Industrial Project: Ecofab Straw House Simulation

A simulation of the Ecofab Straw House, making use of the IES VE software package to compare a range of characteristics of natural wool and straw bale insulation against conventional materials.

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Executive Summary

This document reports on the current status of an ongoing project with Ecofab, a sustainable architecture and construction firm based in Bodmin, Cornwall. IES VE modelling software is used to compare the Ecofab panel, a Structural Insulated Panel using natural sheep's wool or straw bale insulation material, with conventional construction designs. These conventional designs are based on the Code for Sustainable Homes (CSH) legislation (levels 3, 4 and 5). The results demonstrate categorically that the Ecofab panel design is superior to each level of the CSH in terms of efficiency, whilst achieving near zero-carbon embodied energy. Several key aspects of the project as originally laid out are ongoing, including environmental cost assessments of development and brochure design.

Contents

Table of Figures

1 Aims

The original aims of the project are stated below, where the final outcome would be a technical sales document for Ecofab. This is still the key objective of the project, which is ongoing at the time of this document's completion.

- Create a high quality document to be used to re-enforce Ecofab's greater performance credentials over competing and industry standard technologies.
- Compare different structural choices including insulation, glazing and flooring specifications to highlight resultant savings, both in monetary and environmental terms.
- To be used in discussions with prospective clients; it must therefore be relatively easy to read and understand once given some basic explanation by the architect but maintain a strong technical element.

2 Research

2.1 Materials

The Code for Sustainable Homes (CSH) legislation lays out the different requirements of Part L of the building regulations in terms of sustainability, using a levels system between 3 and 6 representing stages of sustainability (Building Regulations, 2013). CSH level 3 (CSH 3) represents the minimum allowable levels of insulation, whilst CSH 6 represents the highest, carbon-neutral standards (Government, 2010). During discussions with Ecofab employees, it was decided that the Ecofab panels should be compared with levels 3, 4 and 5. Research into the U-value and typical construction composition of each of these levels was carried out.

Whilst Ecofab work to the level of CSH 6, from a simulation stand point alone, CSH 5 and CSH 6 will make use of the same quality insulation, i.e. they require the same aspect (wall, roof, floor, window) U-values. Moreover, the main difference between levels 5 and 6 is in the embodied energy of the construction, lifestyle of its occupiers (cycling or working from home) and the integration of renewables (Government, 2010).

A building is typically judged in terms of an overall U-value; found through the averaging of each of its aspects. A U-value is a measure of heat loss expressed in W/m^2K, showing the amount of heat lost in watts (W) per square metre of material when the temperature (K) outside is at least one degree lower (Kingspan, 2015). Each aspect is made up of a collection of materials, for instance a CSH 3 exterior wall may contain a brick outer leaf, cavity, insulation and plasterboard. Each of these materials have their own thermal properties that added together produce the aspect U-value. To model a material's thermal properties, several characteristics must be known:

- Thermal conductivity (λ)
- Thickness (mm)
- Density (kg/m^3)
- Specific Heat Capacity (J/K)

IES has a system database of some of the most common building materials, such as plywood, brick and concrete slabs. It was found that this was sufficient for all three CSH compositions however there although the Ecofab wool and Straw bale data had to be added. As Ecofab has not undergone its own investigation into the thermal properties of their panels, there was no data available for the unit as a whole.

Wool and straw bale were found to have a λ-value of 0.035 W/mK (Black Mountain, 2014) and 0.055 W/mK (Energy Saving Trust, 2010) respectively. This compares favourably with brickwork and insulating blockwork such as Thermalite, 0.150 W/mK (Hanson, 2015) , and is on par with fibreglass and mineral wool such as Rockwool, 0.035 W/mK (Rockwool, 2015). The insulation chosen for each of the CSH compositions was dense foam insulation similar to Celotex (Celotex, 2015), with λ-values of 0.040 W/mK (CSH 3) and 0.025 W/mK (CSH 4 & 5).

On research it was decided that a 'generic' composition design was all that was necessary for the CSH compositions as there are hundreds of potential design paths; for instance, the CSH 3 composition could take account of:

- The specification of the blockwork
- Cavity thickness
- Insulation type
- Internal board type and thickness

As long as the minimum U-values of each aspect was met, the thermal simulation should run effectively. In the case of the Ecofab panels, data became available late into the project from another research project by Rosie Gillam, running in parallel to this work. This gave an informed U-value for each aspect of the Ecofab design, see Table 2.

At this stage there was an attempt to collect data on both the environmental impact and lifecycle costs of each material used. Unfortunately these are not commonly released data, although the Building Research Establishment (BRE) offers data on GWP and lifetime $kgCO_2e$ for specific construction types, e.g. Brickwork outer leaf, insulation, cellular dense blockwork inner leaf, cement mortar, plasterboard on battens, paint (BRE, 2015). Straw bale and natural wool insulation which have zero emissions (NaturalPRO, 2014) (US Dept. Energy, 1995).

