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The carbon reduction potential of strawbale housing

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Abstract

This paper illustrates the role of strawbale as a construction material and using strawbale load bearing construction technique in reducing the whole life impacts of housing by modelling the performance in CO_2 emissions of this method of construction. A detailed analysis has been carried out to investigate the potential of strawbale through analysis of embodied and operational CO_2 emissions in the Waddington social housing project recently completed in Lincolnshire in the UK by comparing some alternative domestic external wall constructions and the effects on the CO_2 emissions that would result.

It is estimated that over fifteen tonnes of CO_2 may be stored in biotic materials of each of the semi detached houses of which around six tonnes are sequestered by straw and the remaining by wood and wood products. Our analysis indicate that the carbon lockup potential of renewable materials used in the construction of the house is capable of reducing the whole life CO_2 emissions of the house over its sixty years design life by 61% compared with the case without sequestration.

The paper also discusses the practical implications of construction, detailing, maintenance, cost and selfbuild potentials of strawbale construction. The paper concludes by demonstrating the potential of loadbearing strawbale walls and compares the whole life performance of strawbale construction with alternative conventional external walling systems.

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Key words: CO_2 emissions, embodied energy, operational energy, strawbale, social housing, cost.

Introduction

Building life cycle demands the consideration of both direct and indirect energy consumed during a life time of a building. The former is associated with construction, operation, maintenance and deconstruction however the latter primarily encompasses the energy needed to produce building materials, i.e. the embodied material burden. The distribution of energy consumption and impacts are generally concentrated in the operational phase of a building however with the improvement in building regulations and zero energy building concepts, this proportion is likely to change in the near future. Sartori and Hestness (2006) in an analysis of 60 residential case studies found that the in-use phase represents by far the largest part of energy demand in a building during its life cycle. They also concluded that there is a linear relation between the in-use and total energy, i.e. the sum of all the energy used by a building during its life cycle, which is valid through all the 60 case studies despite the climate and other contextual differences (e.g. for different size and type of buildings etc.). This is apparently due to the dominant role of the in-use energy that reduces the influence of all other differences. Scheuer *et al.* (2003) emphasize that in-use energy performance should still be the primary emphasis for design, until there is a significant shift in distribution of life cycle burdens.

In the current economic climate customer demand for new low carbon housing might be limited but it is anticipated that low carbon housing will be a growing market especially in wake of the approaching zero carbon homes target. Osmani and O’Reilly (2009) identify many barriers including design, technical, cultural, legislative, and financial barriers in designing and building energy efficient housing in England and assert that in the current financial climate, the Government is likely to face many challenges to meet these zero carbon targets.

As housing is bound by legislation in the UK to become more energy efficient in operational energy with increased insulation levels, better air tightness, and the use of more energy efficient equipment and appliances, the relative importance of other impacts such as the initial and the end of life will become more significant in the whole life impact analysis. To reduce the initial impact, attention should be paid first to embodied energy of materials specified and secondly to the impact of the construction process. To reduce the end of life impact, in addition to an attempt to increase the life span of a building through the application of design principles for adaptability and flexibly, and good maintenance, refurbishment and conversion, recyclability of all materials should also be considered. Ding (2007) states that life cycle energy consumption requires a comprehensive energy analysis to cover energy consumption throughout the buildings' economic lifespan.

By using a social housing project as a case study, the aim of this paper is to demonstrate the potential of renewable materials in meeting a typical construction need in the UK and that design decisions based on carbon emissions must take into account the impacts of all stages throughout the economic lifespan of a building. Embodied and operational emissions could be reduced by careful choice of materials and construction techniques. The paper focuses on illustrating the role of lifecycle analysis of strawbale as a construction material in defining embodied impact and demonstrates the variance in performance between strawbale wall construction in comparison to conventional new build home walling constructions.

Scope and methodology

The paper discusses the potential of strawbale as building material and analyses the CO_2 emissions resulting from constructing and operating a pair of semi-detached homes in a social housing project in the UK. The study specifically analyses the embodied emissions of the materials used in the building and the operational emissions coming from its annually repeating operational energy demand. It also investigates the resulting effect on embodied and on the operational CO_2 emissions based on a 60 years nominal life span by changing the envelope of the houses using other wall construction that are typically used in housing within the UK. Other metrics and criteria for sustainable design and construction have not been discussed in any depth in this paper however the design of the houses has considered these aspects.

Only the embodied emissions of the main materials used in the shell construction of houses are considered and the effects of materials such as interior finishes (such as carpets, skirting boards, fixtures and fittings, sanitary services, electrical and mechanical services, sealants, and other minor elements) are excluded. These elements which have not been specified as part of the base build, would be the same fittings and fixtures in all of the wall construction alternatives modelled, would be selected by the tenant and are considered to be largely of low significance to the total embodied impact.

Carbon emission inventory data was developed mainly from Bath University Inventory of Carbon and Energy (Bath ICE, 2006) and manufacturer's data where the data were not available in Bath ICE. Bath ICE is a publicly available embodied energy and carbon dataset representing typical building materials employed in the British market and hence used to assess most of the installed materials in this study. The range of materials this dataset includes represents conventional construction and composites and there is a need to produce accurate local datasets with the possibility to compare international assessments and further alternative and innovative materials.

Standard Assessment Procedure[1] (SAP) (BRE, 2005) which is adopted by the UK government as part of the national methodology for demonstrating compliance with building regulations and for providing energy ratings for dwellings was used to quantify the annually repeating operational impacts. SAP methodology is well established in the UK to assess housing, and the government dictates conversion rates for services and energy supplies to CO_2 used and are used here to demonstrate operational performance and provide a level platform for comparison, even though there may be criticisms about both the rating methodology and the factors used within it. This study is focused on UK climatic and industry conditions however as strawbale construction is widely used in rest of the world, the analysis drawn by the paper may be applied to other locations.

The alternatives considered are replacing strawbale walls with masonry and timber walling systems. The results provide an insight into the effect of the type of construction on the total amount of CO_2 emissions, and the relevance of carbon storage potential and end of life implications of renewable materials.

