation – causing cracking – if too much is added.
Dusty surface– this is usually caused by lack of appropriate after care, when the plaster dries out too quickly for carbonation to occur. It can also be caused by excessive use of steel floats, that bring the lime binder to the surface, hence most practitioners use wood or plastic.
Crumbling sections, possibly several months after application – this is likely to be frost damage caused by applying plaster when conditions are too cold, and/or by insufficient protection.

4.3 Clay Plaster

Clay plasters are a mixture of pure clay subsoil, sand/aggregates and some natural form of fibre, with clay acting as the binder. If ready-mix products are not being used, then clay subsoil must be tested to determine the appropriate ratio of clay/sand/fibre to use, because subsoils are not always pure clay, and different clays have different properties. Clay absorbs moisture slowly, so clay plasters should be allowed to sit before use to allow this to happen. One day is the minimum but 1 week is preferable.
There is no 'set and hardening' time, clay just dries, so time before use is not a critical factor. If ready-mixed products or pre-mixed clay plasters dry out, then more water can be added. This also means that there should be very little waste, as excess or dropped plaster can be added back to the mix.
Clay plasters can be supplied as ready-mixed products, or as raw materials such as dry 'milled clay' from a brickworks, wet dug clay from a local site, together with sand and chopped straw fibre.

Plaster specifications
Ratios cannot be specified exactly as different clays have different properties. Manufacturers use their own tested recipes, practitioners must determine the correct proportions from raw materials by carrying out a series of physical tests. The proportion of clay to sand is usually within the region of 1: 3-6. The proportion of fibre is usually the same as that of clay, by volume.
Specifiers should either specify a product, or a methodology by which the plaster can be tested[91].

Key coat or slip coat[92]: pure clay slip or clay: sand 1:2
Body coat: clay: sand: chopped fibre.
Finish coat: clay: sand

Clay plasters can be made by manufacturers and practitioners from dug clay, dry milled clay or from clay slip. The body coat is between 25 and 50mm thick and can be applied in one coat if the mix is fibrous and not too wet, or in two or three.
A finish coat is not always specified as a good quality body coat can be rubbed up to provide a finish. Where specified it is between 5 and 10mm thick.
Clay adheres by gripping onto the substrate to which it is applied. The straw should not be wetted before applying slip, and the slip should be rubbed well into the straw leaving a rough surface. Thereafter, each layer should be roughened/scratched if another is to be applied and misted before the next application such that the surface becomes tacky but not liquid.

Mesh and straw fibre reinforcement
See section on lime
Aftercare
Clay plasters dry, they do not have a chemical set. They should not be exposed to direct water during the drying process or thereafter. Drying is usually achieved with natural ventilation and IT IS COMMON for a white

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[91] See Ch 16 Building with Straw Bales by Barbara Jones
[92] A slip is a mix of pure or almost pure clay with water added so that it pours like a thick cream

fuzz of mould to appear during the drying process. This is not problematic or harmful and will disappear or can be wiped off as the plaster dries further. Clay plasters will not dry when there is no air movement and/or low temperatures. Plasters applied during the winter months may not dry until the following May unless artificial methods of drying are used. These methods include constant low heat, fans to create air movement and the opening of windows when there is sun (low humidity) outside.

4.4 Paint finishes for lime and clay

Straw walls and lime and clay plasters are breathable,[93] vapour permeable and non-skin forming so the paints and finishes used on them need to have the same qualities in order to maintain the wall's integrity. The majority of modern internal and external paints are comprised of pigments, binders and solvents from petrochemical origins and if they have any vapour permeability, it is not enough. On top of this they are a large source of VOCs into the indoor atmosphere, therefore they should not be used.

An extensive range of breathable lime, clay, mineral and natural paints is now widely available for internal and external use (clay paints would not be used externally). Water-based paints and washes include lime washes, clay, lime and earth paints and emulsions. and may contain mineral pigments. Usually 4 coats of lime wash would be specified externally after initial plastering, Some lime paint is now supplied dry to be mixed up on-site, which is much better environmentally so as not to transport the water content.

Active silicate paints can be used instead of lime or clay paints on a lime plaster. They have a much longer life before needing to be re-coated, typically 15 years, although are more expensive. Active silicate paints work by binding to the silica in the sand of the plaster and have a much more uniform appearance than the lime washes or paints. A primer coat is applied first, followed by the colour coat.
Natural oil based paints are recommended for timber, or simply pure linseed oil or similar.

Clay plasters may be 'sealed' with linseed oil, or with a proprietary product to prevent dusting and allow for wiping down if needed in kitchens and bathrooms for instance. Some of the lime paints can also be wiped down.

4.5 Rainscreen cladding or ventilated facade

Ventilated rainscreen cladding can be specified for strawbale buildings usually in timber but also other materials to achieve a wide range of design and aesthetic finishes, and in cases of high exposure, contribute to greater weather protection.
The detail for ventilated rainscreen cladding requires the strawbale wall to be covered with a single 9-12mm parge coat of lime or clay plaster, well worked into the straw for a strong bond and levelled to receive battens. The cladding support battens can be applied over the plaster coat fixing to the ringbeams and/or through the plaster coat into timber plugs embedded in the straw behind, or to framing. All air inlets must be covered effectively with rodent-proof mesh.

Fig 46 Steel frame with straw infill warehouse Photo:Barbara JonesTimber clad house Photo: Simon Maxwell

[93] See Briefing Papers from the ASBP in appendices

CHAPTER 5 DESIGN

5.1 Recommended details

Designs have been refined and improved over the last 25 years and many are available in this open resource here
https://strawworks.co.uk/resources/technical-details/

- Plinth wall foundation with limecrete floor pdf
- Plinth wall foundation with suspended timber floor pdf
- Rammed car tyre foundations with suspended timber floor pdf
- Door details with solid floor pdf
- Door details with structural box and timber floor pdf
- Window details pdf
- Truth Window pdf
- Eaves detail single ply and green roof pdf
- Verge detail single ply and green roof pdf
- Eaves detail cedar shingles with truss rafter overhang pdf
- Floor plate structural box beam details (stacked timbers) pdf
- Floor plate structural box beam details (solid timbers) pdf
- Floor plate structural box beam details with timber i-joists pdf
- Ground floor baseplate (on masonry plinth) pdf
- Baseplate on timber box ring beam (GF or above) pdf
- Baseplate details (curved strawbale walls) pdf
- Roofplate details pdf
- Roofplate details (curved strawbale walls) pdf

5.2 Designing with bales

Ideally the dimensions of the bales to be used for construction should be known from the start in order to begin sketch designs that will work through to construction where they will be employed on site, but this is not always possible.