Research suggests that that natural fibres such as straw bale are susceptible to high moisture content and dampness that can lead to decay and loss of structural integrity if the material is not properly protected. A recent study undertaken at the University of Bath looked at the change in moisture content over time of its new straw-cob construction media centre (M. Lawerence, 2009). Their research found straw moisture content varied between 40% and 90% (relative humidity, RH) over the first three months of the study but levelled out to a steady 80% RH after that point, despite worsening winter weather. Whilst it is assumed that the greater protection afforded the Ecofab panels from climate exposure would reduce the RH within the building, it is further assumed that the insulation would not remain dry, as it was originally installed.

2.2 Software

The initial brief, released in September by Ecofab, suggested the use of IES. However it became clear that the software had calculation methodology issues where natural wool or straw bales were incorporated. This was due in part to the software and partially due to the unusual hygroscopic tendencies of these natural materials. IES does not integrate hygroscopic properties (a measure of how well a material can attract and absorb water molecules) of the material into its calculations (IES, 2015). Assuming these properties do in fact change over time, in a similar way to that seen in the Bath Media building case, the U-values of the Straw House will also change, skewing the results of any simulation. With this in mind, research was carried out into other software available that could carry out a similar simulation of the Straw House. The software had to be able to:

- Accept 3D models from Google Sketch-up or AutoCAD or;
- Create its own 3D model with a high level of accuracy
- Have relatively high levels of modelling capacity (high quality meshing)
- Produce clear images for use in the brochure
- Incorporate hygroscopic properties

Other software studied includes:

Ecotect – Identified early on with free student use and support from the entire Autodesk product range. This package integrates well with Revit and has complex modelling capabilities, similar to IES. However, on review, no evidence was found to suggest it would be better at modelling the same complex hygroscopic properties.

WUFI – delivers a “realistic calculation of the transient hygrothermal behaviour of multi-layer building components exposed to natural climate conditions”. The package offers 1D and 2D material analysis but lacks the full house modelling capabilities of IES (Fraunhofer IBP, 2015).

ESP-r – A 3D modeller that carries out moisture analysis however the open source Linux format is unfamiliar, help files “heavy on jargon” and lacks the large integrated database available to IES users (ESRI, 2015).

Overall, IES VE was selected as the best choice in modelling software, based on the low £50 cost and evidence in support of its strong modelling features and usability.

3 Modelling

At the start of the modelling phase, a one hour training session with Dan Lash, a research fellow at the University of Exeter, gave a walkthrough of the basic tools within IES. The program can be broken down into several core systems:

- ModelIT – 3D Modelling
- Apache – Thermal Modelling
- SunCast – Solar Irradiance Modelling
- Macroflow – Ventilation Modelling
- Vista – Results Viewer

3.1 Model Development Process

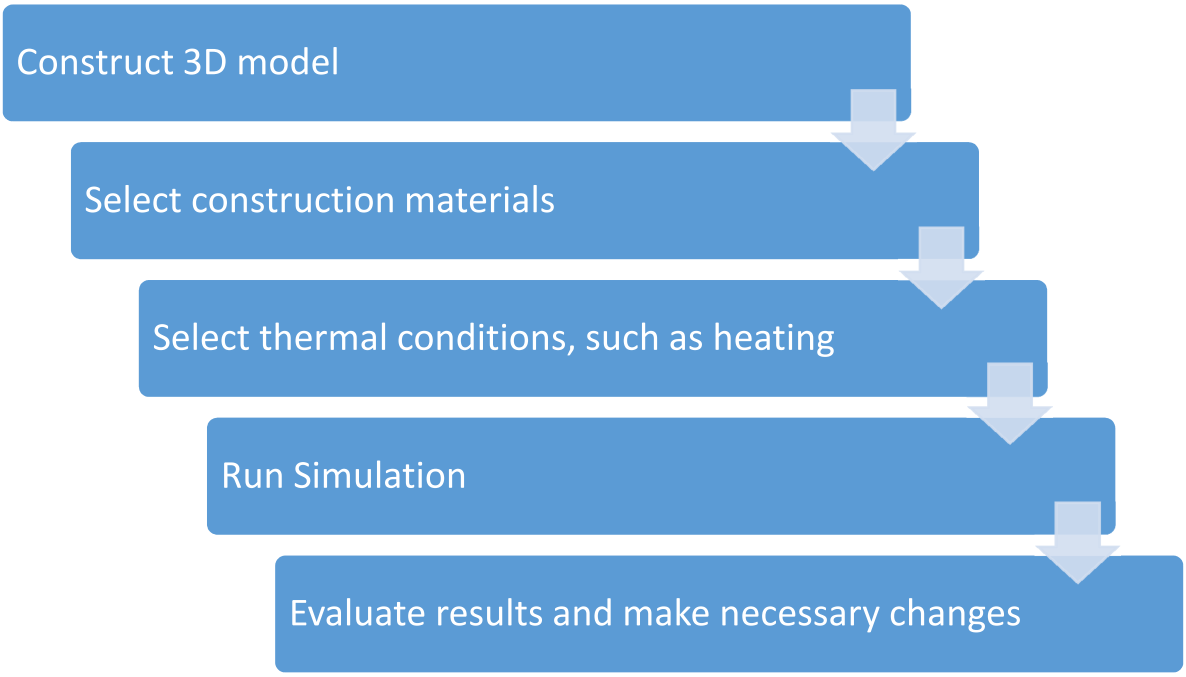

Figure 1: Process for simulation evolution selected

Once the simulations were complete, the next stage would be to carry out cost and environmental assessments using the respective IES packages.