House Description

A pair of semi-detached council houses of loadbearing straw (i.e. no framework) construction and using predominantly natural materials have recently been completed for North Kesteven District Council at Waddington in Lincolnshire, UK. They are based on traditional UK social housing design, standard semi-detached, two-storey, 3-bedroomed houses each with an internal gross area of 85.75m^2 which is 4m^2 above the Housing Quality Indicator[2] (HQI) (Drury *et al.*, 2006). The gross external floor area of each house is 104.50m^2 including strawbale walls of 450mm with 30mm lime on both sides. The party wall between the pair is also of loadbearing straw, plastered both sides with lime, which provides a fire and acoustic break between the houses. Visually, these houses are similar in scale and form to the rest of the council housing estate on which they are built, and have hipped roofs of clay tiles. They differ in that they are rendered with lime and painted a buttermilk colour rather than being clad in cement slabs, as are the nearby post-war council houses. Householders enter from the street via the north, with a green-roofed porch to give protection to the external door, a coat closet and toilet, before entering into the open plan living/dining/kitchen space (Figure 1).

The houses are on east-west axis with the main orientations facing south and north. Forty percent of the south facing elevation is glazed, maximizing passive solar heat gain in early spring, late autumn and the winter months. The northern aspect has much less glazing and fewer windows. Upstairs, the bathroom is located on the north, with the two double bedrooms with balcony access facing south and the smaller single bedroom having a small north window and either an eastern or western full length window (Figure 2). Figures 3 and 4 show cross sections through the houses. Figure 5 shows the southern aspect of the houses. The pair of strawbale houses at Waddington have cost £103,770 per house to build giving a price of £1210/ m².

Construction Philosophy

The primary driver was that the houses would be low carbon in construction and use. Their fabric is designed to minimize the environmental impact by using readily available low–embodied energy natural materials. In addition, materials have been locally sourced to minimize transportation to the site. A standard strawbale is 450mm wide, which determines the foundation width, and by using a 100mm brick outer skin, with a 140mm recycled glass rigid insulation inner skin and 200mm of shredded lightweight recycled insulation aggregate laid like hardcore in the centre (Figure 6), a U-Value of 0.17W/m²K has been achieved within the plinth foundation. Figure 7 shows the detailed section through the wall foundation. It is essential that the plinth is not a cold bridge because the floor construction is dropped below the level of the plinth to keep the finished floor level low to enable wheelchair access and strawbale walls need a plinth foundation to raise the straw above the ground by 300-450mm to protect the straw from splash back from rainfall.

The ground and first floors are constructed of timber joists designed to span the houses without need for intermediate support. The ground floor contains 20mm woodfibre board placed on the flanges of the joists with 200mm sheep's wool insulation and FSC certified SmartPly tongue & groove boarding above, with natural wool underlay and a wool carpet. The first floor utilises hardboard on the flanges to contain 10mm of sand (acoustic barrier) with a similar floor build up to the ground floor but no sheep's wool except in the section directly over the external walls, which is totally filled.

The first floor was constructed beside the foundations and craned onto the walls as a single unit for each house, with a 30mm gap for fire protection between them filled with sand. In this method the bales take the weight of the floors and roof eliminating the need for a structural framework. They are placed together like giant bricks, pinned to the base plate (a continuous timber plate that sits on top of the foundation plinth) and to each other with coppiced hazel, and a continuous rigid timber ring beam on top spreads the floor and/or roof loads across the width of the wall (Figure 8).

For two-storey houses, the floor joists at first-floor level are attached to the ring beam before building up the straw walls again beneath the roof. The roof plate (a continuous rigid plate that sits on top of the walls and under the roof) is fastened to the bales with coppiced hazel and may be fastened down to the foundations with polyester strapping if the roof load is light, or a possibility of strong winds. The roof is constructed on top of the roof plate, following straw bale design principles.

In the Waddington houses the weight of the floor and the roof themselves, together with sacks of sand were used to compress the straw, and fastened the floor/roof structure down by attaching it to the uprights either side of each door and window opening. The change to this method of building, which essentially pre-fabricates a lot of the structure, utilising it as a weatherproof covering and immediately compressing the straw so that no time is lost, has brought significant time and cost savings to the building site, that inevitably makes this a more competitive and viable mainstream choice for construction.

A disadvantage of the load-bearing technique which has been used is how to keep the straw dry throughout the whole building process despite sometimes prolonged wet weather of the UK. Pre-fabrication of building components minimises the vulnerable time of exposure to the weather, and the need to keep the straw waterproofed, can be reduced to a few weeks. The floors and roof themselves are used as main weather protection. This was the preferred method for the Waddington houses; the first floor and roof were constructed separately, temporarily propped and waterproofed and used as shelter for construction to continue below, coupled with sheeted scaffolding externally. As this level of protection is also required for the lime render, it is cost-effective to protect the whole building, ensuring there will be no time lost due to the weather for any aspect of the build. Table 1 lists specifications of the main construction elements with their U-values.

Benefits of straw construction

Straw is an annually renewable natural plant product, formed by photosynthesis, fuelled by the sun, requiring only small amounts of energy to process. It is a by-product of grain production and effectively a waste stream although it is currently already used for animal bedding, biofuel and in fabrication of boards for the construction industry, its potential as an unprocessed building material is currently under explored in the UK. There has however been an increased interest in the use of straw in mainstream construction over the last 15 years (Lawrence *et al*., 2009). Using straw as a building material can mean less pressure to use other more environmentally damaging materials, and if the building is no longer required, it can be re-used in agriculture or even as fuel.

Straw combines very high insulation properties with load bearing potential. The maximum reported loads for plastered bale walls vary between 21 and 66kN/m (Walker, 2004).