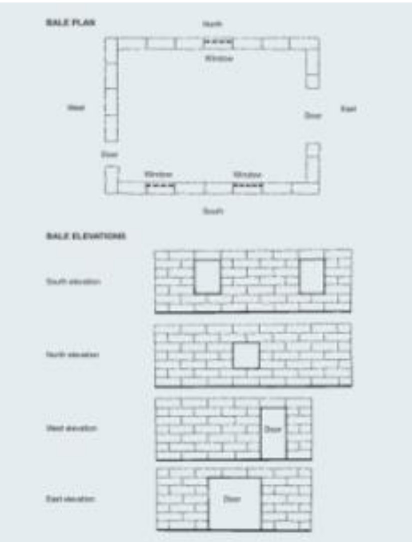



Fig 47 Building with Straw Bales: A practical manual for self-builders and Architects, Barbara Jones, 2015

Key points:

- Designers should use nominal bale sizes of 1m length x 450mm width x 345mm (compressed) height for CAD drawings unless actual bale sizes are known
- In loadbearing designs for example a wall of length 9.15m should be drawn to scale but divided into 9 equal parts to represent bales. A wall of 5.42m should be drawn to scale and show one bale placed round the corner (450mm) and the rest of the length divided into 5 equal parts – practitioners should know how to adapt actual bale sizes for use on site.
- Designs should show bales *after* compression but the designer must understand how compression will be achieved and design it in[94].
- Compression can be achieved by the use of ratchet straps to pull the wall plate and straw down, or by hydraulic jacks to push the wallplate/straw walls down from a fixed point - the roof or a beam above.
- Ratchet straps should be able to create a load of at least 5 tonnes and be located either side of corners, half a bale length away from openings, and then at spacings of no more than 1.2m.
- Infill designs also need to compress the straw. This is often done by placing a metal plate on the penultimate bales and a hydraulic jack on top. The bales below are then compressed down from the beam above and the final bale is inserted into the gap before the jack is removed. The plate should have rope attached as the compressive force can make it difficult to remove it otherwise.
- On average for a construction grade bale there will be no more than 10mm of compression per bale. If the bales are less dense then there will be more compression. An experienced practitioner should know how to deal with any differences to achieve the head heights required.
- Woven Polyester strapping can be used to take the strain after compression has been achieved. This should be 19mm wide with a breaking strain of at least 550kg, used with metal buckles. Straps should be placed at the same intervals as ratchets. Where possible these should be removed just before plastering. In some cases due to excessive wind loads they will need to be retained.
- Structural timber sizes for the box beam on pillar foundations in practice is usually determined by the need for adequate insulation. This will mean using timber depths of 250-300mm which is usually greater than structural engineering requires.
- Structural timber sizes for wall plates and other ring beams will be determined by the number and size of openings below. Where openings are limited to 900mm then timber of depth 150mm is usually adequate. Where openings are greater than this, timber sizes may need to be 200 -250mm in depth. For larger openings it is advisable to use localised flitch beams rather than increase the depth of the wall plate overall.
- In load bearing strawbale construction half bales should only be located beside openings and openings should not be less than 1 bale length from corners. Other designs are possible but these would be classed as hybrids.
- Walls between openings should be no less than one bale wide unless framed with timber.
- Structural openings and distance between framing posts should correspond to bale sizes as far as possible to avoid extra customising and waste.
- In framing techniques the location of the top beam should correspond to a whole number of *compressed* bales between the beam and the baseplate

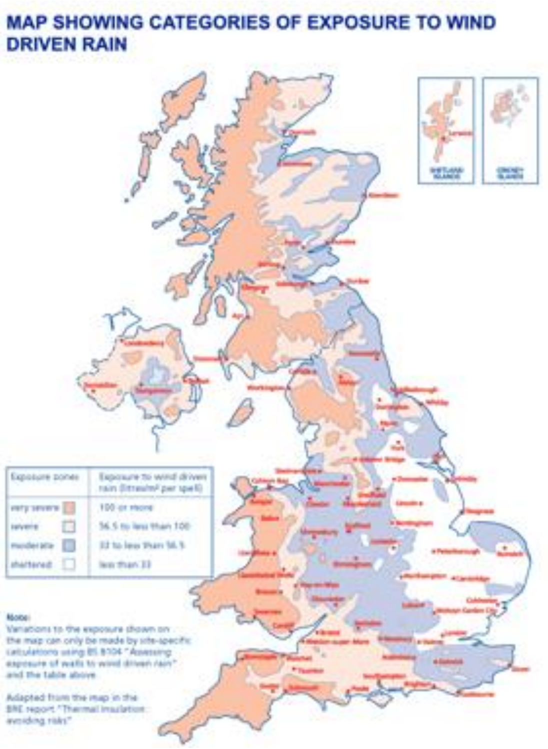
[94] See Ch.13 of 'Building with Straw Bales: A practical manual for self-builders and Architects' by Barbara Jones, 2015.

5.3 Weather protection

Design for a good Hat, a good pair of Boots and a good Overcoat. This means ideally an overhang of 450mm, plinth/stem wall of 300 – 450mm, 30mm lime plaster, rainscreen cladding or ventilated facade[95]
The following suggestions are suitable for all designs, not just those built of straw. Climate change means that we need to pay more attention to weatherproofing and flood resilience as monsoon-type rainfall is now occurring in the UK and areas that have not flooded in the past are experiencing problems now.