3.2 Model Production

Ecofab supplied 2D Autocad elevations of the Straw House along with a collection of images. The ModellT package was a quick and simple tool to carry this out. The only problem here was the roof which is complex, compared with the other cuboid rooms. In this case the roof was produced as a third storey loft space, something not covered in the original Ecofab drawings.

3.3 Constructions

The next stage is to develop the aspect constructions, these include:

- Roof
- External Wall
- Internal Wall
- Ground/Exposed Floor
- Internal Floor/Ceiling
- Windows
- Doors

Both the doors and internal walls used predefined constructions. Internal floor/ceilings were copied from the ground/exposed floors as this was an accurate representation of the Ecofab designs. This maybe something to revisit for CSH models which may use a thinner, less insulating design for internal floor/ceilings.

Materials were assigned to each aspect for the three CSH layouts, based on a best estimate designs. Separate straw bale and natural wool insulated panels were produced for each aspect. It was also decided here to include three distinct Ecofab construction types; all wool, all straw and a combination whereby wool would be used for all aspects apart from the external walls, which would be straw bale. It was believed this was more representative of a standard Ecofab design and was specified in their CAD elevations.

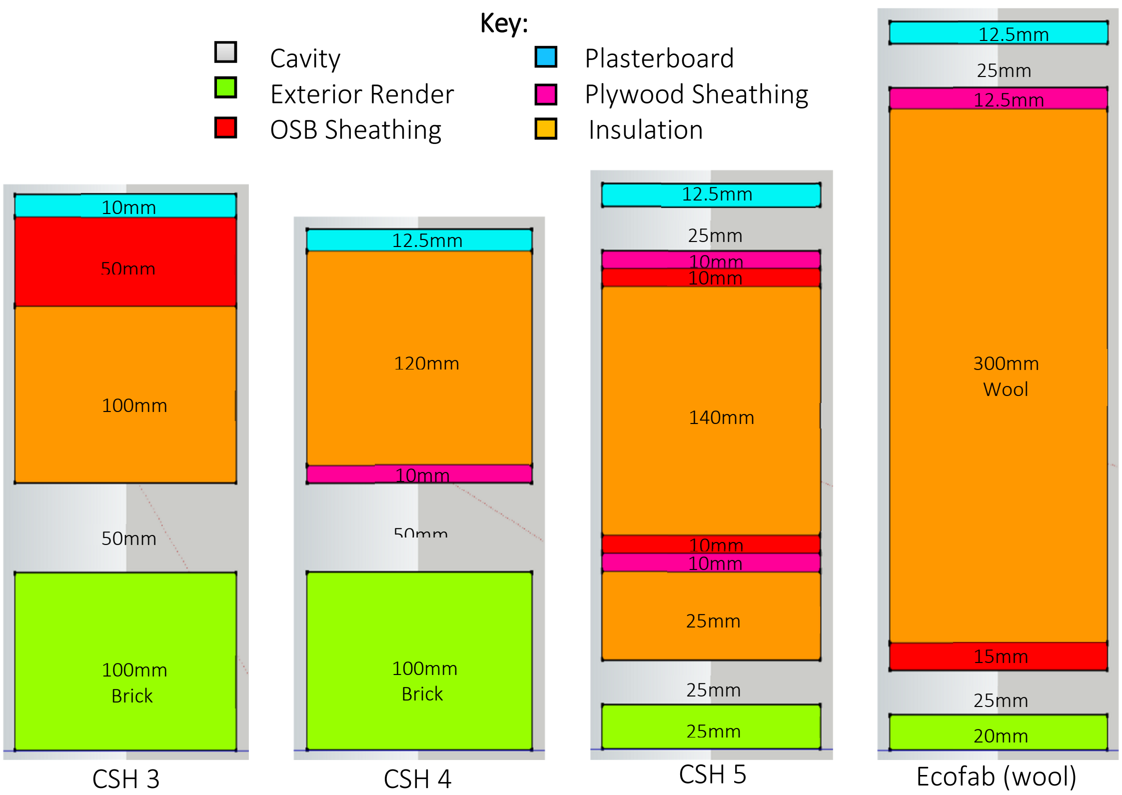

Figure 2: Diagram of exterior wall compositions

The varying U-values across the CSH levels is not representative of the aspect thickness of each level. In fact in the case of external walls, CSH 3 - 5 have thicknesses around 300mm, in comparison to Ecofab panels with thicknesses of 410mm and 610mm for natural wool and straw bale constructions respectively. The composition of CSH 3, 4, 5 and Ecofab (all wool) external walls can be seen in

Figure 2. The thickness of the insulation block used, rather than total wall thickness, was the biggest factor in overall U-value of each composition, shown in Table 1 below.