Straw is a natural and breathable (allowing air exchange through its volume) material, it offers a potential solution for those who find that the paints, chemicals, glues, and toxins embedded in manufactured building materials negatively affect their health. Organically grown straw coated with earth-based and/or lime plasters have received positive feedback from environmentally sensitive people (Magwood *et al.*, 2005). As straw is an organic material, it may however carry particular risks if it is not used properly as a building material. To overcome the risks, good design and attention to details are required (Lawrence *et al.,* 2009).

Embodied carbon assessment

Verbick and Hens (2010) in a Belgian residential case study illustrate that the total embodied energy is relatively small compared to the usage phase and it becomes more valid when comparing the embodied energy of energy saving measures with the savings they realize during 30 years of use. Thormark (2006) in one of the most energy efficient Swedish apartment type housing project shows that during an assumed service life of 50 years; operational energy accounts for the majority (approximately 85–95%) of total energy use. In addition, she also illustrates how material choices could influence recycling potential and total embodied energy for the total building lifetime energy. Adalberth (1997) in a life cycle study of three prefabricated and timber framed single dwellings in Sweden shows approximately 85% and 15% of total life energy consumption occurs during the occupation and manufacturing phases respectively. In a typical Scottish 3 bedroom semi detached house Life Cycle Analysis (LCA) case study, Asif *et al*. (2007) identified that concrete, timber and ceramic tiles are responsible for 61%, 14% and 15% of the total embodied energy of the house.

In the UK wheat is grown for human consumption (milling wheat), animal feed (feed wheat) and is also used for fuel by ethanol production or direct combustion (industrial). Around 40% of wheat straw produced is chopped and ploughed into the field to improve water retention of farmland, 30% is used on the farm where it was grown for animal bedding and the remainder is sold (Biomass Energy Centre, 2010). Straw may be baled at 15-25% moisture content (Biomass Energy Centre, 2010), generally in large round or square bails and used for animal bedding, burnt as fuel or in other manufacturing processes including construction materials. Small square bails suitable for use in wall construction are generally used for domestic pet bedding and represent a very small part of the straw market, smaller machinery is used for this type of baling reducing some of the fossil fuel impact, but this machinery is not generally used on larger commercial farms. It is not though that the tractor used biodiesel although this is also a possibility. Wheat straw has been taken here as a by-product although the straw was baled specifically for the build; the wheat product use was not declared, nor do we know what natural or chemical inputs were administered in the growth stage, or the water content of each bale.

Clearly there is a wide range of possibilities in terms of emissions impact which could arise from the LCA of straw used or indeed any biogenic materials used in construction without a very well documented upstream life cycle information (collection of which in both time and cost may be disproportionate to the cost and time of production of the material itself). The methodology which has been used to deal with this uncertainty is to obtain examples both from literature and calculation from first principles to obtain a median result used by Hammond and Jones (Bath ICE, 2006). Inclusion of sequestration in the growth cycle of the product is included as a negative value due to the possibility of recycling, use of materials as fuel or extending use phase beyond 60 years. The difficulty of predicting end of life emissions impact can only be realistically resolved by comparison with current national data on recycling, energy from waste and landfill impacts (Defra, 2009) in conjunction with the design life of the building. The approach used here is optimistic towards better end of life management following plan which may be set out by the architect, than a more pessimistic approach which assumes current practice of disposing of demolition waste will be maintained or worsened.

Wheat Straw stem consists primarily of cellulose, hemicellulose and lignen. The carbohydrate content of straw may vary due to location, genetic and growth conditions (ReTAP, 1997). Examples reported in literature were used to obtain the median values for cellulose, hemicellulose and lignen of stem dry weight. Examples used include six sets of data reported from literature in ReTAP (ReTAP, 1997), in addition to two further sets of data reported by Renewable Energy Institute (1997) and Csoka *et al.* (2008). The median values calculated as percentages of stem dry weight for cellulose, hemicellulose and lignen are 36.5%, 28.6% and 17.8% respectively. The percentage of carbon within cellulose and lignin can be calculated from their chemical formula, using the relative atomic masses of carbon, hydrogen and oxygen as shown in table 2. The percentage of carbon within cellulose and lignin is about 44.4% and 66.6% respectively.

If we assume that by the time the bales are used in the construction of buildings their moisture content may be of the order of 10%, the carbon content of straw may therefore be calculated as;

$$[(0.365 + 0.286)0.444 + 0.178 * 0.666]0.9 = 0.367$$

Total carbon dioxide sequestered within the bale can be estimated by multiplying the carbon content of the bale (0.367) by the relative molecular mass of carbon dioxide (44g/molecule) divided by the atomic mass of carbon (12g) (Defra, 2009). This gives a total carbon dioxide sequestered in the bale of the order of 1.35kg CO_2 per kilogram of bale. The calculated sequestration figure is in good agreement with the figure of 1.36KgCo2/kg cited by Atkinson (2008).

In this paper, the benefit is shown separately to allow readers to consider the implications of inclusion of sequestration of CO_2 in this form of analysis. For straw a figure of 0.01 $kgCO_2/kg$ has been used for without sequestration (Bath ICE, 2006) and a negative figure of 1.35 $kgCO_2/kg$ for with sequestration as calculated above.

For timber the figures of 0.45 $kgCO_2/kg$ has been used for without sequestration (Bath ICE, 2006). Similar to straw, timber has a negative foot print if sequestration is taken into account because of carbon dioxide fixed by the original living tree. Ragland and Aerts (1991) report that the average carbon content of softwood taken from nine species is 52.7%. Carbon dioxide sequestered within timber is therefore 1.93 kgCo2 per kilogram of dry wood (0.527*44/12). As timber is not a by-product, the emissions associated with harvesting, transporting and processing of wood must be taken into account. Abbott (2008) reports that when energy use for harvesting, transport and processing are taken into account, wood will have a negative cradle to gate carbon footprint of 1.2kgC02/kg.