- Limit exposure to rain, wind-driven rain and snow – see the NHBC exposure map below. In areas of high exposure from one particular side, the building can be designed so that all or part of one façade can be protected by building elements such as large eaves overhang, balconies, a covered veranda or walkway, etc. BS8104 can be used to calculate the exposure considering local conditions.
- Coupled with a plinth wall, design paving to be permeable or provide perimeter filter drains, with a gravel top to disturb rainwater splash-back and avoid ponding. Non-permeable paving should have good surface water drainage away from the building around the building perimeter. Textured paving will minimise and disrupt splash back.
- Use of pillar type foundations such as rammed car tyres provides future proofing against flooding as flood waters can flow harmlessly underneath.
- Specify brown (self- vegetating), green (planted) or blue (storage of rainwater) roofs to store and slowly release rainwater. Alternatively design in rainwater storage for domestic or garden use and help prevent local flooding at times of high rainfall.
- Good-sized gutters and ideally 2 downpipes per gutter to deal with heavy downpours without risk of overflow are becoming more important due to climate change.
- Avoid outdoor taps located against the building. Any waste pipe or outdoor tap gullies should have a high rear upstand to limit effects of splash-back.

[95] More detailed guidance is provided in 'Building with Straw Bales: A practical manual for self-builders and Architects' by Barbara Jones, 2015.



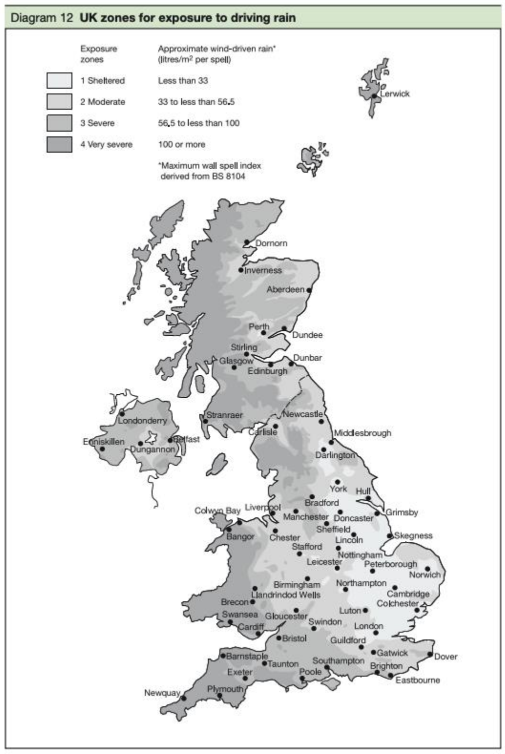


Fig 48 NHBC Standards 2010 Appendix 6.1B

Fig 49 Approved Document C Site Preparation and resistance to contaminants and moisture

5.4 Thermal Bridges & breaks

Thermal bridges are often colloquially called cold bridges, as they amount to colder spots on the inside surface of a building. These cold spots can become condensation risks - the colder temperatures can cause moisture vapour to condense. If this is sustained it can lead to mould growth, which in turn reduces the internal air quality through release of spores. This risk is limited in straw buildings due to the ability of natural fibres to bind water in a dry state. Coupled with appropriate lime or clay plasters these deal with high relative humidity in the surrounding air.

Thermal bridges occur:

- anywhere a less-insulating material forms a path from the inside to the outside of a structure, e.g. timber or steel framing (material thermal bridges).

- anywhere where the external surface area is greater than the internal, e.g. the corners of a building (geometric thermal bridge).

- anywhere else there is an increase in the area through which heat can be conducted to the outside (e.g. at a window or door reveals) (geometric thermal bridges).

Generally, any junction between two or more different building elements or planes is a potential thermal bridge. Without careful design geometric and material thermal bridges can occur together – commonly at window reveals (especially at sills and lintels), floor-wall junctions, and roof-wall junctions.

As the level of insulation increases, the relative percentage of heat loss caused by thermal bridging also increases - making it particularly important to avoid in low energy buildings. They can be avoided by careful design of building junctions.

Basic principles to avoid thermal bridging:

- ensure a continuous insulation layer between internal and external environments
- design out any penetrations to that layer, and ensure insulation covers any non-insulating structural framing
- where windows or doors are fixed to non-insulating materials which bridge the insulation layer (e.g. timber or masonry) ensure the reveals are insulated inside and/or outside
- where possible extend insulation internally and externally onto the face of window and door frames.
- Thermally separate balcony and roof overhang structures from building or internal environments (ensure a layer of insulation separates them)

Fig 50 below shows possible timber structure positions within a strawbale wall (in a horizontal cross section). Positions *a* and *b* will result only in negligible thermal bridging – in both around two-thirds of the wall thickness consists of insulation. In positions *c, d* and *e* the insulation layer is physically bridged by the timbers to differing degrees, with *c* resulting in the greatest thermal bridging (and the greatest additional heat loss). Thermal bridging through *c*, *d* and *e* could be reduced by the addition of further insulation on the outside face of the wall.

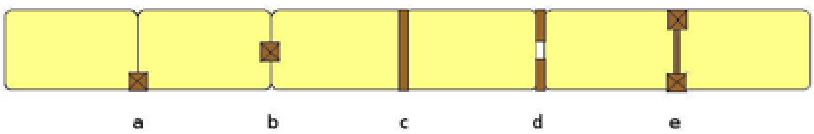


Fig 50 Cross section diagram showing different positions of timber structure in straw bales: a - internal timber stud, b - central timber stud, c - continuous timber called plank frame, d - internal and external timber (Larsen), e – I-Joists I-stud
Hemke, 2009: Investigation of the thermal continuity in straw bale construction using Thermography, Technische Universitat Berlin

The BaleHaus developed at Bath University used type C construction in prefabricated panels and gave the following thermal image results