Test	Insulation Thickness (mm)	Aspect U-value (W/m^2K)
CSH 3	100	0.30
CSH 4	120	0.20
CSH 5	165	0.15
Ecofab – All Wool	300	0.10

Table 1: Insulation thickness vs U-values achieved

3.4 Thermal Properties

Room heating was set to come on below 19°C internal temperature in living areas, and 17°C for bathrooms and hallways, in line with building regulation comfort temperatures (Building Regulations, 2013). IES makes use of profiles to simulate heating schedules, room occupancy and use of equipment, lighting and ventilation. The system database settings were often adequate with minor adjustments. The heating system used was a natural gas boiler with underfloor heating.

3.5 Analysis

Tests were altered slightly to account for the different requirements of each level of the CSH legislation. In particular, the hot water demand (representing various equipment efficiencies and occupant knowledge) as well as infiltration, were changed in line with the building regulations (Building Regulations, 2013).

Finally IES offers three post-simulation packages; Costplan, Lifecycle and Enviroimpact. It had been hoped that a thorough cost and environmental assessment could be carried out for this document however, it has become clear that the data that IES draws on for these calculations is purchase-only from BRE.

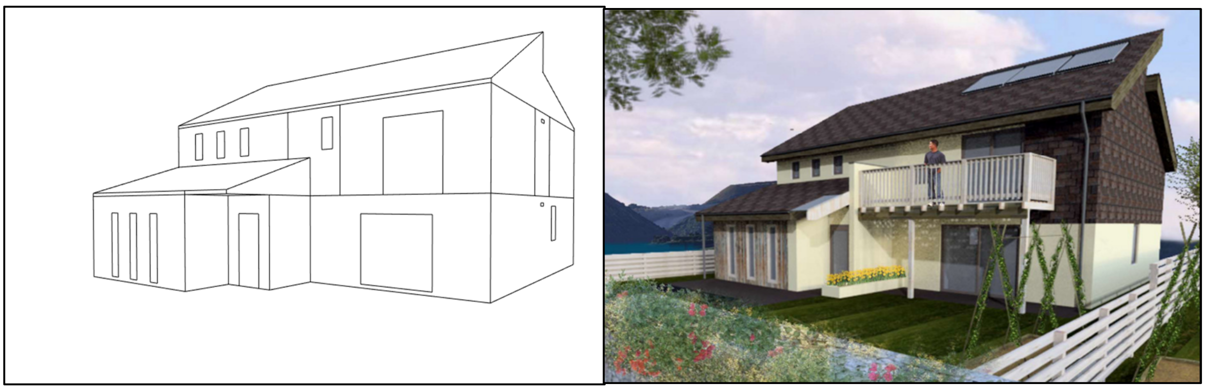

Figure 3: Ecofab Straw House as drawn in IES (left) and as designed by Ecofab

4 Results

In all there were six composition tests finalised, three Ecofab designs and three CSH designs. Of these, the most efficient was the 'all straw bale' Ecofab variant followed in order by the 'combination' and 'all natural wool' Ecofab designs, then each of the CSH variants 5 ,4 and 3, as expected (Table 2). This is mirrored in energy demand and carbon emissions in Table 3.

Aspect	CSH 3	CSH 4	CSH 5	Ecofab (Wool)	Ecofab (Straw)	Ecofab (Combination)
Roof (W/m^2K)	0.20	0.13	0.13	0.12	0.10	0.12
Exterior Wall (W/m^2K)	0.30	0.20	0.15	0.10	0.10	0.10
Ground Floor (W/m^2K)	0.25	0.20	0.15	0.14	0.13	0.14
Windows (W/m^2K)	2.00	1.20	0.80	0.70	0.70	0.70
Air Permeability $m^3/(hr.m^2)$ @50pa	5.50	3.00	1.50	1.00	1.00	1.00

Table 2: U-Values of each aspect in the six tests

Construction Composition	Annual Energy Consumption (MWh)	Annual Emissions ($kgCO_2e/yr$)
Ecofab – SIP (Full Straw Bale)	26.2	7,298
Ecofab – SIP Combination	26.4	7,340
Ecofab – SIP (Full Wool)	26.6	7,377
CSH 5 – Conventional SIP	42.2	10,763
CSH 4 – Brick and Block	79.0	19,023
CSH 3 – Brick and Block	131.6	30,399

Table 3: Annual energy consumption and Carbon emissions of each test

It is clear from Table 3 that the difference in energy consumption between the three Ecofab compositions is negligible, therefore for each comparison below the 'Combination' Ecofab variant will be used.