The embodied energy calculation of materials is mainly based on mass of materials, so conversion to built quantity is required for the materials used in the construction of houses. The bill of quantities was provided by North Kesteven District Council (the client for the houses) for this study. As the pair of houses are identical, the embodied carbon dioxide emissions are the same for each. Embodied emissions of building elements for both with and without sequestration are presented in Table 3. The materials emissions rate for one of the Waddington houses without considering the carbon lock in benefits of straw and timber is 151 $kgCO_2$ per square meter of gross internal floor area, much less than an average 475 $kgCO_2/m^2$ for conventionally constructed new build homes in the UK (BHSF, 2008). Biotic materials are capable of storing more carbon than they release and to this end if their sequestration potential is considered, their embodied impacts might drastically change. If the carbon lock in benefits of straw and timber are taken into account, every square meter of floor area of the house will lock in 82.5 $kgCO_2$ during the lifetime of the building.

Environmental Philosophy

The design of the houses attempts to fully utilize natural light, ventilation, thermal mass and insulation. The U-Value of a typical 450mm thick un-plastered strawbale wall is 0.13W/m^{2}K (Jones, 2009), the thermal conductivity of straw is 0.045W/mK which gives a U-Value including plaster of 0.10W/m^{2}K. UK Building Regulations Approved Document part L1A (DCLG, 2006) require that walls should not have U-Values greater than 0.30 W/m^{2}K. A plastered straw wall 450mm thick also has good thermal storage capacity of the order of 200340 J/m^{2}K that evens out temperature fluctuations and allows the building to benefit from passive heating from solar gain. UK Building Regulations (DCLG, 2006) also stipulate that air leakage must be proven to be no worse than 10m^3/hr/m^2 at 50 Pascals (Pa). Atkinson (2008) has measured an air leakage of 1.56m^3/hr/m^2 at 50 Pascals in a small strawbale holiday home. Air leakage tests at the Waddington houses show a result of 2.62m^3/hr/m at 50 Pascals .

Annually Repeating Impact: Operational carbon dioxide emissions

Operational life of a building becomes an important factor considering the fact that a significant impact of building may occur after constructing and installing it (Sodagar *et al*., 2009). An efficient operational life could be ensured with high performance envelopes, careful selection of materials, and good services design. The operational energy demands of houses can be calculated using Standard Assessment Procedure (BRE, 2005) which utilise standardised regional climatic data.

The space heating of the Waddington houses will be met by a wood burning boiler stove with an efficiency of 75% (Dunsley Heat, 2009) and an electrical secondary heating panel with an efficiency of 100%. The heating is provided 24 hours throughout the course of the year with a mean internal temperature set point of 19^{o}C. Hot water demand is met by the boiler in addition to hot water solar panels ($3.52m^2$) positioned on the south facing pitch of the roof. Table 4 shows the annual energy breakdown requirements and the associated CO_2 emissions for the semi-detached house with the west facing gable wall. The total annual space heating demand of the house provided by the main and secondary heating systems is 3788 KWh indicating a heating demand of the order of 44.2 KWh/m^2 per year. The total annual hot water demand of the house provided by the biomass boiler and the hot water panel is of the order of 3946 KWh, consumption of the order of 46 KWh/m^2. As buildings become more energy efficient in space heating with increased insulation levels and better air tightness, the relative contribution of hot water and household electricity to the total energy demand of the house will become more significant. This is especially the case for small dwellings which usually have a greater energy use for water and electricity per unit of floor area (Gustavsson and Joelsson, 2010).

The annual heating demand of the house with an east facing gable wall is fractionally higher due to the orientation of the end walls. The house with west facing gable wall is equipped with monitoring devices and will be subject to post occupancy evaluations in future, and to this end, this paper concentrates on analysing the design results for this house.

Typically the energy demand of modern family homes in the UK for heating and hot water is 21,500 kWh, and for lighting and small power is 4,000 kWh (Rawlinson, 2007). The total heating and hot water demands of the Waddington house is 7734 kWh per year including the hot water supplied by the hot water panels. Whilst this represents a 64% reduction, in order to achieve highest Codes for Sustainable Homes standards (DCLG, 2008), the Waddington house would require a heat recovery system. The compact and open plan layout of the house should allow convective heat movement to perform this function. Monitoring in use will help to demonstrate that convection is an effective alternative to mechanical recovery. To estimate CO_2 emissions the conversion factors used are 0.025 $kgCO_2/kWh$ and 0.442 $kgCO_2/kWh$ for wood and electricity respectively **(**BRE, 2005) as shown in Table 4. Standard Assessment Procedure (SAP) (BRE, 2005) uses delivered energy for calculating operational CO_2 emissions from residential buildings. Reducing dependence on mains electricity in UK housing through small power and lighting load reduction and micro generation is an effective way to reduce CO_2 emissions as the national grid remains highly dependent on fossil fuels.

Whole Life Impact

Life cycle assessment (LCA) is a key approach to analyse the whole life impact of a building as it allows for the estimation of impacts distribution across all the life cycle stages by integrating upstream and downstream material and energy flows (Rai, *et al* 2010). Many varieties of tools (for e.g. LCA based tools, rating systems, technical guidelines, etc.) have been developed for the building sector to support decision making and improve environmental performance of buildings and building stocks (Haapio and Viitaniemi 2008). In a French study, Peuportier (2001) with the help of the simulation tool EQUER (French for the evaluation of environmental quality of buildings) compared the LCA of two wooden framed houses with a typical reference house (concrete block wall) with the design life of 80 years. The simulation tool EQUER is based upon a building model structured in objects making the comparison of design alternatives easier (Peuportier, 2001). The study emphasized the importance of LCA decision-making tools at design stage. There are many datasets and tools available to assess the embodied impacts of building materials but often their application are limited to user's goals, scope and geographical location. Scheuer *el al.* (2003) in a university building study asserted that because of continuing data limitations, and due to the large range of construction techniques and material choices, many of the available tools are currently not capable of modeling an entire building, or computing the environmental impacts from all life cycle phases and processes. Bath dataset (Bath ICE, 2006) was chosen for this study as it offers a dataset well suited for assessing embodied carbon data of conventional building materials in the UK.