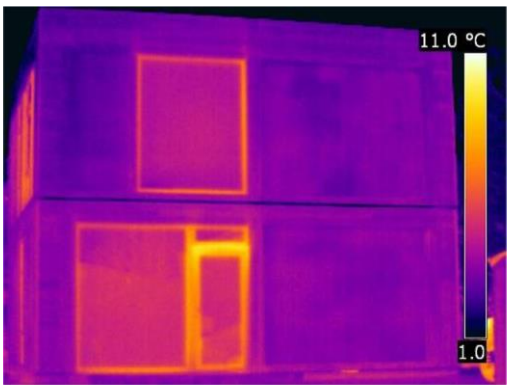
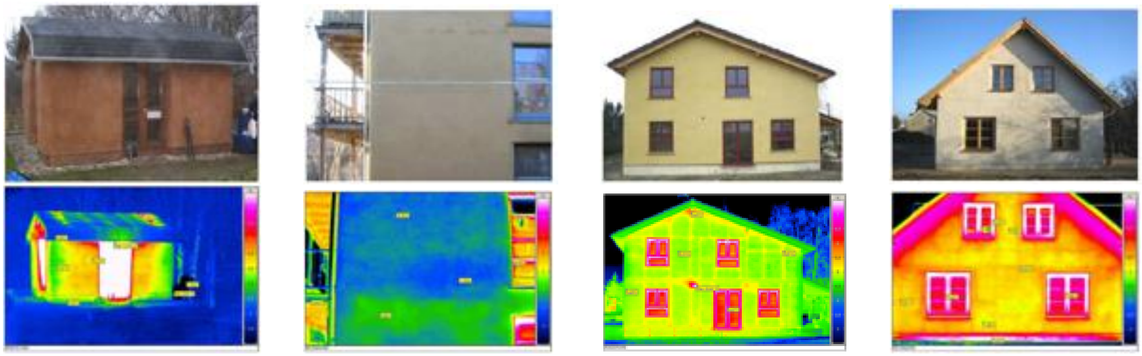


Fig 51 Airtightness test, BaleHaus, University of Bath, 2009 Photos Peter Walker Thermal Camera Image of BaleHaus East facade, University of Bath, 2010

Below are thermographic images for four different construction types:



Load bearing – no frame Internal timber stud (a) Plank frame (c) I-joist (e)

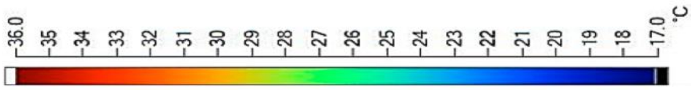
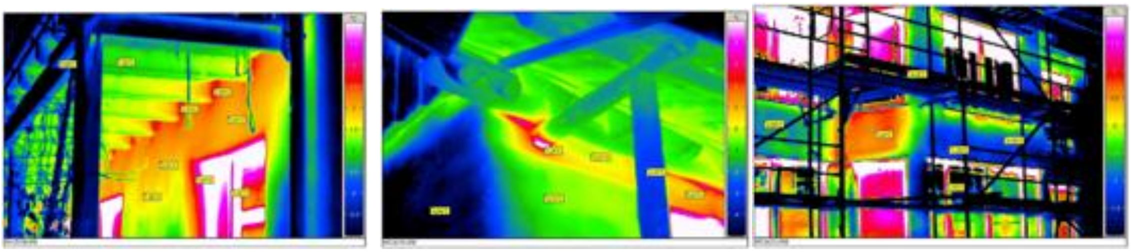


Fig 52 Hemke, 2009: Investigation of the thermal continuity in straw bale construction using Thermography, Technische Universitat Berlin

Fig 52 shows thermal images of different straw constructions. The different colours represent different levels of heat flow from inside to outside, with pink showing greatest heat loss and green or blue the lowest. The most continuous insulation is shown in the load-bearing and internal timber stud constructions above. However, in plank frame and i-joist construction, the timber is transmitting heat through the whole wall from inside to outside and the higher temperature clearly shows as the pattern of the frames in thermographic images.

The study also took comparative images where detailing was not thermal bridge-free at structural elements passing through walls for a continuous balcony, continuous rafters and the complexity of thermal continuity in bay window construction (figure 15). In the lefthand and central images the pink glow where rafters and joists penetrate the straw insulation layer shows heat being conducted along the timbers. Balcony construction should be thermally separated from the internal structure (e.g. supported externally). Similarly supports for roof overhangs should be carefully designed to avoid any continuous structure bridging the insulation layer. In the right hand images the orange blush on the left of the bay window shows where the insulation is thinner, resulting in increased heatloss. It is important to keep a consistent thickness of insulation throughout – any thinner areas will cause greater heatloss, with cooler internal surface temperatures.



Balcony joists with no thermal break Continuous rafters to overhang Bay window with side panels of thinner insulation, and thermal bridges at window head and cill details

Fig 53 Hemke, 2009: Investigation of the thermal continuity in straw bale construction using Thermography, Technische Universitat Berlin

5.5 Setting design targets

The harsh truth is that current design practices and building regulation legal minimums are woefully insufficient in the face of the climate change emergency and the crisis in health and well-being in buildings.

The UN has drawn up 17 Sustainable Development Goals

Fig 54 UN Sustainable Development Goals

Several organisations have developed their own standards, some such as RIBA based particularly on the UN goals. They have drawn out headline targets for designers which are set out in the RIBA Climate Challenge 2030 V2 (referenced November 2021)[96].

2030 targets should be the only design targets we use otherwise new builds will need to be refurbished between now and 2030. The UK already has 27m homes that need refurbishing.

96 https://www.architecture.com/about/policy/climate-action/2030-climate-challenge

Some of these targets are still not far-reaching enough for experienced and aspiring low energy and Passivhaus practitioners; strawbale buildings can and have achieved much better results. Other targets and standards are available and have now become achievable at little or no extra cost.

RIBA 2030 Climate Challenge is made up of these targets:

RIBA Sustainable Outcome Metrics	Business as Usual	2025 Targets	2030 Targets	Notes
Operational Energy $kWh/m^2/y$	120 $kWh/m^2/y$	< 60 $kWh/m^2/y$	< 35 $kWh/m^2/y$	Targets based on GIA. Figures include regulated & unregulated energy consumption irrespective of source (grid/renewables). BAU based on median all electric across housing typologies in CIBSE benchmarking tool. 1. Use a 'Fabric First' approach 2. Minimise energy demand. Use efficient services and low carbon heat 3. Maximise onsite renewables
Embodied Carbon $kgCO_2e/m^2$	1200 $kgCO_2e/m^2$	< 800 $kgCO_2e/m^2$	< 625 $kgCO_2e/m^2$	Use RICS Whole Life Carbon (modules A1-A5, B1-B5, C1-C4 incl sequestration). Analysis should include minimum of 95% of cost, include substructure, superstructure, finishes, fixed FF&E, building services and associated refrigerant leakage. 1. Whole Life Carbon Analysis 2. Use circular economy strategies 3. Minimise offsetting and use as last resort (accredited and verifiable) BAU aligned with LETI band E; 2025 target aligned with LETI band C and 2030 target aligned with LETI band B.
Potable Water Use Litres/person/day	125 l/p/day (Building Regulations England and Wales)	< 95 l/p/day	< 75 l/p/day	CIBSE Guide G.