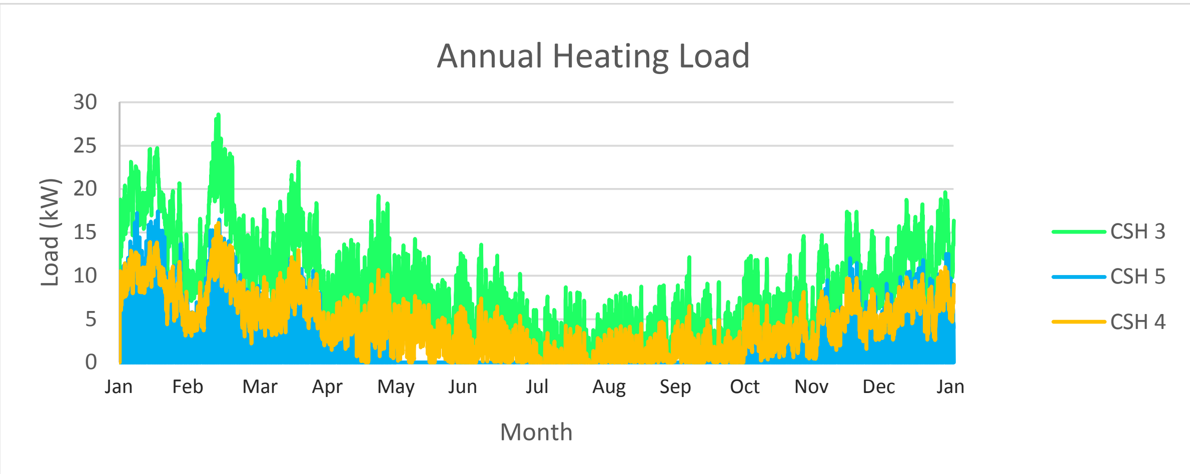

Figure 4: Annual heating load for each CSH composition

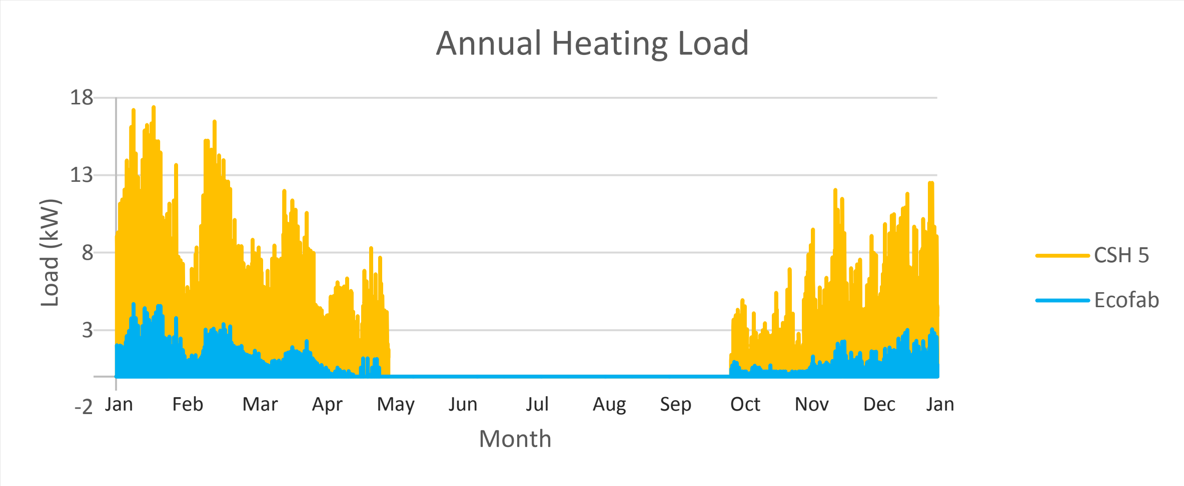

Figure 5: Annual heating load for CSH 5 and Ecofab compositions

It was found through analysis that both Ecofab and CSH 5 compositions could sustain comfortable internal temperatures without the need for heating over the months May to September. In fact, all rooms but the living room were non-heated in Ecofab tests between April and September. The difference here (Figure 5)Figure 5: Annual heating load for CSH 5 and Ecofab compositions in heating demand is surprising given both insulations meet the highest government specified standards.

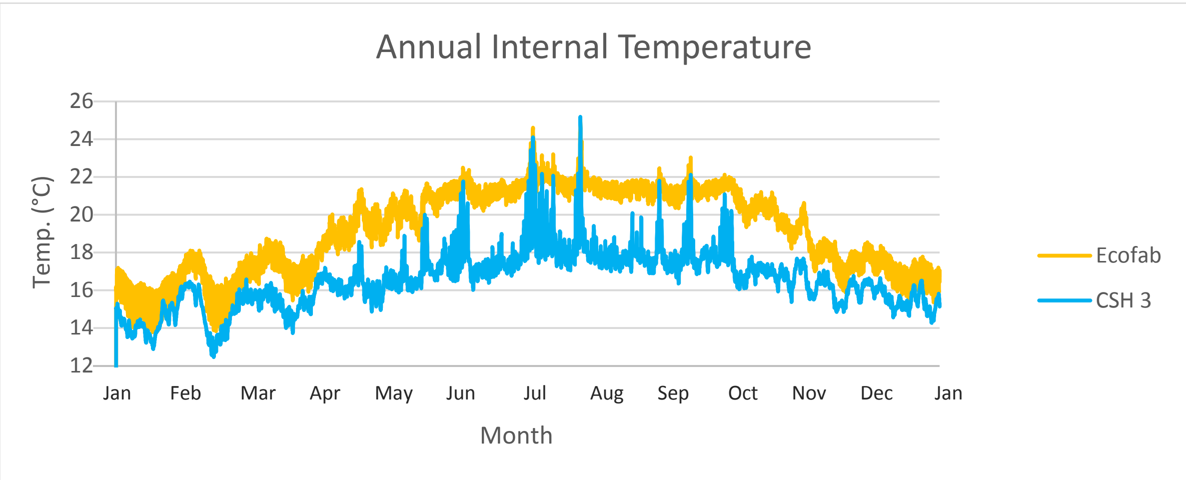

Figure 6: House-wide annual temperatures for Ecofab and CSH 3 compositions

Figure 6 illustrates erratic nature of temperature within the CSH 3 composition when compared to the Ecofab design. The reasons become clear when we study the infiltration, ventilation and external conduction losses across the two designs.