Calculating emissions from the construction process is a relatively new concern for the construction industry and published sources are limited (Sodagar and Fieldson, 2008). The contractor of the Waddington houses was not required to record emissions impact of the construction process and in absence of data, we have assumed that the impact of the construction process is to be of the order of 5% of the material production energy (Gustavsson *et al*., 2010) reflecting the scale of the project and the fact that local contractors and labour force are used in the construction of houses. A figure of 5% waste for all materials is assumed for the Waddington houses as suggested by Gustavsson *et al*. (2010) considering the recovery of wood waste (and straw) for use as a substitute for fossil fuel.

The energy used for demolition of buildings is typically small (1-3%) in relation to the energy used for material production and building assembly (Gustavsson *et al*., 2010). In our analysis, we have assumed that the deconstruction impact of the houses will equal to 1% of the combined impacts of materials and construction process. Consideration of end of life impact of straw and timber is further complicated by the uncertainty associated with how long buildings will be utilised beyond the design life assumed and the manner in which the materials will be disposed of. Currently in the UK diversion from landfill of renewable materials from demolition does readily take place but published rates lag behind current practice (ERM, 2006) and almost certainly will not represent a UK scenario in the future where energy from waste is anticipated to be widespread.

Table 5 lists the emissions for the semi-detached house with west facing gable wall over 60 years for different lifecycle stages. The whole life CO_2 emissions of the semi-detached Waddington house over 60 years design life is 51761.4 kgCO_2 if the storage carbon potential of materials is excluded. The in-use emissions are 72.2% of the total lifetime CO_2 emissions of the house. With sequestration, the total emissions of building elements will be -7070 kgCO_2 instead of 12952 kgCO_2 thus reducing the whole life CO_2 emissions of the house to 31739.4 kgCO_2. In this case, the carbon storage potential of straw and wood has negated the impacts of other stages of LCA and offers a 61% saving over the lifetime of the building compared with the case without sequestration providing that the renewable materials are disposed of in the most resource and fuel efficient way at the end of life.

We cannot know what will happen at the end of life of Waddington house, and examples of redundant buildings in the UK left to decompose, allowing stored carbon from renewable elements to be released as if the materials were in landfill are common. In our analysis we have estimated that 15647 kilograms of CO_2 is stored in each of Waddington houses of which 6079 kilograms of CO_2 is sequestered by straw and the remaining by wood and wood products used in the construction of the house. This is arguably as valuable in terms of climate change and global emissions reduction as are the benefits of further reducing the operational emissions of the building by better design over 60 years of use which in the UK climatic and national grid conditions has yet to be proven realistic.

Alternative Walling Systems

In order to compare the whole life performance of strawbale construction with more conventional house walling systems used in the UK, four alternative external walls were considered. The specifications for alternative external walling systems commensurate with present-day good practice low energy design in the UK. In addition to alternative external walling systems, two alternative party walls were also considered to represent the common practice for the party walls used in the UK meeting Building Control requirements for fire safety and noise transfer between dwellings.

All four external walls have the same U-value as that of the strawbale walls, i.e. 0.10 W/m^2K. The standard of air tightness was also assumed to be the same as for the house with strawbale walls, i.e. an air leakage index of $2.62m^3/hr/m^2$ at a reference pressure of 50 Pascals. Table 6 lists the specifications of alternative external and party walling systems. Table 7 lists CO_2 emissions rates and costs for different walling systems. The estimated costs account for labour, plant and materials although they exclude prelims such as scaffold. For the external walling, strawbale is the most economic option. The other two party walls however are cheaper to construct when compared with strawbale party wall. All other elements of the houses such as windows and roof were considered to be the same. Although all other construction elements are the same in all different scenarios, it was necessary to strengthen the foundations with extra limecrete for cases having the rendered and brick faced masonry walls due to greater weights of these walls compared with strawbale wall, and timber frame construction.

Table 8 compares the total house materials CO_2 emissions of the house with different external walling systems and party walls. Total impacts of materials for different cases are depicted in Figure 9. The house with strawbale walls out performs all alternative walling systems both with and without sequestration. When the carbon storage potential of materials is considered, the difference between strawbale and all other options becomes more significant due to the quantity of straw used and consequently the amount of carbon stored.

More highly processed masonry elements increase the impact of the other walling options. The total house material impacts with different walling systems range from 12952 $kgCO_2$ for strawbale, to 18940 $kgCO_2$ for the house with brick faced masonry walling system, showing that 5988 kilograms of CO_2 is saved by using renewable materials even with excluding sequestration. With sequestration, the maximum savings achieved is 12105 kilograms of CO_2 as a result of using strawbale compared with the case with brick faced masonry walls. It should be noted that infrastructure, foundation and flooring design at Waddington is not conventional and therefore the benchmark offered for UK residential construction (BHSF, 2006) is quite high.

Table 9 compares the whole life impact of houses with different walling systems over their assumed life expectancy of 60 years. The impacts from construction process, materials waste and deconstruction, as a percentage of the corresponding materials impacts were assumed to be the same for all cases. For all cases we have assumed that the impact of construction process and materials waste is 5% each of the corresponding materials impacts (without sequestration). The deconstruction impact is assumed to be equal to 1% of the combined impacts of the relative materials and construction process.

The effect of changing the walling systems on operational energy demands were also analysed using SAP (BRE, 2005). The calculated whole life impacts range from 603.6 $kgCO_2/m^2$ to 681.2 $kgCO_2/m^2$ and 370.1 $kgCO_2/m^2$ to 519 $kgCO_2/m^2$ of internal floor area for without and with sequestration respectively. The house with strawbale walls outperforms all of the conventional walling systems.

Conclusions

This paper has taken a standpoint of aiming to demonstrate the viability and performance benefits of strawbale housing for rural communities. Straw walling clearly offers a low embodied and operational emissions performance and is equally suitable as a walling material as more conventional options. Although not proven to be lower cost in mass housing, the market has not been fully tested at larger scale development level and authors expect that the learning gained in this pilot project and the elemental cost comparison for demonstrating alternative walling systems will lead to more economic strawbale construction in the near future. There are other issues to consider if straw were to become a more common building material and diverted from existing uses. Low straw yield years in the UK due to variable weather conditions, rate of uptake of organic methods and resulting availability would increase the emissions impact of transportation of straw on a project by project basis, and certainly influence cost based decisions.