Fig 55 RIBA Domestic/Residential Targets

RIBA Sustainable Outcome Metrics	Business as Usual	2025 Targets	2030 Targets	Notes
Operational Energy $kWh/m^2/y$	145 $kWh/m^2/y$	< 70 $kWh/m^2/y$	< 60 $kWh/m^2/y$	Targets based on GIA. Figures include regulated & unregulated energy consumption irrespective of source (grid/renewables). Refer to Department for Education Output Specifications for schools: 2025: Primary <55 $kWh/m^2/y$, 2030: Primary <45 $kWh/m^2/y$ 1. Use a 'Fabric First' approach 2. Minimise energy demand. Use efficient services and low carbon heat 3. Maximise onsite renewables
Embodied Carbon $kgCO_2e/m^2$	1000 $kgCO_2e/m^2$	< 675$kgCO_2e/m^2$	< 540 $kgCO_2e/m^2$	Use RICS Whole Life Carbon (modules A1-A5, B1-B5, C1-C4 incl sequestration). Analysis should include minimum of 95% of cost, include substructure, superstructure, finishes, fixed FF&E, building services and associated refrigerant leakage. 1. Whole Life Carbon Analysis 2. Use circular economy strategies 3. Minimise offsetting and use as last resort (accredited and verifiable) BAU aligned with LETI band E; 2025 target aligned with LETI band C and 2030 target aligned with LETI band B.
Potable Water Use m^3/pupil/year	4.5 m^3/pupil/y	< 1.5 m^3/pupil/y	< 0.5 m^3/pupil/y	Refer to Department for Education Output Specifications for schools.

Fig 56 RIBA Non-Domestic/Schools Targets

RIBA Sustainable Outcome Metrics	Business as Usual	2025 Targets	2030 Targets	Notes
Operational Energy kWh/m^2/y	130 kWh/m^2/y DEC D (90)	< 75 kWh/m^2/y DEC B (50) and/or NABERS Base build 5	< 55 kWh/m^2/y DEC B (40) and/or NABERS Base build 6	Targets based on GIA. Figures include regulated & unregulated energy consumption irrespective of source (grid/renewables). 1. Use a 'Fabric First' approach 2. Minimise energy demand. Use efficient services and low carbon heat 3. Maximise onsite renewables
Embodied Carbon $kgCO_2e/m^2$	1400 $kgCO_2e/m^2$	< 970 $kgCO_2e/m^2$	< 750 $kgCO_2e/m^2$	Use RICS Whole Life Carbon (modules A1-A5, B1-B5, C1-C4 incl sequestration). Analysis should include minimum of 95% of cost, include substructure, superstructure, finishes, fixed FF&E, building services and associated refrigerant leakage. 1. Whole Life Carbon Analysis 2. Use circular economy strategies 3. Minimise offsetting and use as last resort (accredited and verifiable) BAU aligned with LETI band E; 2025 target aligned with LETI band C and 2030 target aligned with LETI band B.
Potable Water Use Litres/person/day	16 l/p/day (CIRA W11 benchmark)	< 13 l/p/day	< 10 l/p/day	CIBSE Guide G.

Fig 57 RIBA Non-Domestic/Offices Targets

Non-Domestic (new build office):
Operational Energy 90 kWh/m^2/y (GIA) and/or DEC C(65) and/or NABERS Base build 5;
Embodied Carbon LETI Band D 1180 $kgCO_2e/ m^2$;
Potable Water Use 16 l/p/day

Non-Domestic (schools):
Operational Energy 75 kWh/m^2/y (GIA);
Embodied Carbon LETI Band D 870 $kgCO_2e/m^2$;
Potable Water Use 3m^3/pupil/year

Domestic/Residential:
Operational Energy 60 kWh/m^2/y (GIA) no gas boilers;
Embodied Carbon LETI Band D 1000 $kgCO_2e/m^2$;
Potable Water Use 110 l/p/day

Fig 58 Current Good Practice (RIBA)

AECB Building Standards

Parameter	Target	Notes
Delivered Heat and cooling	≤ 40kWh/(m².a)	According to the methodology described in the PHPP* handbook.
Primary Energy (P.E.)	Varies kWh/(m².a)****	As per PHPP for each country
Primary Energy Renewable (P.E.R)	⩽ 75 kWh/(m².a)	ditto
Air tightness (n50)	≤ 1.5 h^{-1} (≤ 3 h^{-1})	With MVHR (with MEV) **
Thermal Bridges ***	Psiexternal <0.01 W/mK	Calculated if > 0.01 W/mK
Summer overheating	<10%	<5% recommended

Fig 59 AECB Building Standards https://www.aecb.net/aecb-building-certification/

Appliance	Best Practice Requirement – as Good Practice plus:
Showers	≤ 6 l/min plus Good Practice fitting provided for use if required.
Basin and bidet taps (domestic)	≤ 4 l/min with reduced diameter aerator or spray to maintain force of water stream. Single lever mixer taps shall incorporate a water brake or equivalent to encourage a lower default flow rate. A Good Practice outlet fitting must be provided for use if required.
Basin taps (washroom)	As Good Practice. Dead leg ≤ 0.25 litre
Kitchen sink taps	≤ 6 l/min, single lever taps should be fitted with a water brake or some other means of ensuring that default flow is lower. A Good Practice outlet fitting must be provided for retrofit if required.
White Goods	Best energy class available, see Energy Standards for details.
WCs	≤ 4.5 l full flush when flushed with the water supply connected. As Good Practice for other requirements.
Urinals	As Good Practice.
Baths	As Good Practice.
Dead legs	≤ 0.85 litres. (Lower flow rates will permit smaller bore pipework). Baths exempt from dead leg requirement unless the bath filler also feeds a shower.
Dead legs off secondary circulation	≤ 0.25 litres. Where installed in a house, secondary circulation pump is to be controlled by a run on timer to be initiated by a flow switch, presence detection or a manual switch. For flats, hotels, schools and the like, an evaluation of options such as continuous circulation and local hot water generation or storage shall be made. The most appropriate solution will depend on patterns of use, distance between fittings and the nature of the energy source.
Water softeners	As Good Practice.
Water metering, pressure regulation and leak detection	A separate water meter is required on the hot water cold feed to provide an indication of hot water use.
Outdoor	As Good Practice. Garden planting schemes in areas of moderate or severe water stress (as defined by the Environment Agency) shall be designed to avoid the need for mains or borehole water, except in the case of edible crops.