Reducing infiltration (Figure 7) is the greatest factor identified in reducing energy consumption in these tests. Whilst the CSH 3 composition is designed to allow greater infiltration (5.5x more air flow), the issue is amplified during winter when the ΔT between internal and external is much greater than in summer time. Furthermore, during the summer months it can be seen that infiltration can have a heating effect on the structure, where ΔT is reversed. This means the property is more susceptible to both natural heating and cooling.

Ventilation (Figure 8) is vital for cooling, CO_2 and humidity reduction. However it is clear the CSH 3 design has little need for this operation. On closer inspection the few peaks seen are during the few very hot days, prior to external temperatures rising above internal.

External conduction gains (Figure 9) typically represent losses through the fabric of the material, other than via infiltration. The Ecofab composition shows gains similar to infiltration at ~1kW throughout the year whilst the CSH 3 design again suffers in peak winter and summer. All these factors result in vastly increased heating loads across the year for CSH 3 against the Ecofab demand (Figure 10).

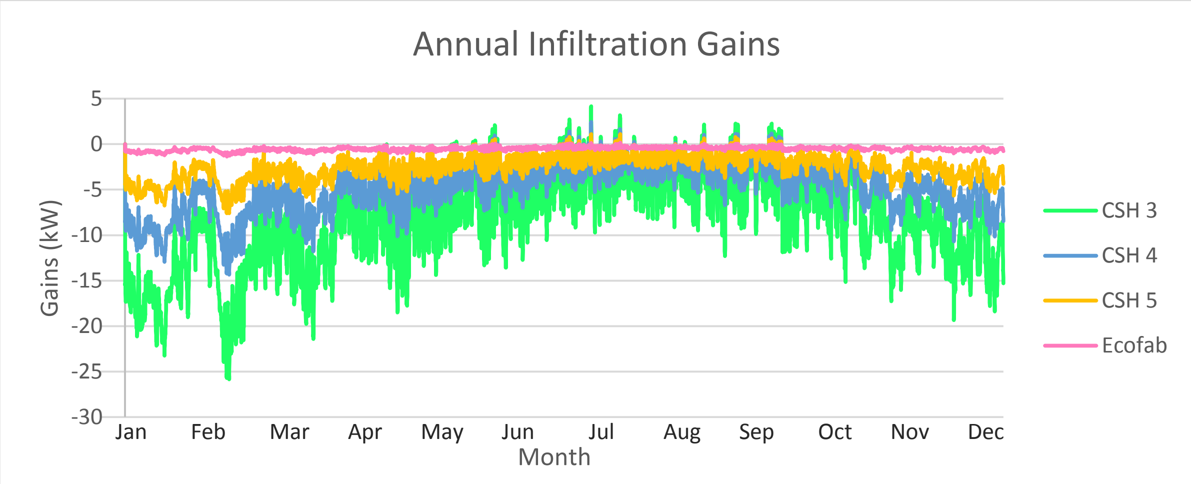

Figure 7: Annual Infiltration gains for each test composition

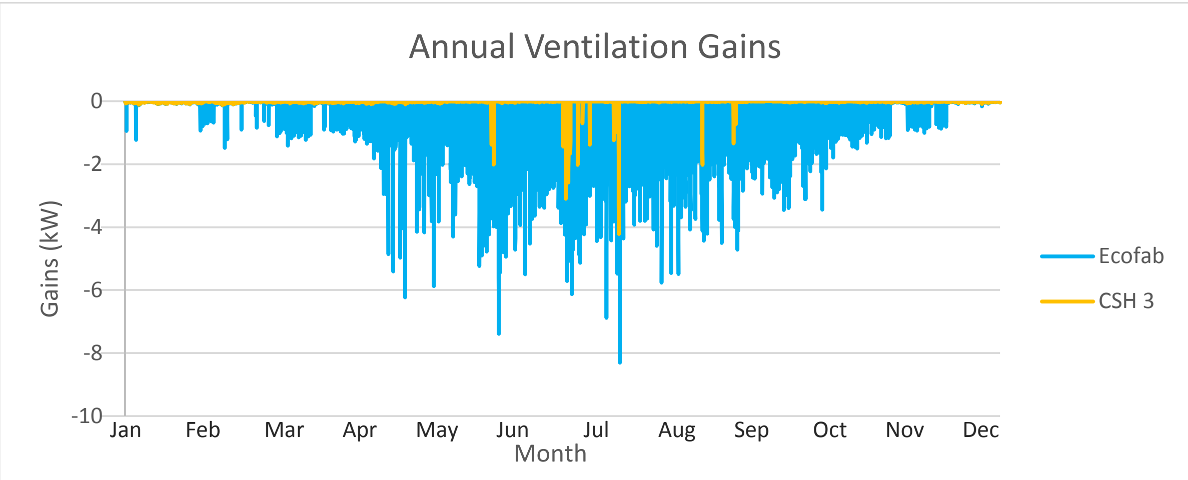

Figure 8: Annual ventilation gains for CSH 3 and Ecofab compositions

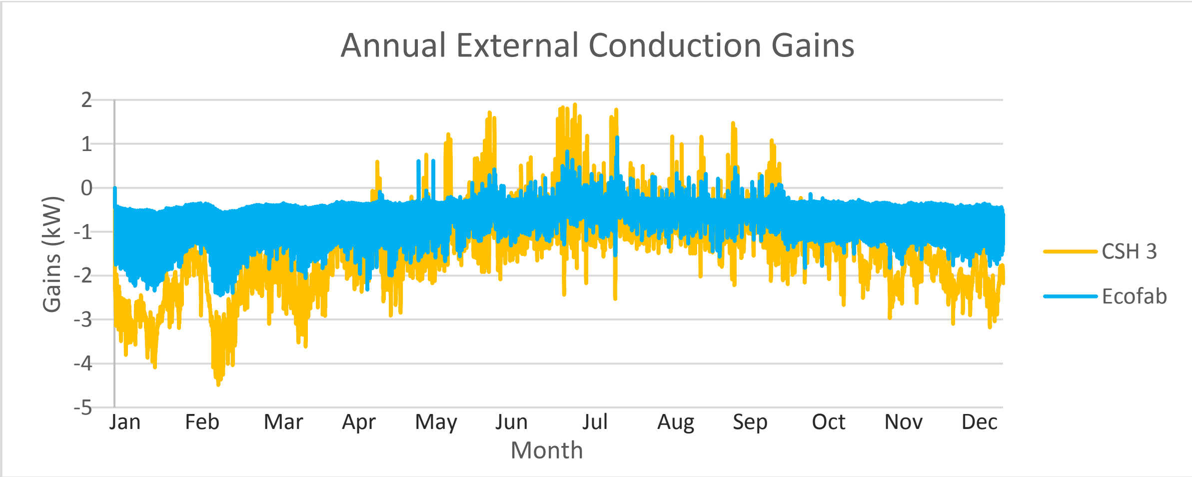

Figure 9: Annual external conduction gains for CSH 3 and Ecofab compositions

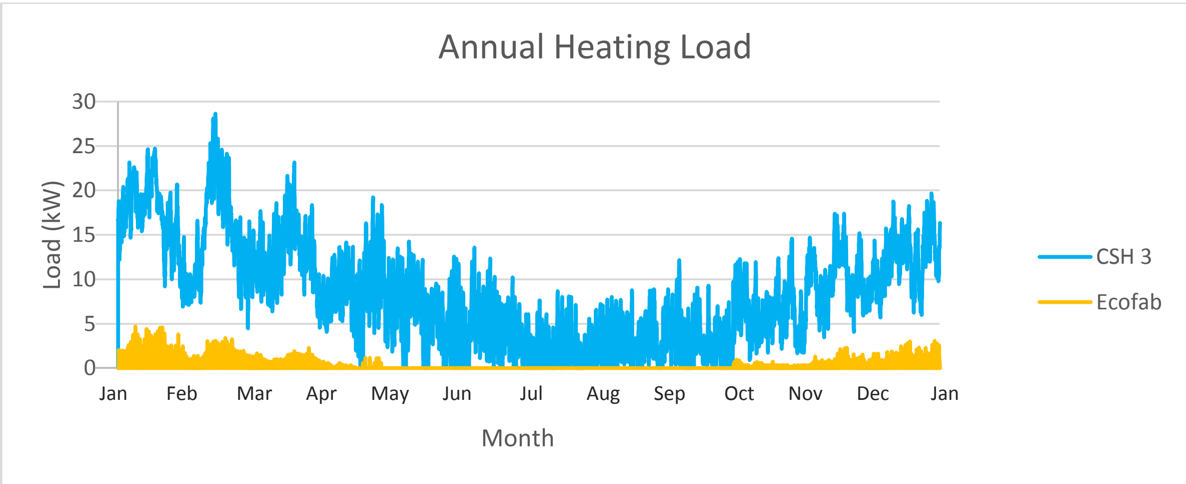

Figure 10: Annual heating loads for Ecofab and CSH 3 compositions

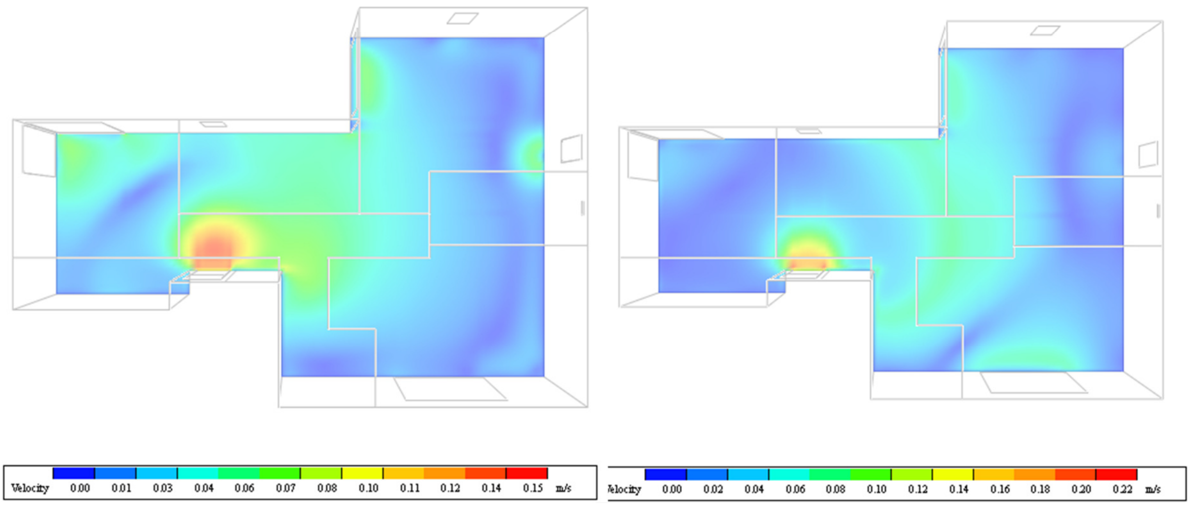

Figure 11: Comparison of CSH 3 (left) and Ecofab (right) air velocity, living room and ground level

5 Evaluation