Monitoring will be required to prove claims of reduced emissions due to the design of the houses and servicing; and it would be expected that future residents and the local authority will be sufficiently satisfied to endorse this approach in meeting housing needs in rural areas.

One of the key areas of significance provided in the paper is the variation in results when LCA boundaries are changed by including carbon sequestration potential of biotic materials. The paper estimates that the total emissions of building elements per dwelling are of the order of 13 tonnes of CO_2 without sequestration. By considering the carbon lock-up potential of straw, wood and wood products, each dwelling may be considered as a carbon sink negating the impacts of non renewable materials resulting in locking up around 7 tonnes of CO_2.

Further research is required to fully support the use of sequestration in embodied impact assessment with end of life implications, particularly where this approach is used to compare very different material options in other construction sectors. It is clear that considerable savings in emissions may be achieved by selecting low carbon and renewable materials, however any carbon lock in claims must be based on clear principles and planning for deconstruction to ensure that the stored benefit is not later lost.

The most significant assertion made here is that the effective management of stored carbon held in renewable materials both entering and being released from building stock as demolition waste may represent a comparable UK wide CO_2 emissions saving to the improvements which may be gained from adopting the very highest levels of operational performance in the Code for Sustainable Homes. Whilst this paper did not set out to demonstrate the case for sequestration and deconstruction control to retain the value of stored carbon, it is clear that a growing preference for using natural materials in order to claim the benefit of stored emissions will provide an increasingly energy rich source of materials in demolition waste in future years.

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Endnotes

[1] The Government’s Standard Assessment Procedure (SAP) is used for energy rating of dwellings as part of the UK national methodology for calculation of the energy performance of dwellings. It is used to demonstrate compliance with the Building Regulations with regards to the Conservation of Fuel and Power.

[2] Following the publication of the Housing Corporation's Design and Quality Standards and Strategy (April 2007), Housing Quality Indicators (HQI's) have been revised to incorporate the design standards that are required of affordable housing providers).

Table 1 Specifications of the main construction elements

Elements	Specific characteristics	
Floors	Ground Floor U-Value=0.12 WK/m^2	10mm carpet and underlay 18mm smartply T&G boarding 200mm sheep's wool insulation 20mm wood fibre board
	First floor	10mm carpet and underlay 18mm smartply T&G boarding 10mm sand (acoustic barrier) 20mm hardboard
Walls	External Walls U-Value=0.10 WK/m^2	30mm lime render 450mm strawbales flat 30mm lime plaster
	Party wall	Same as external walls
	Internal Walls	Timber stud walls plastered both sides
Windows and doors	Windows* U-Value=1.3 WK/m^2	Triple glazing with one low E coating and argon gas
	Doors	Wooden
Roof/first floor Ceiling U-Value=0.11WK/m^2	12.5mm plasterboard 300mm cellulose fibre insulation Loft space Clay tiles	

*Information available at http://www.swedishtimberproducts.co.uk/pages.php?view=35)

Table 2 Percentage of carbon within cellulose and lignin

	carbon	hydrogen	oxygen	Atomic mass	% of carbon
Cellulose $(C_6H_{10}O_5)_n$	6	10	5	162 (6*12+10*1+5*16)	44.4
Lignin $C_9H_{10}O_2$, $C_{10}H_{12}O_3$, $C_{11}H_{14}O_4$	30	36	9	540 (30*12+36*1+9*16)	66.6

Table 3 Breakdown of CO_2 emissions of building elements per dwelling of the Waddington houses

Building Elements	$kgCO_2$ Without Sequestration	$kgCO_2$ With Sequestration
Substructure	2537	2353
Floors and ceilings	3988	-5037
Roof	2696	-594
External walls	375	-4923
Repainting of external walls (every 10 years)	321	321
Party wall	58	-768
Internal walls	629	-174
Windows and doors	665	69
Internal finishes	1682	1682
Total Emissions per dwelling	12951	-7071
Dwelling emissions $kgCO_2/m^2$ gross internal floor area	151	-82.5

Table 4 Breakdown of annual in use energy and the associated CO_2 emissions for the semi-detached house with west facing gable wall

Energy requirements	KWh	$kgCO^2/KWh$	$kgCO^2$	Relative KWh %	Relative CO^2 %
Main Space Heating (Biomass boiler)	3496.56	0.025	87.41	40.8	14
Secondary Space Heating (electrical)	291.38	0.422	122.96	3.4	19.7
Hot Water Heating (Biomass boiler)	2251.7	0.025	56.29	26.3	9
Hot Water Heating (Hot water panels)	1694.09	0.0	0.0	19.7	0.0
Pumps and fans	205	0.422	86.51	2.4	13.9
Electricity for lighting	639.33	0.422	269.8	7.4	43.4
Total	8578.06		622.97	100	100
Per m^2 gross internal floor area	100.04		7.27		

Table 5 Whole life emissions for the Waddington semi-detached house with west facing gable wall over 60 years

Stages	Without Sequestration		With sequestration
	$kgCO_2$	Relative CO_2 %	$kgCO_2$
Materials	12952	25.02	-7070
Construction process*	647.6	1.25	647.6
Materials waste*	647.6	1.25	647.6
In-use	37378.2	72.2	37378.2
Deconstruction process**	136	0.26	136
Total	51761.4	100	31739.4
Total $kgCO_2/m^2$	603.6		370.1
$kgCO_2$ per year	862.7		529

* 5% of the materials emissions (without sequestration)