Fig 60 AECB Water Standards Summary https://www.aecb.net/aecb-water-standard/

The table below shows the Daylight Factors required by the AECB Standard and other standards.

Target Daylight Factor				
Room Type	**AECB Standard**	**HQM**	**BREEAM**	**BS:8206**
**** DWELLINGS/MULTI-RES ****				
Kitchen	> 2	> 2	> 2	> 2
Utility	> 2			
Living Room	> 1.5	> 1.5, > 1.8, > 2.0	> 2	> 1.5
Dining	> 1.5	> 1.5, > 1.8, > 2.0	> 2	
Study/Office	> 1.5	> 1.5, > 1.8, > 2.0	> 2	
Bedroom	> 1			> 1
Bathroom (guideline only)	> 1			
MULTI-RES: Non-residential spaces	> 2		> 2	
MULTI-RES: Communal occupied spaces	> 2		> 2	
**** EDUCATION ****				
Preschools	> 2		> 2	
Schools	> 2		> 2	
Further education	> 2		> 2	
Higher education-	> 2		> 2	
occupied spaces	> 2		> 2	
**** HEALTHCARE ****				
Staff and public areas	> 2		> 2	
Occupied patient's areas (dayrooms, wards)	> 3		> 3	
Consulting rooms	> 3		> 3	
**** RETAIL ****				
Sales areas	-		-	
Other occupied areas	> 2		> 2	
**** OTHER BUILDINGS: Courts, Industrial, Office, Prison buildings etc.**				
Cells and custody cells	> 1.5		> 1.5	
Internal association or atrium area	> 3		> 3	
Patient care spaces	> 3		> 3	
Teaching, lecture and seminar spaces	> 2		> 2	
All occupied spaces, unless indicated	> 2		> 2	

Fig 61 AECB Daylight Standard Summary https://www.aecb.net/aecb-daylight-standard/

Performance targets for a European climate

	Passivhaus	EnerPHit
Primary energy demand	≤ 120 kWh/m^2. yr	≤ 120 kWh/m^2. yr + heat load factor
Space heating demand	≤ 15 kWh/m^2. yr	≤ 25 kWh/m^2. yr
Space cooling demand	≤ 15 kWh/m^2. yr	≤ 25 kWh/m^2. yr
Specific cooling load	≤ 10 W/m^2	≤ 10 W/m^2
Airtightness	≤ 0.6 air changes/ hr @ n50	≤ 1.0 air changes/ hr @ n50

Fig 62 Passivhaus performance targets https://www.passivhaustrust.org.uk/what_is_passivhaus.php#2

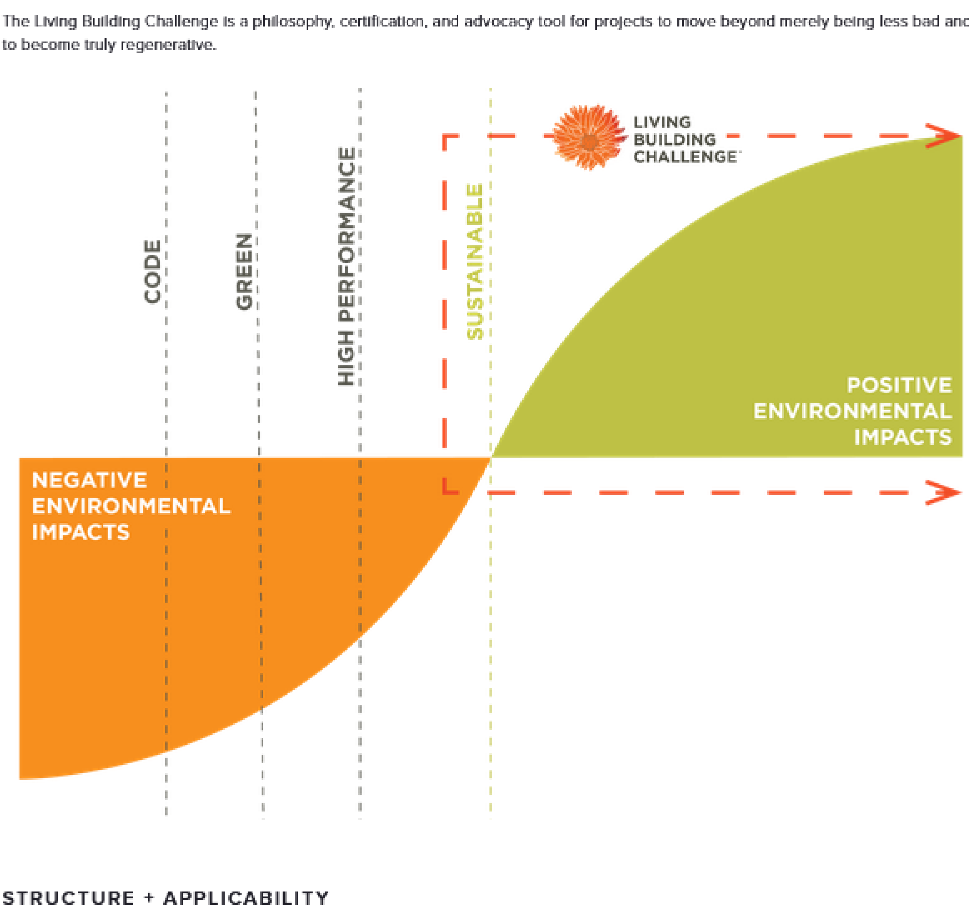


Fig 63 Living Building Challenge https://living-future.org/lbc/basics4-0/

5.6 Building information management/modelling (BIM)

12 BIM objects have been created in SketchUp, ArchiCAD and Revit formats as part of the Up Straw Interreg project, see below, most designs based on French techniques. In the UK design no.4 & 7 are not recommended due to thermal bridging see the research cited on p.68 of this document