Without exception, the data presented above is exactly what was expected when the project was originally set out. The model is evidently reasonably accurate, perhaps a better designed roof section applying eaves would have a small impact on shading and insulation. A better understanding of how each floor interacts with the others, specifically where internal floor depths are assigned, could help refine the simulation.

The evidence collected during the research phase of this project generally agrees with the results. The tests can be split, in terms of uncertainty, between the CSH and Ecofab compositions. There is little doubt in the construction of each aspect, excusing thin membranes, as each is well documented; whether in building standards or from Ecofab. Furthermore all three CSH constructions make use of manmade Celotex like insulation, which has well documented, well understood thermal and hygroscopic properties. IES VE, a leading modelling software, has a well-informed calculation methodology, supported by the Chartered Institute of Building Services Engineers (CIBSE) (IES, 2015).

A potential solution to the lack of hygrothermal integration maybe to use a software package, such as WUFI, that can manage these issues to produce a series of states that could be run in IES. Together a more accurate account of the overall thermal properties maybe produced.

5.1 Further Work

Further work on this project includes:

- Expand on simulation to include cost and environmental data.
- Expand range of competing conventional insulation methods
- Learn design software and produce technical sales document, as per the original brief

Further work in addition to this work:

- Work to assess a range of structures. The Straw House is a rarity in dwelling design, with five bedrooms and fully detached. The benefits of Ecofab insulation in more typical properties and work spaces should be identified.
- Consider using a different software package to undergo modelling, for instance Ecotect.

6 Conclusions