** 1% of the combined impacts of materials emissions (without sequestration) and construction process.

Table 6 Alternative external and party walling systems

	Engineering Timber Frame	Brick-Clad Timber Frame	Rendered Masonry	Brick-Faced Masonry
External Walls	9mm Lime Rendering 12mm Carrier Board 300mm wood fibre 24mm Plasterboard	55mm Brickwork 30mm Air gap 10mm Plywood 300mm mineral wool 12.5mm Plasterboard	25mm Lime 100mm lightweight blockwork 300mm mineral wool 100mm lightweight blockwork 25mm Lime	102mm Brickwork 300mm mineral wool 140mm lightweight blockwork 12.5mm Plasterboard
Party Walls	Two layers of 12.5mm plaster boards, both sides 60 mm mineral wool 80mm cavity 60 mm mineral wool (in houses with engineering timber and brick-clad timber frames)		12.5mm plaster boards, both sides 100mm lightweight blockwork both sides 100 mm mineral wool batts (in houses with rendered masonry and Brick-faced masonry)	

Table 7 Comparison between different external and party walling systems per dwelling

Construction	U-Value W/m^2 K	kgCO_2/m^2 without sequestration	kgCO_2/m^2 with sequestration	Cost £/m^2
Strawbale external and party walls	0.10	4.32	-56.75	115
Engineering Timber Frame	0.10	13.76	7.45	146.5
Brick-Clad Timber Frame	0.10	36.99	33.84	150
Rendered Masonry	0.10	17.61	17.61	120
Brick-Faced Masonry	0.10	54.19	54.19	135
Timber party wall	0.24	4.22	-0.56	68.5
Masonry party wall	0.24	0.14	0.14	85

Table 8 Comparison of the total house materials impacts per dwelling

Construction	without sequestration		with sequestration	
	Total $kgCO_2$	$kgCO_2/m^2$ floor area	Total $kgCO_2$	$kgCO_2/m^2$ floor area
Strawbale	12952	151.04	-7071	-82.46
Engineering Timber Frame	13769	160.57	-760	-8.86
Brick clad timber frame	15464	180.34	-400	-4.66
Rendered masonry	16088	187.62	2182	25.45
Brick faced masonry	18940	220.87	5034	58.71

Table 9 Comparison of the whole life impact of houses with different walling systems over 60 years

Construction	without sequestration		with sequestration	
	Total $kgCO_2$	$kgCO_2/m^2$ floor area	Total $kgCO_2$	$kgCO_2/m^2$ floor area
Strawbale	51761	603.6	31739	370.1
Engineering Timber Frame	53022	618.3	38493	448.9
Brick clad timber frame	54904	640.3	39040	455.3
Rendered masonry	55069	642.2	41163	480
Brick faced masonry	58411	681.2	44506	519