1. SBW-01 Straw bale infill wall with simple timber frame wall, timber structure towards outside
2. SBW-02 Straw bale infill wall with simple timber frame wall, timber structure towards inside
3. SBW-03 Straw bale infill wall with double timber frame
4. SBW-04 Straw bale infill wall with i-joists
5. SBW-05 Straw bale infill wall with a non-load-bearing central light timber frame
6. SBW-06 Straw bale infill wall with glue-laminated timber frame
7. SBW-07 Straw bale infill wall with Larsen truss timber frame
8. SBW-08 Load-bearing straw bale wall with small bales
9. SBW-09 Load-bearing straw bale wall with large bales, with lime external render and interior plaster
10. SBR-10 Load-bearing straw bale roof with small bales
11. SBR-11 Roof with straw bale insulation infill between timber structure (not discussed in this guide)
12. SBR-12 Roof terrace/flat roof with straw bale insulation and ventilated deck (not discussed in this guide)

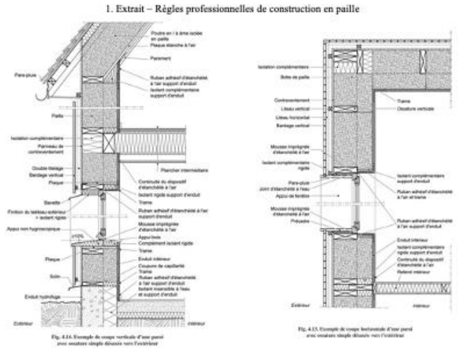
Cocon BIM

Cocon-bim - Eosphere, 45 les Coteaux de Marras, 31650 Lauzerville
www.cocon-bim.com

I.A.1 Elément constructif : SBW_01 - OssSimpleDesaxExt

R. thermique (m2.K/W) : 7,8 Déphasage Δt (h) : 17,80 Chaleur transmise vers l'intérieur (%) : 0,95 Inertie quotidienne kJ/(m².K) : 40 Inertie séquentielle 12 jours - kJ/(m².K): 476 Vol. produits biosourcés (m3/m²) : 0,39	U.	Qté.	λ	M. vol.	Capacité thermique	Poids	Q. air	MU	GES (GWP)	E. Grise (PENRT)	Id. Inies	Sources	Matériau
			W/m°C	kg/m3	Wh/kg.K	kg/m²			kg. eq. CO2	MJ			
1. Bardage	mm	17	0,130	600,0	0,75	10,78			+0,97	+99,00	4112-1.1	DEP vérifiée	Bardage douglas non traité pour un usage de classes 2 et 3
2. lame d'air ventilée	mm	54	0,192	1,3	0,28	0,06		1	+0,00	+0,00	0000-1,0		Lame d'air ventilée
7. Contre - liteaux	__x__x__	2000x40x27	0,120	490,0	0,44	1,06			+0,11	+11,38	10604-1.2	DEP vérifiée	Bois d'ossature en Douglas sans traitement de préservation
8. Liteaux	__x__x__	2000x40x27	0,120	490,0	0,44	1,06			+0,11	+11,38	10604-1.2	DEP vérifiée	Bois d'ossature en Douglas sans traitement de préservation
3. Pare pluie	m2	1.0	2,300	700,0	0,64	0,22			+1,99	+54,72	7990-1.1	MDEGD	Pare-pluie en polypropylène - DED
4. Contreventement	mm	12	0,250	864,0	0,28	10,37	A+		+2,76	+53,18	12273-1.2	DEP vérifiée	Plaque de plâtre - pare-pluie rigide provisoire et support ITE - WEATHER DEFENCE BD13
5. Bottes de paille	mm	370	0,052	100,0	0,44	35,69	A+	2	-13,61	+39,56	3248-1.3	DEP vérifiée Règles pro RFCP	Remplissage isolant en bottes de paille (issue de l'agriculture conventionnelle)
9. Montants	__x__x__	2000x45x145	0,120	490,0	0,44	6,39			+0,67	+68,77	10604-1.2	DEP vérifiée	Bois d'ossature en Douglas sans traitement de préservation
6. Enduit terre	mm	35	1,000	1042,5	0,28	36,49			+66,93	+361,13	10870-1.1	MDEGD	Enduit en terre argileuse pour revêtement intérieur [ép.3/4mm] [A4 = 0 - 100km] - DED
TOTAL	**mm**	**489**				**102**			**+59,93**	**+699,13**			

1. Extrait – Règles professionnelles de construction en paille



SW_01_Nomenclature

SBW_01	
N°	Matériau
1	Bardage
2	Lame d'air ventillée
3	Pare pluie
4	Contreventement
5	Botte de paille
6	Enduit terre

Ossature	
N°	Matériau
7	Contre-liteaux
8	Liteaux
9	Montant de 45x145 mm

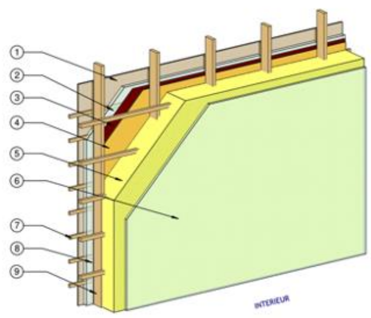


Fig 64

Fig 65

CHAPTER 6 STRAW CONSTRUCTION SYSTEMS/COMPONENTS/PRODUCTS AVAILABLE in UK/EU

6.1 Available

- EcoCocon – pre fabricated straw panels.
  https://www.ecococon.co.uk/

- EcoFab – prefabricated panels
  https://www.eco-fab.co.uk/ecofab-system.html

- Ekopanely- pressed straw boards
  https://www.ekopanely.com/

- Modcell – pre-fabricated straw panels
  https://www.modcell.com/

- Novofibre – OSSB (oriented strand straw) panel board products.
  https://www.novofibre.com/products/overview.php