Whilst the original targets of this project are yet to be met, there is strong confidence in the data collated so far. Ecofab panel designs meet CSH maximum levels of efficiency and are close to zero-carbon, which will help developments meet prestigious CSH 6 standards, the level conventional construction will have to meet by 2019 under current guide lines. Ecofab compositions out-perform CSH requirements in every aspect of the structure which results in a saving of some 23 Tonnes of CO_2 savings annually, compared to CSH 3 standards. Access to BRE environment and costing data will enable thorough analysis of the lifetime benefits of Ecofab construction over conventional designs.

References

Black Mountain. (2014). *NatuWool.* Bradwell: Black Mountain.

BRE. (2015, 01 28). *Green Guide Ratings*. Retrieved from BRE Global: http://www.bre.co.uk/greenguide/ggelement.jsp?buildingType=Housing&category=1005&parent=6&elementType=10117

Building Regulations. (2013). *Conservation of fuel and power.* London: HM Government.

Celotex. (2015). *CW4000 Data sheet.* Coventry: Celotex.

Energy Saving Trust. (2010). *Insulation Materials Chart.* London: Energy saving trust.

ESRI. (2015, 01 28). *ESP-r Overview*. Retrieved from ESP-r: http://www.esru.strath.ac.uk/Programs/ESP-r_overview.htm

Fraunhofer IBP. (2015, 01 28). *WUFI Introduction*. Retrieved from WUFI Pro: http://www.wufi-pro.com/

Government. (2010). *Technical Guide.* London: Communities and Local Government.

Hanson. (2015). *Acheiving the Code.* Sevenoaks: Hanson.

IES. (2015). *Apache Sim Calculation Methods.* London: IES.

Kingspan. (2015, 01 28). *What is a U-value?* Retrieved from Kingspan Insulation: http://www.kingspandirect.com/category-s/164.htm

M. Lawerence, e. a. (2009). *Monitoring moisture content of straw bale walls.* Bath: University of Bath.

NaturalPRO. (2014). *Sheeps Wool Fact sheet.* Sheffield: NaturalPRO.

Rockwool. (2015). *Cavity Data sheet.* Bridgend: Rockwool.

US Dept. Energy. (1995). *Straw Bale Construction.* San Francisco: US Dept. Energy.