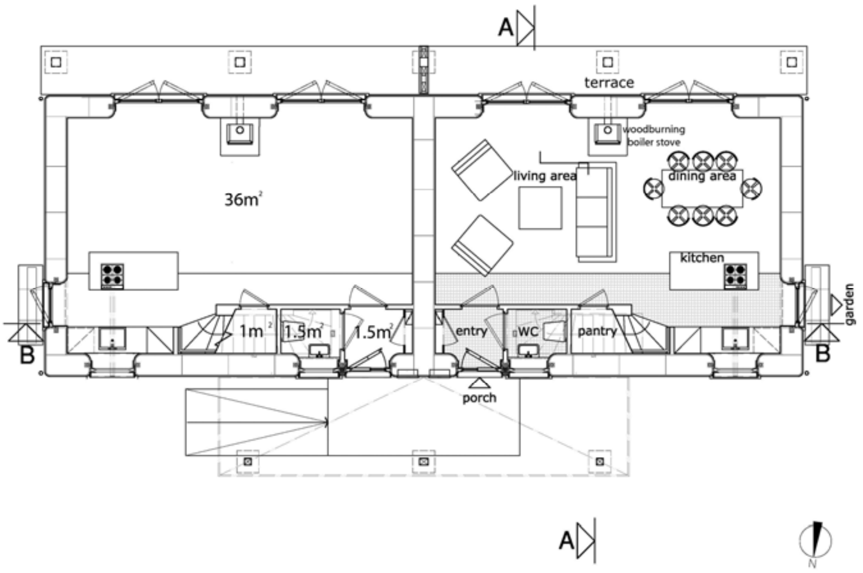


Figure 1 Ground Floor layout, Waddington social housing

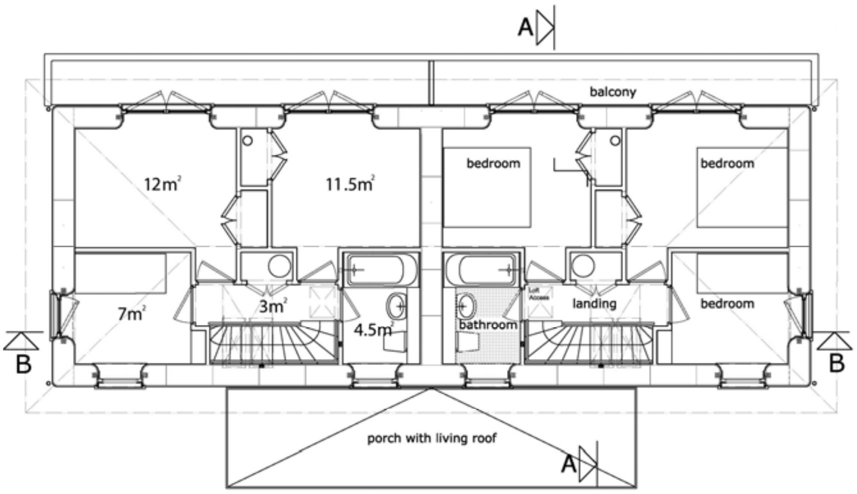


Figure 2 First Floor layout, Waddington social housing

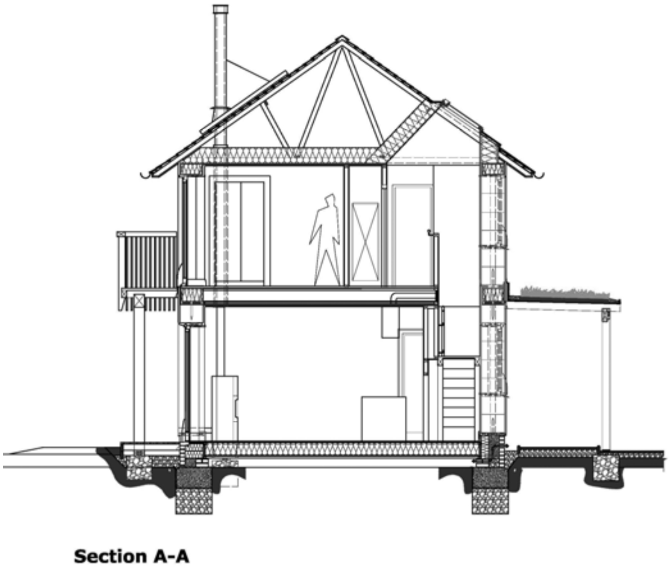
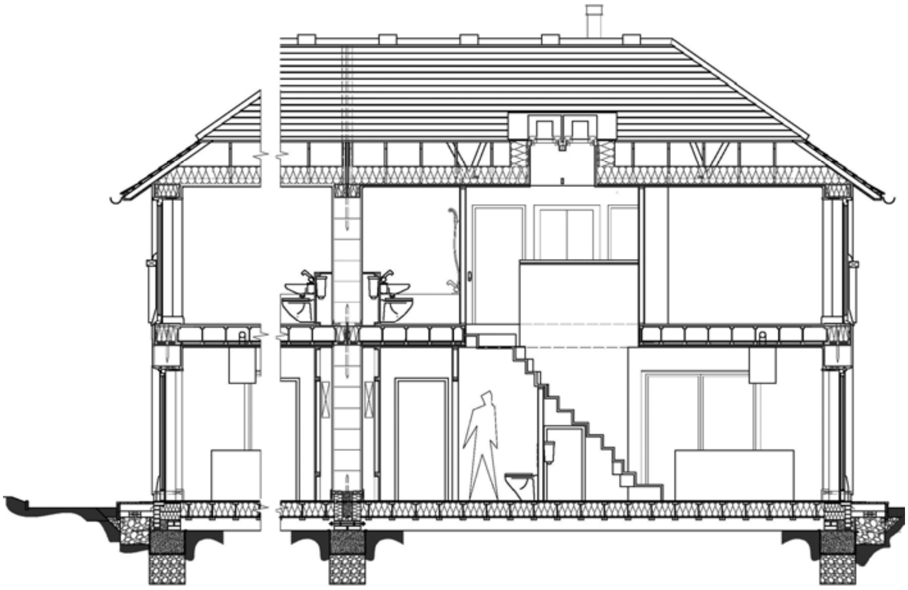


Figure 3 Cross section



Section B-B

Figure 4 Cross section

Figure 5 South elevations of the pair of Waddington houses

Figure 6 Foundation of Waddington houses

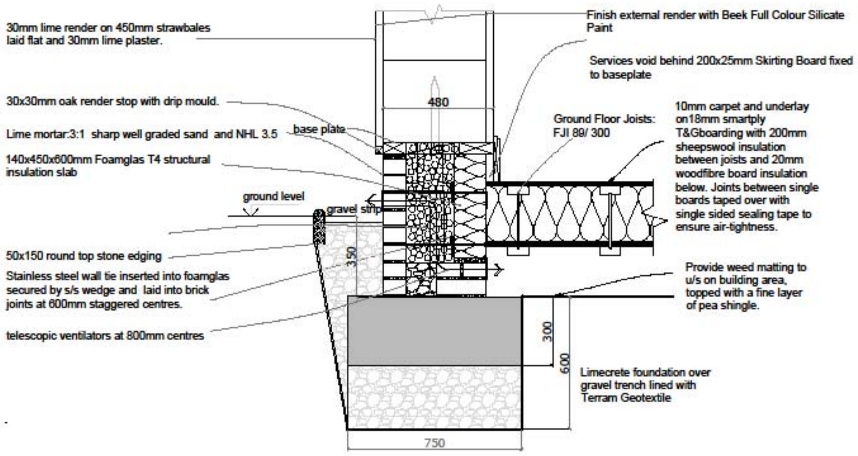


Figure 7 Section through the wall foundation

Figure 8 Details - load bearing strawbale walls of Waddington houses

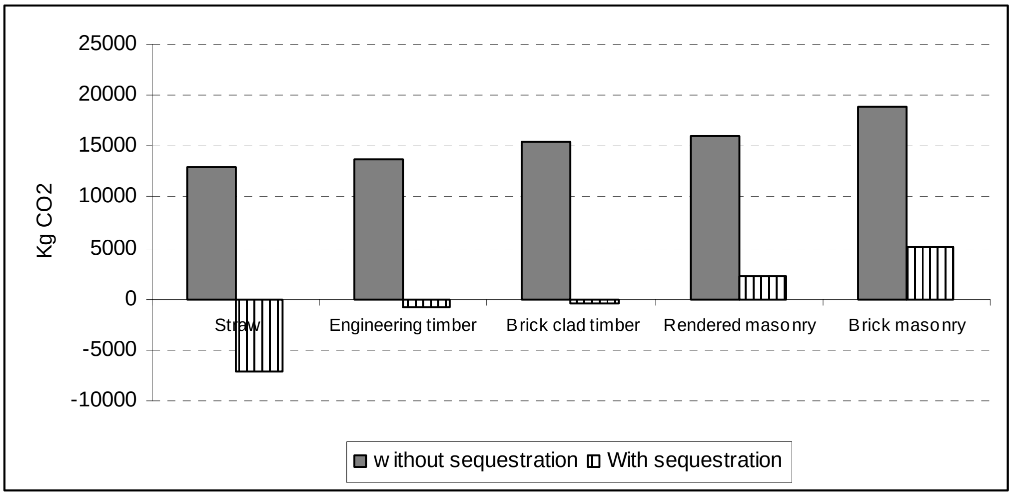


Figure 9 Total house materials CO_2 emissions of one of the houses with different external walling systems