- TAM Homes from Agile Homes.
  https://agile.property/about/

6.2 In development

- Iso-Stroh – blown-in insulation.
  https://www.iso-stroh.net/

- Vivihouse – design your own house.
  https://www.vivihouse.cc/

APPENDICES

Appendix A: Straw Works Construction Bale Standard
https://strawworks.co.uk/resources/bale-standard/

Appendix B: Loadbearing capacity of straw walls – a summary of results from peer-reviewed literature, John Butler/ UP STRAW, 2020

Appendix C: Thermal conductivity of strawbale – a review of published results meeting ISO 10456 requirements, analysed to provide robust straw lambda values, John Butler, 2020

Appendix D: Straw Works Psi and fRsi calculations for SAP, John Butler 2020

Appendix E: Straw Works Psi and fRsi calculations to PHI conditions, John Butler 2020

Appendix F: Safety of Strawbale walls in the event of a fire, John Butler, 2020

Appendix G: Safe working with bales in agriculture, HSE, 2012
https://www.hse.gov.uk/pubns/indg125.htm

Appendix H: Passive House Fact Sheet 2020/17 Straw as an insulation material, iPHA, 2020

Appendix I: UP STRAW Context Report 2020

Appendix J: Haven Cottage Acceptance Airtightness Test Report, JAldas, July 2015

Appendix K: Sound Insulation Report for Strawbale Housing at Brumby Crescent, Waddington, North Kesteven

Appendix L: Building Regulations and Standards for Straw Construction

Appendix M: Load Test results for rammed stone car tyre foundations

Appendix N: Report on cracks and damage to lime plaster

ORGANISATIONS AND RESOURCES

ACAN – Architects Climate Action Network
https://www.architectscan.org/about

AECB – Association for Environment Conscious Building
https://aecb.net/

Anthropocene Architecture School
https://www.facebook.com/Anthropocene.A.S/

Architects Declare – UK Architects Declare Climate and Biodiversity Emergency
https://www.architectsdeclare.com/

ASBP – Alliance for Sustainable Building Products
https://asbp.org.uk/

BLF – Building Limes Forum - to encourage expertise and understanding in the appropriate use of building limes and education in the standards of production, preparation, application and after-care
https://www.buildinglimesforum.org.uk/ https://www.buildinglimesforum.org.uk/lime-publications/

Centre for Alternative Technology (CAT) - an educational charity dedicated to researching and communicating positive solutions for environmental change
www.cat.org.uk

EBUKI – Earth Building UK and Ireland
http://ebuki.co/resources.htm#sthash.LvY0s0fg.dpbs

ESBA - the European strawbale network
https://strawbuilding.eu/

GBE – Green Building Encyclopaedia – design advice and technical detail
https://greenbuildingencyclopaedia.uk/
https://greenbuildingcalculator.uk

Greenspec – green building design & products for sustainable construction
https://www.greenspec.co.uk/

Historic England
https://historicengland.org.uk/images-books/publications/

Living Building Challenge
https://living-future.org/lbc/

Material Considerations: A Library of Sustainable Building Materials
https://www.ads.org.uk/a-library-of-sustainable-building-materials/

Passivhaus Trust
https://www.passivhaustrust.org.uk/

SBUK – Strawbale Building UK. Cooperative, membership organisation
https://strawbalebuildinguk.com/

Scottish Lime Centre Trust

https://scotlime.org/

Scottish Ecological Design Association
https://www.seda.uk.net/

SNaB - School of Natural Building
http://schoolofnaturalbuilding.co.uk/

SPAB - the Society for the Protection of Ancient Buildings – great resource for training and technical literature
https://www.spab.org.uk/ https://www.spab.org.uk/advice/spab-briefings

Straw Works – information and directory website
https://strawworks.co.uk/

RECOMMENDATIONS FOR FURTHER RESEARCH

This preliminary list of ideas for further research and investigation comes from the writers and the reviewers.

- Measurement of hygrothermal performance of straw bale houses (indoor environmental quality and durability)
- In-situ U value measurements of existing straw bale buildings
- Decrement delay measurements in existing straw bale buildings
- In-situ acoustic measurements of multi-dwelling buildings
- Gathering and collating more air tightness test data from existing straw bale buildings
- More infra-red thermography of completed buildings
- Load-bearing capacities - reverse engineering to prove what loads are being carried by real houses
- Load bearing capacity of 'bare' re-baled bales
- Check thermal conductivity of bales made to Straw Works standard against the proposed 0.08 design baseline in the review " Thermal conductivity of strawbale – a review of published results meeting ISO 10456 requirements, analysed to provide robust straw lambda values", John Butler, 2020
- Development of the supply chain is an area to be explored further with organisations such as the Agriculture and Horticulture Development Board, AHDB.
- Consider a LinkedIn or WhatsApp group for straw bale artisans to compliment (or instead of) an AHDB idea.
- Collect more data on current suppliers and then
    1. establish most common baling machine used for construction bales in UK
    2. get samples of these bales from different suppliers
    3. commission formal strawbale conductivity testing.

  Item 3. should involve testing 10 samples/panels in the same conditions. The calculated lambda 90/90 (official thermal conductivity according to ISO 10456) would probably be lower in that case than current calculations based on tests in different conditions. Would give a more accurate idea of the lambda of the bales actually being used most of the time. (This research is likely to go ahead in 2022 as a collaboration between Bath University, the School of Natural Building, and Sustainable Building Consultancy)
- Further in situ acoustic testing of construction types and development of formal alternatives to Robust Details for Part E.
- Durability of straw bale construction: comprehensive study needed. Assess performance of existing buildings; evaluate different straws; details etc
- Green Building Calculator Version 3 or Version 4 to include Straw bale construction methods and proprietary product elemental assemblies and product and material datasets.
- Green Building Encyclopaedia to include a Straw bale construction Jargon Buster and Checklist.
- Green Building Specification - translate the BSI PAS Code of Practice into a Specification template with Guidance notes and reference documents and linked to Products information

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